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THE POLLUTION HAVEN HYPOTHESIS

Trade Pessimists vs Technology Optimists: Induced Technical Change and Pollution Havens

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Trade Pessimists vs Technology Optimists: Induced Technical Change and Pollution Havens*

Corrado Di Maria and Sjak A. Smulders

Abstract

Our paper focuses on the role of endogenous technology and technology spillovers in explaining cross country differences in pollution and the pollution haven effect of international trade. In our North-South trade model, technology is endogenously developed by the North and imitated by the South. Environmental regulators choose national environmental policies by trading off the income gains and the disutility from a rise in pollution. Differences in environmental stringency are entirely driven by differences in investment opportunities and distortions that follow from the difference in intellectual property rights protection. We show that without goods trade and in the absence of technology subsidies, the North imposes more stringent environmental regulation than the South. When opening up to trade, the South experiences a rise in prices for pollution-intensive goods and tends to raise pollution as in a standard trade model. Induced technical change, however, may reverse this pollution haven effect.

KEYWORDS: Pollution Havens, Endogenous Technical Change, International Trade

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In the debate on pollution havens, trade pessimists disagree with technology optimists.¹ From the perspective of standard trade theory, the international flows of goods and investment across countries with different environmental standards are likely to concentrate pollution in countries with lax environmental regulations; these countries acquire a (real or apparent) comparative advantage in pollution-intensive activities. The natural concern is that international trade would allow rich countries in the North to clean up their environment at the expense of environmental quality in poorer countries in the South. Opposite to this view is the argument that pollution in different countries is much more technology-driven than trade-driven: while trade liberalization has been important over the last decades, the role of technological change in determining trade patterns and income levels has been at least as important. Technology transfer by multinational firms and the diffusion of clean technologies are often claimed to be a powerful counterbalance to the pollution haven tendencies. When trade induces the North to specialize in clean production, it might also shift its innovation efforts towards cleaner technology. If this technology diffuses to the South, the environment might benefit.

This paper formalizes the interconnection between trade, technological change, and environmental regulation. We model two regions which we call the North and the South. Each region produces two tradable goods, with pollution stemming from only one of them. In both regions local environmental regulators choose environmental policy by trading off the income gains from a rise in pollution against the disutility due to the lower environmental quality. Regulators, households and firms all take prices as given, with the exception of producers of intermediate goods in the North. They set their own price and invest in new technology to maximize profits. A fraction of these new technologies diffuse to the South since firms there can copy technologies at no cost.

We show that indeed trade may induce the North to develop pollution-saving technologies and the South to reduce pollution, thus reversing traditional reallocation and specialization effects from trade. However, such support for technology optimism is not the only possible outcome. If it is hard to find substitutes for pollution-intensive goods, an increase in innovation efforts by the North in clean sectors results in an increased demand for pollution-intensive goods from the South; in this case, trade induces pollution-using technical change and the induced technology response to trade reinforces the incentive for South to increase pollution. Low substitution thus results in technology pessimism.

Our analysis involves two main steps. First, we study how costs and benefits of environmental policy in the innovating region differ from those in the imitating region. The resulting differences in environmental stringency provide one of the regions with a comparative advantage in pollution-intensive production as a basis for trade. Second, we study whether international trade leads to more or less pollution in the South when the technologies developed in the North diffuse to the South. We identify two effects by which trade affects environmental policy: The conventional *terms of trade effect*, by which trade

¹For a comprehensive review of this literature see, for example Zarsky (1999). Antweiler et al. (2001) and Copeland and Taylor (2004) provide a thorough discussion of the role on international trade on the environment, both from the theoretical and the empirical point of view.

affects domestic producers' prices and induces them to reallocate production according to comparative advantage; and the *induced technology effect*, which arises since trade affects profits in the two sectors in the North so that innovation effort shifts from one sector to another. This affects the mix of technologies that are available not only in the North, but also - through imitation - in the South.

The existing literature mainly focuses on trade aspects, identifying different sources of comparative advantages. First, if environmental quality is a normal good, increases in the level of income will induce a higher demand for environmental quality. Richer countries will thus tend to have more stringent environmental regulation relative to poorer countries, and to develop a comparative advantage in the production of less polluting goods (see Cole (2004)). Second, the comparative advantage for the South in the polluting (resource-intensive) sector may arise as a consequence of ill-defined property rights on the common pool resource (as in Chichilnisky (1994)). As South does not regulate access to resources, it over-exploits them, leading to the emergence of an apparent comparative advantage vis-à-vis an otherwise identical country. Finally, comparative advantage in pollution-intensive production may originate from differences in the relative endowments of productive factors (Copeland and Taylor (2004)). If capital-intensive goods are also relatively more pollution-intensive, and rich countries are relatively more endowed with capital, they might enjoy a comparative advantage in the pollution-intensive good. This might explain the fact that most production of pollution-intensive goods takes place in developed countries, in spite of their stringent regulation.

We complement this literature with our finding that differences in investment-innovation opportunities and distortions between the innovating North and the imitating South provide a source of comparative advantage in pollution-intensive goods. We isolate this effect by abstracting from the sources of comparative advantage discussed in the previous paragraph. In particular, our assumptions on preferences imply that being richer does not lead *per se* to more stringent environmental policy; we assume that the property rights on the resource base are perfectly defined and enforced; and that the relative factor endowments are identical across regions. Instead, in our setting comparative advantage stems from the difference in enforcement of intellectual property rights in the two regions: the North protects innovators and generates innovation, the South cannot protect innovators and imitates technology from the North.²

By almost exclusively relying on trade theory, the theoretical literature on the pollution haven hypothesis seems to have placed insufficient weight on the technology aspects of the debate. Indeed, there is also a small literature that deals with endogenous innovation and pollution havens, e.g. Golombek and Hoel (2004) and Ben Youssef (2003). We differ from these papers in that we do not assume *a priori* that technological change always results in cleaner production. Instead we derive the nature of technological change endogenously from profit incentives (following Acemoglu's (2002) theory of directed technological change). We also differ from these papers by allowing firms, rather than a planner, to

²To avoid confusion, notice that here we refer to intellectual property rights protection, while the above discussion refers to resource property rights.

decide on innovation, so that innovation externalities and second-best policies play a role.

The organization of the paper is as follows: section 1 introduces the model, while section 2 discusses the equilibrium. In particular, we address environmental regulation in section 2.5. Section 3 discusses the pure terms of trade effect by modelling innovation opportunities such that trade induces neither pollution-saving nor pollution-using technical change. Section 4 is instead devoted to the analysis of the induced technology effect. Finally, in section 5 we collect and compare our main results and conclude the paper.

1. The Model

Our economy is made up of two regions, each comprising a set of small countries, which we call the North and the South. These two regions only differ in the institutions regulating intellectual property rights (IPR's) protection. In particular, we assume that IPR's are perfectly enforced in the North, while they are not enforced in the South.

