Endogenous Technical Change and Pollution Havens
A Two-Country Dynamic Framework

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Abstract

Our paper focuses on the role of endogenous technology and technology spillovers in explaining cross country differences in pollution and in influencing the pollution haven effect of international trade. We present a North-South trade model, in which technology is endogenously developed in the North and adopted in the South. The model features environmental regulators who choose national environmental policies by trading off the income gains from a rise in pollution against the disutility from additional pollution. We rule out both differences in environmental stringency through income effects and from differences in factor-endowments which traditionally give raise to pollution havens. We show that without goods trade and in the absence of technology subsidies the North imposes more stringent environmental regulation than the South. Moving to the trading equilibrium, we show that with exogenous technology the standard results arise in our model: trade makes the South specialise in pollution-intensive goods. We furthermore show that when technological change is endogenous this pollution haven effect can be reversed, depending on how well polluting inputs can be substituted by other inputs.

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1 Introduction

In the debate about the international aspects of environmental policy, two main issues are important. On the one hand, the studies that go under the general heading of the Environmental Kuznets Curve (EKC) point out a specific relationship between income levels and environmental policy. According to this literature, when income grows, pollution increases at first but it tends to decrease at higher income levels. On the other hand, the literature on the so called pollution haven hypothesis

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states that poor countries tend to specialise in the production of pollution-intensive goods when they are engaged in international goods trade. While the first hypothesis focuses on the effects of income growth on pollution, the second analyses directly the effects of international trade. Combining the two hypotheses, we may state that rich countries choose more stringent environmental policies than poorer countries and that international trade between these countries creates further incentives for rich countries to impose even more stringent environmental policies and for poor countries to loosen theirs.

Copeland and Taylor [5] have shown that the argument of the pollution haven effect needs qualification, due to the endogeneity of policy responses and to differences in factor endowments. In the first place, international trade raises national income by the standard gains from trade effect and it gives poor countries incentives to impose more stringent environmental policy, provided that the demand for environmental quality resembles that of a "normal good". Secondly, international trade expands the pollution-intensive industry in the country that has the comparative advantage in pollution-intensive production. Since it can be argued that capital-intensive goods are often also pollution-intensive and that rich countries are likely to be relatively more endowed with capital, it may well be the case that rich countries would actually benefit from expanding pollution-intensive production when intensifying international trade. Hence, also differences in factor endowments could reverse the pollution-haven effect.

Other arguments have been made against the pollution haven effect. If the North has an interest in cleaning up the environment, it will invest in, and introduce, cleaner technologies. However, these technologies are also likely to be applied in the poorer countries. Developing countries usually exhibit poor protection of intellectual property rights and can thus imitate the cleaner technologies at low cost. Also, multinational enterprises may use the same technologies in high-income and low-income countries alike. Golombek and Hoel [6] and Ben Youssef [3] study the relationship between R&D spillovers and environmental policy in multi-country models.

What have attracted less attention in the theoretical literature so far are the dynamic aspects and the micro-foundations underlying technology spillovers. Indeed, although the arguments of the Environmental Kuznets Curve literature are of an essentially dynamic nature, the prevailing modelling is static. Also in the trade literature, though, the dynamics of the system are neglected. Indeed, trade may raise income, but these income gains are dwarfed by the gains from economic growth over time, driven by factor accumulation or technological change. Both sources of growth are endogenous outcomes of private investment and government policy. Hence, environmental policy, international trade and economic growth all interact, which may either reverse or exacerbate the pollution haven effect. As regards technological change and technology diffusion, moreover, we must note that most models on technology spillovers focus only on investments aimed to reduce emissions but ignore other types of technological change. This appears to be an unreasonable simplification since it is difficult to imagine that firms would only be interested in saving on one particular factor, pollution in this case, while foregoing every other kind of potentially cost-reducing innovations. Firms would indeed welcome any type of cost reduction and will thus also invest in technology aimed at economising on other factors (for example labour). The seminal work on directed technological change carried out by Acemoglu [1] provides a suitable dynamic general equilibrium framework to include not only pollution-saving, but also labour-saving technological change in our framework.

Our paper focuses on the role of endogenous technology and technology spillovers in explaining the existence of pollution havens and the pollution haven effects of international trade. We model two regions that we call the North and the South. Firms in the North invest in the development of new technology and endogenously determine whether, and how much, to invest in labour-saving or in pollution-saving technological change. Firms in the South, on the other hand, copy these technologies at no cost. In both regions, local environmental regulators choose environmental policy by trading off the income gains from a rise in pollution against the disutility arising from a lower environmental quality. In our benchmark setting, being richer does not lead *per se* to more stringent environmental policy and relative factor endowments are the same across regions. In so doing, we mute the two traditional factors behind the pollution haven hypothesis, viz. differences in environmental stringency due to income effects (the EKC argument), and Copeland and Taylor's factor-endowments theory of pollution havens. This allows us to fully concentrate on the role of endogenous technical change in this framework.

We show that without international trade in goods the North imposes a more stringent environmental regulation than the South. Hence, differences in intellectual property rights protection (and the resulting differences in innovations efforts), lead the South to produce in a more pollution-intensive way. We next study the effects of international goods trade and its implications for environmental stringency, highlighting the role of endogenous technological change. We start by showing that when technology is exogenous the standard pollution haven result arises in our model: trade makes the South specialise in pollution-intensive goods. We then show that endogenous technological change in the North, with imitation in the South, may either mitigate or reinforce this pollution haven effect, depending on how well the pollution-intensive goods can be substituted by other goods. In particular, we find that under gross complementarity, technology spillovers from the North to the South tend to reinforce the negative effects of international goods trade on pollution in the resource-abundant country. This result reverts those obtained in the static models mentioned above. With good substitutability, on the other hand, the pollution haven effect is mitigated. Finally, we identify the conditions under which international trade actually reduces pollution in the South, thus reverting the pollution haven hypothesis.

The organization of the paper is as follow: the next sections discuss our framework and introduce the model which we will use, in section 4, to address the issue of environmental regulation. Section 5 discusses the equilibria which obtain in the autarchy case, while section 6 is devoted to the analysis of the consequences of trade liberalisation on the world economy. Section 7 finally wraps up the paper and concludes.

2 The framework

In this paper, we present a simple framework to analyse environmental policy in a stylised world economy which is initially closed with respect to trade in goods, but where international technological spillovers are present, and which subsequently opens up to goods trade. The economy is made up of two regions, each comprising a set of small countries, which we will call the North and the South in what follows. The two regions only differ for the institutions regulating intellectual property rights protection. In particular we assume that intellectual property rights are perfectly enforced in the North while they are not enforced in the South. As will be discussed below, this implies that the development of new technology will only take place in the North, whereas the South will adopt (at no cost) the northern technology.

The model has three building blocks representing preferences, technology and the ecological relationships characterising our economy. We will introduce these building blocks in the next subsection and we will make use of them to derive the policy rule that describes the optimal environmental policy in our framework. In the second part of this section we will provide a more detailed description of the technology part of the model.

2.1 The structure of the model and the environmental policy rule

We start with a simplified, static version of the model, to gain some intuition about the relevant forces at play. After discussing the environmental policy rule and the connections of our setup with the existing literature, we will present the full, dynamic model in the next subsection.

The representative agent in our model derives utility (U) at each moment in time from produced consumption goods (C) and from environmental amenities (E). More consumption goods can be produced if more polluting inputs (R) are used in production, yet more pollution comes at the cost of environmental quality. In particular we assume the following:

$$U = U(C, E), \tag{1}$$
$$C = F(R, \mathbf{Z_1}) - \mathbf{Z_2}, \tag{2}$$
$$E = \bar{E} - R. \tag{3}$$

We model environmental quality, E, as a flow variable, at each moment in time environmental quality is at its pristine level $\bar{E}$ if there is no pollution, but it is reduced by each unit of pollution according to equation (3). The polluting inputs R can alternatively be interpreted as resource inputs. In particular, production requires extractive use of natural resources, like clean air and clean water. Total production of goods takes hence place accordingly to the production function in (2), where the polluting input (extracted resources) is only one of the factors of production (the vector of other inputs, $\mathbf{Z_1}$, will be discussed below). Total production is allocated to consumption goods, C, and to non-consumption goods, $\mathbf{Z_2}$. As we will discuss in the following subsection, we will take the latter to represent intermediate goods and investment goods.

Resource use and environmental quality are subject to the traditional externalities, as private agents take environmental quality as given and ignore the effect of their choices on the environment. Accordingly, resource use would be in excess of the socially optimal level in an unregulated economy and the corrective intervention of some regulatory agency becomes necessary. We assume that the environmental regulator determines the level of pollution (resource use) in the economy. We will not discuss here how this level can be implemented in the economy - both a system of pollution taxes and tradeable pollution quotas would do - since what we are interested in, at this stage, is what governs the choice of the pollution level. We assume that the regulator maximises the utility of the representative agent at each moment in time, taking the agents' choice of other inputs and non-consumption goods, $\mathbf{Z_1}$ and $\mathbf{Z_2}$, as given. Maximising (1) subject to (2) and to (3), we find the following first order condition:

$$\left(\frac{\partial U}{\partial C}\right)\frac{\partial Y}{\partial R}-\left(\frac{\partial U}{\partial E}\right)=0,$$

which we rewrite, in terms of elasticities, as:

$$\left(\frac{\partial Y}{\partial R}\frac{R}{Y}\right)\frac{Y}{C}=\left(\frac{(\partial U/\partial E)E}{(\partial U/\partial C)C}\right)\frac{R}{\bar{E}-R}. \tag{4}$$

This equation can be interpreted as the condition that determines the optimal supply of polluting inputs by the environmental regulating agency. It balances the marginal benefits and the marginal costs of pollution. As long as the left hand side exceeds the right hand side, the marginal benefits from pollution (in the form of additional consumption goods) exceed the marginal costs (in the form of lower environmental amenities), both measured in terms of consumption. Pollution supply would then be below its equilibrium level. In equilibrium, the condition must hold with equality. In a graph with R on the horizontal axis (see Figure 1), we can depict the lhs and rhs as curves MB and MC respectively. An interior solution to the maximisation problem exists if MB cuts MC from above.

