Technological Knowledge Diffusion between Ecological and Dirty Countries

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Abstract

A general equilibrium based on an endogenous Schumpeterian R&D growth model is developed to understand how international trade of intermediate goods between ecological and dirty countries can affect the structure of technological knowledge progress and thus, the growth rate levels in each country. Each country is assumed to have got different environmental quality levels and different available technological knowledge and is capable of conducting R&D activities (innovative in ecological-country and imitative in dirty-country). We concluded that under international trade, a higher probability of successful imitation improves the Dirty-country ability to benefit from Ecological-country innovations inducing an efficient allocation of production in the Dirty-country, where marginal cost is lower, and increasing the steady-state world growth rate. Furthermore, when subsidies are equal in both countries and/or are different between countries, but under international trade of intermediate goods, a rise in their rates leads to a permanent increase in the world steady-state, since they promote technological knowledge progress. Therefore, international trade of intermediate goods induces an increase in the Ecological-technological bias through the price channel (stimulated by government policy).

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1. Introduction

This paper aims to understand how the diffusion of technological knowledge, through international trade of intermediate goods between Ecological (Leader-*L*) and Dirty (Follower-*F*) countries, affect the structure of technological knowledge progress and thus, their ecological goods production. For that, a dynamic general equilibrium based on a standard economic structure with endogenous Shumpeterian R&D-growth model is considered (Acemoglu 2002).

We consider two countries - the Ecological innovator and the Dirty imitator. Each one produces final goods with labour and intermediate goods. These economies differ in the exogenous levels of productivity (directly related with the environmental quality of domestic institutions), labour endowments, technological knowledge stocks and R&D capacity. These differences are assumed to have historical reasons, which are reflected in the current institutional characteristics of each country. The ecological country has got a better environmental quality (is cleaner) than the dirty country and it is endowed with a higher initial level of both ecological/cleaner resources and ecological skilled labour. Its technological knowledge is more ecologically advanced and its R&D activities result in innovations that improve the quality of the ecological intermediate goods quality – Schumpeterian R&D (Aghion et al., 1992). The dirty country has got a marginal cost advantage in the production of final goods and also performs R&D activities, although its best results are imitations of the ecological country innovations (Grossman et al., 1991).[1] The Ecological country never has an incentive to imitate, as there is never foreign technological knowledge to imitate.

[1] It is assumed that dirty country is not too backward relative to the ecological country so that technological diffusion can be undertaken through international trade.

We introduce international trade for intermediate goods only, because, as they are the ones that embody technological knowledge progress, they are the most relevant to understand technological knowledge diffusion. Final goods, in contrast, are only concerned with the competition of complementarity in inputs and substitutability between technology types (Acemoglu et al., 2001).

The present paper aims to develop a simple endogenous growth model with international trade of ecological and dirty intermediate resources to study its effects on the direction of technological knowledge progress of environmental friendly countries and less environmentally concerned countries. It also intends to analyse how a tax on dirty intensive resources and a subsidy on ecological intensive resources can affect the development of better environmental quality inputs to production.

The remainder of the paper is organised as follows. Section 2 presents the Ecological and Dirty countries' economies. Section 3 introduces the international trade in intermediate goods. Section 4 analyses the steady-state equilibrium and section 5 stresses some concluding remarks.

2. The Domestic Economy Model

In this section, the Ecological country will be characterized and the differences with the Dirty country will be highlighted.

Each ecological and dirty country has got three productive sectors: the final goods (FGs), the intermediate goods (IGs) and the research and development (R&D). Since this is a dynamic general equilibrium model, all markets clear throughout time.