The economy admits a representative consumer who derives utility (U) at each moment in time from produced consumption goods, C , and from environmental quality, $E = \bar{E} - R$, where $\bar{E}$ is the maximum level of environmental quality and R is resource use. Here we view environmental quality as the amount of natural resources ($\bar{E}$) not devoted to productive use (R) at each point in time. We model it as a flow variable, since at every moment in time it returns to its maximum level, $\bar{E}$. Hence, our variable R represents pollution, or more precisely, extractive use of natural resources - clean water and clean air, say - for use in production. We specify the following (intertemporal) CRRA utility function:

$$(1) \quad \int_0^{\infty} \frac{(C(t)(\bar{E} - R(t))^{\phi})^{1-\zeta} - 1}{1-\zeta} e^{-\rho t} dt,$$

where ρ is the rate of time preference and ζ is the inverse of the intertemporal elasticity of substitution.³

Each consumer maximizes the utility in (1) subject to the budget constraint⁴:

$$(2) \quad C + M + D \leq Y \equiv \left(Y_L^{\frac{\varepsilon-1}{\varepsilon}} + Y_R^{\frac{\varepsilon-1}{\varepsilon}} \right)^{\frac{\varepsilon}{\varepsilon-1}},$$

where M is physical investment (machines), and D is the total amount of research and development (R&D) expenditure. The production function in (2) shows that final output (Y) 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 (2) states that consumption, investment and R&D expenditure are all the possible uses of the final good.

³As is usual in growth theory, the Cobb-Douglas/CRRA structure allows for a balanced growth path with constant environmental quality and a constant rate of growth of consumption. We touch again on this issue on page 11 below. For a complete discussion see Bovenberg and Smulders (1995).

⁴To simplify notation, as long as no confusion arises, we suppress time arguments from now on.

The pollution-intensive good (Y_R) is produced using resources and a set of differentiated man-made inputs which we refer to, for simplicity, as “machines”, $m_R(j)$. The range of machines that can be used to produce pollution-intensive goods 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:

$$(3) \quad Y_R = \frac{1}{1-\beta} \left(\int_0^{N_R} m_R(j)^{(1-\beta)} dj \right) R^\beta,$$

and

$$(4) \quad Y_L = \frac{1}{1-\beta} \left(\int_0^{N_L} m_L(j)^{(1-\beta)} dj \right) L^\beta.$$

For simplicity we have modeled pollution, R , as an input. Stokey (1998) has shown, however, that the Cobb-Douglas specification in (3) can be seen as the reduced form of a technology with pollution as an output and abatement possibilities. The key property is that a reduction of pollution can be achieved either by a reduction of market output or by an increase in machine inputs.

Technological change arises from costly innovation: private firms invest in R&D labs in which blueprints for new machine varieties are developed (as in Rivera-Batiz and Romer (1991)). Since the R&D stage has to be finished before production of new machines can take place, R&D costs are sunk. As a consequence, only innovators who expect to wield some monopoly power in the future will actually engage in R&D activities. This means that innovation will only take place in the North, where intellectual property rights are protected, while southern producers are able to copy these innovations.

Since R&D generates new blueprints, the total range of machines, N , increases with R&D investments, D . We consider two alternative specifications. In the first, R&D decisions affect the rate at which new blueprints are developed, but innovators cannot know in advance in which of the two sectors their specific innovation will prove most useful. In this case, which we label as “undirected technical change”, blueprints in sector i expand at the following rate:⁵

$$(5) \quad \dot{N}_i = \frac{\gamma_i D}{(N_R + N_L)^\psi / \eta},$$

where D is total R&D investment in the economy and the γ_i is the exogenous probability ($\gamma_R + \gamma_L = 1$) that an individual researcher’s effort results in a successful new machine design for sector i . The denominator at the right-hand side of (5) represents the “difficulty of R&D” (cf. Segerstrom (1998)), which depends on two opposing effects. On the one hand, we assume that the more innovations in any sector already have been generated, the harder it is to come up with the next innovation. We capture this by the factor $(N_R + N_L)^\psi$, where $\psi > 0$. On the other hand, new innovation opportunities may arise exogenously

⁵Throughout the paper dotted variables indicate time derivatives, that is, $\dot{x} = dx/dt$.

over time. This can be viewed as reflecting any kind of innovation not driven by sector-specific profit incentives. We capture the level of innovation opportunities by parameter η , which we assume to grow at an exogenous rate ψg .⁶

In our second specification of innovation possibilities, technical change is directed, following Acemoglu (2002), so that innovators can target their efforts at a specific sector, and blueprints in sector i expand at the following rate:

$$(6) \quad \dot{N}_i = \frac{D_i}{(N_R + N_L)^\psi / \eta}.$$

While the denominator is the same and motivated by the same arguments as in (5), the rate of innovation in each sector depends on the total R&D effort taking place in it, D_i , with $D_L + D_R = D$.

Although we think the directed technical change variant is more realistic, contrasting undirected to directed technical change allows us to disentangle the terms of trade effect and the induced technology effect.

Finally, we assume that labour supply is exogenously fixed at L , while the environmental regulator in each country puts an endogenously determined cap on pollution R .

2. Equilibrium

Firms maximize profits and households maximize utility. They all take as given prices and factor rewards, with one notable exception: producers of machines in the North can set their own price as they operate under monopolistic conditions. Finally the environmental regulator in each country maximizes the utility of the representative agent by choosing the nation-wide level of pollution (resource supply), taking as given international prices. All markets clear and the resource constraint is satisfied. The final good is chosen as the numeraire.

In what follows we 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 output, consumption, investment and R&D outlays, as well as N_R and N_L , all grow at the (exogenous) rate g .⁷

⁶Assuming $\psi = 0$, we would have an endogenous growth model, in which the long-run growth rate is endogenous. Although generating very similar results, the fully endogenous growth version of this model involves a more complicated analysis so that we ignore it here.

⁷With constant factor supply R and L , the constant returns to scale production functions (2)-(4) imply that output grows at the same rate as N_R and N_L . The goods market equilibrium condition (2), moreover, requires Y , C , M and D to grow at a common rate. The innovation functions (5) and (6) imply that the growth rate of N_i can be constant only if $(N_R + N_L)^\psi / \eta$ is constant (cf. Jones (1995)). Hence, the growth rate of this economy equals $(\dot{N}_i / N_i) = (\dot{\eta} / \eta) / \psi = g$. Given the choice of the final good as numeraire, prices are constant along the balanced growth path.

