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Global emissions, Trade and Innovation: the Tragedy of the Locals*

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Abstract

This paper looks at the production of *locally* and *globally* polluting goods in a trade model with two countries, North and South, one with high environmental concerns and the other with cheap and unregulated fossil fuel resources. In this asymmetric setting, trade and path dependency in innovation cause the North to specialize in non-polluting production and the South in energy-intensive goods, produced with fossil fuels that cause global environmental spillovers. We show that the North can stop the use of fossil fuels with two opposite strategies: either combining innovation and trade policies to redirect the competitive advantage of the South towards clean production, or compensating the South for the forgone revenue derived from giving up fossil fuels, with a systematic transfer scheme. These two policies have opposite implications in terms of costs and environmental outcomes for the North, and the choice between the two depends on the time preferences, valuation of the environment and starting point of the policy.

Keywords: Resource endowments, technical change, international trade, comparative advantage

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1. Introduction

Sustainable development is one of the key challenges for the future of the world economy. Currently, however, most productive activities use as inputs energy from fossil fuels, which causes unsustainable damages to the global environment. How can the world phase out fossil fuels and avoid a global climate disaster? The easiest solution would be for the countries owning, producing and exporting minerals like coal to take action, but this is the least likely option. Many resource-rich countries built their competitive edge on fossil fuel extraction, and several are still at a point in their development process where consumption growth is more valuable than environmental protection – such is the case of China, India, Indonesia or South Africa. So what can the rest of the world do to restrict the emissions of CO_2 in the global atmosphere, if the fossil fuels responsible for climate change are controlled by uncooperative nations?

The problem of curbing global emissions is directly related to the local ownership of fossil fuels, but also more broadly to the location of dirty production: energy-intensive manufacturing entails environmental costs for the countries specialized in it, even if production inputs do not harm the global environment. Alternative resources to fossil fuels still cause localized environmental externalities: nuclear energy production imposes rare but sizable risks on the countries producing it, and the cost of managing radioactive waste; hydroelectric energy requires the flooding of entire valleys to build dams; biomass burning releases local air pollutants like SO_X and NO_X; wind turbines produce noise and landscape impacts. Even if none of these energy sources have significant global spillovers, their local impact is far from neutral.

The dilemma is then whether to leave dirty production in pollution havens in developing countries, which are less demanding with regards to environmental standards (Copeland and Taylor, 1994; Taylor, 2005), but at the risk of global spillovers if fossil fuels are burnt for production; or to relocate it to countries with more stringent environmental controls, which can curb global emissions, but which are also those with a stronger interest in a clean environment and thus no willingness to face local pollution.

This paper analyses the trade-offs in the policy options to avoid global environmental disasters, taking as starting point i) the misaligned incentives of resource-rich countries versus the rest of the world and ii) the local damages of pollution from energy-intensive manufacturing. We build a two-country (North and South), two-sector (clean and dirty) dynamic trade model with endogenous sectoral innovation, and a fossil fuel resource present only in the South. In this model, no international agreement or cooperation is possible as the South does not want to forego the revenues from fossil fuel use. Hence, our model examines different choices faced by the North if it decides to improve the global environment and cut out fossil fuels unilaterally. In this context, trade is fundamental to link economic activity between the two countries, but can also amplify environmental damages through countries' specialization. Similarly, endogenous innovation can be a double-hedged sword, because policy-makers can use it to redirect production, but otherwise, without policy intervention, it can lock economies in dirty paths of development.

This analysis contributes to the literature on environmental policies in conjunction with resources, trade and innovation. Other papers have investigated the role of natural resources in driving trade specialization; for example Peretto and Valente (2011) consider resource endowments, trade and innovation, focusing on the effects of resource-based specialization on income. Bretschger and Valente (2012) also use a trade and innovation framework to analyze the relative income shares of oil-rich versus oil-poor countries experiencing different productivity growth. Here however we focus on the environmental consequences of asymmetric resources in an open economy with path dependent innovation. In particular, we analyze the role of unilateral policies aimed at avoiding global climate change and their local environmental impact.

One standard finding of the trade literature on environmental policies is that the classic instruments used to correct for externalities, such as carbon taxes, can lead to carbon leakages and pollution haven effects when implemented only by few countries. This effect derives not only from a static distortion in prices (higher prices for taxed polluting goods encourages production in unregulated countries), but also dynamically from its influence on innovation and growth paths. As the directed technical change literature pointed out, when productivity exhibit path-dependence, specialization in one activity is self-reinforcing (Acemoglu, 2002). At the same time, policies that redirect innovation can be quite effective at switching to green growth paths (Acemoglu et al., 2012, 2014; Aghion et al., 2014; Gupta, 2015). This can change in an open economy context, even though a combination of innovation and trade policies can still shift production and environme (Di Maria and Smulders, 2005; Di Maria and Werf, 2008; Hémous, 2014). These papers, however, do not account for the role of asymmetric fossil fuel endowments or for local pollution from energy production.

Our paper takes into account local resource ownership and local environmental damages to compare two diametrically opposite policy proposals that have recently appeared in the literature: one that exploits trade specialization and innovation policies, as suggested by (Hémous, 2014), and the other based on a supply side policy to purchase the natural resource (Harstad, 2012). These two strategies achieve the same objective - a halt to the use of fossil fuels - but with different world configurations. In the first case, the comparative advantage of the two regions is exchanged, so that the South starts producing clean products that do not make use of fossil fuels, while the North specializes in dirty manufacturing now produced without global emissions. The advantage of this policy is that, thanks to the endogenous innovation process driving specialization, it can be temporary. The disadvantage is that dirty production relocates to the North, imposing a permanent local pollution damage to that region. Viceversa, the North could leave the specialization for dirty production in the South, while buying the right to exploit the fossil fuel resources and not burning it. This policy, however, cannot be discontinued because the productivity of fossil fuel intensive activities remains higher in this scenario, and the South would always choose to go back to fossil fuel use if the international payment was terminated.

This analysis highlights the driving forces behind policy choices to reduce emissions from resource-rich economies. The North would choose to implement instruments such as innovation and trade policies to reduce resource exploitation if it values relatively less local environmental damages and if it discounts the future significantly, so to ignore future accumulation of local damages. On the contrary, if the local damages to the environment were relatively large and the cost of purchasing the resource relatively low, a transfer of income to the South to keep fossil fuels under the ground would be the preferred policy.

The remainder of the paper is structured as follows: Chapter 2 presents the theoretical model; Chapter 3 characterizes the autarky equilibrium; Chapter 4 discusses the laissez-faire outcome under free trade and the policy options for the North; Chapter 5 discusses the implications and robustness of our results and Chapter 6 concludes.

2. Model

We consider a dynamic model with two regions of the world, North, N, and South, S, linked by international trade and transboundary pollution emissions. The North has higher per capita income levels thus stricter regulation on CO_2 emissions, while the South does not regulate fossil fuel usage. For simplicity, we characterize the difference between the two countries with the assumption that the South can use in production cheap and abundant fossil fuels, while the North cannot, as if it did not have any.[1] The model then focuses

[1] The North could have some fossil fuel resources in its territory, but it is not willing to exploit them for production, given its stronger concern for climate change. This could be because of higher income levels, following the empirical evidence of high correlation between a country's income per capita and

on the consequences that this asymmetry in productive inputs generates. Each economy $k \in \{N, S\}$ comprises two sectors of production, 'clean' and 'dirty', corresponding broadly to light manufacturing versus energy-intensive production. Countries trade internationally their final products so that each economy specializes based on relative factor abundance and technological productivity, according to a classic Heckscher-Ohlin/Ricardian mechanism. We now discuss in detail the building blocks of these economies.

2.1 Welfare

Aggregate welfare in an economy is defined as the discounted sum of the utility derived from consumption, C, and environmental quality, E. For the social planner, welfare is given by:

$$W = \sum_{t=0}^{\infty} \beta^t \; \frac{\left(C_t \, \mu \left(E_t\right)\right)^{1-\sigma}}{1-\sigma} \tag{1}$$

where $1 > \beta > 0$ indicates the social discount factor, $1/\sigma$ represents the elasticity of intertemporal substitution, μ the weighting function that determines the amenity value of the environment E, such that $\mu'(E) > 0$, $\mu''(E) < 0$ and $\mu(0) = 0$. Consumption C is a Cobb-Douglas aggregate of two types of goods, clean and dirty

$$C = (C_c)^{\upsilon} (C_d)^{1-\upsilon} \qquad \text{where} \quad C_d = C_{dL} + C_{dG} \tag{2}$$

dL and dG capture the pollution content of the dirty goods, the first referring to *local* damages, the second to *global* ones. Their damage to the environment is defined in the next section.

the stringency of environmental regulation, (Gupta, 2015). Alternatively, one could think of the North having signed some binding agreement that forbids the use of any R, while the South is not bound by the agreement, such as in the case of non-Annex I countries in climate change negotiations. Theoretically, we could have both countries exploiting the resource, with the South using it more intensively: to keep the illustration simple, we assume that the North uses only a negligible amount of it.

Note that if the value of environmental quality $\mu(E)$ reaches zero, welfare falls to zero independently of the level of consumption. This is what we define as a scenario of environmental disaster

Definition D.1 – *An environmental disaster is the instance when environmental quality falls below a critical threshold,* $E_t = 0$*, for some* $t < \infty$*.*

2.2 Environment

An essential feature of the model is that production of energy-intensive manufacturing goods generates two different types of pollution. Global, transboundary emissions derive from fossil fuel burning and affect both regions, independently of where the resource is being used. Nonetheless, even the production of manufacturing goods that does not make use of fossil fuels creates environmental damages, but this are localized and have no transnational spillovers. We define this as local pollution, since the damages fall exclusively within the boundaries of the nation producing it.

The environment is a sink cost for productions' pollution and waste, with a fixed regeneration capacity. In each period, environmental quality falls within the interval $E_t \in [0, \overline{E}]$: $\overline{E}$ denotes the initial, pristine level of environment before industrialization, and $E_t = 0$ is an irreversible level of environmental degradation, such that the environment looses any regeneration capacity. Environmental quality evolves according to the following law of motion:

$$E_t^k = (1 + \Delta)\, E_{t-1}^k - \zeta\, {Y^k}_{dL_{t-1}} - \xi\, Y_{dG_{t-1}} \tag{3}$$

Thus, environmental quality in country k depends on the previous environmental state given some regeneration capacity - Δ -, cross-border pollution arising from natural resource exploitation in the South- ξ - and local pollution, - caused by either countries-, through dirty production without the depletion of the resource - ζ - [2].

In order to capture the urgency of global climate change and how rapidly is bringing the word economy towards an environmental disaster, we assume that globally polluting goods are more harmful to the environment. Moreover, we assume that the locally polluting goods, while lowering environmental quality, would not produce and environmental disaster. This formalizes as follows.

Assumption A.1 - *Environmental damages derived from burning the fossil fuel resource are higher than the damages caused in terms of local pollution*

$$\xi > \zeta > 0$$

Assumption A.2 - *Environmental damages deriving from local pollution do not generate environmental catastrophes, that is the initial value of the environment is sufficiently high and the polluting factor ζ is low relative to the regeneration capacity of the environment, Δ (See Appendix D for the formal condition).*

This stylized formulation for environmental dynamics does not fully capture the complexities of carbon cycles, feedback effects and other important elements that climate scientists have identified. Acknowledging that, we aim at capturing in a simple framework the key difficulty in international environmental negotiations; namely, the transnational and intergenerational externality created by burning fossil fuels. Even if physically located in the South, the natural resource R, pollutes equally both hemispheres. At the same time, production and consumption decisions taken at one point in time have repercussions on future generations that permanently cumulate in the environment, once they surpass its regeneration capacity.

[2] We omit the superscript in the last term as the production of Y_{dG} can only take place in the South.

2.3 Production

These economies use four factors of production: labour, scientists, capital and a natural resource, such as coal or other fossil fuels. Each country has a fixed endowment of these inputs available in each period, respectively L_k, s_k, K_k, and R. Labour is used to produce clean goods and to operate capital in the dirty sector, while scientists generate innovation. Capital and natural resources are both polluting inputs, yet, only the resource is harmful for the global environment.