Equation (4) shows how the supply of pollution depends on the production elasticity of polluting inputs, on the consumption to output ratio, and, finally, on the share of environmental amenities in utility.

- *Ceteris paribus*, a higher production elasticity of resources, $\partial Y/\partial R\ R/Y$, makes resources more valuable in production and increases the marginal benefits of pollution. In terms of the graph in Figure 1, the MB curve shifts up and the supply of pollution increases. In other words, the costs of reducing pollution become larger, or, equivalently, the opportunity cost of environmental policy increases.
- *Ceteris paribus*, a higher share of amenities in utility, $\frac{(\partial U/\partial E)E}{(\partial U/\partial C)C}$, increases the marginal benefits of environmental quality (i.e. it increases the marginal costs of pollution), shifts the MC curve up, and hence decreases equilibrium pollution.

- *Ceteris paribus*, a lower consumption to output ratio C/Y increases the equilibrium supply of pollution. Recall that consumption equals output excluding non-consumption goods, see (2), the latter of which can be considered as a fixed cost, that is, production needed independent of the level of consumption. If this fixed cost is high relative to output Z_2/Y, a one percent increase in output is more desirable than when the share of the fixed cost in output is small, since such an increase results a in larger increase in consumption. Intuitively, an economy with low consumption per unit of output spends most of its resources on fixed cost, which makes consumption relatively scarce and raises the marginal value of production relative to the marginal value of environmental quality.

Expression (4) can also help us to further discuss the literature on the international differences in environmental stringency, which was briefly presented in the introduction. We will try to highlight the role of each of the three determinants of pollution we just discussed and to clarify the role of our contribution within this literature.

- We first focus on income effects. The EKC-literature argues that rich countries pollute less because they have a higher preference for environmental quality. In the context of equation (4), this would imply that the share of amenities in utility, $\frac{(\partial U/\partial E)E}{(\partial U/\partial C)C}$, is larger for rich countries (the North, n say), than for poor ones (the South, s). Note that this ratio is, in general, a function of both E and C. If E and C are poor substitutes in utility (i.e. with an elasticity of substitution below 1), the share will be increasing with C/E, i.e. the marginal cost of pollution will be higher, the higher the level of consumption. To isolate the implications of this poor substitution from other effects, assume that $C = Y = R^{\omega} Z_1^{\gamma}$, where Z_1 is now a scalar, so that both $\partial Y/\partial R : R/Y = \omega$ and $C/Y = 1$ are constants. Furthermore, assume that the endowment of environmental quality, $\bar{E}$, is the same in both countries. The optimal environmental policy rule (4) now reads:

  $$\omega = \phi\left(\frac{R^{\omega} Z_1^{\gamma}}{\bar{E} - R}\right) \frac{R}{\bar{E} - R} \text{ with } \phi' > 0$$

  Now assume that country n has a larger endowment of the input Z_1 than country s, so that output (and consumption) is larger in the former. For given R, the rich country will also have a higher amenity preference share and it will supply less pollution in equilibrium (the MC curve for country n will indeed lie above that of country s, while both countries will share the same MB curve, given our assumptions).

- Second, we discuss relative factor endowment effects. Copeland and Taylor [5] have argued that rich countries pollute relatively more because they are relatively more endowed with a factor of production (usually capital), that is complementary to pollution. In the context of equation (4), this is related to the production elasticity $(\partial Y/\partial R)(R/Y)$. Note that this elasticity is, in general, a function of all factor inputs. For simplicity, and in line with the analysis of Copeland and Taylor, we assume that there are two factors of production apart from R, so that $Y = F(R, Z_K, Z_L)$, and that $(\partial Y/\partial R)(R/Y)$ increases with Z_K/Z_L. The interpretation is that Z_K is relatively more complementary to R than Z_L. To isolate the implications of this complementarity, further assume that $C = Y$ and $U = U(CE^{\phi})$, so that now both C/Y and $\frac{(\partial U/\partial E)E}{(\partial U/\partial C)C} = \phi$ are constant, and that $\bar{E}$ is the same in both countries. If we assume that country n has a higher Z_K/Z_L ratio than country s, it follows that the former will choose a higher equilibrium supply of pollution than the latter (indeed its MB curve is above that of country s, while both countries' MC curves are the same).

- Finally, a third source of differences in the degree of environmental stringency can be found in differences in natural conditions. Indeed, if $\bar{E}$ differs among countries, that is, if one of the countries has a more resilient environment, this is *per se* a sufficient reason for differences in the stringency of environmental regulations to arise.

As we already mentioned in the introduction, we feel that two important elements are missing in this literature. In the first place, all models are static, indeed it is typically assumed that either income itself or, as in our representation of the literature above, the determinants of income, are exogenous and that total income is consumed. In the present paper we instead present a dynamic model in which part of total production is used for investment, which affects future output providing a link between periods. Second, the models discussed above ignore changes in technology. We want to introduce technological change, both as a result of investment and as a result of technology spillovers. This implies that we have to extend the above three-equation static model to allow for investment and dynamics. In the rest of this section we will present a model extended along these lines and we will introduce the formal framework we will use in the rest of the paper.

It is clear that our aim in this paper is to focus on the technological side of the economy. In order to isolate the new implications, we want to abstract from the income effects and from ecological differences. In particular, we choose a utility function that features a constant share of amenities $\frac{(\partial U/\partial E)E}{(\partial U/\partial C)C}$, and we abstract from differences in natural resource endowments, assuming that both regions share the same endowment, $\bar{E}$. The utility function follows Bovenberg and Smulders [4], while for the modelling of production and innovation we follow Acemoglu [1].

Referring to (4), it is possible to illustrate some aspects of technical change. Neutral technical change would not affect the production elasticity $(\partial Y/\partial R)(R/Y)$ and could affect the supply of pollution through income effects (if $\frac{(\partial U/\partial E)E}{(\partial U/\partial C)C}$ increases with income, pollution supply falls with technical progress) and through the changes it induces in the consumption-output ratio (technical change increases Y relative to the fixed cost of research, thus making consumption less scarce and raising the incentives to reduce pollution). Biased technical change, on the other hand, affects by definition the production elasticity $(\partial Y/\partial R)(R/Y)$. In particular, resource-saving technological change reduces it, thus reducing the marginal benefits of pollution. In contrast, resource-using technological change increases the production elasticity of resources and makes environmental policy more costly. Hence, resource-saving technological change is good for the environment, while resource-using technical change is bad. In the model below we explore how the bias of technological change is endogenously determined by trade and how it affects the supply of pollution.

2.2 Production and investment

The representative consumer has preferences over consumption (C) and environmental quality ($E = \bar{E} - R$), which can be represented through the following (intertemporal) CRRA utility function:

$$\int_0^\infty \frac{(C(t)(\bar{E} - R(t))^\phi)^{1-\frac{1}{\sigma_c}} - 1}{1 - \frac{1}{\sigma_c}} e^{-\rho t} dt. \tag{5}$$

Where ρ is the rate of time preference and σ_c is the intertemporal elasticity of substitution. From now on we will suppress the time arguments in order to simplify notation.

Each consumer maximises the present value of her life time utility subject to the budget constraint:

$$C + I + X \leq Y \equiv \left[Y_L^{\frac{\varepsilon-1}{\varepsilon}} + Y_R^{\frac{\varepsilon-1}{\varepsilon}} \right]^{\frac{\varepsilon}{\varepsilon-1}}, \tag{6}$$

where I is investment, and X is the total amount of research expenditure. The production function in (6) shows that final output is obtained as a CES aggregate of two (intermediate) goods, Y_R and Y_L, with an elasticity of substitution equal to ε. Moreover expression (6) requires that consumption, investment and R&D expenditure represent all the possible competing uses of the final good.

The resource-intensive good (Y_R) is produced using resources and a set of differentiated machines, the range of machines that can be used to complement R is indicated by N_R. The labour-intensive good (Y_L) is produced using labour and a different set of machines, whose range is N_L. The production functions for the two intermediate goods are then:

$$Y_R = \frac{1}{1-\beta} \left(\int_0^{N_R} k_R(j)^{(1-\beta)} dj \right) R^\beta, \tag{7}$$

and

$$Y_L = \frac{1}{1-\beta} \left(\int_0^{N_L} k_L(j)^{(1-\beta)} dj \right) L^\beta. \tag{8}$$

For a given state of the technology, both (7) and (8) exhibit constant returns to scale, anyway the returns will be increasing once N_L and N_R are endogenously determined. We model innovation assuming that only the final good is used in generating innovations, this is often referred to as a lab equipment specification, following Rivera-Batiz and Romer [7]. We assume that the development of new types of machines takes place according to the following production functions:

$$\dot{N}_R = \eta_R X_R \text{ and } \dot{N}_L = \eta_L X_L, \tag{9}$$

where we assume that each unit of the final good invested in innovation generates an amount of innovation equal to η_i $(i = L, R)$. R&D is thus a costly process and the costs incurred for the development of new machines varieties are sunk. As a consequence only innovators which expect to wield some monopoly power in the future will actually engage in R&D activities, this means that innovation only takes place in the North where intellectual property rights are protected, while southern producers will only be able to copy the innovations produced by their northern counterparts.