2.1 Intermediate Goods and Machines

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

$$(7) \quad \max_{S_i, \{m_i(j)\}} p_i Y_i - w_i S_i - \int_0^{N_i} p_{m_i}(j) m_i(j) dj,$$

subject to the production functions (3) and (4), and taking as given goods' prices p_i , machine prices $p_{m_i}(j)$, and factors' prices w_i .⁸ The demands for machines resulting from the above maximization are:

$$(8) \quad m_i(j) = \left(\frac{p_i}{p_{m_i}(j)} \right)^{\frac{1}{\beta}} S_i.$$

Consider first the supply of machines in the North. Since intellectual property rights are perfectly enforced, ownership of blueprints allow northern producers to act as monopolists. Assuming that v units of the final good are required to produce each machine and that machine production is subsidized at rate τ_m , the expression for the profits of a monopolist supplying the i -complementary machine j is given by $\pi_i(j) = (p_{m_i}(j) - v(1 - \tau_m)) m_i(j)$, $j \in (0, N_i]$. Given the demand function in (8), the profit-maximizing price will be set as a mark-up over marginal cost, and will equal $p_{m_i}(j) = v(1 - \tau_m)/(1 - \beta)$. To simplify the algebra, we assume v to be equal to $1 - \beta$, so that $p_{m_i}(j) = (1 - \tau_m)$. Substituting for machine prices and demand functions in the expressions for the profits of the technology monopolist, one gets:

$$(9) \quad \pi_i(j) = (1 - \tau_m)^{-(1-\beta)/\beta} \beta p_i^{1/\beta} S_i.$$

Using machine demands (8) and prices in the sectorial production functions (3) and (4), we obtain the supply functions for northern firms, that we identify with an n superscript:

$$(10) \quad Y_i^n = \left(\frac{1}{1 - \beta} \right)^{1/\beta} \left(\frac{1 - \beta}{1 - \tau_m} \right)^{(1-\beta)/\beta} (p_i^n)^{(1-\beta)/\beta} N_i^n S_i^n.$$

Next, turn to the South. IPR's are not enforced in the South, patent protection is not effective and the sunk costs associated with the development of new blueprints cannot be recouped. This effectively rules out the possibility that a local R&D sector may arise in the South. We assume, though, that southern producers can copy at no cost some of the

⁸For simplicity, we assume that machines depreciate fully after use. As discussed by Acemoglu (2002), assuming slow depreciation of machinery would not change the balanced growth equilibrium path.

blueprints developed in the North. In particular, a fraction $\delta \in (0, 1)$ of the blueprints from North becomes available in the South, so that

$$N_i^s = \delta N_i^n.$$

Diffusion is incomplete due to a time lag between innovation and imitation, or because some blueprints are inherently too complex (and thus too costly) to copy.

As no institutional arrangement protects the monopoly power of machine producers, and no sunk costs prevent copying by more than one producer, perfectly competitive markets ensue. The price of machines in the South will then equal marginal cost: $p_{m_i}(j) = (1 - \beta)$. Substituting machine demands (8) and prices into the sectorial production functions (3) and (4), we obtain:

$$(11) \quad Y_i^s = \left(\frac{1}{1 - \beta} \right)^{1/\beta} (p_i^s)^{(1-\beta)/\beta} \delta N_i^n S_i^s.$$

Comparing (11) and (10), we see that for $\delta < ((1 - \beta)/(1 - \tau_m))^{(1-\beta)/\beta}$, productivity (per unit of factor S_i) is lower in the South than in the North, so that the diffusion parameter δ realistically allows the South to be poorer than the North.

2.2 Final Goods and the Production Elasticity of Pollution

Final goods' producers demand intermediate goods up to the point where marginal productivity equals price. This implies $\partial Y / \partial Y_i = p_i$, which from (2) implies the following relative demand for intermediate goods:

$$(12) \quad \frac{p_R}{p_L} = \left(\frac{Y_R}{Y_L} \right)^{-\frac{1}{\epsilon}},$$

where Y_i represents the demand for intermediate good i .

In the rest of the analysis, the production elasticity of polluting inputs will play a central role. We can write this elasticity as

$$(13) \quad \frac{\partial Y}{\partial R} \frac{R}{Y} = \beta \theta_R = \beta \frac{p_R Y_R}{Y},$$

where we made use of (3) to write $(\partial Y_R / \partial R)(R / Y_R) = \beta$ and we introduced the production elasticity (and cost share) of pollution-intensive goods in final goods production, $\theta_R \equiv (\partial Y / \partial Y_R)(Y_R / Y) = p_R Y_R / Y$. Since the production elasticity of pollution and θ_R move together for any given β , we will find it easier to refer to the latter in the discussion that follows. Moreover, note that since (2) features constant returns to scale, $1 - \theta_R = p_L Y_L / Y$. Using (10) or (11), we can express the relative costs share $p_R Y_R / p_L Y_L$ in each region as:

$$(14) \quad \frac{\theta_R}{1 - \theta_R} = \left(\frac{p_R}{p_L} \right)^{1/\beta} \frac{N_R R}{N_L L}.$$

This reveals that the share of pollution-intensive goods in production, θ_R , depends on relative prices, relative factor supply, and technology.

2.3 R&D and Innovation

Firms in the North have an incentive to innovate whenever innovation earns a rate of return that is at least equal to the market interest rate. This implies the following arbitrage equation for innovator j :

$$(15) \quad \frac{\tilde{\pi}_j}{v_j} + \frac{\dot{v}_j}{v_j} = r$$

where $\tilde{\pi}_j$ is the per period flow of expected revenues (dividends) for the holder of a blueprint j , v_j is the market value of blueprint j , and r is the interest rate. In the model of undirected technical change, expected dividends equal $\tilde{\pi}_j = \gamma_R \pi_R + \gamma_L \pi_L$; in the model of directed technological change they equal $\tilde{\pi}_j = \pi_i$ if j 's effort is directed to sector $i = R, L$.

We assume free entry in research activities, which implies that the value of a blueprint cannot exceed its cost. From (5) and (6), this implies $v_j \leq (N_R + N_L)^\psi / \eta$. In particular, in the undirected technical change model, this condition must hold with equality whenever innovation occurs, that is, whenever $D > 0$; in the directed technical change model, there are two type of innovators, $j = R, L$, and the expression holds with equality whenever innovation occurs in sector j (i.e. whenever $\dot{N}_j > 0$).

In the undirected technical change model, the long-run ratio N_R/N_L equals γ_R/γ_L , as follows from (5). Hence, the relative supply of machine variety only depends on research technology and cannot be affected by e.g. trade. Once in a balanced growth path, only shocks to N_i or γ_i can bring the economy from its balanced growth path. This allows us to treat N_R/N_L as a constant in the undirected technical change model.

In the directed technical change model, along the balanced growth path innovation takes place in both sectors, the cost and value of a blueprint is the same in both sectors ($v_R = v_L$) and to satisfy the condition (15), we must have $\pi_R = \pi_L$. After substitution of (9), this implies the following “no-arbitrage” condition:

$$(16) \quad \left(\frac{p_R}{p_L} \right)^{1/\beta} \frac{R}{L} = 1.$$

The relative profitability of innovations in each sector thus increases with the price of the intermediate good they are used to produce (the price effect), and with the relative supply of the factor they complement (the market-size effect). By these two channels trade or changes in environmental policy affect innovation.

2.4 Households

Households maximize their lifetime utility (1), subject to the usual intertemporal budget constraint. This results in the Keynes-Ramsey rule stating that consumption grows

at a rate proportional to the difference between the interest rate and consumer's rate of time preference.

Along the balanced growth path, consumption and output grow at the same rate, g , so that we may express this equation as:

$$(17) \quad r = \rho + \zeta g.$$

2.5 Environmental Regulation

We assume that the environmental regulator determines the level of pollution in the economy.⁹ We model the regulator assuming that she only aims at correcting the environmental externality from production mentioned above. She chooses the supply of pollution to maximize the utility of the representative agent at each moment in time, taking as given the choices made by the other economic agents in the economy, concerning the level of consumption and of investment in both machines and R&D.