This fossil fuel resource has two important characteristics: it is only used in the South, as mentioned before, and it is abundant, in the sense that the South is not constrained by scarcity considerations in the use of this input. Previous models of directed technical change have included a fossil fuel resource, however, the focus is on its exhaustion which can act as a positive catalyst for a switch to clean production: as the resource is depleted, scarcity increases its price and reduces its use, encouraging R&D in clean technologies (Acemoglu et al., 2012). We depart from this approach and consider the case where fossil fuels are in excess supply relative to the time scale of critical climate degradation. In our model, the R is constantly available in every period, and the problem is rather the opposite, namely how to leave some of these fossil fuels like coal under the ground. Even if fossil fuels are potentially exhaustible, the time horizon for their complete depletion is way longer than that of an environmental disaster caused by their use[3]. This reflects what the scientific literature on climate change has highlighted in many occasions, if we burn all coal and oil currently available we will move well beyond any safe target for global warming (McGlade and Ekins, 2015). The core contribution of our paper is exactly focusing on this point: fossil fuels are exhaustible, but not scarce enough to avoid climate catastrophes.

[3]Oil is the only fossil fuel resource expected to become significantly more expensive to extract in the near future. On the contrary, coal reserves are forecasted to last for several hundred years from now, so globally polluting fossil fuels as a whole can hardly be considered exhaustible before climate change damages reach dangerous tipping points (Van der Ploeg and Withagen, 2012).

Therefore we need to acknowledge how they are used in dirty production as if they were virtually inexhaustible, and to conceive policies to ensure that they do not get used, given their local ownership.

Both regions produce a basket of final goods which aggregates non-polluting goods, Y_c and polluting goods, Y_d, that require energy and environmental resources in their production. Given the availability of the natural resource, dirty production in the South can take two forms: Y_{dL} if produced without the exploitation of R, while Y_{dG} is produced by burning fossil fuels. The North, on the other hand, due to its lack of R can only produce Y_{dL}. All final goods are produced under perfect competition and are traded internationally.

Good *c* - The production of the clean goods does not involve any polluting activity and requires labour plus c - specific intermediate goods. Following Acemoglu et al. (2014) and Hémous (2014), the good is produced according to

$$Y_c = (L_c)^{1-\gamma} \int_0^1 A_{ci} x_{ci}^{\gamma} di \tag{4}$$

where L_c is the amount of labour employed in the assembly of the clean goods, x_{ci} is the quantity of machines used as intermediate inputs specific to good c, and A_{ci} is the technological productivity level associated to machine i in the clean sector. The parameter γ is the share of machines used in the production of final goods. The intermediate sector of x_i and A is the core of innovation activities, as explained in the next section.

Good *dL* - Based on empirical evidence showing a positive correlation between pollution and capital intensity (Cole and Elliott, 2005), we add capital as a polluting input in dirty production:

$$Y_{dL} = \left(L_{dL}^{\psi} K_{dL}^{1-\psi} \right)^{1-\gamma} \int_0^1 A_{di} x_{dLi}^{\gamma} di \tag{5}$$

where ψ is the share of labour used to produce Y_{dL}.[4]

Good *dG* - In addition to labour, capital and machines, the globally polluting good also uses R:

$$Y_{dG} = \left(L_{dG}^{\beta} K_{dG}^{1-\alpha-\beta} R^{\alpha}\right)^{1-\gamma} \int_0^1 A_{di} x_{dGi}^{\gamma} di \tag{6}$$

where α represents the share of fossil fuel resource used in production.[5]

Note that machines, x_i, are specific to locally and globally polluting dirty goods but their productivity level, A_{di}, is common to all dirty goods so that the overall technological level of the dirty sector is the same. This is because the processes that lead to local and global pollution have to do mostly with the use of R rather than with the production technique: producers of manufactured goods do not consider if their electricity is coming from burning coal or renewable resources. Thus, technological innovation in the manufacturing sector is common to all products and the choice is just relative to what inputs to use.

Intermediate inputs - In line with standard models of endogenous technical change, machines are produced under monopolistic competition. This allows producers of intermediate inputs to have temporary profits that justify their investments in R&D. Following the structure of (Acemoglu et al., 2012), firms in the intermediate sector face a fixed cost of production given by $\varsigma = \gamma^2$. Each monopolist sells a variety i of the machine within its country and no international trade or transfers of technology is allowed[6]. There is an infinite number of varieties with $i \in [0, 1]$.

[4]For now we simplify the model assuming the same ψ across different countries. An extension of this work could study the implication of asymmetric factor shares between the North and the South.

[5]We don't make any assumption on the substitutability among inputs and the relation between ψ, α and β, but later on we will consider separately the case in which R is a direct substitute for K ($\psi = \beta$), R is a direct substitute for L ($1 - \psi = 1 - \alpha - \beta$), or R is a substitute for both L and K ($\psi \neq \beta$ and $1 - \psi \neq 1 - \alpha - \beta$).

[6]We leave the possibility of tradeable machines with embodied technology for future work. (Bond and Yomogida, 2014) examine the effects that innovation in the home country's energy sector has on environmental quality when trade in machinery is allowed. However, in their model, innovation cannot occur in the foreign country due to its lower level of economic development.

2.4 Consumption

Consumers in the two countries demand a basket of clean and dirty goods, both essential.[7]

$$C = (C_c)^{\upsilon} (C_d)^{1-\upsilon}$$

where

$$C_d = C_{dL} + C_{dG}$$

where υ is the share of clean goods, c, in the consumption basket. Consumers cannot distinguish between the production techniques of dirty goods and thus, between Y_{dL} and Y_{dG}. Therefore, from their point of view, these goods are perfect substitutes and consumers will simply demand the cheaper available in the market[8].

2.5 Innovation

Innovation occurs in each sector due to a cumulative learning by doing process, with knowledge growing in the clean and dirty sector independently and pushing the frontier of the A - technological productivity - used for production (Arrow, 1962; Romer, 1986). In the clean sector the set-up is similar to Acemoglu et al. (2012):

$$A^k_{cit} = \left[1 + \varphi \left(\vartheta^k_c s^k_{cit}\right)\right] A^k_{cit-1} \tag{7}$$

where φ is the size and significance of the discovery, s_{cit} the number of scientists that chose to work on machine i in the clean sector at time t, and ϑ the probability of a successful

[7] In order to simplify notation, we omit the time subscript whenever equations are not dynamic and the country specific k whenever the analysis is symmetric for both countries.

[8] As the model focuses on the effects of trade on production patterns and innovation, we do not want consumer preferences driving the results of our model and assume consumers are indifferent between the two types of dirty goods. The model could be extended to a case when consumers have a preference for climate-change mitigation, and the two dirty goods are not perfect substitutes.

innovation.

For the dirty sector, the evolution of dirty technology in the North follows symmetrically the clean one. The situation is more complex in the South due to the existence of the two substitutable dirty goods - dL and dG :

$$A^S_{dit} = \left[1 + \varphi\left(\vartheta^k_{dG} s^S_{dGit} + \vartheta^k_{dL} s^S_{dLit}\right)\right] A^S_{dit-1} \tag{8}$$

No matter if scientists decide to innovate in the sector line dL or dG, they will still contribute to increase the overall productivity of the dirty sector. To put it in a different way, there are full spillovers in the dirty sector between goods dL and dG.

The crucial choice for innovative activities is the allocation of a mass of scientists, s - normalized to one-, to the various sectors $z \in \{c, dL, dG\}$:

$$\int_0^1 s^k_{cit} + s^k_{dLit} + s^k_{dGit}\ di = s = 1 \tag{9}$$

In every period a scientist decides in which sector to operate, depending on the profitability of an industry, and then he is randomly allocated to a machine. Its chances of a successful innovation are $\vartheta_z \in (0, 1)$, with $z \in \{c, dL, dG\}$, leading to an improvement of $(1 + \varphi)$ in the quality of the machine. At last, the productivity of all i machines in a sector can be aggregated to an average productivity of:

$$A_{jt} = \int_0^1 A_{jit}\ di \tag{10}$$

with $j \in \{c, d\}$.

3. Autarky

We start our analysis from the case of two closed economies. First of all, we examine the market equilibrium without any policy intervention. In this autarky scenario, each country has to be self-sufficient and produce exactly the quantity of goods that it consumes. The goods produced depend completely on the endowments and technology of the region, since no exchanges or technology spillovers are allowed.

The autarky equilibrium without any policy intervention is characterized as follows: the goods and inputs markets clear thanks to the utility maximization of consumers and profit maximization of final and intermediate goods producers. In each period, depending on factors allocations, final goods prices and the relative levels of technology, scientists chose the sector towards which to direct their research, influencing the future evolution of the corresponding sector's technology. The environment evolves accordingly, depending on how much and what type of dirty goods are produced in equilibrium.

Definition D.2 – *In autarky, an equilibrium is defined as a sequence of domestic demands for inputs* (L_z, K_d, R_{dG}) *and prices for inputs (wages -w-, interest rates -r-, and price for the natural resource -q-), demands for machines* (x_{jit}) *and prices for machines, scientists' allocations* (s_z)*, and quality of environment* (E_t) *such that, for every period t: (i) the price of machines and their quantity,* x_{jit}*, maximizes profits by the producers of machine i in sector j; (ii)* L_{zt}, K_{zt} *and* R_{zt} *maximize profits by producers of input j; (iii)* Y_{zt} *maximizes the profits of final good producers, subject to the demand of consumers in country k; (iv)* s_{zt} *maximizes the expected profit of a scientist at date t; (v) factor prices clear the input markets, and final goods prices clear the market for* Y_c *and* Y_d*; and (vi) the evolution of the environment* E_t *is given by (3) .*

We analyze the equilibrium in the two regions separately. For a full derivation of the equilibrium conditions, see the Appendix A.

North - Given the absence of natural resources, there is no choice in the North over which goods to produce and consume within the dirty sector: the only possibility is to produce and consume dL.

The equilibrium demands for each factor of production and the consequent factors prices are:[9]

$$L_c^{N*} = \frac{\bar{L}^N}{\left(1 + \frac{(1-\upsilon)}{\upsilon}\psi\right)} \tag{11}$$

$$L_{dL}^{N*} = \frac{1-\upsilon}{\upsilon}\frac{\bar{L}^N}{\left(1 + \frac{(1-\upsilon)}{\upsilon}\psi\right)}\psi \tag{12}$$

$$K_{dL}^{N*} = \bar{K}^{N\,10} \tag{13}$$

$$r^{N*} = \left(A_c^N\right)^{\frac{1}{1-\gamma}} \frac{\bar{L}^N}{\bar{K}^N} (1-\gamma)(1-\psi) \frac{(1-\upsilon)}{\upsilon + (1-\upsilon)\psi}. \tag{14}$$

where variables with an upper bar indicate initial fixed endowments and r and w the rewards to capital and labour. At each time t, scientists in the North have the option of allocating themselves to sector of production c or dL, based on the relative ratio of profits between the two sectors:

$$\frac{\pi_{ci,t}^N}{\pi_{dLi,t}^N} = \frac{\vartheta_c^N}{\vartheta_{dL}^N} \frac{L_c^{N*}}{\left(L_{dL}^{N*}\right)^{\psi}} \frac{1}{\left(K_{dL}^{N*}\right)^{1-\psi}} \left(\frac{p_c^N}{p_{dL}^N}\right)^{\frac{1}{1-\gamma}} \left(\frac{A_{ci,t-1}^N}{A_{di,t-1}^N}\right)^{\frac{1}{1-\gamma}} \tag{15}$$

Everything else equal, scientists prefer (i) the largest sector, as captured by the ratio of labour and capital inputs, (ii) the most valuable sector, where the price ratio is higher, and (iii) the more advanced sector - where the productivity levels are higher, as indicated by the ratio of A_j. Such a structure mimics perfectly the three innovation driving forces

[9] All of the following analyses are conducted under the normalization $p_c = 1$. It follows that $w = A_c^{\frac{1}{1-\gamma}}(1-\gamma)$.

[10] Since the only good produced in the North making use of capital is dL, all the endowment available in each period will be allocated to the production of Y_{dL}^N.

found in (Acemoglu et al., 2012): size effect, price effect and technological effect.

South - For what concerns the South, two possible situations can arise:

1) $p_{dL} \leq p_{dG}$

2) $p_{dL} > p_{dG}$

Case 1) represents a situation where the availability of the natural resource does not really bring a comparative advantage to the southern region, making it preferable to produce as if no resource was available. In such a scenario, the productivity path of the South will mimic exactly the one of the North and no compelling implications will arise even when opening to trade: the globally polluting resource will not be exploit and both regions will consume the cheapest possible good without damaging the global environment.

Case 2) is the most interesting one as the presence of fossil fuel reserves actually gives to the South a comparative advantage. The basic condition for this case to arise in the model is:

$$\left[\frac{\psi^{\psi}}{\beta^{\beta}} \frac{\left(\bar{K}^{S}\right)^{\alpha+\beta-\psi}}{\left(\bar{R}\right)^{\alpha}} \left(\frac{1-\upsilon}{\upsilon}\bar{L}^{S}\right)^{\psi-\beta} \frac{\left(1+\frac{1-\upsilon}{\upsilon}\beta\right)^{\beta-1}}{\left(1+\frac{1-\upsilon}{\upsilon}\psi\right)^{\psi-1}}\right]^{1-\gamma} = \frac{p_{dG}}{p_{dL}} < 1 \tag{16}$$

where $\bar{R}$ is the endowment of the natural resource available in every period.