3 Equilibrium analysis

In this section we give a definition of an equilibrium and characterise it in the present context, in the following sections we will derive the different outcomes which obtain under autarchy and under free trade.

An equilibrium for this economy is given by a set of machine prices, $p_{k_i}(j)$ $(i = L, R)$, that maximise the profits of the technology monopolists, machine demands by the two sectors, $k_i(j)$, that maximise profits for the producers of the intermediate goods, amounts invested in R&D for each sector, X_i, which maximise profits to innovators, an amount of resources used in production which maximises social welfare, and factors and products prices which clear markets. Here we will only focus on the long run balanced growth path of this economy, where prices and the amount of natural resources used in production are constant and where N_R and N_L grow at the same rate.

We start from the production of intermediate goods, to simplify notation, we let $S_R \equiv R$ and $S_L \equiv L$. Firms which employ factor i $(i = L, R)$ maximise their profits choosing the amount of factor S_i to employ and the amount of machines $k_i(j)$ of each type to use. Their maximisation problem is then:

$$\max_{S_i, \{k_i(j)\}} p_i Y_i - w_i S_i - \int_0^{N_i} p_{k_i}(i) k_i(j)^{(1-\beta)} dj, \tag{10}$$

subject to the production function (8) and taking both goods' and factors' prices as given. For simplicity, we assume that all machines depreciate fully after use, although, as discussed by Acemoglu [1], assuming slow depreciation of machinery would not change the balanced growth equilibrium path. The (isoelastic) demands for machines resulting from the above maximisation are:

$$k_i(j) = \left(\frac{p_i}{p_{k_i}(j)}\right)^{\frac{1}{\beta}} S_i, \tag{11}$$

In the North, where intellectual property rights are perfectly enforced, blueprints for machines can be developed and allow producers to act as monopolists in the supply of each machine. Assuming υ units of the final good are required to produce each machine and that a tax τ_k is levied on machine production costs, the expression for the profits of a monopolist supplying the i-complementary machine j is given by $\pi_i(j) = (p_{k_i}(j) - \upsilon(1+\tau_k))\, k_i(j),\ j \in [0, N_i]$. Given the demand function in (11), the profit-maximising price will be set as a mark-up over marginal cost, and will equal $p_{k_i}(j) = \upsilon(1+\tau_k)/(1-\beta)$. To simplify the algebra, we assume υ to be equal to $1-\beta$, so that $p_{k_i}(j) = (1+\tau_k)$. Substituting for machine prices and demand functions in the expressions for the profits of the technology monopolist, one gets:

$$\pi_i(j) = (1+\tau_k)^{-(1-\beta)/\beta} \beta p_i^{1/\beta} S_i. \tag{12}$$

Substituting machine demands (11) and prices into the sectorial production functions (7) and (8), we obtain the sectorial supply function for Northern firms:

$$Y_i = \frac{(1+\tau_k)^{-(1-\beta)/\beta}}{1-\beta} p_i^{(1-\beta)/\beta} N_i S_i, \tag{13}$$

Things are different in the South, here patent protection is not effective and the impossibility to recoup the sunk costs necessary to develop new machines varieties rules out the possibility that a local R&D sector may arise. We assume, though, that southern producers can copy, at no cost, blueprints developed in the North. As there is no institutional arrangement to protect the monopoly power of machine producers, and no sunk cost to prevent copying by more than one producer, perfectly competitive markets will arise. In addition, southern producers are not taxed. The price of machines in the South will then be equal to marginal cost. In what follows we also want to allow for the possibility that marginal costs are lower for the inventor then for the southern imitators, so we set marginal costs for southern producers to $\kappa^{-\beta/(1-\beta)}$. One can imagine that this difference in costs arise because of the fact that southern imitators don't have access to the developer's knowledge base, or because imperfections in the capital markets drive the cost of capital up in the South, or because of other distortions.

Since the sets of machines used in the production of the two intermediate goods are different, technical change can be directed to only one factor of production. Profit maximising firms will produce more innovations in response to greater profits, thus more resources will be devoted to innovations in the sector where they are expected to yield the higher return. In this context, what matters to the monopolists, though, is not the instantaneous profits, but rather the net present discounted value of the life-time flow of profits. For a technology monopolist the value of producing an i-complementary machine at time t is given by:

$$V_i(t) = \int_t^\infty \exp\left[-\int_t^\tau r(\omega) d(\omega)\right] \pi_i(\tau) d\tau, \tag{14}$$

where we have allowed for a time varying interest rate. Expression (14) can be more conveniently rewritten as $rV_i - \dot{V}_i = \pi_i$. One blueprint in sector i costs $1/\eta_i$ units of final output, which we take as the numeraire. The price of a final good thus equals unity and the following relation between the two goods prices holds:

$$\left[p_L^{1-\varepsilon} + p_R^{1-\varepsilon}\right]^{1/(1-\varepsilon)} = 1. \tag{15}$$

Free entry in research activities implies that the price, cost and value of a blueprint are the same whenever there is innovation, that is $V_i = 1/\eta_i$ and $\dot{V}_i = 0$ if $\dot{N}_i > 0$, so that

$$r = \pi_i \eta_i. \tag{16}$$

Hence, if both sectors innovate, we have the following "no-arbitrage" condition

$$\pi_R \eta_R / \pi_L \eta_L = 1, \tag{17}$$

which after substitution of (12) implies:

$$\frac{\eta_R}{\eta_L} \left(\frac{p_R}{p_L} \right)^{1/\beta} \frac{R}{L} = 1 \tag{18}$$

We can now solve for the interest rate by substituting (18) into (15), solving for p_i, substituting the result into (12) and finally substituting this into (16). This yields:

$$r = \beta (1 + \tau_k)^{-(1-\beta)/\beta} \eta_L L \left[1 + \left(\frac{\eta_R R}{\eta_L L} \right)^{\sigma - 1} \right]^{1/(\sigma - 1)}, \tag{19}$$

where $\sigma = 1 + (\varepsilon - 1)\beta$ is the (derived) elasticity of substitution between factors of production.

Households maximize their intertemporal utility, subject to the usual intertemporal budget constraint. This result in the Keynes-Ramsey rule. In the steady state, consumption and output grow at the same rate,g say, so that we may write this equation as:

$$r = \rho + g/\sigma_c. \tag{20}$$

Finally, to conclude this section, we note that, as there exists no market for resources, producers will have an incentive to fully exploit the resource base each period, but this would impose an excessive burden on consumers, whose welfare also depends on the amount of environmental services that they can consume. The correct price for resources will then need to be established by an environmental regulator, aiming at maximising consumers' utility by correcting the pollution externality. To this aspect of the equilibrium we devote the next section.

4 Environmental regulation

The environmental regulators in both countries wish to choose, at each moment in time, the supply of pollution in order to maximise the respective representative consumer's utility. In doing so they take as given the choices made by the other economic agents in the economy concerning the level of consumption and of investment in both intermediates and R&D. They adhere to the policy rule we have derived in the static context,[1] see (4). We can rewrite this equation by eliminating

[1] Since pollution is a flow variable that can be newly determined in each period just as in a static model, this is a reasonable assumption. Clearly, this is not a first-best policy, since there is not only an environmental distortion but also a distortion from monopoly pricing, while the

the share of environmental amenities, the production elasticity of pollution, and the consumption output ratio. First, the share of environmental amenities equals ϕ, given the instantaneous utility function in (5). Second, the production elasticity of pollution can be written in terms of the share of pollution intensive goods in gross production, which we define as $\theta_R \equiv \frac{\partial Y}{\partial Y_R}\frac{Y_R}{Y}$. Indeed, from (7) we have that $\frac{\partial Y_R}{\partial R}\frac{R}{Y_R} = \beta$, so that we can write: $\frac{\partial Y}{\partial R}\frac{R}{Y} = \left(\frac{\partial Y}{\partial Y_R}\frac{Y_R}{Y}\right)\left(\frac{\partial Y_R}{\partial R}\frac{R}{Y_R}\right) = \theta_R\,\beta$.

Substituting these results into (4), we find that:

$$\underbrace{\theta_R \beta \frac{Y}{C}}_{MB} = \underbrace{\phi \frac{R/L}{\bar{E}/L - R/L}}_{MC}. \tag{21}$$

We now show that both C/Y and θ_R are functions of the R/L ratio, so that we can examine this condition graphically by depicting the lhs and rhs of expression (21) as a function of R/L. Concerning the share of pollution-intensive goods in production, given that $\partial Y/\partial Y_R = p_R$, because of perfect competition in the goods market, and that $Y = p_R Y_R + p_L Y_L$, we may write:

$$\frac{\theta_R}{1-\theta_R} = \frac{p_R Y_R}{p_L Y_L}. \tag{22}$$

This reveals that θ_R depends on relative prices and on relative good supplies, which are ultimately driven by factor supply. Since relative prices will be different with and without trade, we postpone solving for θ_R until we discuss the autarchy and trade equilibria in detail in Sections 5 and 6 respectively.

Here we want, instead, to derive an expression for the consumption to output ratio that we can use to substitute in expression (21). To do this we need to make use of the final good market equilibrium condition (6) and to determine how much of the final output is devoted to investment in machines and to R&D expenditures by the agents. We start by noting that in both the North and the South, the total cost of producing i-complementing machines amounts to $\upsilon^c k_i N_i$ $(i = R, L)$, where υ^c represents the unit cost of production in country c $(c = n, s)$ and $k_i N_i$ is the total amount of intermediates purchased. Algebraic manipulation of this expression yields[2] $(\upsilon^c/p_{k_i})(1-\beta)p_i Y_i$. Substituting the appropriate expressions for prices and marginal costs gives the level of final goods invested in intermediate goods in the North and in the South, respectively, as:

$$\left(\frac{I}{Y}\right)^n = \frac{(1-\beta)^2}{1+\tau_k}, \text{ and } \left(\frac{I}{Y}\right)^s = 1-\beta. \tag{23}$$

We have enough information now to characterise the C/Y ratio in the South, indeed, whatever is left after investment has been optimally decided will be consumed, so

regulator has only one instrument. The policy rule in (4), moreover, implies that the regulator ignores the possibility that environmental policy affects the supply of machines by monopolistic firms. Hence, the regulator ignores that she could correct the distortion from monopoly pricing using environmental policy as a second-best instrument.