To gain some intuition, we first derive the environmental policy rule in general terms. As in a static context, the maximization of $U(C, \bar{E} - R)$ subject to a budget constraint of the form $C = F(R, \cdot) - D - M$, where D and M are the (given) amounts of investment in R&D and in machines, yields the following first-order condition

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

that we can rewrite, in terms of elasticities, as

$$(18) \quad \left(\frac{\partial Y}{\partial R} \frac{R}{Y} \right) \frac{Y}{C} = \left(\frac{\partial U / \partial E}{\partial U / \partial C} \right) \frac{R}{\bar{E} - R}.$$

This equation balances the marginal benefits from pollution (in the form of additional consumption goods) and its marginal costs (in the form of lower environmental amenities), both measured in terms of consumption.

Equation (18) also shows how the supply of pollution depends, all other things equal, on the production elasticity of polluting inputs, on the consumption to output ratio, and, finally, on the share of environmental amenities in utility. First, a higher production elasticity of resources, $\left(\frac{\partial Y}{\partial R} \frac{R}{Y} \right)$, makes resources more valuable in production and increases the marginal benefits of pollution. In other words, the costs of reducing pollution become larger. Second, a lower consumption to output ratio C/Y increases the equilibrium supply of pollution by increasing its marginal benefits. Intuitively, in an economy with lower consumption per unit of output consumption is perceived as relatively scarce, raising the marginal value of production. Finally, a higher share of amenities in utility, $\frac{(\partial U / \partial E)E}{(\partial U / \partial C)C}$,

⁹We also assume that environmental policy is perfectly enforced in both regions.

increases the marginal costs of pollution, shifts the MC curve up, and hence decreases equilibrium pollution.

We can rewrite (18) noting that the share of environmental amenities equals ϕ , see (1), and that the production elasticity of pollution is given in (13). This yields the following expression for the marginal benefits and the marginal costs of pollution:

$$(19) \quad \underbrace{\frac{\theta_R \beta}{C/Y}}_{MB} = \phi \underbrace{\frac{R/L}{\bar{E}/L - R/L}}_{MC}.$$

Rearranging terms and subtracting R/L from both sides of the previous equation we obtain,

$$\left(\frac{\beta}{\phi C/Y} \right) \frac{\bar{E}}{L} - \left(\frac{\beta}{\phi C/Y} + 1 \right) \frac{R}{L} = \left(\frac{1 - \theta_R}{\theta_R} \right) \frac{R}{L},$$

which we can rewrite, using (14), and letting $\frac{\beta}{\phi C/Y} = \Omega$,¹⁰ as:

$$(20) \quad \Omega \frac{\bar{E}}{L} - (\Omega + 1) \frac{R}{L} = \left(\frac{p_R}{p_L} \right)^{-1/\beta} \left(\frac{N_R}{N_L} \right)^{-1}.$$

This expression will prove more tractable in the analysis that follows than (19), but bear in mind that this condition still states that pollution will be set at a level that equates marginal benefits to marginal costs. We will use this expression to determine the level of pollution chosen by each region's regulator under autarchy and under free trade, and to discuss how these decisions will be influenced by the directedness of technical change.

In the introduction, we pointed out that our model rules out international differences in environmental policy due to differences in income, factor endowments, or resource property right regimes. We do so in order to isolate the effect of endogenous technology from other mechanisms explaining pollution haven effects in the existing literature. Equation (20) reveals how we do this. First, if output and consumption grow at the same rate, $\Omega \equiv \beta/(\phi C/Y)$ is constant over time. With growth, then, the equilibrium supply of pollution must be the same for each level of income. This is due to the Cobb-Douglas specification of the utility function (1), which implies that the larger demand for environmental quality due to higher income is exactly offset by the higher benefit of pollution generated by the increasing productivity of polluting inputs that drives growth. Second, we assume that relative factor endowments, $\bar{E}/L$, and preferences, reflected by ϕ , are the same in both regions. This leaves us with three determinants for the differences in R/L , as shown in equation (20): differences in the consumption-to-output ratio across countries, prices, and technology.¹¹

¹⁰It is important for the analysis that follows to bear in mind that Ω is a constant along the balanced growth path in each country. Yet, its value depends on the country-specific level of C/Y . Thus, a country with more consumption per unit of final output, will have a lower Ω .

¹¹From (20), it is straightforward to see that our analysis using the C/Y ratios can be alternatively carried out through differences in ϕ and $\bar{E}/L$. As long as North has higher ϕ and/or lower $\bar{E}/L$, the analysis is qualitatively similar to the analysis that follows where the North has an higher C/Y ratio than the South.

In the next section we discuss the differences in the C/Y ratios between North and South. We will show that they do not depend either on the trade regime, or on the assumptions concerning the innovation process. With this in mind, we can explain the different outcomes of the model under the different trade regimes in terms of price and technology effects only.

In the remainder of the paper we will be able to separate price and technology effects since we will first focus on undirected technological change - in which case the bias N_R/N_L is exogenous - and later on directed technological change - with the bias N_R/N_L endogenously determined. For each technology regime, moreover, we will discuss and compare autarchy, where prices differ across countries, and free trade, where price equalization obtains.

2.6 The Consumption to Output Ratio

As mentioned above, the consumption to output ratio constitutes one of the central elements of our analysis. Here we provide an expression for this ratio in each country that we can use to substitute into expression (20). The Appendix shows that the C/Y ratio in the South is

$$(21) \quad \left(\frac{C}{Y}\right)^s = 1 - (1 - \beta) = \beta,$$

while its northern homologue is

$$(22) \quad \left(\frac{C}{Y}\right)^n = 1 - (1 - \beta) \left(\frac{1 - \beta}{1 - \tau_m}\right) - (1 - \beta) \beta \frac{g}{r}.$$

Comparing the two expressions above, we note two differences. First, the North will invest less in physical capital, since northern producers of intermediate goods face higher machine prices than their southern counterparts. Indeed, in the North monopolistic competition, fostered by IPR's enforcement, drives prices above marginal cost, while this cannot happen in the South where patent protection is not enforced. This first effect is reflected by the second term on the right-hand side of (22). As long as the monopolistic distortion is not offset by an appropriate subsidy ($\tau_m = \beta$), the North will spend less for machines than the South. Second, the North consumes less than the South out of its gross output, since part of it is invested in developing new technology (research expenditures, the second term at the right-hand side of the equation above). Northern innovators find it profitable to forego some consumption in order to invest in R&D, whereas this is impossible for southern (potential) innovators. It is clear that these two effects work in opposite directions, and that, depending on the level of the subsidy, either of the two can dominate. In particular, it is easy to show that $(C/Y)^n > (C/Y)^s$ whenever $\tau_m < \frac{\beta(r-g)}{r-g\beta}$.