Assumption A.3 – *We assume that the regularity condition (16) holds so that, $p_{dG} < p_{dL}$ and the fossil fuel resource in the South is sufficiently cheap to be always preferred for the production of dirty goods.*

Whenever A.3 does not hold, we are back in the situation of two countries not endowed with any significant fossil fuels resources, a case already well analyzed by (Hémous, 2014).

With no policy interventions, southern consumers will prefer to buy the cheaper dirty good, dG, with the consequent massive exploitation of the natural resource. Given the absence of trade, the North cannot benefit from the lower prices for the dirty goods produced from natural resources but yet, is affected by the externality from its production. In this case, the North will receive the full spillover from the globally polluting good produced in the South, which combined with the local pollution from its own production of dL, will push the North to an environmental disaster sooner than the South.

In the South, factors demands and prices in equilibrium are:

$$L_c^{S*} = \frac{\bar{L}^S}{\left(1 + \frac{(1-\upsilon)}{\upsilon}\beta\right)} \tag{17}$$

$$L_{dG}^{S*} = \frac{1-\upsilon}{\upsilon} \frac{\bar{L}^S}{\left(1 + \frac{(1-\upsilon)}{\upsilon}\beta\right)} \beta \tag{18}$$

$$K_{dG}^{S*} = \bar{K}^S \tag{19}$$

$$R_{dG}^{*} = \bar{R} \tag{20}$$

$$r^{S*} = \left(A_c^S\right)^{\frac{1}{1-\gamma}} \frac{\bar{L}^S}{\bar{K}^S} (1-\gamma)(1-\alpha-\beta) \frac{(1-\upsilon)}{\upsilon + (1-\upsilon)\beta} \tag{21}$$

$$q^{*} = \left(A_c^S\right)^{\frac{1}{1-\gamma}} \frac{\bar{L}^S}{\bar{R}} (1-\gamma)\,\alpha \frac{(1-\upsilon)}{\upsilon + (1-\upsilon)\beta}{}^{11} \tag{22}$$

where q indicates the exploitation price of the natural resource R (see Appendix A).

Given that $p_{dG} < p_{dL}$, southern scientists have the option to allocate themselves to

[11] Since the resource R is only present in South we will always omit the superscript S from q.

the clean sector or to the dirty sector which depletes R, depending on which one is more profitable. Each period they face a relative profits ratio of:

$$\frac{\pi^S_{ci,t}}{\pi^S_{dGi,t}} = \frac{\vartheta^S_c}{\vartheta^S_{dG}} \frac{L^{S*}_c}{(L^{S*}_{dG})^\beta} \frac{1}{(K^{S*}_{dG})^{1-\alpha-\beta}(R^*)^\alpha} \left(\frac{p^S_c}{p^S_{dG}}\right)^{\frac{1}{1-\gamma}} \left(\frac{A^S_{ci,t-1}}{A^S_{di,t-1}}\right)^{\frac{1}{1-\gamma}} \tag{23}$$

This condition captures again the aforementioned effects - size, price and technology, but here we can add a fourth one: a natural abundance effect, which pushes scientists towards the dirty polluting sector for a larger endowment of R.

Proposition 1 – *Fossil fuel resources drive innovation through their effect on the relative profits of the dirty sector. Cheap natural resources re-allocate scientists towards the dirty sector, creating a* resource-abundance *effect on innovation.*

Proof. By inspection of equation (23), given assumption A.3.

In this context, it is clear why an environmental disaster occurs: the South keeps producing the globally polluting dirty goods with increasingly efficient technology and with the depletion of the environment characterized by equation (3). Eventually, the world reaches the point of no return with $E = 0$. This autarkic setting, however, does not capture any economic interaction between the two countries since production choices are disjoint.

In the next section, we open the model to international trade and allow countries to exchange goods and specialize in the production. With this extended structure, we can analyze a variety of policy tools related to productive choices.

4. Open Trade

We now analyze the role of local resource endowments when the two countries can trade their final goods. In Section 4.1 we present the laissez-faire scenario in which no policy interventions are implemented [12]. In this situation, the economy can reach a natural disaster even sooner than in autarky due to the heavy exploitation of the natural resource. Sections 4.2, 4.3 and 4.4 examine possible policies implemented by the North to avoid the disaster. We show that in a setting with locally owned fossil fuel resources and a non-cooperative South, the North can stop the use of fossil fuels with two opposite strategies: either applying innovation subsidies and trade policies to switch the comparative advantages of the South towards clean production or, buying from the South the right to exploit the globally polluting good.

4.1 Laissez Faire

Without any policy intervention, the two regions are free to exchange goods and to consume not only their local productions, but also goods made in the other country. Input factors and technology, on the other hand, are immobile. Three goods are effectively available on the global market: c, dL and dG. Due to perfect competition, no price discrimination is possible and the law of one price holds for all three consumption goods (we abstract from trade costs). Since consumers cannot differentiate between the production techniques of dirty goods, and thus between dL and dG, they will consume the cheapest ones available on the market.

In order to define the effect of trade on the environment of the two regions, we require some further assumption about their specialization. Since the South is endowed with

[12] See Appendix B1 for derivations

abundant natural resources, it is likely that its competitive advantage relative to the North will be in dirty production.

Assumption A.4 – *North has an absolute technological advantage in both clean and dirty production, namely* $A_c^N > A_c^S$ *and* $A_d^N > A_d^S$*; South has a relative advantage, compared to North, in dirty production, that is to say* $A_d^S/A_c^S > A_d^N/A_c^N$.

We refrain from making any specific assumption about the role of fossil fuel resources, - the presence of R makes the comparative advantage of the South in dirty more pronounced and could even give the South an absolute advantage in dirty-, and only impose some conditions on the initial values of technological productivity. This assumption implies that both countries have a path of specialization once they open up to trade, leading to the following proposition under free trade:

Proposition 2 – *Given that the following conditions apply: i) South is endowed with a larger labour force than North:* $\overline{L}^S > \overline{L}^N$*; ii) South has access to a larger capital stock:*[13] $\overline{K}^S > \overline{K}^N$ *iii) the factor endowments for both countries are non-negative and sufficiently large to allow a local production of the goods iv) Assumption A.4 is met; then, if Assumption A.3,* $p_{dL} > p_{pG}$*, is satisfied, when opening to trade, the globally polluting goods* Y_{dG} *will still be cheaper than the locally polluting ones,* Y_{dL}*, and it will be fully produced by the South.*

Proof. See Appendix B.2.

Therefore, in the absence of policy interventions, all consumers prefer to buy goods Y_{dG} rather than Y_{dL} and world production of the latter stops. The open economy equilibrium requires:

[13] $\overline{K}$ refers to the amount of polluting capital goods in each country: South can afford more of them - due to scarce environmental regulation- while North has fewer units

$$\frac{1}{p_{dG}} = \frac{\upsilon}{(1-\upsilon)} \frac{Y_{dG}}{Y_c^N + Y_c^S} \tag{24}$$

and, consequently, the equilibrium factors demands and prices are:

$$L_{dL}^{S*} = L_{dL}^{N*} = 0 \tag{25}$$

$$L_c^{N*} = \bar{L}^N \tag{26}$$

$$L_c^{S*} = \bar{L}^S - \frac{\beta(1-\upsilon)}{\upsilon + \beta(1-\upsilon)} \frac{\left(A_c^{N\frac{1}{1-\gamma}} \bar{L}^N + A_c^{S\frac{1}{1-\gamma}} \bar{L}^S\right)}{A_c^{S\frac{1}{1-\gamma}}} \tag{27}$$

$$L_{dG}^{*} = \frac{\beta(1-\upsilon)}{\upsilon + \beta(1-\upsilon)} \frac{\left(A_c^{N\frac{1}{1-\gamma}} \bar{L}^N + A_c^{S\frac{1}{1-\gamma}} \bar{L}^S\right)}{A_c^{S\frac{1}{1-\gamma}}} \tag{28}$$

$$K_{dG}^{*} = \bar{K}^S \tag{29}$$

$$K_{dL}^{S*} = K_{dL}^{N*} = 0 \tag{30}$$

$$R_{dG}^{*} = \bar{R} \tag{31}$$

$$r^{S*} = \frac{(1-\upsilon)(1-\gamma)(1-\alpha-\beta)}{\upsilon + \beta(1-\upsilon)} \frac{\left(A_c^{N\frac{1}{1-\gamma}} \bar{L}^N + A_c^{S\frac{1}{1-\gamma}} \bar{L}^S\right)}{\bar{K}^S} \tag{32}$$

$$q^{*} = \frac{\alpha(1-\gamma)(1-\upsilon)}{\upsilon + \beta(1-\upsilon)} \frac{\left(A_c^{N\frac{1}{1-\gamma}} \bar{L}^N + A_c^{S\frac{1}{1-\gamma}} \bar{L}^S\right)}{\bar{R}} \tag{33}$$

In such a scenario, scientists in the North do not have a choice on which sector to enter, since the only remaining active sector is the clean one. As a result, the northern clean technology grows unambiguously under free trade with no active policies. In the South, on the other hand, both sectors c and dG are active and the choice of southern inventors is based on the profit ratio between the two sectors, as per equation (23).

We simulate the evolution of the environment in free trade under no policy implementations for the North and the South.[14] We use a simple calibration with a 200 period horizon and parameters similar to that of Hémous (2014) (see Appendix E for details). Figure 1 shows with some stylized parameters how opening to free trade brings both countries to an environmental disaster much more rapidly when compared to autarky. This occurs since all production of the dirty good is stirred by trade openness towards the cheapest, globally polluting one. Production specializes immediately: the South produces in the first years of free trade a little bit of clean goods as well (Y_c), but after few years it fully specializes in Y_{dG}, as its productivity builds up with the evolution of A_d. In a world of free trade, policy interventions to avoid environmental disasters are then more urgent than with closed economies. International trade expands markets and induces the countries to specialize in their most competitive sectors, thus the ownership of natural endowments like fossil fuels becomes extremely significant. The larger exploitation of polluting resources under free trade makes this regime more prone to global disasters.

[14] Since we are analysing the case $p_{dG} < p_{dG}$, in equilibrium there is no production of Y_{dL}, therefore the path of the environment in both regions is symmetric.

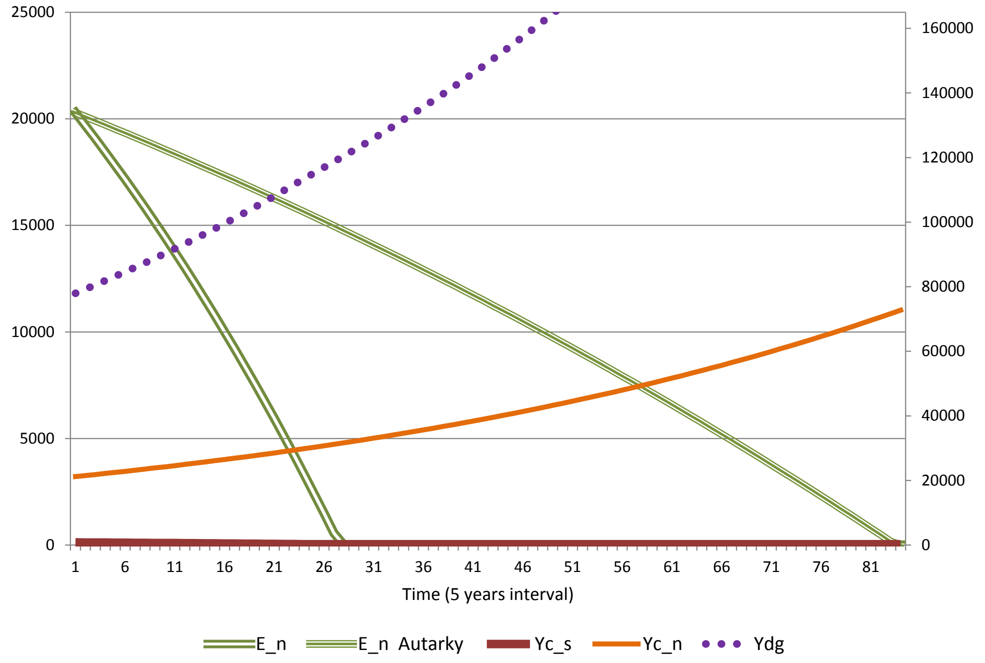

Figure 1: Evolution of the environment and production

In the next sections, we will analyze the possible policy options available to avoid the rapid approach of a global disaster described in this open economy, laissez-faire scenario. The focus is set on the role of fossil fuel resources owned by the South and how to stop their exploitation.