[2]Here we made use of the assumption that the sectorial production functions are Cobb-Douglas.

that:

$$\left(\frac{C}{Y}\right)^s = \beta. \tag{24}$$

To characterise the same ratio in the North, instead, we still need to derive the optimal amount of R&D investment which takes place there. We start by observing that from (9), it is possible to write the investment in each sector as $X_i = gN_i/\eta_i$, where g is the growth rate of the economy. From (12), (13), and (16) we find $N_i/\eta_i = p_i Y_i \beta(1-\beta)/r$. Summing over both sectors, we write the total expenditure in research and development $X = X_L + X_R$ as

$$X = \frac{g}{r}\beta(1-\beta)Y. \tag{25}$$

We now have all the elements to write the consumption to output ratio in the North, which turns out to be:

$$\left(\frac{C}{Y}\right)^n = \frac{\tau_k + \beta + \beta(1-\beta)}{1+\tau_k} - \frac{\beta(1-\beta)g}{r}. \tag{26}$$

Comparing the consumption output ratios in North and South, we see that the following differences. First, as can be seen from the second term on the right hand side of (26), the North consumes less than the South out of its gross output since part of it is needed for investment in technology (research expenditures). Second, the amount of gross output devoted to the purchase of machines differs between North and South. Two special cases deserve special attention. First, if there is no tax in the North, this region produces relatively less intermediates as their producers charge a monopoly price while Southern producers charge production costs and its consumption output ratio is larger than in the South.

$$\left(\frac{C}{Y}\right)^n = \beta\left[1 + (1-\beta)\left(\frac{r-g}{r}\right)\right].$$

Second, if the North subsidizes intermediates production so as to offset this monopoly distortion (that is, if $\tau_k = -\beta$), both regions devote a fraction $1-\beta$ to intermediates and the North has a lower consumption output ratio if there is growth ($g > 0$).

$$\left(\frac{C}{Y}\right)^n = \beta\left[1 - (1-\beta)\left(\frac{g}{r}\right)\right].$$

5 Equilibrium under autarchy

In this section and in the next we will complete our analysis of the equilibria under different assumptions concerning the degree of openness of the economy, we start here with the autarchy case and move on, in the following section, to the free trade case. In what follows we analyse how pollution levels differ between the North and the South when there is no trade in goods and the only interdependence between the two regions derives from the international technological spillovers.

First of all, we note that since the markets for products are competitive, the relative price of the two goods must satisfy:

$$\frac{p_R}{p_L} = \left(\frac{Y_R}{Y_L}\right)^{-\frac{1}{\varepsilon}}. \tag{27}$$

Clearly, the higher the relative supply of the R-intensive good relative to the L-intensive good, the lower its relative price in equilibrium.

Without goods trade, the domestic relative demand for final goods equals the domestic supply. Substituting supply (13) into (27), we can solve for the domestic price ratio as a function of the technological bias and factor supply only,

$$\frac{p_R}{p_L} = \left(\frac{N_R R}{N_L L}\right)^{-\beta/\sigma}. \tag{28}$$

Making use of (28), (13) and (22), we can obtain an expression for the share of the polluting good under autarchy:

$$\theta_R = \left[1 + \left(\frac{N_R R}{N_L L}\right)^{(1-\sigma)/\sigma}\right]^{-1}. \tag{29}$$

5.1 Exogenous technology

We can now analyse the equilibrium supply of pollution for given technology. In particular, we take one step back and we treat N_R/N_L as a parameter, common to the North and the South, to study the case of exogenous technology. In this setting, the set of available machines of each type, N_i, may expand exogenously over time at a common rate, which implies exogenous neutral technological change, but no cost of innovation has to be incurred so that g can be set to zero in equation (26). We can now determine the equilibrium supply of pollution from the policy rule (21), which can be written as a function of R/L only, upon substitution of (29), and (24) or (26) for the North and South, respectively. This equilibrium can be determined graphically as the point of intersection between the curves representing the left-hand and right-hand sides of equation (21), see Figure 2. The line labeled MC depicts the right-hand side of the policy rule (21), and represents the marginal costs of pollution. This curve applies to both the North and the South. The left-hand side of the policy rule (21), which represents the marginal benefits of pollution, boils down to θ_R for the South since $\beta Y/C = 1$ in the South, see (24). Therefore the marginal benefits for the South are defined by (29) and depictied by the MB^s line in the Figure. We have drawn the case in which the resource-intensive and labour-intensive goods are gross complements (i.e. $\sigma < 1$). Hence the point of intersection A^s represents the equilibrium supply of pollution and the associated resource share in the South.

To find the equilibrium for the North, we need to plot the marginal benefits of pollution as given by $\theta_R \beta Y/C$ at the left-hand side of the policy rule (21). The line labeled MB^n represents this and lies below (above) the MB^s line if $\beta Y/C$ is smaller (larger) than unity. Given that the point of intersection between the MC

and MB^n curves determines the equilibrium supply of pollution in the North, it is clear that the North pollutes less (more) than the South if $\beta Y/C$ is smaller (larger) than unity[3].

From (26), it is apparent that with $g = 0$, as $\tau_k > -\beta$, the MB curve for the North lies below that of the South, while the two regions share the same MC curve. As a result the North pollutes less than the South.

The differences in the pollution levels in the two regions arise, in this framework, neither because of income-related differences in demand for environmental quality nor due to the differences in natural endowments, but only because of differences in consumption-output ratios. The high consumption-output ratio in the North makes increases in output less valuable there than in the South. The environmental regulator takes as given spending on machines, which is not available for consumption. Since Northern machine producers charge monopoly prices above marginal cost, production of machines is small in the North as compared to the South, where machines are priced at marginal costs. Hence, when taking production of machines as given, an increase in gross output increases consumption more, in percentage terms, in the South than in the North.

Things change if an optimal tax is levied on machines. Optimally, policy should, in fact, correct for the monopoly distortion by subsidising the use of machines such that users pay the marginal cost (i.e. $\tau_k = -\beta$). When this happens, bot regions face the same MB curve and there is no reason for them to have different pollution supplies.

5.2 Endogenous technology

Allowing for endogenous technological change means that the long-run relative technology bias N_R/N_L will be determined in the North by the condition that the values from innovation in both sectors are equal, that is from the no-arbitrage equation derived in section 3. From (12) and (28) we find the following expression for the technological differences across sectors:

$$\left(\frac{N_R}{N_L}\right)^{(1-\sigma)/\sigma} = \left(\frac{\eta_R}{\eta_L}\right)^{1-\sigma} \left(\frac{R^n}{L^n}\right)^{-(1-\sigma)^2/\sigma}, \tag{30}$$

where the superscript n denotes northern values. This equation represents the sources of the direction of technological change. Note from (29) than an increase in $(N_R/N_L)^{(1-\sigma)/\sigma}$ reduces the cost share of resources in output and hence represents resource-saving technological change; similarly, a decrease represents resource-using technological change. From (30) we see that a decrease in the relative supply of pollution results in resource-saving technological change. Hence, in autarchy, resource-scarce countries develop resource-saving technologies.

We can now analyse how the endogeneity of technological change affects the equilibrium supply of pollution. Compared to exogenous technological change, two

[3] The same result applies for the case of good substitutes ($\sigma > 1$). In this case both the MB^s and the MB^n curves slope upwards, but the MB curve for the North remains below (above) that of the South, if $\beta Y/C$ is smaller (larger) than unity

differences arise. First, technology in both regions, N_R/N_L, depends on pollution policy in the North (R^n/L^n). Substituting (30) into (29), we see how this affects the share of pollution intensive goods in total production for each region:

$$\theta_R^{nAUT} = \left[1 + \left(\frac{\eta_R}{\eta_L}\right)^{1-\sigma} \left(S^{Bn}\right)^{1-\sigma}\right]^{-1}, \tag{31}$$

$$\theta_R^{sAUT} = \left[1 + \left(\frac{\eta_R}{\eta_L}\right)^{1-\sigma} \left(S^{Bn}\right)^{1-\sigma} \left(\frac{S^{Bs}}{S^{Bn}}\right)^{\frac{1-\sigma}{\sigma}}\right]^{-1}, \tag{32}$$

where $S^{Bc} \equiv R^c/L^c$ denotes the factor intensity[4] in region c. Second, technological change entails a cost and lowers the C/Y ratio, since g can no longer be set to zero in (26).