3. Undirected Technical Change

In this section we analyze the pollution supply by the two regions assuming that innovators cannot change the long-run composition of technology N_R/N_L . We analyze both the autarchy case, where the only interdependence between the two regions stems from the international diffusion of technology, and the free trade situation. In this context the only effect of trade is through changes in prices. This section will provide us with a benchmark for the analysis of the directed technical change case, in the following section.

3.1 Autarchy

Under autarchy, domestic relative demand for final goods equals domestic supply. Substituting supply (10) or (11) into the expression for demand (12), we find that the domestic price ratio is given by the following function of relative factor supply and technology:

$$(23) \quad \frac{p_R}{p_L} = \left(\frac{N_R R}{N_L L} \right)^{-\beta/\sigma},$$

where $\sigma = 1 + (\varepsilon - 1)\beta$ is the elasticity of substitution between R and L in aggregate production. Substituting this into (20), we obtain the following expression that determines pollution supply under autarchy:

$$(24) \quad \Omega \frac{\bar{E}}{L} - (\Omega + 1) \frac{R}{L} = \left(\frac{N_R}{N_L} \right)^{\frac{1-\sigma}{\sigma}} \left(\frac{R}{L} \right)^{\frac{1}{\sigma}}.$$

We have thus obtained a (relatively) simple equation in the relative factor supply only. We note that $\bar{E}/L$, N_R/N_L , and σ are the same across countries, while Ω differs. Recalling that $\Omega = \beta/(\phi C/Y)$, it is straightforward to see that the region with the highest C/Y has the lowest Ω , and thus chooses the lowest R/L , according to (24).

Since a closed form solution cannot be obtained analytically, we derive further results graphically. The left-hand side of the equation above is linear in pollution supply and negatively sloped, while the right-hand side is an increasing function of R/L with a curvature that depends on σ . We plot the left- and the right-hand sides of (24) in Figure below, as *LHS* and *RHS, aut*, respectively.¹² The solid lines describe the situation under autarchy.

It is easy to see from (24) that the line depicting the left-hand side will be steeper and higher for larger Ω (that is, for smaller consumption to output ratio). In the picture we depicted the situation in which the North has the largest C/Y and thus the lowest line.

¹²The figure is drawn for the case where $\sigma < 1$. The curves depicting the right-hand side would be concave for $\sigma > 1$, but qualitatively nothing would change in our analysis.

Figure 1: Equilibrium with Undirected Technical Change under Autarchy and Free Trade

The right-hand side is shared by the two countries, so that the equilibrium will obtain at a point characterized by less pollution in the North than in the South.

Intuitively, the reason for this result lies in the difference in the marginal benefits from pollution. Remembering the first-order condition in (19), it is immediate to see that, while the marginal cost term (on the right-hand side) is the same for every country, the marginal benefit term (on the left-hand side) depends negatively, *ceteris paribus*, on the C/Y ratio. Loosely speaking, the more consumption each country obtains from any unit of output, the lower the marginal benefit (in terms of consumption) it derives from any marginal increase in pollution.

3.1 International Trade

Once goods are traded internationally without frictions, a single world price p_i^w for each good $i = R, L$ will prevail. This implies that in equilibrium the right-hand side of (20) has the same value across countries. Equating the left-hand side of (20) for both regions, and rearranging, we find:

$$(25) \quad \frac{R^s}{L^s} = \frac{R^n}{L^n} + \left(\frac{\Omega^s - \Omega^n}{1 + \Omega^s} \right) \left(\frac{\bar{E}}{L} - \frac{R^n}{L^n} \right),$$

This shows that, as long as $\Omega^s > \Omega^n$ (that is, as long as $(C/Y)^s < (C/Y)^n$), the South will

pollute more than the North also under free trade. More generally, we can conclude that countries that consume relatively less tend to impose laxer environmental regulation and hence to pollute more. From now on we state that $\Omega^s > \Omega^n$ corresponds to a situation in which South has a comparative advantage in polluting goods (if $\Omega^n > \Omega^s$, the North has it).

When international trade is allowed, the equilibrium world relative price is determined by the market clearing condition on the world markets, that is, from (12) and relative supply: $(p_R/p_L)^{-\varepsilon} = (Y_R^n + Y_R^s)/(Y_L^n + Y_L^s)$.

Substituting (10) and (11), we find the following solution for the world relative price:

$$(26) \quad \frac{p_R}{p_L} = \left(\frac{N_R}{N_L} \left[\lambda^n \frac{R^n}{L^n} + \lambda^s \frac{R^s}{L^s} \right] \right)^{-\frac{\beta}{\sigma}},$$

where $\lambda^n = 1 - \lambda^s = [1 + (\frac{1-\tau_m}{1-\beta})^{(1-\beta)/\beta} \delta L^s/L^n]^{-1}$. The term in the brackets on the right-hand side in (26) is the world supply of pollution relative to labour, in efficiency terms, written as a weighted average of the national relative factor supplies R^n/L^n and R^s/L^s .

By substituting (26) and (25) into (20), we find:

$$(27) \quad \Omega^n \frac{\bar{E}}{L} - (\Omega^n + 1) \frac{R^n}{L^n} = \left(\frac{N_R}{N_L} \right)^{\frac{1-\sigma}{\sigma}} \left[\frac{R^n}{L^n} + \lambda^s \frac{\Omega^s - \Omega^n}{1 + \Omega^s} \left(\frac{\bar{E}}{L} - \frac{R^n}{L^n} \right) \right]^{\frac{1}{\sigma}}.$$

By interchanging the s and n superscripts we get the condition that determines equilibrium pollution in the South. To understand the effect of free trade when technical change is undirected, we need to compare this expression with the corresponding one for autarchy, (24). We do this using once more a graphical treatment for clarity. First of all, we notice that the left-hand side does not change, so that the relevant curves are still the solid downward sloping lines in Figure . As for the right hand side, all else equal it will be below the corresponding autarchy curve whenever the own country's Ω is larger than the foreign one. Assuming once more that the North consumes relatively more than the South, this means that the northern curve will shift up, while the southern one will shift down, relative to autarchy. This is represented by the two dotted lines in of Figure .¹³ Under these conditions, including $\Omega^s > \Omega^n$, free trade in Figure increases pollution in the South and decreases it in the North. Thus the case of undirected technical change corresponds to the position of the trade pessimist.

North and South are interdependent through goods trade and diffusion of technology from North to South. The literature on international technology diffusion argues that the two are connected: international communication and contacts stimulate technology

¹³To construct the diagram in Figure , it would be sufficient to draw only one of the dotted lines. As noted above, with international price equalization, the right-hand side of (20) must be the same for every country, in equilibrium. Thus both crossing points F^n and F^s will lie on the same horizontal line, as drawn in the figure above. We will make use of this in the next section.

spillovers, e.g. Keller (2004). We therefore now study how our results depend on our parameter for technology diffusion, δ . An increase in δ , the fraction of northern technologies copied in the South, raises production levels in the South, see (11). In autarchy, this raises aggregate production without changing relative variables. In particular, the equilibrium pollution/labour ratio is independent of δ , see (20). In free trade, the increased supply from the South affects the world price: if the South has a comparative advantage in pollution-intensive goods ($\Omega^s > \Omega^n$), the world relative supply of these goods increases with δ (for given relative factor supplies in the regions) and their relative price falls. This lower price for polluting goods makes it less attractive for both countries to pollute. Indeed, in (27) an increase in diffusion parameter δ lowers λ^n and increases λ^s so that both dashed curves in Figure shift up and both regions pollute less. A change in δ , however, can never reverse our finding that the country with comparative advantage in pollution-intensive goods pollutes more in free trade than in autarchy; this result holds for any $0 < \lambda^n = 1 - \lambda^s < 1$ and hence for any δ , see (27).