4.2 Policy instruments

The policy tools that the Northern government can use to avoid an environmental disaster are the following: i) research subsidies or taxes to correct for the path dependency in innovation, which is not accounted for by myopic investors with short term patents; ii) import tariffs or export subsidies on the polluting goods, to correct for the other country's pollution externality; iii) international transfers to purchase the supply of fossil fuels, so that they do not get used. Carbon taxes, the classic instrument to correct environmental externalities in a closed economy, are not effective in this open economy context if implemented unilaterally, due to carbon leakage. The South would in fact get even more competitive at producing the globally polluting dirty good, Y_{dG}, both for its own market and for the rest of the world. The North can take two opposite approaches to avoid the use of fossil fuels: either combine trade and innovation policies to redirect the comparative advantage of the South towards clean production, or compensate the South for the forgone revenues derived from giving up fossil fuels, with a systematic transfer scheme. The next two sections deal in turn with each of these strategies.

4.3 Innovation and Trade policies

The first policy strategy corresponds to what is suggested by the green directed technical change literature, namely innovation policies, combined with trade restrictions. First of all, we examine a baseline policy scenario parallel to Hémous (2014), with no local natural resource or local pollution damages, and reach a conclusion similar to his model. This policy entails a research subsidy for the Northern dirty sector and a trade tax on Y_d imports coming from the South, which discourages the consumption of foreign dirty goods in the North. The innovation subsidy, coupled with trade protectionism, causes a switch in the comparative advantage of the two countries, so that the North becomes more competitive in the dirty sector, while the South acquires a comparative advantage in the clean one. Once the switch of comparative advantage has been achieved, innovation and trade policy can be discontinued.

The key element is that the North leaves its comparative advantage in clean industries to the South and starts producing exclusively dirty goods. Once the policy is removed, production experiences a short discontinuity as dirty production is no longer subsidized and trade-protected, but in the long run the two countries specialize in the opposite industry than what they had under free trade (North in dirty, South in clean). Note that, differently from classical green directed technical change papers in a closed economy Acemoglu et al. (2012), innovation subsidies alone are not sufficient to achieve this result in an open economy. Even if the North relocated all its scientists to dirty innovation, it could reach the same growth rate of productivity A_d as the South, but not its absolute value. Trade needs to be partly reduced so that the Southern market for dirty goods shrinks. while the Northern one develops, justifying the need for a trade tax (Hémous, 2014).

The same result can be achieved in the presence of fossil fuel resources located only in the non-cooperative region. However, switching comparative advantage and trade specialization between the two countries becomes more challenging, since the resource endowments provides the South a further source of comparative advantage in dirty industries (recall from A.4 that technologically, the South is relatively more advanced in dirty production). The South, in this case, has a local input that makes dirty production even more competitive: with the same quantities of labour and capital employed, and with the same productivity levels, the South can produce more units of dirty goods due to the presence of R and thus, sell a cheaper product. Simplifying the problem to its core, Southern comparative advantage in the dirty sector is stronger than in other models that do not introduce a local natural resource.

Comparative advantage in the South for dirty production without any fossil fuels is given by

$$\frac{Y_d^S}{Y_c^S} \geq \frac{Y_d^N}{Y_c^N} \quad \Rightarrow \quad \left(\frac{A_d^S}{A_c^S}\right)^{\frac{1}{1/\gamma}} \left(\frac{K^S}{L^S}\right)^{1-\psi} \geq \left(\frac{A_d^N}{A_c^N}\right)^{\frac{1}{1/\gamma}} \left(\frac{K^N}{L^N}\right)^{1-\psi} \tag{34}$$

However, if the South owns a unique input to produce dirty goods, the comparative advantage condition becomes

$$\left(\frac{A_d^S}{A_c^S}\right)^{\frac{1}{1/\gamma}} \left(\frac{K^S}{L^S}\right)^{1-\beta} \left(\frac{R}{K^S}\right)^{\alpha} \geq \left(\frac{A_d^N}{A_c^N}\right)^{\frac{1}{1/\gamma}} \left(\frac{K^N}{L^N}\right)^{1-\psi} \tag{35}$$

The third term on the left, containing R, represents the boost to comparative advantage given by the fossil fuel resources. This will be larger the more useful R is in producing dirty goods (higher α) and and the larger the endowment of fossil fuels, R.

Thus we can state that

Remark 1 – *Trade and innovation policies to reverse comparative advantage than without resources; thus, ceteris paribus, they need to be introduced sooner in order to prevent an environmental disaster. See equation (35) relative to (34).*

The strength of this Remark depends on the amount of R present in the South, on its price relative to capital and labour and on its substitutability with other inputs of production. But since we assumed that this resource is cheap and abundant for the production of Y_{dG} as illustrated in eq. (6), fossil fuel endowments can be a sizable concern in terms of the timing of such policy.

There is one further implication about this policy strategy, beyond the risk that, if implemented too late, it will not be effective: even when it does avoid the environmental disaster, all production of dirty goods will shift to the North. This has environmental costs associated to the locally polluting production. Thus, depending on how much the North values its own environment and how different locally and globally polluting goods are in terms of pollution intensity, this policy can have significant drawbacks. We turn next to supply side policies and thereafter, compare the two strategies discussing their respective advantages and costs.

4.4 Supply side policies

The alternative solution to avoid the disaster is for the North to buy from the South the supply of fossil fuels paying a cost equal to the exploitation rent: $p_R = q^*$. This idea has been proposed by the literature in other contexts; for instance, to avoid carbon leakages, Harstad (2012) suggests to the most environmentally–concerned countries to get in a coalition to buy foreign deposits of coal and preserve them. In our model, the removal of the R endowment from the South, redirects the developing region towards the production of Y_{dL}, where it still has a comparative advantage due to higher endogenous productivity from its relatively advanced dirty technology: $A_d^S/A_c^S > A_d^N/A_c^N$. This policy, however, cannot be suspended after some time because, once the North stops buying R, the South would go back to the old habit of producing dG instead of dL. Given that the purchase of the resource does not remove the incentive in the South to produce the cheaper Y_{dG} for domestic consumption, the North may face extra costs associated with the monitoring and enforcement of such measure. A mechanism that would ensure the incentive compatibility of this policy would be to compensate the South for all the foregone income from abandoning the resource and having to substitute it with a more expensive factor, and not just to pay its market price. In our calibrations we adopt this latter approach, which provides an upper bound to the costs of this strategy.

Proposition 3 – *If the North purchases the fossil fuel resource R from the South optimally, so to eliminate incentives to use the resource, it can certainly avoid the environmental disaster. This policy, however, cannot have a finite duration, but needs to be in place forever.*

Proof. This follows from the assumption that the damage of local pollutants cannot by itself cause an environmental disaster (A.2). Thus, even if the environment already has reached low levels, stopping completely the burning of fossil fuels can avoid the disaster.

Of course this statement relies on the simplified environmental dynamics adopted in the model. What it highlights, in a more realistic context, is how this supply side policy has much more direct and immediate impacts that the switch in comparative advantage proposed in the previous section. Furthermore, from the point of view of the North, the advantage is also in terms of its local environmental quality since dirty production remains confined to the South and with it, all local damages.

5. Discussion - policy choice

The goal of the Northern government, in order to avoid the environmental disaster, is to encourage a global substitution away from the emission intensive Y_{dG} and into goods that do not harm the global climate, Y_{dL}. The two strategies previously described can achieve this goal, however, there are quite stark differences in the overall economic outcomes depending on which one is implemented. As described above, innovation and trade policies can revert comparative advantages, but create an environmental cost for the North as it starts producing dirty goods. Viceversa, with supply-side policies, dirty production remains confined to the Southern pollution haven, with no damages to the northern local environmental but with a permanent income loss for the North derived from the income transfer to the South. This section discusses the driving forces behind the choice between these two alternative policy options.

Fig.2 shows a comparison of the two strategies, displaying both the evolution of the environment and that of production. In both cases the policy is introduced at time t=5. Production of Y_{dG} comes to a halt as soon as any of the two policies start (thus, not displayed in the graph). In both cases, the environment of the North stably remains above the critical disaster levels. However, in the case of policy A the production of Y_{dL} takes place exclusively in the North, with a discontinuity when the switch of comparative advantage takes place and the policy is removed. Under policy B, even if initially both countries produce Y_{dL} as the use of fossil fuels is banned, over time only the South specializes in it while the North specilizes in clean products. Because of these different specialization patterns, we observe a slow deterioration in environmental quality under policy A, while policy B unambiguously sees the Northern environment improve.

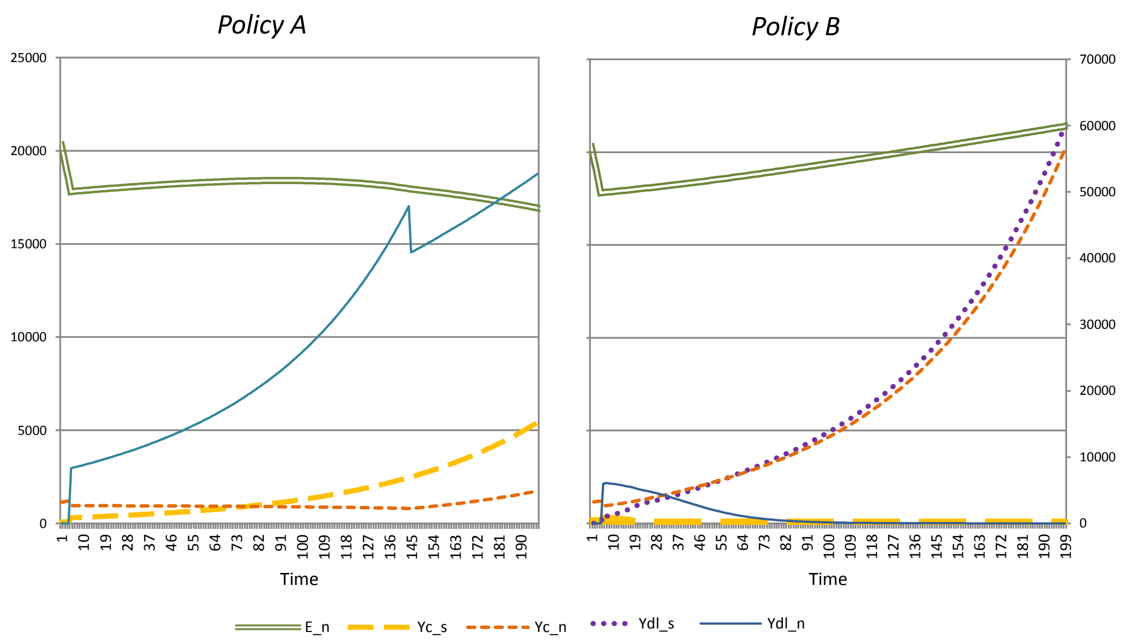

Figure 2: Production with innovation and trade policies (no natural resource)

The changes shown above translate in different welfare outcomes, depending on the value that environment and consumption have. The overall welfare if the trade and innovation policy is implemented (called in short policy A) is given by the welfare function in equilibrium:

$$W(A) = \sum_{t=0}^{\infty} \beta^t \ \frac{\left(C^* \mu\left(E\right)\right)^{1-\eta}}{1-\eta} \tag{36}$$

We derive welfare as a function of prices and income by plugging in 36 the Marshallian demand function for each good:

$$\begin{aligned} W(A) \ &= \sum_{t=0}^{T} \tfrac{\beta^t}{1-\eta} \ \left[\left(\tfrac{v\widehat{I}}{\widehat{p}_c}\right)^v \left(\tfrac{(1-v)\widehat{I}}{\widehat{p}_{dL}}\right)^{1-v} \mu\left((1+\Delta)E_{t-1} - \zeta\left(\left(\tfrac{(1-v)\widehat{I}}{\widehat{p}_{dL}}\right) + C_{dL}^S - Y_{dL}^S\right)\right)\right]^{1-\eta} + \\ &\sum_{t=T}^{\infty} \tfrac{\beta^t}{1-\eta} \left[\left(\tfrac{vI}{p_c}\right)^v \left(\tfrac{(1-v)I}{p_{dL}+p_{dG}}\right)^{1-v} \mu\left((1+\Delta)E_{t-1} - \zeta\left(\left(\tfrac{(1-v)I}{p_{dL}+p_{dG}}\right) + C_{dL}^S - Y_{dL}^S\right)\right)\right]^{1-\eta} \end{aligned} \tag{37}$$

where

$$\widehat{I} = I - s + \tau_1 p_{dG} C_{dG} - \tau_2 p_{dL} C_{dL}^*$$

is income under the policy, and $\widehat{p}$ the prices when the policy is active.