Following Acemoglu and Zilibotti (2001), Barro and Sala-i-Martin (2004, ch. 7) and Afonso (2005) each perfectly competitive FG $n \in [0,1]$ is produced either by Ecological or Dirty technology. The former is environmentally friendly and produces ecological /clean goods contributing to reduce pollution. The latter produces dirty goods contributing to increase pollution. Firms producing with ecological (dirty) technology use ecological (dirty) labour together with a continuum set of ecological (dirty) IGs indexed by $j \in \left]J,1\right]$ $\left(j \in \left[0,J\right]\right)$. Thus, the n FG production function, at time t is given by:

$$Y_n(t) = \left\{ A_{D,L}\left[\int_0^J \left(q^{k(j,t)} x_n(k,j,t)\right)^{1-\alpha} dj\right] \left[(1-n)\, d\, D_n\right]^\alpha + A_{E,L}\left[\int_J^1 \left(q^{k(j,t)} x_n(k,j,t)\right)^{1-\alpha} dj\right] \left[n\, e\, E_n\right]^\alpha \right\} \quad (1)$$

A is the exogenous productivity level, dependent, among other features, on the country's environmental quality. Indexing the ecological-country by L (Leader-country) and the dirty-country by F (Follower-country), we consider $\left(A_{E,L}/A_{D,L}\right) > \left(A_{E,F}/A_{D,F}\right)$ as the only difference between the two countries in (1).[2] The integrals denote the contributions of the two IG-types, which are environmental quality adjusted by an exogenous constant $q>1$ obtained with each successful research. $k(j,t)$ is the highest environmental quality of the j^{th} IG until t. $\alpha \in \left]0,1\right[$ and $(1-\alpha)$ denote, respectively, labour and IG shares in production. Individuals with higher ability (E-labour) are assumed to perform better using ecological technology, while those with lower ability (D-labour) are assumed to perform better using dirty technology. $e>d\geq 1$ guarantees an absolute productivity advantage of E- over D-labour. n and $(1-n)$ imply that E is relatively more productive in FGs indexed by larger n.

Solving the profit maximisation problem of the FG producer, we get the aggregate output of the Ecological economy:

$$Y(t) = \int_0^1 p_n(t) Y_n(t) dn = \exp\left[\ln 1\right] \exp\left[\int_0^1 \ln Y_n(t)\, dn\right] = \exp\left[\int_0^1 \ln Y_n(t)\, dn\right] \quad (2)$$

where, for simplicity, we normalize its price to one. All resources of the economy, Y, can be consumed, C, converted into quality adjusted IGs, X, or applied to R&D, RS:

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[2] $A_{D,L}$ ($A_{E,L}$) is a negative (positive) exogenous productivity level resulted from an environmental quality degradation (improvement) in the Ecological country.

$$Y(t) = X(t) + RS(t) + C(t) \tag{3}$$

IGs are provided by a monopolist supplier that employs Y. Therefore, the production function of the IGs is identical to the composite FG (1) and their marginal costs (MC) are equal: MC=1.[3] Following Romer (1990), the production of IG j requires a start-up cost of R&D that is recovered by a domestic patent law.

The profit maximization price is:

$$p(k, j, t) = p = \frac{1}{1-\alpha} \tag{4a}$$

It is, though, worth mention that the use of dirty resources often leads to the degradation of environmental quality associated with pollution. Hence, they should be discouraged in favour of less polluted ones. In the literature, there is a conventional wisdom that, from an efficiency perspective, market-based instruments are preferred over command-and-control instruments, since they equalize marginal abatement costs across firms, yielding statically efficient outcomes (Baumol and Oates 1994). Furthermore, market-based instruments are believed to be more effective in inducing technological change than command-and-control instruments as they offer a permanent incentive to use lesser environmental commodities. Consequently, we use market-based instruments (taxes and subsidies) as government policy.

Assuming, then, that government can subsidise (tax) the E (D)-IG j by paying (charging) an ad-valorem fraction, s_x (τ_x), of each firm's cost, the after subsidy (tax) MC of producing j is ($MC+\varphi_x$), that is, ($1+\varphi_x$), where φ_x denotes subsidies ($-s_x$) or taxes (τ_x).[4] Thus, the profit maximization price becomes:

$$p(k, j, t) = p = \frac{1+\varphi_x}{1-\alpha} \tag{4b}$$

[3] Without international trade, marginal cost of production is the same in both types of countries.