4. Directed Technical Change

When innovators can direct innovation at a particular sector, the nature of technological change becomes endogenous and responds to shocks, for example to changes in international prices. International trade thus naturally affects environmental policy in both regions, not only directly through prices, but also indirectly, through the induced changes in technology. Furthermore, even when there is no international trade in goods, innovation in the North affects technology and environmental policy in the South, through the international diffusion of northern technologies.

4.1 Pollution-using vs Pollution-saving Technical Change

Under directed technical change, international trade endogenously induces either pollution-using or pollution-saving technical change. In this subsection we provide a definition these concepts.

If innovation occurs at a faster pace in one of the sectors, the N_R/N_L ratio changes. The effect of this change on the composition of production in the long run depends on the elasticity of substitution between factors of production, σ . In general, a change in the composition of technology affects the production elasticity of pollution. This either increases or reduces the benefits of pollution in terms of output. When this elasticity increases, the marginal benefits from pollution increase and thus the supply of pollution will increase in equilibrium, recall (18). We call this kind of technical change *pollution-using*. The opposite occurs when the elasticity decreases, making pollution less beneficial. In this case we speak about *pollution-saving* technical change. The two concepts correspond to higher and lower abatement costs, respectively. An inspection of equations (24) and (27) shows that the right-hand side of both expressions increases with $(N_R/N_L)^{(1-\sigma)/\sigma}$. We can

interpret this as showing that an increase in this term, which we label the technology bias, represents pollution-saving technical change.

We can make this point more formal by recalling, from our discussion in section 2.2, that we can proxy the production elasticity of pollution by the cost share of polluting goods θ_R . Using equation (14) and substituting the autarchy prices from (23), for example, we get

$$(28) \quad \frac{\theta_R}{1 - \theta_R} = \left(\frac{N_R}{N_L} \right)^{-\frac{1-\sigma}{\sigma}} \left(\frac{R}{L} \right)^{-\frac{1-\sigma}{\sigma}},$$

which clearly shows that, when the technology bias $(N_R/N_L)^{(1-\sigma)/\sigma}$ increases, θ_R falls for given factor supply, which implies pollution-saving technical change.¹⁴ This also shows that the nature of technical change not only depends on the direction (the change in N_R/N_L) but also on the elasticity σ . For example if firms in the pollution-intensive sector innovate more than in the other sector, the ratio N_R/N_L increases. Whether this raises or reduces the production elasticity of pollution, depends of the elasticity of substitution σ . If the two goods are gross substitutes ($\sigma > 1$), the relatively fast productivity improvements in the pollution-intensive sector induce a shift towards this sector and technological change is pollution-using. If however gross complementarity applies ($\sigma < 1$), the same productivity improvements trigger a relative increase in the demand for the complementary input and technological change is labour-using, and hence pollution-saving.

4.2 Autarchy

The long-run technology bias is determined in the North by the condition that the profits from innovation are equal across sectors, that is, from the no-arbitrage equation derived in section 2.3. We first focus on autarchy, finding the following expression for the technological differences across sectors using (16) and (23):

$$(29) \quad \left(\frac{N_R}{N_L} \right)^{\frac{1-\sigma}{\sigma}} = \left(\frac{R^n}{L^n} \right)^{-\frac{(1-\sigma)^2}{\sigma}}.$$

This equation shows that under autarchy the bias of technology in both regions depends only on pollution policy in the North, R^n/L^n . Moreover, we can immediately see that a decrease in the relative supply of pollution results in pollution-saving technological change. Hence, the more stringent the environmental policy in the North, the more pollution-saving technological change.

To determine equilibrium pollution supply under autarchy, we can substitute the long-run bias derived above into the environmental policy rule (24). The expression differs

¹⁴The corresponding expression for θ_R under free trade is obtained by substitution of the international prices from (26). In the resulting expression θ_R still decreases with $(N_R/N_L)^{(1-\sigma)/\sigma}$ for given factor supply. Our classification is thus independent of the trade regime.

across countries. For the North the equilibrium condition reads:

$$(30) \quad \Omega^n \frac{\bar{E}}{L} - (\Omega^n + 1) \frac{R^n}{L^n} = \left(\frac{R^n}{L^n} \right)^{2-\sigma},$$

while for the South we get,

$$(31) \quad \Omega^s \frac{\bar{E}}{L} - (\Omega^s + 1) \frac{R^s}{L^s} = \left(\frac{R^n}{L^n} \right)^{2-\sigma} \left(\frac{R^s/L^s}{R^n/L^n} \right)^{1/\sigma}.$$

In Figure we construct a diagram analogous to the previous one, to illustrate the situation in this case. Once again, we indicate the curves that are relevant for the discussion of the autarchy case with solid lines.

Figure 2: Equilibrium under Directed Technical Change under Autarchy and Free Trade

We start from the curves for the North. The curve that depicts the left-hand side is identical to the straight line we drew in Figure . The right-hand side is increasing for $\sigma < 2$ and decreasing for $\sigma > 2$. In the picture we depict the case where $\sigma < 1$ and $\Omega^n < \Omega^s$. The intersection point A^n represents the equilibrium for the North.¹⁵ We can

¹⁵As long as $\sigma \leq 2$ this equilibrium always exists and is unique. When $\sigma > 2$, the line describing the right-hand side is decreasing and convex, it can intersect the straight line either once, twice, or never. When multiple crossings occur, we must rule out the intersection at which RHS cuts LHS from above, since starting

use the corresponding value of R^n/L^n to construct the curve for the South. This curve intersects the northern one at A^n , and is drawn as the lighter curve in the figure. Point A^s represents the equilibrium for the South.

This picture enables us to draw some conclusions for the autarchy case.

In the first place, we notice that, as in the undirected technical change case, also here the country with the highest Ω will pollute more. In this sense the regime of technical progress does not influence the outcome. As long as the North enjoys a higher C/Y ratio, it will choose a lower equilibrium level of pollution than the South.

Second, comparing equations (24) and (30), we immediately conclude that the line depicting the right-hand side for the North is steeper under undirected technical change than under directed technical change. This has the important consequence that any shock (such as changes in Ω through preferences or subsidies, or in relative endowments, $\bar{E}/L$) has a larger impact on pollution supply under directed technical change than under undirected technical change. Intuitively, this happens because under directed technical change the adjustment occurs not only through policy but also through changes in the composition of technology. For example, assume that preferences become greener (ϕ increases), this leads to the adoption of more stringent environmental policy and to a reduction in pollution supply. Under directed technical change this leads firms to develop pollution-saving technologies, which would not have occurred had technical change been undirected, and thus to curb pollution further.