Welfare under this policy is made of two components: the first one, summing all periods up to year T, represents the years in which the policy is in place; the second one, sums the periods where the policy is discontinued as there is no further need for government intervention. During the policy implementation period, the government can design the research subsidies and import taxes in such a way that the net cost for the population is zero, so income remains constant and $\widehat{I} = I$. In the second period, there will be only the cheapest free trade price, either p_{dL} or p_{dG}. Note however, that the welfare is reduced in both period by the cumulative local pollution, $\zeta(Y_{dl})$. This in turn is made of the Northern consumption and the Southern consumption of Y_{dl} (production of Y_{dl} goes to zero due to full specialization deriving from the continuous growth in productivity, A_{dl}).

For the supply side policy (called here B), the northern welfare is permanently reduced as follows:

$$W(B) = \sum_{t=0}^{\infty} \frac{\beta^t}{1-\eta} \left[\left(\frac{v(I-r)}{p_c} \right)^v \left(\frac{(1-v)(I-r)}{p_{dL}} \right)^{1-v} \mu\left((1+\Delta)E_{t-1}\right) \right]^{1-\eta} \tag{38}$$

where r is the cost of purchasing effectively all supplies of fossil fuels.

The choice between these two scenarios then depends on a number of factors.

Value of the environment. First and foremost, the difference between the two policies is enhanced by the welfare valuation of the environment for the North. This is captured by the μ function in aggregate utility. If there was not environmental difference between the two policies, clearly the purchase of fossil fuel supplies would be more expensive, and no policy-maker would ever prefer that. However, since there are local environmental costs involved with strategy A - the trade and innovation policies aimed at swapping specialization and comparative advantage - the choice between the two policies hinges directly on the valuation of the environment. The higher the value of the environment, the lower the welfare gains from policy A, (see Fig. 5. below, top-left panel). At low levels of environmental amenity values, the two policies are more or less equivalent: over time, however, the cumulative improvement of environmental quality provides higher welfare benefits with policy B (buying the supply of fossil fuels but leaving dirty production in the South), because the Northern local environment is not compromised.

Preferences for clean goods. One could think that, similarly to the previous point, if consumers have a strong preference for clean goods and in their demand they require a higher share of them, this would be similar to a high valuation of the environment. However in this context it does not make a difference for the choice between the two policy strategies. It does not matter in open trade where clean goods are produced, if they are imported from the South after Policy A, or if they would still be produced in the North as for Policy B. Assuming there are no significant trade costs, both policies would be affected equivalently by a sudden increase or decrease in the desired share of clean goods, so their reltive welfare outcome would remain the same (see Fig. 5., top-right panel).

Starting time of the policy. As discussed earlier, policy A is not always effective: if the two countries have reached a level of environmental quality too low, and their comparative advantages have diverged too much, it will take too long for innovation and trade policies to enforce the swap in specialization, and the disaster will not be avoidable. Therefore, if the decision to intervene is taken relatively late in the North, policy B might be the only feasible one. The bottom-left panel of Fig. 5. illustrates this. Of course, if the North waits too long, even policy B will be ineffective, simply because the world will have reached an environmental disaster:the later that policy is implemented, the more of a degraded environment it will sustain.

Discount rate and time preferences. A key difference between the two policies, as highlighted by the previous point, is how the North perceives time. The discount rate is then a fundamental factor in determining which policy is optimal. The more impatient the North is (higher discount rate), the more it will prefer policy A, the inversion of specialization patterns, because it would weight less the future cumulative damages on the environment, while it would notice more the fall in income due to the transfer to the South in policy B. As the bottom-right panel of Fig 5. illustrates, different discount

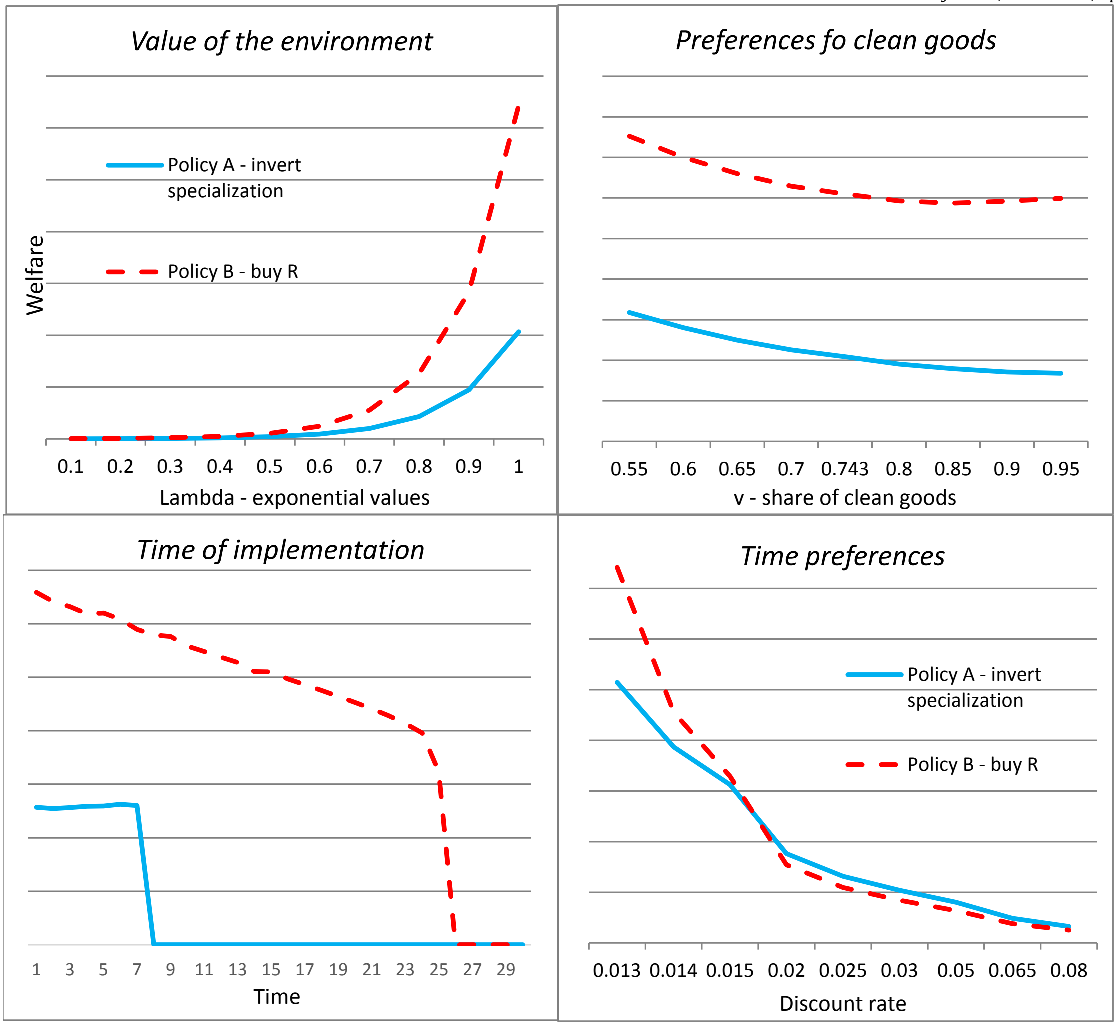

Figure 3: Policy choice with different parameter changes

rates can produce extremely different welfare evaluations of the two policies. This is because environmental quality is a cumulative function that evolves over time, and thus imposes dynamic costs and benefits on a country. Viceversa, the monetary transfer to the South required by policy B is a stable, fixed cost that remains constant over time. Time preferences therefore can change significantly the valuation of the stream of welfare over time.

6. Conclusions

Countries abundantly endowed with fossil fuels are unlikely to give up the use of their resources gratuitously, as they provide them with a source of competitiveness and profits in the production of polluting goods. This competitiveness builds up over time, since innovation tends to concentrate in the most profitable sectors. Therefore, the countries that worry most about global environmental outcomes must recognize this issue and structure their policy actions accordingly. Our model shows that halting the consumption of fossil fuels is not a free lunch. Trade policies and innovation subsidies are one option to redirect specialization, giving resource-rich countries a new source of competitiveness, different from fossil fuels. Alternatively, the resource-rich countries must receive a compensation for abandoning a key source of income. The contribution of this paper is two-fold: first of all, it introduces fossil fuel resources and local damages deriving from energy-intensive production in the debate about green directed technical change. Furthermore, it compares the two broad alternative policy strategies available to the countries that do not own fossil fuels to stop environmental disasters in a non-cooperation scenario. We conclude that there is no costless way for the North to get rid of fossil fuel use in the South. This is what we refer a the "tragedy of the locals": fossil fuels, even if they produce a global externality, are still locally owned by few countries, while the production of energy for manufacturing, which can be located anywhere globally, causes local harm in the countries that specialize in it. To avoid the climatic disaster, the North will either have to renounce to part of its income to pay the other region not to use its local resources, or it will need to take on its own soil the production of dirty goods and the local pollution that comes with it.

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Appendices

A Autarky

In this appendix we derive the laissez – faire autarky equilibrium for the North and the South, distinguishing between the scenarios $p_{dG} > p_{dL}$ and $p_{dL} > p_{dG}$. To simplify notation we omit the superscript k when the analysis is symmetric for the two countries.

We start the analysis from the profit maximization problem of final goods producers in each sector,

$$\underset{K_c, x_{ci}}{Max} \left\{ p_c Y_c - rK_c - \int_0^1 p_i x_{ci} di \right\}$$

$$\underset{K_{dL}, L_{dL}, x_{dLi}}{Max} \left\{ p_{dL} Y_{dL} - rK_{dL} - wL_{dL} - \int_0^1 p_i x_{dLi} di \right\}$$

$$\underset{K_{dG}, L_{dG}, R, x_{dGi}}{Max} \left\{ p_{dG} Y_{dG} - rK_{dG} - wL_{dG} - qR - \int_0^1 p_i x_{dGi} di \right\}$$

leading to the following intermediate inverse demands:

$$x_{ci} = \left(\frac{\gamma p_c A_c}{p_i} \right)^{\frac{1}{1-\gamma}} L_c \tag{A.1}$$

$$x_{dLi} = \left(\frac{\gamma p_{dL} A_d}{p_i} \right)^{\frac{1}{1-\gamma}} L_{dL}^{\psi} K_{dL}^{1-\psi} \tag{A.2}$$

$$x_{dGi} = \left(\frac{\gamma p_{dg} A_d}{p_i} \right)^{\frac{1}{1-\gamma}} L_{dG}^{\beta} K_{dG}^{1-\alpha-\beta} R^{\alpha} \tag{A.3}$$

Monopolistic input producers set their prices to maximize their profit $\pi_i = (p_i - \varsigma) x_{zi}$, with $z \in \{c, dL, dG\}$. Given the final producers' inverse demands and a fixed cost of $\varsigma = \gamma^2$, the profit maximizing price for input producers is $p_i = \gamma$. Thus, the equilibrium demands for intermediate inputs are:

$$x_{ci} = (p_c A_c)^{\frac{1}{1-\gamma}} L_c \tag{A.4}$$

$$x_{dLi} = (p_{dL} A_d)^{\frac{1}{1-\gamma}} L_{dL}^{\psi} K_{dL}^{1-\psi} \tag{A.5}$$

$$x_{dGi} = (p_{dG} A_d)^{\frac{1}{1-\gamma}} L_{dG}^{\beta} K_{dG}^{1-\alpha-\beta} R^{\alpha} \tag{A.6}$$

which yields to the following equilibrium profits for input producers:

$$\pi_{xci} = \gamma (1-\gamma) L_c (p_c A_c)^{\frac{1}{1-\gamma}} \tag{A.7}$$

$$\pi_{xdLi} = \gamma (1-\gamma) L_{dLi}^{\psi} K_{dLi}^{1-\psi} (p_{dL} A_d)^{\frac{1}{1-\gamma}} \tag{A.8}$$

$$\pi_{xdGi} = \gamma (1-\gamma) L_{dGi}^{\beta} K_{dGi}^{1-\alpha-\beta} R^{\alpha} (p_{dG} A_d)^{\frac{1}{1-\gamma}} \tag{A.9}$$

Plugging the equilibrium input demands on equations (4), (5) and (6), we obtain the following equilibrium production of final goods:

$$Y_c = A_c^{\frac{1}{1-\gamma}} L_c p_c^{\frac{\gamma}{1-\gamma}} \tag{A.10}$$

$$Y_{dL} = A_d^{\frac{1}{1-\gamma}} L_{dL}{}^{\psi} K_{dL}{}^{1-\psi} p_{dL}{}^{\frac{\gamma}{1-\gamma}} \tag{A.11}$$

$$Y_{dG} = A_d^{\frac{1}{1-\gamma}} L_{dG}{}^{\beta} K_{dG}{}^{1-\alpha-\beta} R^{\alpha} p_{dG}{}^{\frac{\gamma}{1-\gamma}} \tag{A.12}$$

The relative prices of final goods are derived by combining the equilibrium intermediate demands with the first order derivative with respect to labour for each sector. [15]

$$\frac{p_c}{p_{dL}} = \frac{A_d}{A_c} \left(L_{dL}^{\psi-1} K_{dL}^{1-\psi} \psi \right)^{1-\gamma} \tag{A.13}$$

$$\frac{p_c}{p_{dG}} = \frac{A_d}{A_c} \left(L_{dG}^{\beta-1} K_{dG}^{1-\alpha-\beta} R^{\alpha} \beta \right)^{1-\gamma} \tag{A.14}$$

$$\frac{p_{dG}}{p_{dL}} = \left(\frac{\psi}{\beta} \frac{L_{dL}^{\psi-1}}{L_{dG}^{\beta-1}} \frac{K_{dL}^{1-\psi}}{K_{dG}^{1-\alpha-\beta}} \frac{1}{R^{\alpha}} \right)^{1-\gamma} \tag{A.15}$$

[15] The analysis is conducted under the normalization $p_c = 1$. It follows that $w = A_c^{\frac{1}{1-\gamma}} (1-\gamma)$.