Let us now consider under what conditions with endogenous technology the South pollutes more than the North. Since the equilibrium in the South is affected by the actions taken in the North through the technology spillovers, we can no longer depict southern marginal benefits and cost of pollution as a function of its supply of pollution only, but need to take into account the northern supply as well. In Figure 3 we therefore plot the marginal costs and benefits in the South, both measured relative to those in the North, as a function of the supply of pollution in the South relative to that in the North. That is, we use the following version of the policy rule (21):

$$\frac{MB^s}{MB^n} = \frac{MC^s}{MC^n} \Leftrightarrow \underbrace{\left(\frac{C^n}{\beta Y^n}\right) \frac{\theta_R^s}{\theta_R^n}}_{MBX} = \underbrace{\left(\frac{S^{Bs}}{S^{Bn}}\right) \frac{\bar{E}/L - S^{Bn}}{\bar{E}/L - S^{Bn}\left(S^{Bs}/S^{Bn}\right)}}_{MCX} \tag{33}$$

We plot the left-hand and right-hand side of the second equation as MBX and MCX respectively in Figure 3 after substituting (31) and (32) and assuming an arbitrary value of $S^{Bn} < \bar{E}/L$. We draw the figure for $\sigma > 1$ and $C^n/\beta Y^n > 1$, but the reader may easily construct the three other cases. The MCX curve is upward sloping and passes through points (0,0) and (1,1). The MBX curve is downward (upward) sloping if $\sigma < 1$ ($\sigma > 1$) and passes through point (1, $C^n/\beta Y^n$). It then follows that the two curves intersect at a point with $S^{Bs}/S^{Bn} \gtreqless 1$ if $C^n/\beta Y^n \gtreqless C^s/\beta Y^s = 1$ (in the Appendix we prove that there is at most one such point of intersection in the positive orthant). Our conclusion for the endogenous technology case is therefore similar as under exogenous technology: the country with the lowest consumption share out of gross output pollutes most, since it has highest marginal benefits from using polluting resources in production.

The issue now, however, is whether $C^n/\beta Y^n$ is smaller or larger than $C^s/\beta Y^s = 1$. For $\tau_k = 0$, $C^n/\beta Y^n > 1$ and the South pollutes more than the North. However, if $\tau_k = -\beta$, $C^n/\beta Y^n > 1$ and the North pollutes more in equilibrium. This latter results is in contrast with the case of exogenous technology in which any tax $\tau_k > -\beta$ caused the South to be a bigger polluter than the North. The difference here is that, with endogenous technology, the North has to devote a part of gross output

[4] Throughout the paper we will indicate ratios with a B superscript.

to innovation. This cost of innovation makes consumption scarcer in the North and makes increases in output more valuable. Hence, the faster the rate of innovation and growth, the higher the incentives for the North to pollute, and the more likely it is that it pollutes more than the southern region, that does not bear the cost of innovation.

6 International trade, directed technical change and pollution havens

In the previous section we have assumed that the only linkage between the two regions occurred via the technological spillovers: the South copies at no cost technology from the North, where research and development activities are carried out. We now introduce international trade in the two goods, the resource-intensive good (Y_R) and the labour-intensive one (Y_L), as a second linkage between the two regions, leaving the rest of the model remains unchanged.

Since the two regions differ with respect to property rights and innovation incentives, they choose different levels of factor supplies as shown above. This asymmetry provides the incentives for international trade, and the country that chooses an abundant supply of pollution tends to have a comparative advantage in resource-intensive goods.

International trade induces shifts in the production structure, which will affect the marginal benefits of pollution, so that environmental policy responds to trade. Moreover, the changes in the production structure also affects the incentives for innovation. As a result, trade, technological change and environmental policy interact, and it is our task in this section to investigate how.

Once goods are traded internationally at zero trade costs, one single price p_i^w for each good $i = R, L$ will prevail at the world level, with the equilibrium world relative price determined by the market clearing condition on the world markets. World supply of goods that use factor $i = R, L$ intensively is given by, see (13):

$$Y_i^n + Y_i^s = \frac{1}{1-\beta} \left(p_i^w\right)^{\frac{1-\beta}{\beta}} N_i \left[(1+\tau_k)^{-\frac{(1-\beta)}{\beta}} S_i^n + \kappa S_i^s \right], \tag{34}$$

respectively, where the term in brackets is the world supply of factor i measured in efficiency terms.

Using (27) one gets the world relative price, given by:

$$\frac{p_R^w}{p_L^w} = \left(\frac{N_R}{N_L} [\lambda S^{Bn} + (1-\lambda) S^{Bs}] \right)^{-\frac{\beta}{\sigma}}, \tag{35}$$

where $\lambda = [1 + \kappa(1+\tau_k)^{(1-\beta)/\beta} L^s / L^n]^{-1}$. The term in brackets appearing on the right hand side is the world supply of pollution relative to labour, measured in efficiency terms and written as a weighted average of the national relative factor supplies S^{Bn} and S^{Bs}.

Substituting (13) and (35) into (22), we can write the resource cost share in country $c = n, s$ under free trade as:

$$\theta_R^{cFT} = \left[1 + \left(\frac{N_R}{N_L} S^{Bc}\right)^{(1-\sigma)/\sigma} \left(\frac{\lambda S^{Bn} + (1-\lambda) S^{Bs}}{S^{Bc}}\right)^{1/\sigma}\right]^{-1}. \qquad (36)$$

For us to analyse the effects of the opening up of international trade on the world economy, it is crucial to understand how prices change in the process. Since we want to separate the pure effect of trade from the effect of directed technological change, which is the main focus of our analysis, we will first consider what happens when technology is assumed to be exogenous. Next, we will move on to analyse the case in which technological change is endogenous.

6.1 Exogenous technology

To investigate the effect of international trade when technology is exogenous, we perform the following experiment, we start from the autarchy equilibrium and consider what happens once we allow for international trade in goods. We assume $\tau_k > -\beta$, which implies that machines use in the North is not excessively subsidized so that the North pollutes less than the South and the South constitutes the pollution haven[5]. The technological bias is assumed to be constant in this subsection: we treat N_R/N_L as a parameter that is the same in both regions and the same in autarchy and free trade.

To determine how the equilibrium supply of pollution changes when moving from autarchy to free trade, we need to know how the marginal costs and benefits of pollution change when opening up to trade. We analyse this by sorting out how the MB and MC curves in Figure 2 shift. Recall that the environmental policy rule for both autarchy and free trade is given by equation (21) whose left-hand and right-hand sides are plotted as a function of S^B in the diagram. Trade does not affect the MC curve while it affects the MB curves only through changes in θ_R. When shifting from autarchy to free trade, θ_R is no longer given by (29) but by (36). Denoting the former by θ_R^{cAUT} and comparing these expressions for given relative supplies in the two regions, S^{Bc} and $S^{B\neg c}$, we see that we have $\theta_R^{cFT} \lesseqgtr \theta_R^{cAUT}$ if $S^{Bc} \lesseqgtr S^{B\neg c}$. This pins down the shifts in the MB curves, that are reproduced[6] in Figure 4. Suppose that S^{BnFT} and S^{BsFT} are the equilibrium relative supplies under free trade in the North and the South, respectively. Then the free-trade-MB curve for North must intersect the autarchy-MB curve for North at S^{BsFT} with a flatter slope (and similarly for the South). But this can only happen if $S^{BnFT} < S^{BnAUT} < S^{BsAUT} < S^{BsFT}$, as can be seen from Figure 4. Hence international trade reinforces the international differences in pollution supply: the polluting region becomes even more polluting and the clean region less so.

The reason for this is that, as trade is opened, resources become less scarce in the world economy than in the less polluting country (the North in our case), thus

[5]Noticethat this assumption is immaterial to the result of this section. We would get the same result assuming fully corrective taxation. Of course in that case the pollution haven would be in the North and the effect of trade would be beneficial to the South and detrimental to the North.

[6]In order to simplify the graph, we magnify the area where the actual crossings occur.

the relative price of resource intensive goods is lower on the world market than in the domestic one. For given S^B, then, θ_R decreases (see expression (22)) and consequently the MB curve shifts down. In this new situation, the environmental regulator finds it optimal to reduce the amount of resources used in production, thus S^B, and pollution, falls. The opposite happens in the pollution-abundant region.

To sum up, in this section we have shown that trade opens up the possibility for the pollution intensive countries to trade with countries that pollute less and that are, therefore, willing to pay a higher price for pollution-intensive goods. Hence, trade makes the abundant factor of production more valuable in each country so that countries with laxer environmental regulations have incentives to relax their environmental standards even more, while countries with lower emissions, further reduce them. This is a well-known mechanism, that we may call the *pollution haven effect* of international trade.

6.2 Endogenous technology

Once we allow for technological change to be driven by the returns to R&D in the different sectors, trade liberalisation influences the world economy through an additional channel. Indeed, in this case price changes act through two different channels, that is through their direct effect on resource use as before, and through the change in the incentives for innovation. In this section, we will show that, under endogenous technological change, liberalising international trade needs not lead to a pollution haven *effect.* Indeed, we will show that, depending on the size of the elasticity of substitution between factors of production, σ, the opposite effect can obtain, i.e. that international trade can actually be beneficial for the environment.

We perform the same experiment as in the previous section, assuming that we start from an autarchy equilibrium where the North is the less polluting region[7], and we proceed to opening up trade.

We first calculate the long-run technology bias. From the no arbitrage condition (17), using (16) and (35), one gets:

$$\left(\frac{N_R}{N_L}\right)^{(1-\sigma)/\sigma} = \left(\frac{\eta_R}{\eta_L}\right)^{1-\sigma} \left(S^{Bn}\right)^{1-\sigma} \left[\lambda S^{Bn} + (1-\lambda) S^{Bs}\right]^{-(1-\sigma)/\sigma} . \tag{37}$$

Recall that an increase in $(N_R/N_L)^{(1-\sigma)/\sigma}$ implies resource-saving technological change, i.e. technological change that increases the production elasticity of resources θ_R, see (36). Equation (37) shows that changes in the relative supply of factor affect the direction of technological change through two terms: $\left(S^{Bn}\right)^{1-\sigma}$, which represents the market size effect, and $\left[\lambda S^{Bn} + (1-\lambda) S^{Bs}\right]^{-(1-\sigma)/\sigma}$ which captures the price effect. For given goods' prices a smaller supply of resources reduces the market for innovations that are used in the resources-intensive sector, profits fall (see (12)), and N_R/N_L declines. The price effect works in the opposite way. If resources become scarcer in the world economy, while the domestic market

[7]In particular we again assume that τ_k is set to zero.

size for resources stays the same - for example because the South reduces resource supply - the prices of resource-intensive goods increase, see (35), and innovation in the resource-intensive sector becomes more attractive relative to that in the labour-intensive sector, see (12). Under autarchy a change in the northern supply of resources has a market size effect and a price effect and the result is that technical change is resource-saving if the supply of resources goes down, see (30). However, this is no longer necessary in the presence of international trade, since now it is the world supply of factors rather than northern one to determine the price effect. As a result a decrease in the northern supply of resources mainly results in a market size effect as the influence of North on world prices is smaller. A decrease in the supply of resources makes innovation in the resource-intensive sector less attractive by the market size effect and this tends to reduce N_R/N_L. Whether this implies resource-using or resource-saving technical change depends on whether resources and labour are gross substitutes ($\sigma > 1$) or gross complements ($\sigma < 1$). In the former case, the shift in innovation raises the effective supply of labour and makes resources less productive so that technical change is resource-saving. In the case of gross complements, instead, the increase in the effective supply of labour raises demand for its complementary factor, resources, so that technical change proves to be resource-using.