Third, shocks in the North affect the South even without international trade in goods, through the international technology spillovers. Indeed, once a shock hits the North, both pollution and technology adjust. Technology diffusion will then induce the South to modify its pollution decisions according to the new available technology. This means, for example, that the South will benefit from pollution-saving technical change that occurs in the North following a tightening in the stance of environmental policy.

4.3 International Trade

When technical change is directed, the effects of a liberalization in international trade are twofold. First, price changes affect pollution supply through the traditional terms-of-trade mechanism as with undirected technological change. Second, price changes now also affect the direction of technological change. In this section we will show that, while the terms-of-trade effect tends to increase differences in pollution supply, the effects of changes in technology can either exacerbate or dampen this tendency. In particular, we show that the effect of the induced technical change may prove strong enough for the non-innovating country to reverse the terms-of-trade effect. Thus, provided that factors

from such a point, slightly increasing pollution supply raises marginal benefits relative to marginal costs of pollution. In other words, second order conditions are violated. Moreover, the case of no intersection is not of interest to our discussion, as it implies a corner solution in which both regions produce with zero pollution in the long run. In the rest of the paper we thus focus on interior solutions, which can always be constructed by choosing low enough a value for ϕ .

of production are sufficiently good substitutes, both regions might end up changing their environmental policy in the same direction.

As in the previous section, we obtain the long-run technology bias from the no-arbitrage condition (16), but we now use (26) to substitute for prices. This yields:

$$(32) \quad \left(\frac{N_R}{N_L}\right)^{\frac{1-\sigma}{\sigma}} = \left(\frac{R^n}{L^n}\right)^{1-\sigma} \left[\lambda^n \frac{R^n}{L^n} + \lambda^s \frac{R^s}{L^s} \right]^{-\frac{1-\sigma}{\sigma}}.$$

This equation shows that changes in the relative factor supply affect the bias of technological change through two terms: $(R^n/L^n)^{1-\sigma}$, which represents the market-size effect; and $[\lambda^n R^n/L^n + \lambda^s R^s/L^s]^{-(1-\sigma)/\sigma}$, which captures the price effect.

The market-size effect relates the direction of technical change to the potential market for factor-specific innovations. For example, for given prices, a reduction in pollution (relative to a constant labour supply) reduces the potential profits from innovations in the pollution-intensive sector, and directs R&D expenditure to the labour-intensive sector. The price effect works in the opposite direction. Imagine, for example, a reduction in pollution at the world level for given domestic supply (because pollution is reduced elsewhere). This leads to higher prices for dirty goods. As a consequence, innovation in the pollution-intensive sector becomes more attractive.

As we discussed above, under autarchy a pollution reduction in the North always results in pollution-saving technological change. In the presence of international trade, this is no longer necessary. In this case, indeed, it is the world supply of factors rather than the northern one to determine the price level. Accordingly, changes in the northern pollution supply have a relatively weaker impact on prices than before. As northern pollution is reduced, innovation in the pollution-intensive sector becomes less attractive through the market-size effect and this tends to reduce N_R/N_L . Compared to autarchy, the mitigating effect of an increase in the relative price of the polluting goods is now less salient. Hence, more stringent environmental policy makes N_R/N_L decrease more under free trade than under autarchy. Whether this implies a pollution-saving or pollution-using technical change relative to autarchy depends once more on whether polluting inputs and labour are gross substitutes or gross complements, see section 4.1.

Substituting (25) into (32) and using the new expression to substitute for the technology bias in (27), we find the condition that determines equilibrium pollution supply in the North:

$$(33) \quad \Omega^n \frac{\bar{E}}{L} - (\Omega^n + 1) \frac{R^n}{L^n} = \left(\frac{R^n}{L^n}\right)^{1-\sigma} \left[\frac{R^n}{L^n} + \lambda^s \frac{\Omega^s - \Omega^n}{\Omega^s + 1} \left(\frac{\bar{E}}{L} - \frac{R^n}{L^n}\right) \right]$$

This equation solves for pollution in the North under free trade and can be compared to the corresponding equation for autarchy, (30). Notice that, for given R^n/L^n , the right-hand side of (33) is larger than the one in (30), provided that $\Omega^s > \Omega^n$ (and smaller otherwise). Hence, when opening up to trade, the North reduces pollution supply if it was relatively clean in autarchy. Thus, the effect of trade on pollution in the North is similar to

the undirected technology case. The reason is that the technology response to trade in the North is governed by the same incentives as the environmental policy response: to exploit the comparative advantage and benefit from the trade-induced increase in the relative price for labor-intensive goods, the North shifts production to the the labour-intensive sector not only by polluting less but also by innovating more in that sector.

In contrast, the effects of trade in the South might change due to fact that trade induces technical change and that this change is determined by conditions in the North.

In terms of Figure , when opening up to trade, the right-hand side curve of the North (the dashed line) shifts up so that the intersection necessarily moves to the left for North. The equilibrium under trade in the North is indicated by the point F^n . Just as in section 3, we know that prices and technology are common to the two regions. To determine the equilibrium for the South we just need to find the intersection of the LHS^s curve with the horizontal line through F^n . It is clear that this intersection might be above or below A^s , implying opposite effects of international trade on pollution in the South. The rest of this section is devoted to discussing this point.

Let's continue assuming $\Omega^s > \Omega^n$ for concreteness. This implies that the North pollutes relatively less than the South in the autarchy equilibrium. When the South opens up to trade with the relatively cleaner North, the price of the pollution-intensive goods increases for any given level of pollution in the South, see (26). This is the conventional terms-of-trade effect that makes it attractive for the South to specialize in the production of the dirty good and hence to increase pollution.

The increase in p_R/p_L might be mitigated and even offset by a fall in the technology bias N_R/N_L , see (20). Indeed, when the North opens up to trade, N_R/N_L falls.¹⁶ The North changes the direction of technical change towards the sector in which it has a comparative advantage. When this happens, the South faces pollution-using technical change if $\sigma < 1$, but pollution-saving technical change if $\sigma > 1$. From (27) we see that we need an increase in the technology bias $(N_R/N_L)^{(1-\sigma)/\sigma}$ (that is, pollution-saving technical change) to offset the terms of trade effect (i.e. the fact that the term in brackets falls when opening up to trade).

This means that, as long as the goods are gross complements, the induced technical change effect has the same direction as the terms-of-trade effect, while it has an opposite effect when $\sigma > 1$. In other words, if $\sigma < 1$, not only for the North but also for the South, trade has the same effect as with undirected technological change. When goods are gross substitutes, instead, it is possible that the effects of international trade on pollution decisions in the South are reversed.

In Figure we present numerical examples to show that it is indeed possible that the South reduces pollution upon opening up to trade. The parameters values we used were such that $\Omega^s > \Omega^n$, so that the South pollutes more than North.¹⁷ Above the line,

¹⁶We know that when the North opens up to trade its pollution supply (R^n/L^n) falls. From (16) this implies that the northern relative price of pollution-intensive goods p_R/p_L will then rise. Finally, from (20), this implies that N_R/N_L falls.