Final good producers choose their factors demand by minimizing their costs. In the North, the active sectors of production are c and dL while in the South, given $p_{dG} < p_{dL}$, the sectors are c and dG. Thus, the factors demand are

$$L_c = \frac{Y_c}{A_c^{\frac{1}{1-\gamma}}} \tag{A.16}$$

$$L_{dL} = \frac{Y_{dL}}{A_d}(1-\gamma)^{\gamma}\left(\frac{A_c^{\frac{1}{1-\gamma}}(1-\gamma)}{\psi}\right)^{\psi(1-\gamma)-1}\left(\frac{r}{1-\psi}\right)^{(1-\gamma)(1-\psi)} \tag{A.17}$$

$$L_{dG} = \frac{Y_{dG}}{A_d}(1-\gamma)^{\gamma}\left(\frac{A_c^{\frac{1}{1-\gamma}}(1-\gamma)}{\beta}\right)^{\gamma+(1-\gamma)(\beta-1)}\left(\frac{r}{1-\alpha-\beta}\right)^{(1-\gamma)(1-\alpha-\beta)}\left(\frac{q}{\alpha}\right)^{\alpha(1-\gamma)} \tag{A.18}$$

$$K_{dL} = \frac{Y_{dL}}{A_d}(1-\gamma)^{\gamma}\left(\frac{A_c^{\frac{1}{1-\gamma}}(1-\gamma)}{\psi}\right)^{\psi(1-\gamma)}\left(\frac{r}{1-\psi}\right)^{\psi(\gamma-1)-\gamma} \tag{A.19}$$

$$K_{dG} = \frac{Y_{dG}}{A_d}(1-\gamma)^{\gamma}\left(\frac{A_c^{\frac{1}{1-\gamma}}(1-\gamma)}{\beta}\right)^{\beta(1-\gamma)}\left(\frac{r}{1-\alpha-\beta}\right)^{(1-\gamma)(1-\alpha-\beta)-1}\left(\frac{q}{\alpha}\right)^{\alpha(1-\gamma)} \tag{A.20}$$

$$R_{dG} = \frac{Y_{dG}}{A_d}(1-\gamma)^{\gamma}\left(\frac{A_c^{\frac{1}{1-\gamma}}(1-\gamma)}{\beta}\right)^{\beta(1-\gamma)}\left(\frac{r}{1-\alpha-\beta}\right)^{(1-\gamma)(1-\alpha-\beta)}\left(\frac{q}{\alpha}\right)^{\alpha(1-\gamma)-1} \tag{A.21}$$

Also from the final goods producers' minimization problem we obtain P_{dL} and P_{dG} as

$$p_{dL} = \frac{1}{A_d}\left(\frac{1}{1-\gamma}\right)^{(1-\gamma)}\left(\frac{r}{1-\psi}\right)^{(1-\gamma)(1-\psi)}\left(\frac{A_c^{\frac{1}{1-\gamma}}(1-\gamma)}{\psi}\right)^{\psi(1-\gamma)} \tag{A.22}$$

$$p_{dG} = \frac{1}{A_d}\left(\frac{1}{1-\gamma}\right)^{(1-\gamma)}\left(\frac{r}{1-\alpha-\beta}\right)^{(1-\gamma)(1-\alpha-\beta)}\left(\frac{A_c^{\frac{1}{1-\gamma}}(1-\gamma)}{\beta}\right)^{\beta(1-\gamma)}\left(\frac{q}{\alpha}\right)^{\alpha(1-\gamma)} \tag{A.23}$$

Consumers maximize their utility subject to their budget constrain given the state of the environment. The consumer's Lagarangian problem is

$$\Lambda = W + \lambda[I - p_c C_c - p_{dL} C_{dL} - p_{dG} C_{dG}] \tag{A.24}$$

which yields the following first order conditions with respect to consumption

$$C_c \quad : \qquad v\left(\frac{C_{dG} + C_{dL}}{C_c}\right)^{1-v} \mu\left(E\right) = \lambda p_c \tag{A.25}$$

$$C_{dL} \quad : \qquad (1-v)\left(\frac{C_c}{C_{dL} + C_{dG}}\right)^{v} \mu\left(E\right) = \lambda p_{dL} \tag{A.26}$$

$$C_{dG} \quad : \qquad (1-v)\left(\frac{C_c}{C_{dG} + C_{dL}}\right)^{v} \mu\left(E\right) = \lambda p_{dG} \tag{A.27}$$

Combining (A.26) and (A.25) we get

$$\frac{1-v}{v}\frac{C_c}{(C_{dL} + C_{dG})} = p_{dL}$$

and analogously with (A.27) and (A.25)

$$\frac{1-v}{v}\frac{C_c}{(C_{dL} + C_{dG})} = p_{dG}$$

With dirty goods being perfect substitutes, it follows that

$$C_{dL} = 0 \ \text{ if } p_{dL} > p_{dG}$$

$$C_{dG} = 0 \ \text{ if } p_{dG} > p_{dL}$$

as consumer always prefer the cheaper one [16]. Thus, the Marshallian demands are

$$C_c = vI \tag{A.28}$$

$$C_{dL} = \frac{(1-v)\,I}{p_{dL}} \tag{A.29}$$

$$C_{dG} = \frac{(1-v)\,I}{p_{dG}} \tag{A.30}$$

[16] Due to the lack of trade, the choice between dL and dG goods is relevant only in the South.

Given the two price scenarios, it follows that

$$Y_{dL} = \frac{1-\upsilon}{\upsilon}\frac{Y_c}{p_{dL}} \tag{A.31}$$

when $p_{dG} > p_{dL}$ and

$$Y_{dG} = \frac{1-\upsilon}{\upsilon}\frac{Y_c}{p_{dG}} \tag{A.32}$$

when $p_{dL} > p_{dG}$.

Pugging the expressions for p_{dL} and p_{dG} into equations (A.31) and (A.32) respectively, and solving for L_{dL} and L_{dG} we obtain

$$L_{dL} = \frac{1-\upsilon}{\upsilon}L_c\psi \tag{A.33}$$

$$L_{dG} = \frac{1-\upsilon}{\upsilon}L_c\beta \tag{A.34}$$

The labour market clearing condition are given by $L_c + L_{dL} = \overline{L}$ and $L_c + L_{dG} = \overline{L}$ when $p_{dG} > p_{dL}$ and $p_{dL} > p_{dG}$ respectively. Combining equations (A.33) and (A.34) with the labour market clearing conditions, we derive for each region the labour equilibrium demands presented in the paper. Following the same logic for K_{dL}, K_{dG} and R we calculate the consequent equilibrium factors prices for both regions. Combining the equilibrium factors demand and the price ratio between goods d_G and d_L yields the regularity condition implied in equation (16).

Finally, the evolution of the clean and dirty technology is determined by the scientists allocations among the two sectors. In the North, scientists can only choose between the sector of production c or dL while in the South the choice is between the sectors c and d_G or c and dG, depending on the price scenario. Given $\vartheta_z \in (0,1)$, with $z \in \{c, dL, dG\}$, and $(1+\varphi)$, we can calculate the relative profit ratios simply by combining the equilibrium factors demand with equilibrium profits for input producers.

B Free Trade

B1 Solution

In this section we alter the autarky equilibrium allowing trade interactions among the regions under the two price scenarios. We continue the analysis under the normalization $p_c = 1$ but with country specific labour rent. Consumers still maximize their utility subject to their budget constraint with the choice between domestically or internationally produced goods.

Starting with the $p_{dG} < p_{dL}$ case, the new maximization problem imposes

$$\frac{1}{p_{dG}} = \frac{\upsilon}{1-\upsilon} \frac{Y_{dG}}{Y_c^N + Y_c^S} \tag{B.1}$$

where

$$Y_c{}^N = A_c{}^{N\frac{1}{1-\gamma}} L_c{}^N \tag{B.2}$$

$$Y_c{}^S = A_c{}^{S\frac{1}{1-\gamma}} L_c{}^S \tag{B.3}$$

and likewise in autarky,

$$Y_{dG} = A_d{}^{S\frac{1}{1-\gamma}} L_{dG}{}^{\beta} K_{dG}{}^{1-\alpha-\beta} R^{\alpha} p_{dG}{}^{\frac{\gamma}{1-\gamma}} \tag{B.4}$$

Plugging the equations for $Y_c{}^N$, $Y_c{}^S$ and Y_{dG} into the consumer's maximization problem and knowing that $L_c{}^S = \overline{L^S} - L_{dG}$ from the market clearing, we derive an expression for p_{dG} as

$$p_{dG} = \left(\frac{1-\upsilon}{\upsilon} \frac{A_c^{N\frac{1}{1-\gamma}} \overline{L}^N + A_c^{S\frac{1}{1-\gamma}} \left(\overline{L}^S - L_{dG} \right)}{A_d{}^{S\frac{1}{1-\gamma}} L_{dG}{}^{\beta} K_{dG}{}^{1-\alpha-\beta} R^{\alpha}} \right)^{1-\gamma} \tag{B.5}$$

Despite free trade, d_G goods are produced exclusively in the South where the natural resource is available. As a result, final producers in the dirty sector face the same cost minimization problem as in autarky, leaving the factors demands and the expression for p_{dG} unchanged. Taking ratios of the factors demand and imposing the market clearing conditions

$K_{dG} = \overline{K^S}$ and $R_{dG} = \overline{R}$, we derive the following relations

$$q^* = \frac{\overline{K}^S}{\overline{R}} \frac{r^{S*}}{(1-\alpha-\beta)} \alpha \tag{B.6}$$

$$L^*_{dG} = \overline{K}^S \frac{\beta}{(A_c^S)^{\frac{1}{1-\gamma}}(1-\gamma)} \frac{r^{S*}}{(1-\alpha-\beta)} \tag{B.7}$$

Finally, combining the two expressions for p_{dG} and solving for r^S gives

$$r^{S*} = \frac{(1-\upsilon)(1-\gamma)}{\beta(1-\upsilon)+\upsilon} \frac{(1-\alpha-\beta)}{\overline{K}^S} (A_c^{N\frac{1}{1-\gamma}} \overline{L}^N + A_c^{S\frac{1}{1-\gamma}} \overline{L}^S) \tag{B.8}$$

Under the $p_{dG} > p_{dL}$ scenario, the active final sectors are c and dL and the production of dirty goods is no longer restricted to the South. Allowing international trade, both goods can be produced and consumed in the North and the South without globally damaging the environment. Given the cheaper price of dL, the consumer's maximization problem leads to

$$\frac{1}{p_{dL}} = \frac{\upsilon}{1-\upsilon} \frac{Y^N_{dL} + Y^S_{dL}}{Y^N_c + Y^S_c} \tag{B.9}$$