Substituting (37) into (36), the expression for the cost share in the long run can be rewritten, for the North, as

$$\theta_R^n = \left[1 + \left(\frac{\eta_R}{\eta_L}\right)^{1-\sigma} \left(S^{Bn}\right)^{1-\sigma} \left(\frac{\lambda S^{Bn} + (1-\lambda)S^{Bs}}{S^{Bn}}\right)\right]^{-1}, \tag{38}$$

and for the South, as

$$\theta_R^s = \left[1 + \left(\frac{\eta_R}{\eta_L}\right)^{1-\sigma} \left(S^{Bn}\right)^{1-\sigma} \left(\frac{S^{Bs}}{S^{Bn}}\right)^{\frac{1-\sigma}{\sigma}} \left(\frac{\lambda S^{Bn} + (1-\lambda)S^{Bs}}{\left(S^{Bn}\right)^{1-\frac{1}{\sigma}}\left(S^{Bs}\right)^{\frac{1}{\sigma}}}\right)\right]^{-1}. \tag{39}$$

We can now analyse how trade affects the supply of pollution in both regions when technology is endogenous. We will proceeed in three steps. First we show that if the North pollutes more (less) than the South in autarchy, this will also be the case in free trade. Second, we show that the North always reduces (increases) pollution supply when opening up to trade if it pollutes less (more) than the South in autarchy. Third, we show that the response of South depends on substitutability: if $\sigma < 1$ and the South pollutes more (less) than the North in autarchy, the South increases (reduces) pollution supply when opening up to international trade; if $\sigma > 1$, the South's response may be reversed. We derive a sufficient condition under which both regions reduce pollution when exposed to international trade.

First, to sort out which region is the most polluting area under free trade and endogenous technology, we could construct a diagram analogous to Fig 3. The cross country marginal costs and benefits should be equalised, as stated in (33). Substituting (38) and (39) into (33), we end up with an expression[8] in S^{Bs}/S^{Bn} and

[8] The details of this derivation and the proof of the result are in the Appendix.

S^{Bn}, which we could plot for given S^{Bn}. Following the same argument as above, it is possible to show that $S^{Bs}/S^{Bn} \gtrless 1$ if $C^n/\beta Y^n \gtrless C^s/\beta Y^s = 1$. Our conclusion for free trade is therefore similar to the one we had under exogenous technology: the country with the lowest consumption share out of gross output pollutes the most, because it has the highest marginal benefits from using polluting resources in production, and this happens irrespective of the trade regime.

Second, we will consider what happens in the North when it opens up to trade. We construct a diagram similar to Fig 4 to sort out how the marginal benefits and costs of pollution shift once trade is introduced and when technology is endogenous. Recall that the environmental policy rule for both autarchy and free trade is given by equation (21) whose left-hand and right-hand sides were plotted as a function of S^B in the diagram. Trade does not affect the MC curve and affects the MB curves only by affecting θ_R. When shifting from autarchy to free trade, θ_R is no longer given by ((31) but by (38). Denoting the former by θ_R^{nAUT} and comparing these expressions for given relative supplies in the two regions, S^{Bn} and S^{Bs}, we see that we have $\theta_R^{nFT} \lesseqgtr \theta_R^{nAUT}$ if $S^{Bn} \lesseqgtr S^{Bs}$. This pins down the shift in the MB curve. From the previous step we know when S^{Bn} is smaller than S^{Bs} or not. In particular, suppose $C^n/\beta Y^n > 1$ so that $S^{Bn} < S^{Bs}$. Then the free trade cost share is below the autarchy cost share and the North pollutes less under free trade than under autarchy. By the same token, if $C^n/\beta Y^n < 1$ so that $S^{Bn} > S^{Bs}$, free trade induces the North to pollute more. Notice that this conclusion is the same as with exogenous technology: if the North is the pollution-scarce region, trade leades the North to cut (expand) the supply of pollution even further.

Third, we will consider what happens in the South when it opens up to trade. To make things concrete, let us start with the case in which the South is the pollution-abundant country ($S^{Bn} < S^{Bs}$ both in autarchy and free trade - this requires $C^n/\beta Y^n > 1$) and sort out how the curves representing the marginal benefits and costs of pollution (defined by the left-hand and right-hand side of (21), respectively) change through trade. Trade does not affect the MC curve and, once again, affects the MB curves only through θ_R. From (39) and (32), we see that

$$\theta_R^{sFT} \lesseqgtr \theta_R^{sAUT} \text{ if } [\lambda S^{Bn} + (1-\lambda)S^{Bs}] \gtrless (S^{Bn})^{1-\frac{1}{\sigma}}(S^{Bs})^{\frac{1}{\sigma}}$$

As long as $\sigma < 1$ and $S^{Bn} < S^{Bs}$, we have $[\lambda S^{Bn}+(1-\lambda)S^{Bs}] < (S^{Bn})^{1-\frac{1}{\sigma}}(S^{Bs})^{\frac{1}{\sigma}}$ so that $\theta_R^{sFT} > \theta_R^{sAUT}$. This implies that trade raises the marginal benefits of pollution for the South, so that it will increase pollution supply. Similarly, if $\sigma < 1$ and $S^{Bn} > S^{Bs}$, trade will induce the South to pollute less. The conclusion for the case of gross complementarity is therefore the same with endogenous and exogenous technology: trade makes the abundant factor of production more valuable in each country so that countries with laxer environmental regulations have incentives to relax their environmental standards even further, while countries with lower emissions will reduce them even more (the pollution haven effect). Endogenous technology does not change this conclusion for the following reason. When opening up to trade, the North increases production in the sector that employs the abundant factor. This redirects innovation to this sector and thus increases the effective supply of this factor in the world economy. Since the two factors are poor substitutes, the other factor will thus become more valuable in production so that the South, which already had a comparative advantage in production with this other factor, has an incentive to focus even more on this other factor by adjusting factor supply. Hence, technological change reinforces the specialization tendencies that are already induced by trade *per se*.

Things are more complicated when we consider the case where $\sigma > 1$. Under this circumstances it is actually possible that both countries pollute less in free trade than in the autarchy equilibrium. Let us first give a sufficient condition under which this happens before we say something on the more general case. Suppose $C^n/\beta Y^n > 1$ so that $S^{Bn} < S^{Bs}$ both in autarchy and free trade; that is the South constitutes the pollution haven. Furthermore, assume that $\sigma > 1/1-\lambda > 1$. This implies that $[\lambda S^{Bn} + (1-\lambda)S^{Bs}] > (S^{Bn})^{1-\frac{1}{\sigma}}(S^{Bs})^{\frac{1}{\sigma}}$ for any $S^{Bn} < S^{Bs}$ so that $\theta_R^{sFT} < \theta_R^{sAUT}$. Then the marginal benefits of pollution for the South are lower under free trade than under autarchy and the South reduces its pollution supply when opening up. Figure 5 illustrates this case. In general in order for the two countries to reduce pollution we need the following. First, $C^n/\beta Y^n > 1$. This implies $S^{Bn} < S^{Bs}$ and is required for the North to reduce pollution (see above). Second, we need $[\lambda S^{Bn} + (1-\lambda)S^{Bs}] > (S^{Bn})^{1-\frac{1}{\sigma}}(S^{Bs})^{\frac{1}{\sigma}}$ so that the resource share in the South is lower with free trade than in autarchy. This requires λ small, σ large, or S^{Bs}/S^{Bn} large.

Since S^{Bs} and S^{Bn} are endogenous, nothing more can be said from an analytical point of view. For this reason we resort now to a numerical example. In Figure 6 we present the results of a simulation exercise aimed at analysing the effect of changes in σ on the equilibrium level of S^{Bn} and S^{Bs}, under autarchy and under free trade. The parameters values we used[9] were such that $C^n/\beta Y^n > 1$, so that the pollution haven obtains in the South, and that $(1-\lambda)^{-1} = 2.67$. The curves behave accordingly to our prediction, for values of σ smaller than unity, the North reduces its pollution to labour ratio while the South tends to pollute more. As σ increases the latter pattern becomes less and less pronounced until also the South starts polluting less. From the picture we see that indeed $\sigma > (1-\lambda)^{-1}$ is only a sufficient condition for pollution in the South to decrease when moving from autarchy to free trade. The southern pollution to labour ratio under free trade (the thick dotted line) in fact falls below its autarchy level for a value of σ around 1.7, well below the critical value of 2.67.