¹⁷For the simulations, the following values of the parameters were used: $L^n = 1, L^s = 3, \bar{E}/L = 0.5, g =$
<http://www.bepress.com/bejeap/advances/vol4/iss2/art7>

Figure 3: Pollution Policy in the South under Free Trade

combinations of the elasticity of substitution σ and the diffusion parameter δ are such that the South pollutes less in free trade than in autarchy; below the line, the opposite holds. As derived above, if $\sigma < 1$, trade always increases pollution in the South. The figure further reveals that better substitution or more diffusion of technologies make it more likely that trade improves the environment in the South. The reason is, first, that with a larger elasticity of substitution trade results in smaller price changes so that the conventional terms-of-trade effect that drives pollution havens is small. Second, with more diffusion (larger δ), the effective size of the South, as measured by λ^s , is larger and any change in Northern pollution supply has a smaller effect on world prices and a relatively larger effect on the market size for innovations in the labour-intensive sector. Thus, more diffusion implies a large change in the technology bias.¹⁸

We end this section by discussing the case with $\Omega^n > \Omega^s$, in which the North pollutes more than the South, reversing our earlier assumption on comparative advantage. Indeed, now the North has a comparative advantage in the production of polluting goods and starts innovating more in the pollution-intensive sector, once trade is opened. As a result, N_R/N_L now rises. If $\sigma < 1$, this implies pollution-saving technical change, and the South reduces pollution after trade is opened. This result is qualitatively similar to the one

0.015, $\beta = 0.2$, $\rho = 0.025$, $\varsigma = 1$, $\phi = 0.06$, $\tau_m = 0$.

¹⁸In Figure , a larger σ makes the *RHS* curves flatter, while a larger δ , by increasing λ^s , shifts the *RHSⁿ, FT* curve up. As a result, the vertical distance between the autarchy points A^n and A^s is small and the vertical distance between A^n on the one hand, and F^n and F^s on the other hand, is large, such that it becomes more likely that F^s is above A^s .

obtained with terms-of-trade effects only in section 4. If $\sigma > 1$, however, trade induces pollution-using technical change, so that the technology effect might offset the terms-of-trade effect. For sufficiently large σ and δ , the South will increase pollution. Hence, if the innovating region has a comparative advantage in pollution-intensive goods, if these goods are good substitutes for other goods, and if a large fraction of the new technologies diffuse to the imitating region, then trade is bad for the environment in both regions.

5. Summary and Conclusions

In our model the North innovates and technologies diffuse to the South. Since only a fraction of the technologies diffuse, the South is less productive and has lower income than the North. By construction, this income difference does not lead to differences in environmental stringency in our model. Instead, a country that consumes a relatively large part of income has a relatively large demand for environmental quality, as produced consumption goods and environmental amenities are traded off in utility. Whether the South or the North has higher demand for environmental quality thus depends on investment opportunities and distortions. On the one hand, the North has to incur the cost of innovation (while the South gets innovations for free), which makes consumption scarce and reduces demand for environmental quality in the North. On the other hand, intermediates are priced above cost in the North. This introduces a distortion not present in the South and reduces investment. Which of the two effects will prevail will depend on the level of subsidies to technological change.

In the paper we have discussed the two possibilities separately, one in which the North pollutes less than the South, and the other in which it pollutes more. These situations correspond to a comparative advantage for pollution-intensive goods in the South or in the North, respectively. When trade is opened, prices change and the regions exploit their comparative advantage. By this terms-of-trade effect, environmental quality always improves in the country that has most stringent environmental policy in autarchy and always deteriorates in the other. Induced technological change never reverses this pattern in the North, but may do so in the South provided that pollution-intensive and labour-intensive goods are gross substitutes ($\sigma > 1$).

While the terms-of-trade effect has opposite effects on environmental quality in the two regions, the induced technology effect affects environmental quality in both regions in the same direction. The reason is that technology is determined by profit conditions in the North and then diffuses to the South. Northern innovation activities will shift in the direction of the sector that uses intensively the relatively abundant factor (pollution or labour) and thus increases the relative supply from this sector. If these goods are gross substitutes for goods from the other sector, world demand shifts away from goods in which the South has a comparative advantage. Hence, if the South has a comparative advantage in pollution-intensive goods, the induced technology effect nevertheless makes production of these goods less profitable and tightening environmental policy become less costly in the South. Thus, effectively, abatement costs have fallen. The net effect may be that trade

induces more stringent environmental policies in both regions. However, if the North started as the dirty region, the net effect may be that trade induces more pollution in both regions by raising abatement costs.

Technology diffusion from North to South is therefore not unambiguously good for the environment in the South, since whether technologies are pollution-using or pollution-saving depends on the profitability of different innovation projects, which in turn depends on comparative advantages and substitutability between goods with different pollution-intensity. Our results highlight that endogenous technological change is potentially but not necessarily a blessing. The main reason is that the lack of intellectual property rights protection in the South creates distortions. Innovating firms cannot recoup their costs in the South and only direct their efforts to Northern markets, so that the resulting technologies cannot be in the interests of the South in all respects. Moreover, innovation costs are asymmetrically born by Northern consumers, which creates asymmetries in the costs associated with environmental policies, the driving force behind pollution havens.

Appendix: The Consumption to Output Ratio in the Two Regions

Consider the final good market equilibrium condition (2). In both the North and the South, the total cost of producing machines in sector i amounts to $v m_i N_i$ ($i = R, L$), where v represents the unit cost of production and $m_i N_i$ is the total amount of machines produced. Since the machines share in intermediate producers' output is given by $1 - \beta$, we rewrite total cost as $(v/p_{m_i})(1 - \beta)p_i Y_i$. Substituting the appropriate expressions for prices and marginal costs in the two regions, $p_m^n = (1 - \tau_m)$ and $p_m^s = v = 1 - \beta$, and summing over the two sectors, we find total expenditure in machines in the North and in the South, respectively, as:

$$M^n = (1 - \beta) \left(\frac{1 - \beta}{1 - \tau_m} \right) Y^n, \text{ and } M^s = (1 - \beta) Y^s.$$

In the South, whatever is not needed for physical investment will be consumed. The C/Y ratio in the South will then be given by:

$$\left(\frac{C}{Y} \right)^s = 1 - (1 - \beta) = \beta.$$

To characterize the same ratio in the North, we need to derive the equilibrium R&D investment outlays. Starting with the directed technical change case, from (6) it is possible to write the R&D investment in each sector as $D_i = g N_i (N_R + N_L)^\psi / \eta$, where g is the growth rate of the economy. From (9), (10), and the definition of the interest rate along the balanced growth path ($r = \eta (N_R + N_L)^{-\psi} \pi_i$), we find $N_i / (\eta (N_R + N_L)^{-\psi}) = p_i Y_i \beta (1 - \beta) / r$. Summing over both sectors, we can write the total expenditure in research and development, $D = D_L + D_R$, as

$$D = (1 - \beta) \beta \frac{g}{r} Y.$$

Following the same steps it is straightforward to obtain the same expression for the case of undirected technical change.

Accordingly, we can write the consumption to output ratio in the North as follows:

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

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