[4] Since subsidy and tax rates are relatively stable over t, they are assumed stationary and exogenously given.

The top environmental quality good is q units better than the following environmental quality good. Therefore, its price is $(1+\varphi_x)/(1-\alpha)$ and the price of the next environmental quality good is at most $(1+\varphi_x)/q(1-\alpha)$. Following Grossman and Helpman (1991, chap.7), if $(1+\varphi_x)/q(1-\alpha)<(1+\varphi_x)$ all lower environmental quality producers cannot compete against the leader's monopoly price and the monopoly pricing will prevail. If $(1+\varphi_x)/q(1-\alpha)\geq(1+\varphi_x)$ the providers of IGs can engage in Bertrand competition and the limit pricing will be used to capture the whole market:[5]

$$p = q(1+\varphi_x),\ \text{where}\ (1+\varphi_x)<q(1+\varphi_x)\leq\left((1+\varphi_x)/(1-\alpha)\right) \tag{5}$$

In equilibrium, there will be a threshold FG $\bar{n}\in[0,1]$, such that only dirty (ecological) technology is used to produce FGs indexed by $0\leq n\leq\bar{n}$ ($\bar{n}<n\leq 1$).

Given the labour supply and the technological knowledge (TK), $\bar{n}$ (that arises from the profit maximisation of FG and IG firms and from the full-employment in factor markets) is:

$$\bar{n} = \left\{\left[\left(\frac{A_{E,L}}{A_{D,L}}\right)^{1/\alpha}\frac{e}{d}\,\frac{E}{D}\,\frac{Q_{E,L}}{Q_{D,L}}\right]^{1/2}+1\right\}^{-1} \tag{6}$$

$$Q_D(t)\equiv\int_0^J q^{k(j,t)(1-\alpha)/\alpha}dj \quad \text{and} \quad Q_E(t)\equiv\int_J^1 q^{k(j,t)(1-\alpha)/\alpha}dj \tag{7}$$

where Q_D and Q_E are aggregate domestic quality indexes that evaluate the domestic TK in each range of IGs and $B\equiv Q_E/Q_D$ measures the (ecological) TK bias.

Eq.(6) indicates that the switch from dirty to ecological technology is advantageous. $\bar{n}$ is smaller the larger the productivity advantage of ecological over polluted environmental

[5] If the leader prices at a price slightly below $q(1+\varphi_x)$, for example $q(1+\varphi_x)$-ε, then the closest follower can charge at most $(1+\varphi_x)$-ε/q, a price that results in negative profits, driving the lower environmental quality goods out of the market.

quality and/or the larger the relative ecological labour supply and/or the larger the use of ecological TK. Thus, $\bar{n}$ represents the FG sector bias or the technological margin.

The price indexes ratio of FGs produced with both technologies is expressed by:

$$p(t) = p_E(t)/p_D(t) = (\bar{n}(t)/(1-\bar{n}(t)))^{\alpha}, \text{ where } \begin{cases} p_D = p_n (1-n)^{\alpha} = \exp(-\alpha)\bar{n}^{-\alpha} \\ p_E = p_n n^{\alpha} = \exp(-\alpha)(1-\bar{n})^{-\alpha} \end{cases} \quad (8)$$

Small $\bar{n}$ implies a small relative price of FGs produced with ecological technology. Hence, the demand for *E*-IGs is low, discouraging R&D activities that improve their environmental quality. Thus, labour and environmental quality levels affect the R&D direction through the FG price channel.