Intuitively, trade can only induce the South to pollute less in the case it is pollution abundant, if technological change is resource saving and sufficiently strong to offset the *terms-of-trade effect* (or *pure-trade effect*). The pollution-abundant South has an incentive to increase pollution supply as the terms of trade move in favour of pollution-intensive goods when opening up to trade (this is the pure trade effect). At the same time, trade induces the North to specialize in L-intensive goods and innovate more in this sector than in autarchy. This is a resource-saving technological development if L-intensive goods are gross substitutes for R-intensive goods. Then, a given increase in pollution anywhere in the world increases output

[9]For the simulations, the following values of the parameters were used: $L^n = L^s = 1, \bar{E} = 10, \eta_L = 1.5, \eta_R = 2, \beta = 0.2, \rho = 0.01, \sigma_c = 0.5, \phi = 5, \kappa = 0.6, \tau_k = 0$.

less than under autarchy, which reduces the incentives to pollute (this is the *induced technology effect*). If the induced technology effect dominates the pure trade terms-of-trade effect, pollution is reduced in the South.

To see under which circumstances the induced technology effect is strong enough, we need to go back to (37), which links changes in technology to changes in factor supplies in both regions. Resource-saving technological change requires an increase in $(N_R/N_L)^{(1-\sigma)/\sigma}$. Before technology adjusts, the pure trade effect causes the North to pollute less and the South more. This affects innovation incentives in the North through the market size and the price effects. The market size for innovations in the L-sector increases so that innovation rises in this sector. The price effect is small (as compared to a closed economy): the North reduces pollution supply which tends to increase the price of pollution-intensive goods, but this increase is offset by the rise in pollution supply in the South. The price effect makes innovation in the R-sector more attractive, but, on balance, innovation shifts to the L-sector if the price effect is small. If σ is larger than one this decrease in N_R/NL is resource saving. Once both the North and the South adjust their policies in response to the technological change, this triggers new market size and price effects. With resource-saving technological change both regions face lower marginal benefits of pollution and thus reduce pollution supply. This reinforces the market size effect (innovation in the R-sector in North becomes less attractive since S^{Bn} falls), but also the price effect, which has an opposite effect on innovation: pollution becomes scarcer in the world economy, which might give the North an incentive to shift innovation to the R-sector. The incentives only remain in the direction of resource-saving technological change if the price effect remains limited relative to the market size effect. This requires a large elasticity of substitution (σ large) or a large share of the South in the world economy (λ small). A large elasticity of substitution implies small price responses to changes in factor supply. Since the South is the pollution-abundant country, a high share of the South in the world market (λ small) implies that world supply of pollution remains high relative to supply in the North, which keeps the prices of pollution-intensive goods low, thus reducing the price effect.

7 Concluding remarks

In this paper we have discussed the role of endogenous technology and technology spillovers in explaining cross country differences in pollution and in influencing the pollution haven effect of international trade. We have presented a North-South trade model in which the only asymmetry is to be found in the imperfect enforcement of intellectual property rights in the South. We have modelled endogenous technology, in the spirit of Acemoglu [1], as being determined by the relative profitability of innovations complementing different factors of production. Given the lack of patent protection in the South and the necessity to recoup sunk costs incurred to develop the new technologies, R&D only occurs in the North and the new technologies will be adopted (at no cost) in the South. Contrary to the previous literature on pollution havens we have ruled out both differences in environmental stringency through income effects and in factor endowments both of which may give raise to pollution havens. Instead, we have completed the model by introducing environmental regulators choosing national environmental policies by trading off the income gains from a rise in pollution against the disutility from additional pollution.

Our results provide some new answers to the question why the South may choose a different degree of environmental protection than the North, i.e. why a pollution haven is likely to arise in one of the two regions. Differences in environmental stringency arise in our framework from the fact that firms are innovating in the North but not in the South. Two opposing effects result from this asymmetry. First, intermediate goods are sold at monopoly prices in the North, while they are sold at competitive prices in the South. Northern producers are protected by patents and must recoup the cost of innovation, whereas southern producers cannot wield any monopoly power due to the lack of property rights. Hence, intermediate goods are expensive relative to final consumption goods in the North, but cheap in the South, and a larger fraction of production is allocated to consumption in the North than the South. In our model, moreover, consumers do not only care about not final consumption of goods but also about a the quality of their environment. Since consumption goods are relatively abundant in the North, the demand for environmental quality in the North is higher than in the South, where produced consumption goods are scarce. A second implication of the asymmetry in intellectual property rights protection is that North can profitably allocate production factors to research activities, while in the South such activities are not profitable due to costless imitation. Production factors are thus more productive in the North than in the South and any environmental policy that reduces output has a higher cost, since it not only directly reduces consumption but also depresses future consumption by lowering the incentives to innovation. Hence, the North has lower incentives to clean up the environment by cutting pollution and output, because it comes at the expense of innovation. In our analysis we have found that, if the monopoly prices set by intermediate goods producers are not corrected through policy, the monopoly distortion dominates and the North finds it optimal to pollute less than the South. However, if corrective subsidies are used, the North finds it optimal to pollute more than the South.

The results of our analysis, also provide some new answers to the question whether international goods trade induces pollution to increase in countries that pollute relatively more under autarchy. Without endogenous technology, the answer is usually affirmative: trade induces countries to specialize in the production of goods that use intensively the factor that is more abundant, and it increases the reward to this factor. Trade provides the incentive to increase pollution if this is the abundant factor, since the marginal benefits from using this factor in production increase due to the specialisation. Thus trade in goods not only induces specialization in production, but also specialization in factor supply. With endogenous technology, this effect may change. If trade induces resource-saving technological change, the pollution-abundant country may have an incentive to reduce pollution. The bias of technical change is endogenous in our model, and is determines by the innovation incentives for northern intermediate goods producers, who only make profits in the North (they cannot sell in the South due to lack of intellectual property rights protection). If the North pollutes less than the South in autarchy, it moves away from pollution-intensive goods when opening up to trade. Thus innovation in sectors that produce resource-intensive goods becomes less attractive, since the market becomes smaller. Innovation thus increases the supply of labour-intensive goods in the world. This is only resource-saving if these goods are gross substitutes for the resource-intensive goods for which the South has a comparative advantage. Indeed, if resource-intensive and labour-intensive goods are gross substitutes and the North is cleaner than the South, trade may induce the South to pollute less, despite its comparative advantage in polluting goods. In contrast, if the goods are gross complements, the North brings to the world market new goods which require pollution-intensive goods as complements, so that the demand for the latter type of goods increases, and the South has an incentive to increase pollution. As a key result, we therefore find that technology spillovers from the clean North to the dirty South are not necessarily good for the environment in the South, since they may induce an increase in the demand for pollution rather than reduce emissions.

Many topics are left for future research. For example, we have not considered the dynamics of pollution over time in the two countries, nor did we discuss how the tax on the intermediate goods in the North is determined, both of which could be interesting extensions to the present paper. Furthermore, we assumed that both regions adjust policy, it might be interesting to consider alternative policy settings, for example fixed pollution taxes, or fixed pollution quota in one of the countries.

References

[1] Acemoglu, D. [2002] "Directed Technical Change", *The Review of Economic Studies*, 69, 781-809.

[2] Acemoglu, D. and F. Zilibotti [2001] "Technological Differences", *The Quarterly Journal of Economics*, 116, 563-606.

[3] Ben Youssef, S. [2003] "Transboundary Pollution, R&D spillovers and International Trade", *FEEM working paper* 39.2003.

[4] Bovenberg, L. A. and S. Smulders [1995] "Environmental Quality and Pollution-augmenting Technological Change in a Two-sector Endogenous Growth Model", *Journal of Public Economics*, 57, 369-391.

[5] Copeland, B. R. and M. S. Taylor [2003] *Trade and the Environment: Theory and Evidence*, Princeton, NJ: Princeton University Press.

[6] Golombek, R. and M. Hoel [2003] "Climate Policy under Technology Policy", *FEEM working paper* 38.2003.

[7] Rivera-Batiz, L. A. and P. M. Romer [1991] "Economic Integration and Endogenous Growth", *Quarterly Journal of Economics*, 106, 531-555.

A Appendix

Proposition 1. *Irrespective of the trade regime, the pollution to labour ratio in the North (S^{Bn}) will be smaller (larger) than the ratio prevailing in the South (S^{Bn}), depending on whether $1/\beta(C/Y)^n$ is larger (smaller) than unity.*

Proof. First of all, remmember that, from (33), we can rewrite the ratio of the policy rules in the two regions as

$$\left(\frac{C^n}{\beta Y^n}\right)\frac{\theta_R^s}{\theta_R^n} = X\frac{\bar{E}/L - S^{Bs}}{\bar{E}/L - S^{Bn}X}, \tag{A.1}$$

where we let $X \equiv S^{Bs}/S^{Bn}$ to simplify the notation. To prove the proposition we need to show that (A.1) will have a solution such that $X > 1$ if $C^n/\beta Y^n > 1$, irrespective of the trade regime.

Let us start with the autarchy case. In this case we can rewrite the left hand side of(A.1) as follows:

$$\left(\frac{C^n}{\beta Y^n}\right)\frac{\theta_R^s}{\theta_R^n} = \left(\frac{C^n}{\beta Y^n}\right)\frac{1+(S^{Bn})^{1-\sigma}}{1+(S^{Bn})^{1-\sigma}X^{(1-\sigma)/\sigma}}. \tag{A.2}$$

We start by noticing that the expression in (A.2) is strictly increasing and strictly concave in X for $\sigma > 1$, and strictly decreasing when $\sigma < 1$. Inspection of the right hand side of equation (A.1) shows, instead, that it is strictly increasing and strictly convex in the X ratio. Furthermore the slope of $\left(\frac{C^n}{\beta Y^n}\right)\theta_R^s/\theta_R^n$ goes to infinity as X approaches zero, while the slope of the right hand side of (A.1) goes to zero. This establishes that the two curves intersect only once for positive X and that $\left(\frac{C^n}{\beta Y^n}\right)\theta_R^s/\theta_R^n$ will cross the right hand side form above.