Following the same steps as before, but now with $L_c{}^N = \overline{L}^N - L_{dL}{}^N$ and $L_c{}^S = \overline{L}^S - L_{dL}{}^S$, we derive p_{dL} as

$$p_{dL} = \left(\frac{1-\upsilon}{\upsilon} \frac{A_c^{N\frac{1}{1-\gamma}} \left(\overline{L}^N - L^N_{dL}\right) + A_c^{S\frac{1}{1-\gamma}} \left(\overline{L}^S - L^S_{dL}\right)}{A_d{}^{S\frac{1}{1-\gamma}} L_{dG}{}^{\beta} K_{dG}{}^{1-\alpha-\beta} R^{\alpha}} \right)^{1-\gamma} \tag{B.10}$$

Final producers continue to minimize their costs in both regions, so by taking ratios again, we obtain two symmetrical expression for L_{dL}

$$L^{N*}_{dL} = \frac{\psi}{A_c^{N\frac{1}{1-\gamma}}(1-\gamma)} \frac{r^{S*}}{1-\psi} \overline{K}^S \tag{B.11}$$

and

$$L^{S*}_{dL} = \frac{\psi}{A_c^{S\frac{1}{1-\gamma}}(1-\gamma)} \frac{r^{N*}}{1-\psi} \overline{K}^N \tag{B.12}$$

Abstracting from trade costs and assuming that the law of one price holds, we express r^S as a function of r^N by taking ratios of the expressions for p_{dL} obtained through the cost minimization problem in both regions. Thus,

$$r^{S*} = \frac{r^{N*}}{\left[\left(\frac{A_c^S}{A_c^N} \right)^{\frac{\psi}{1-\gamma}} \left(\frac{A_d^N}{A_d^S} \right)^{\frac{1}{1-\gamma}} \right]^{\frac{1}{1-\psi}}} \tag{B.13}$$

Finally, combining (9) with the p_{dL} expression derived from the southern cost minimization, and solving for r^N we obtain

$$r^{N*} = \frac{A_c^{N\,\frac{1}{1-\gamma}} \overline{L}^N + A_c^{S\,\frac{1}{1-\gamma}} \overline{L}^S}{H} \tag{B.14}$$

where

$$H = \frac{\upsilon}{(1-\upsilon)(1-\gamma)} \frac{1}{A_d^{S\,\frac{1}{1-\gamma}}} \frac{A_c^{S\,\frac{\psi}{1-\gamma}} (1-\gamma)^{\psi}}{1-\psi} \frac{1}{G} \left[A_d^{N\,\frac{1}{1-\gamma}} \frac{\overline{K}^N}{A_c^{N\,\frac{\psi}{1-\gamma}} (1-\gamma)^{\psi}} + A_d^{S\,\frac{1}{1-\gamma}} \frac{\overline{K}^S}{A_c^{S\,\frac{\psi}{1-\gamma}} (1-\gamma)^{\psi}} \frac{1}{G^{\frac{\psi}{1-\psi}}} \right]$$
$$+ \left[A_c^{N\,\frac{1}{1-\gamma}} \frac{\psi}{A_c^{N\,\frac{\psi}{1-\gamma}} (1-\gamma)^{\psi}} \frac{\overline{K}^N}{1-\psi} + A_c^{\frac{1}{1-\gamma}} \frac{\psi}{A_c^{S\,\frac{\psi}{1-\gamma}} (1-\gamma)^{\psi}} \frac{\overline{K}^S}{1-\psi} \frac{1}{G^{\frac{1}{1-\gamma}}} \right] \tag{B.15}$$

and

$$G = \left[\left(\frac{A_c^S}{A_c^N} \right)^{\frac{\psi}{1-\gamma}} \left(\frac{A_d^N}{A_d^S} \right)^{\frac{1}{1-\gamma}} \right] \tag{B.16}$$

B2 Regularity Condition

Under autarky the prices for the dirty goods are respectively:[17]

$$p_{dL}^A = \frac{1}{A_D^S} \left(\frac{1}{1-\gamma} \right)^{1-\gamma} \left(\frac{r^S}{1-\psi} \right)^{(1-\gamma)(1-\psi)} \left(\frac{A_c^{S\,\frac{1}{1-\gamma}} (1-\gamma)}{\psi} \right)^{\psi(1-\gamma)} \tag{B.17}$$

[17]In order to differentiate the situation of autarky from the one of free trade we introduce here respectively the superscripts ^{A} and ^{FT}

$$p_{dG}^{A} = \frac{1}{A_D^S}\left(\frac{1}{1-\gamma}\right)^{1-\gamma}\left(\frac{r^S}{1-\alpha-\beta}\right)^{(1-\gamma)(1-\alpha-\beta)}\left(\frac{A_c^{S\,\frac{1}{1-\gamma}}(1-\gamma)}{\beta}\right)^{\beta(1-\gamma)}\left(\frac{\alpha}{q}\right)^{\alpha(1-\gamma)} \tag{B.18}$$

therefore our *regularity condition*, $p_{dL}^{A} > p_{pG}^{A}$, is satisfied whenever

$$\left(\frac{\overline{R}}{\overline{L}^S}\frac{\nu+\beta(1-\nu)}{1-\nu}\right)^{\alpha(1-\gamma)} > 1 \tag{B.19}$$

When opening to free trade prices adjust to meet the new conditions of the market, they become respectively:

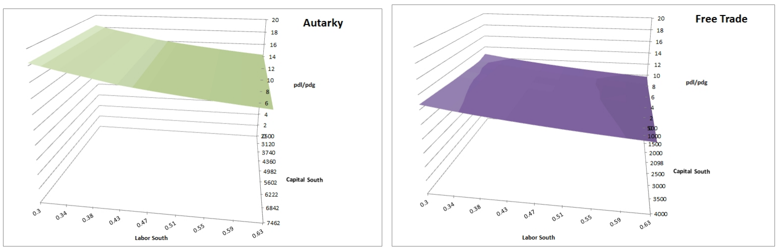
$$p_{dL}^{FT} = \frac{1-\nu}{\nu}\frac{A_c^{N\,\frac{1}{1-\gamma}}\left(\overline{L}^N - L_{dL}^N\right) + A_c^{S\,\frac{1}{1-\gamma}}\left(\overline{L}^S - L_{dL}^S\right)}{A_d^{N\,\frac{1}{1-\gamma}} L_{dL}^{N\ \psi} K_{dL}^{N\ (1-\psi)} + A_d^{S\,\frac{1}{1-\gamma}} L_{dL}^{S\ \psi} K_{dL}^{S\ (1-\psi)}} \tag{B.20}$$

$$p_{dG}^{FT} = \frac{1-\nu}{\nu}\frac{A_c^{N\,\frac{1}{1-\gamma}}\overline{L}^N + A_c^{S\,\frac{1}{1-\gamma}}\left(\overline{L}^S - L_{dG}\right)}{A_d^{S\,\frac{1}{1-\gamma}} L_{dG}{}^{\beta} K_{dG}{}^{(1-\alpha-\beta)} R^{\alpha}} \tag{B.21}$$

Due to more cumbersome calculation we were unable to find an explicit solution, as before, for $p_{dL}^{FT} > p_{pG}^{FT}$, but with the help of a dedicated software we could still verify that this condition is met whenever Equation (B.19) is satisfied, given that the reciprocal order of magnitude of factors remains unchanged (see Proposition 2).

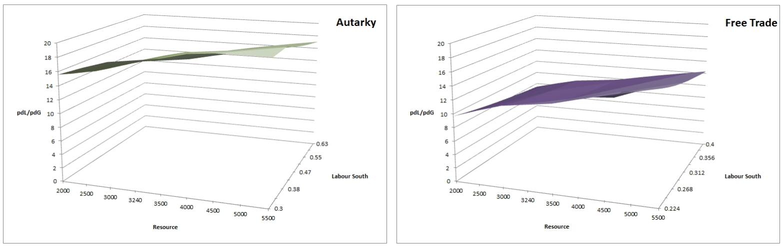
Figures 4, 5, 6 explore the relation between the regularity condition under autarky and free trade while the main endowment factors (namely capital[18], $\overline{K}$, labour, $\overline{L}$, and the natural resource, $\overline{R}$) are varied. Whenever $p_{dL}^{A} > p_{pG}^{A}$ is satisfied we can also confirm $p_{dL}^{FT} > p_{pG}^{FT}$, as the ratio of prices is, in both cases, above the unity.

[18]In the figures endowments of South are represented, but equivalent results can be found when the parameters of North are taken as controls



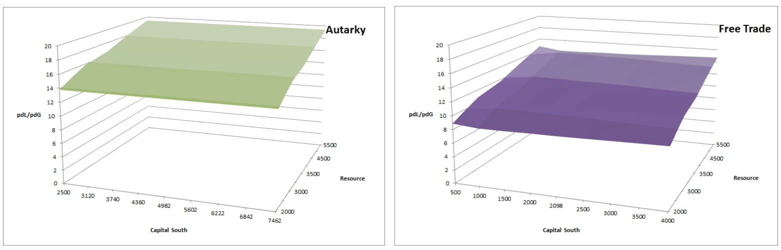
(a) Autarky (b) Free Trade

Figure 4: Regularity Condition under Autarky and Free Trade - $\overline{R}$ fixed



(a) Autarky (b) Free Trade

Figure 5: Regularity Condition under Autarky and Free Trade - $\overline{K}$ fixed



(a) Autarky (b) Free Trade

Figure 6: Regularity Condition under Autarky and Free Trade - $\overline{L}$ fixed

C Policy implementation

C1 North bans the purchase of Y_{dG}

Under this policy, consumers in the North can only demand Y_{dL} goods produced either in the North or the South,

$$\frac{1}{p_{dL}} = \frac{\upsilon}{1-\upsilon} \frac{Y_{dL}^N + Y_{dL}^S}{Y_c^N + Y_c^S} \tag{C.1}$$

while in the South, the decision is still based on the price of the two goods. If $p_{dG} > p_{dL}$, the result from the consumer maximization problem mimics the North and we fall into the laissez-faire free trade equilibrium with Y_{dL} being the cheaper good. If $p_{dG} < p_{dL}$, consumers in the South demand Y_{dG} from the dirty sector given by

$$\frac{1}{p_{dG}} = \frac{\upsilon}{1-\upsilon} \frac{Y_{dG}}{Y_c^N + Y_c^S} \tag{C.2}$$

Applying the market clearing conditions and following the same logic applied in the laissez-faire scenario, we derive the equilibrium factors demand and prices:

$$L_{dL}^{N*} = \frac{\psi}{A_c^{N\,\frac{1}{1-\gamma}}(1-\gamma)} \frac{r^{N*}}{1-\psi} \overline{K}^N \tag{C.3}$$

$$L_c^{N*} = \overline{L}^N - \frac{\psi}{A_c^{N\,\frac{1}{1-\gamma}}(1-\gamma)} \frac{r^{N*}}{1-\psi} \overline{K}^N \tag{C.4}$$

$$L_{dL}^{S*} = \frac{\psi}{A_c^{S\,\frac{1}{1-\gamma}}(1-\gamma)} \frac{r^{S*}}{1-\psi} K_{dL}^{S*} \tag{C.5}$$

$$L_{dG}^{S*} = \frac{\beta}{A_c^{S\,\frac{1}{1-\gamma}}(1-\gamma)} \frac{r^{S*}}{(1-\alpha-\beta)} \left(\overline{K}^S - K_{dL}^{S*}\right) \tag{C.6}$$

$$L_c^{S*} = \overline{L}^S - \frac{r^{S*}}{A_c^{S\,\frac{1}{1-\gamma}}(1-\gamma)} \left[\frac{\beta}{(1-\alpha-\beta)} \left(\overline{K}^S - K_{dL}^{S*}\right) - \frac{\psi}{(1-\psi)\, K_{dL}^{S*}}\right] \tag{C.7}$$

$$K_{dL}^{N*} = \overline{K}^N \tag{C.8}$$

$$K_{dL}^{S*} = \frac{A_d^{S\frac{1}{1-\gamma}} \frac{\overline{K}^S}{(1-\alpha-\beta)H} - A_d^{N\frac{1}{1-\gamma}} \frac{\overline{K}^N}{(1-\psi)}}{\left(\frac{A_c^N}{A_c^S}\right)^{\frac{\psi}{1-\gamma}} \frac{A_d^{S\frac{1}{1-\gamma}}}{(1-\psi)H^{\psi}} + \frac{A_d^{S\frac{1}{1-\gamma}}}{(1-\alpha-\beta)H}} \tag{C.9}$$