When X equals one we know that (A.2) is equal to $1/\beta(C/Y)^n$, while the expression on the right hand side of (A.1) equals one. Thus if $1/\beta(C/Y)^n > 1$ the right hand side will still be below (A.2) for $X = 1$, implying that the two lines will cross at a point where $X > 1$ or, which is equivalent, where $S^{Bs} > S^{Bn}$. The opposite clearly happens if $1/\beta(C/Y)^n < 1$. This proves the claim for the case of autarchy.

Let us now consider the case of free trade under endogenous technology. In this case we can rewrite the left hand side of (A.1) as

$$\left(\frac{C^n}{\beta Y^n}\right)\frac{\theta_R^s}{\theta_R^n} = \left(\frac{C^n}{\beta Y^n}\right)\frac{1+(S^{Bn})^{1-\sigma}\left[\lambda+(1-\lambda)X\right]}{1+(S^{Bn})^{1-\sigma}\left[\frac{\lambda+(1-\lambda)X}{X}\right]}. \tag{A.3}$$

This expression is strictly increasing and strictly concave in X irrespective of σ, so that also in this case at most one intersection occurs in the positive orthant. Whenever the two lines actually cross, the same reasoning as before goes true. Indeed, as long as $1/\beta(C/Y)^n > 1$ the slope of (A.3) is steeper than that of the right hand side of (A.1) and, moreover, it will still be above the right hand side for $X = 1$, thus are claim is maintained also in this case. When $1/\beta(C/Y)^n$ decreases, the graph of (A.3) pivots clockwise around the origin, when it goes below unity the two curves will cross at a point where $X < 1$. This concludes our proof.

Finally, we want to remark that, as $1/\beta(C/Y)^n$ decreases, the equilibrium level of X tends to zero. For $1/\beta(C/Y)^n$ small enough, finally, the rotation of (A.3) around the origin will make its slope at the origin smaller than the one of the right hand side of (A.1). When this happens the two lines will only cross at the origin and no resources are used for production in the South. □

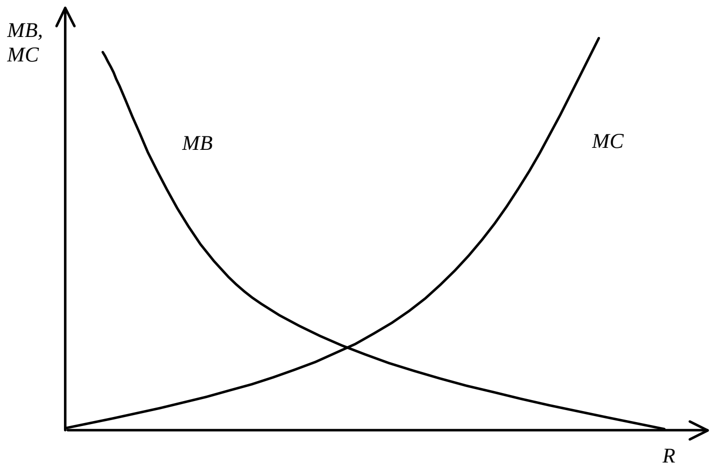

Figure 1: *The marginal benefits and marginal costs of pollution*

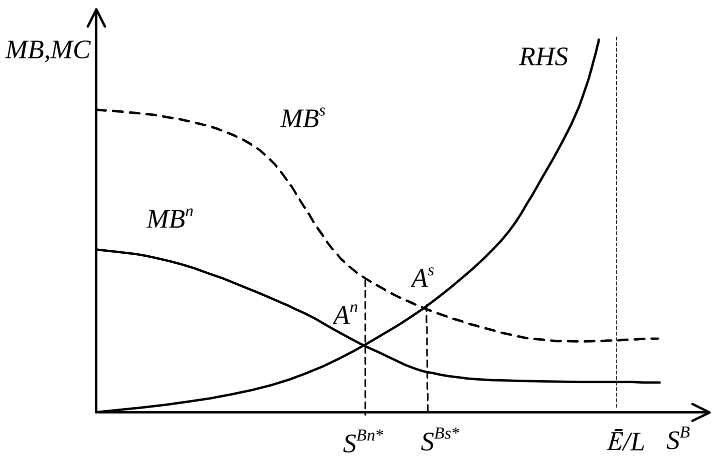

Figure 2: *Equilibrium under autarchy*

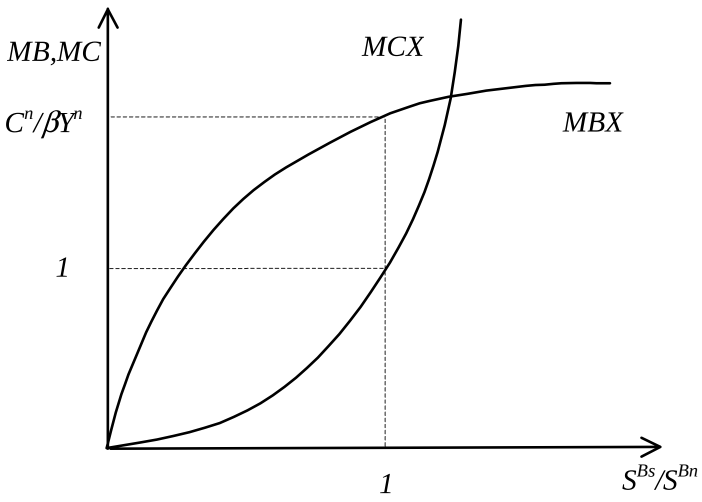

Figure 3: *Cross-country relative pollution supplies.*

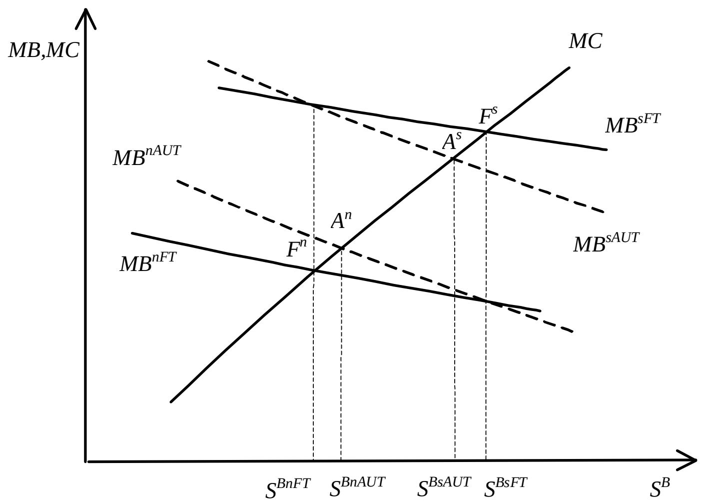

Figure 4: *Equilibrium under free trade: exogenous technology*

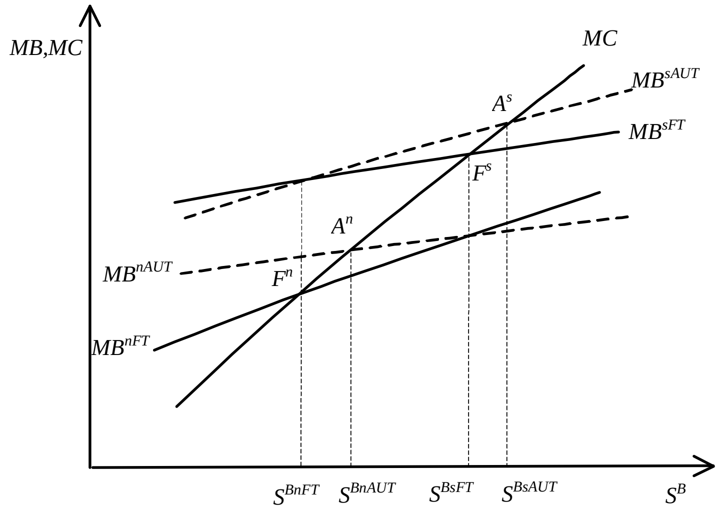

Figure 5: *Equilibrium under free trade: endogenous technology*

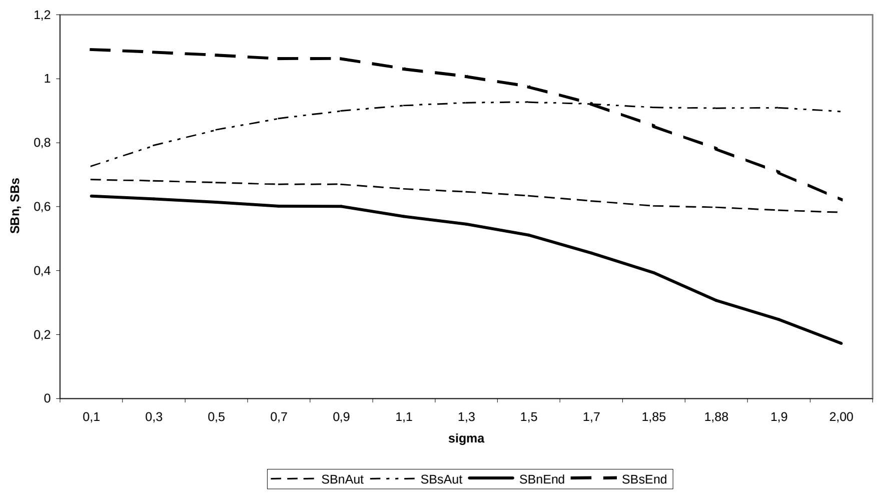

Figure 6: *Simulation results: pollution to output ratios in the two regions under autarchy and free trade*