$$K_{dG}^{S*} = \overline{K}^S - \frac{A_d^{S\frac{1}{1-\gamma}} \frac{\overline{K}^S}{(1-\alpha-\beta)H} - A_d^{N\frac{1}{1-\gamma}} \frac{\overline{K}^N}{(1-\psi)}}{\left(\frac{A_c^N}{A_c^S}\right)^{\frac{\psi}{1-\gamma}} \frac{A_d^{S\frac{1}{1-\gamma}}}{(1-\psi)H^{\psi}} + \frac{A_d^{S\frac{1}{1-\gamma}}}{(1-\alpha-\beta)H}} \tag{C.10}$$

where

$$H = \left(\frac{A_c^S}{A_c^N}\right)^{\frac{\psi}{(1-\gamma)(1-\psi)}} \left(\frac{A_d^N}{A_d^S}\right)^{\frac{1}{(1-\gamma)(1-\psi)}} \tag{C.11}$$

$$R_{dG} = \overline{R} \tag{C.12}$$

$$r^{N*} = \frac{(1-\upsilon)(1-\gamma) A_d^{N\frac{1}{1-\gamma}}}{\upsilon} \left[\frac{A_c^{N\frac{1}{1-\gamma}} \overline{L}^N + A_c^{S\frac{1}{1-\gamma}} \overline{L}^S}{O}\right] \tag{C.13}$$

where

$$O = J\left[\frac{K_{dL}^S}{H}\left(\frac{\psi}{(1-\gamma)(1-\psi)} - \frac{\beta}{(1-\gamma)(1-\alpha\beta)}\right) + \frac{\psi\overline{K^N}}{(1-\gamma)(1-\psi)} + \frac{\beta\overline{K^S}}{(1-\gamma)(1-\alpha-\beta)}\right] + \frac{A_d^S}{H(1-\alpha-\beta)\left(\overline{K^S} - K_{dl}^S\right)} \tag{C.14}$$

and

$$J = \frac{A_d^N (1-\gamma)(1-\upsilon)}{\upsilon} \tag{C.15}$$

$$r^{S*} = \frac{r^{N*}}{\left[\left(\frac{A_c^S}{A_c^N}\right)^{\psi} \left(\frac{A_d^N}{A_d^S}\right)^{\frac{1}{1-\gamma}}\right]^{\frac{1}{1-\psi}}} \tag{C.16}$$

$$q^* = \frac{K_{dG}^{S*}}{\overline{R}} \frac{r^{S*}}{(1-\alpha-\beta)}\alpha \tag{C.17}$$

C2 North buys the natural resource at q^*

By removing the endownment of R, the South redirects its production towards Y_{dL} and consumers will no longer be able to choose between Y_{dG} and Y_{dL}^S. Thus, the consumer maximization problem is symmetrical in both regions and we fall into the free trade laissez-faire equilibrium with $p_{dG} > p_{dL}$.

C3 North buys the natural resource at q^* and bans all dirty goods from the South. Trade war

In this subsection we assume an active South that reacts against the northern banning of all dirty goods produced in the South by banning imports of Y_{dL}^N goods. Given that dirty goods will not be traded, we allow the two prices, p_{dL}^N and P_{dL}^S, to differ.

Once again, from the consumer's maximization problems in the North and South, the following relations are derived:

$$\frac{1}{p_{dL}^N} = \frac{\upsilon}{1-\upsilon}\frac{Y_{dL}^N}{Y_c^N + Y_c^S} \tag{C.18}$$

and

$$\frac{1}{p_{dL}^S} = \frac{\upsilon}{1-\upsilon}\frac{Y_{dL}^S}{Y_c^N + Y_c^S} \tag{C.19}$$

respectively.

Under this scenario, the equilibrium factors demand and prices are as follows

$$L_{dG} = K_{dG} = R_{dG} = 0 \tag{C.20}$$

$$L_{dL}^{N*} = \frac{\psi}{A_c^{N\frac{1}{1-\gamma}}(1-\gamma)}\frac{r^{N*}}{1-\psi}\overline{K}^N \tag{C.21}$$

$$L_c^{N*} = \overline{L}^N - \frac{\psi}{A_c^{N\frac{1}{1-\gamma}}(1-\gamma)}\frac{r^{N*}}{1-\psi}\overline{K}^N \tag{C.22}$$

$$L_{dL}^{S*} = \frac{\psi}{A_c^{S\frac{1}{1-\gamma}}(1-\gamma)}\frac{r^{S*}}{1-\psi}\overline{K}^S \tag{C.23}$$

$$L_c^{S*} = \overline{L}^S - \frac{\psi}{A_c^{S\frac{1}{1-\gamma}}(1-\gamma)}\frac{r^{S*}}{1-\psi}\overline{K}^S \tag{C.24}$$

$$K_{dL}^{N*} = \overline{K}^N \tag{C.25}$$

$$K_{dL}^{N*} = \overline{K}^N \tag{C.26}$$

$$r^{S*} = r^{N*} \frac{\overline{K}^N}{\overline{K}^S} \tag{C.27}$$

$$r^{N*} = \frac{\frac{(1-\gamma)(1-\psi)}{\psi \overline{K}^N} \left(A_c^{S\,\frac{1}{1-\gamma}} \overline{L}^S + A_c^{N\,\frac{1}{1-\gamma}} \right)}{2 + \frac{\upsilon}{\psi(1-\upsilon)}} \tag{C.28}$$

C4 North buys the natural resource at q^* and bans all dirty goods from the South. No trade war

In this case, we assume a passive South that chooses consumption based on the p_{dL}^S/p_{dL}^N ratio. Thus, for $p_{dL}^S < P_{dL}^N$, it is true that

$$\frac{1}{p_{dL}^S} = \frac{\upsilon}{1-\upsilon} \frac{Y_{dL}^S}{Y_c^N + Y_c^S} \tag{C.29}$$

and we fall into the previous case.

If instead,$p_{dL}^S > P_{dL}^N$, the utility maximization of the consumers lead to

$$\frac{1}{p_{dL}^N} = \frac{\upsilon}{1-\upsilon} \frac{Y_{dL}^N}{Y_c^N + Y_c^S} \tag{C.30}$$

and the South produces only the clean good.

Following the usual steps, we derive the equilibrium factors demands and prices.

$$L_c^{S*} = \overline{L}^S \tag{C.31}$$

$$L_{dL}^{N*} = \frac{\psi r^{N*} \overline{K}^N}{A_c^{N\,\frac{1}{1-\gamma}} (1-\gamma)(1-\psi)} \tag{C.32}$$

$$L_c^{N*} = \overline{L}^N - \frac{\psi r^{N*} \overline{K}^N}{A_c^{N\,\frac{1}{1-\gamma}} (1-\gamma)(1-\psi)} \tag{C.33}$$

$$r^{N*} = \frac{(1-\upsilon)(1-\psi)}{\upsilon \overline{K}^N} \frac{\left[A_c^{N\,\frac{1}{1-\gamma}} \overline{L}^N + A_c^{S\,\frac{1}{1-\gamma}} \overline{L}^S \right]}{\frac{1}{1-\gamma} + \frac{(1-\upsilon)\psi}{\upsilon} (1-\gamma)} \tag{C.34}$$

D Environment dynamics with only Y_{dL}^{N}

In order to ensure that the environment of the producing country does not reach an environmental disaster from the production of Y_{dL}, we need the following condition to hold.

Environment in North at a final time T reads:

$$E_T^N = (1+\Delta)^T E_0 - \zeta Y_{dL,1}^N \left[\sum_{t=0}^{T-1} (1+\Delta)^t (1+\overline{g})^{T-1-t} \right] \tag{D.35}$$

where $\overline{g}$ is the constant growth rate of Y_{dlN}. Since we want to find where $E_T > 0$ we need to impose

$$(1+\Delta)^T E_0 > \zeta Y_{dL,1}^N \left[\sum_{t=0}^{T-1} (1+\Delta)^t (1+\overline{g})^{T-1-t} \right] \tag{D.36}$$

which re-adapting coefficients reads

$$(1+\Delta)^T E_0 > \zeta Y_{dL,1}^N \left[\sum_{k=0}^{T-1} (1+\Delta)^{T-1-k} (1+\overline{g})^{k} \right] \tag{D.37}$$

readjusting

$$(1+\Delta) E_0 > \zeta Y_{dL,1}^N \left[\sum_{k=0}^{T-1} \left(\frac{1+\overline{g}}{1+\Delta} \right)^k \right] \tag{D.38}$$

now since we want to analyze it in an infinite setting we can rewrite

$$(1+\Delta) E_0 > \zeta Y_{dL,1}^N \left[\sum_{k=1}^{\infty} \left(\frac{1+\overline{g}}{1+\Delta} \right)^k \right] \tag{D.39}$$

which requires as regularity condition to be convergent

$$\Delta > \overline{g}$$

then knowing that a geometric series with argument smaller than one converges to

$$\sum_{k=1}^{\infty} z^k = \frac{1}{1-z} - 1$$

we can easily find our solutions

$$\frac{(1+\Delta)}{(1+\overline{g})}(\Delta - \overline{g}) > \zeta \frac{Y_{dL,1}^{N}}{E_0} \tag{D.40}$$

where E_0 and $Y_{dL,1}^{N}$ refer respectively to the pristine value of environment and to the initial value of production of goods dL in North when the policies are removed and the overall economy goes back to a situation of free trade; Whenever this condition is not met we should interpret that it is not possible anymore to avoid a natural damage and the disaster will be reached sooner or later.

E Calibration

For the calibration exercise we wanted to stay as close as possible to what has been done in the literature, in order to be able to capture possible discrepancies arising from our new analysis in considering the specific location of a natural resource. Initial values for our simulations are based on the 2003-2007 world economy (from the UNIDO database). A standard approach[19] is to identify with North Annex I countries[20] and with South non-Annex I countries,[21] among which South Africa. Sector d is identified with chemical, petrochemical, non-ferrous metals, non-metallic minerals and iron and steel, while sector c is identified with all other sectors. L is the total employment in both sectors c and d of each country, and K is the total capital formation in both sectors for the country. We recover data for R from the Statistical Review World Energy 2013; we picked the coal production for non-Annex I countries (in million tonnes oil equivalent) across years under consideration.[22] The discount rate is, as Nordhaus (2008), 0.0015. From Hémous (2014) we set the share of goods c consumed at 0.257, and the share of machines used in the production at 0.33. We rely on Hemous calibration also for the initial values of environment and productivity in both sectors in North and South. The polluting factor associated to production of goods Y_{dG} is equalized to the polluting factor of South in Hemous analysis, which is the most polluting country among the two, while the pollution of Y_{dL} is scaled down of a factor of 20, in order to maintain the polluting scales hypothesized in the theoretical framework. We do not include a regeneration rate in our simulations in order to analyze the "worst" scenario, but its inclusion does not change qualitatively the conclusions of the paper. For what concerns the λ, which represents how much each government cares about environmental degradation in its welfare evaluation function, we adopt a conservative approach setting $\lambda^N = 0.2$, underlying

[19] See Hémous (2014);

[20] Australia, Austria, Belgium, Bulgaria, Canada, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Latvia, Lithuania, Netherlands, Norway, Poland, Portugal, Romania, Russia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States;

[21] Albania, Azerbaijan, Brazil, China, Colombia, Cyprus, Georgia, India, Indonesia, Macedonia, Mexico, Moldova, Pakistan, Philippines, Qatar, South Africa, South Korea, Thailand;

[22] In our sample we have some of the most coal-producing countries in the world: among which China, India and South Africa;

a northern government which cares about environment but only partially if compared to consumption, which fully enters the welfare function of the policy maker.

Table 1: Calibration parameters

Parameter	Description	Value
υ	share of goods c consumed	0.743*
γ	share of machines used in production	0.33*
$\bar{R}$	endowment of R	3240
K_S	endowment of K in South	4982*
K_N	endowment of K in North	2098*
L_S	endowment of L in South	0.43*
L_N	endowment of L in North	0.29*
ψ	share of L in production of Y_{dL}	0.7
α	share of R used in production of Y_{dG}	0.5
β	share of L in production of Y_{dG}	0.2
Ac_S	initial level of technology in sector c in South	82.75*
Ac_N	initial level of technology in sector c in North	512.58*
Ad_S	initial level of technology in sector d in South	107.53*
Ad_N	initial level of technology in sector d in North	666.02*
ξ	pollution factor from Y_{dG}	0.008*
ζ_S	pollution factor from Y_{dL} in South	0.0004
ζ_N	pollution factor from Y_{dL} in North	0.0004
Δ	regeneration rate of the environment	0.001
E_S	initial state of the environment is South	20289.01
E_N	initial state of the environment is North	20289.01
η	elasticity of intertemporal substitution	0.2
ϑ	probability that scientists will succeed in innovation	0.01
μ	environment contribution in North welfare	0.144
ρ	discount factor	0.015

Values with an asterix indicate that the parameter is the same as (Hémous, 2014)