The aggregate equilibrium of *X* and *Y* is respectively:

$$X = \exp(-1)\left[(1-\alpha)/q(1+\varphi_x)\right]^{1/\alpha}\left[\left(A_{D,L}{}^{1/\alpha} Q_D\, d\, D_n\right)^{1/2} + \left(A_{E,L}{}^{1/\alpha} Q_E\, e\, E_n\right)^{1/2}\right]^2 \quad (9)$$

$$Y = \left[(1-\alpha)/q(1+\varphi_x)\right]^{-1} X \quad (10)$$

The incentive to support R&D relies on the expected present value of the profits flow:

$$V(k,j,t) = \Pi(k,j,t)/\left[r(t) + pb(j,k,t)\right] \quad (11)$$

The denominator is the interest rate plus the rate of Schumpeter's creative destruction. R&D improves IGs and, thus, the indexes quality (7), while creatively destroying the profits from the previous improvement.

The instantaneous probability of a successful innovation in the next higher quality, $k(j,t)+1$, at each *t*, in the Ecological-country, is (Barro and Sala-i-Martin, 2004, ch. 7):

$$pb_L(k,j,t) = rs_L(k,j,t)\,\beta_L\, q^{k_L(j,t)}\,\xi_L^{-1} q^{-(1/\alpha)k_L(j,t)} M_L^{-\zeta_L} \quad (12)$$

(i) $rs_L(k,j,t)$ is the flow of domestic *Y* devoted to R&D in IG *j* at *t*; (ii) $\beta_L q^{k(j,t)}$, $\beta_L>0$, is the positive learning effect of accumulated TK from past successful R&D in *j*.[6] (iii)

[6] If the country has got no innovative (imitative) experience, then $q^{k_L(j,t)}=0$ ($q^{k_F(j,t)}=0$). It is assumed that each country has got experience in at least one type of research.

$\xi_L^{-1} q^{-(1/\alpha)\, k_L(j,t)}$, $\xi_L > 0$, is the adverse effect caused by the increasing complexity of environmental quality improvements in j; (iv) $M_L^{-\zeta_L}$, with $M_L = D_L$ if $0 \le j \le J$ and $M_L = E_L$ if $J < j \le 1$ and $\zeta_L > 0$, is the adverse effect of market size.[7]

We assume a time invariant number of heterogeneous individuals, $a \in [0, 1]$, who decide between working with ecological or dirty technology and between consumption and savings. For simplicity, individuals with high ability, $a > \overline{a}$, are assumed to be Ecological, whereas individuals with lower ability, $a \le \overline{a}$, are considered to be Dirty.

Each individual solves the Hamiltonian optimal control maximization problem of the utility (13), subject to the intertemporal budget constraint, (14):

$$U(a,t) = \int_0^{\infty} \left[\frac{c(a,t)^{1-\theta} - 1}{1-\theta} \right] \exp(-\rho t)\, dt \tag{13}$$

where $c(a,t)$ is the consumption of Y by a, at t; $\rho > 0$ is the homogeneous subjective discount rate and $\theta > 0$ is the inverse of the intertemporal elasticity of substitution.

$$\dot{K}(a,t) = (1-\tau_k)\, r(t)\, K(a,t) \, + \, (1-\tau_{w,M})\, w_M(t)\, M(a) \, - \, c(a,t) \tag{14}$$

(i) $\dot{K}(a,t)$ is the individual a savings, at t; (ii) τ_k and $\tau_{w,M}$ are *ad-valorem* taxes on assets and wages respectively; (iii) $K(a,t)$ is the total asset holdings of a, with return r in the form of IGs firms; (iv) r depends only on t due to the assets market arbitrage; (v) $M=E$ if $a > \overline{a}$ and $M=D$ if $a \le \overline{a}$; (vi) w_M is the wage per labour type.

The solution for the individual consumption path is the standard Euler equation:

$$\dot{c}(a,t)/c(a,t) = \dot{c}(t)/c(t) = \dot{C}(t)/C(t) = (1/\theta)\, [(1-\tau_k)\, r(t) - \rho\,] \tag{15}$$

where $\dot{c}(t)/c(t)$ yields the growth rate of consumption.

[7] The difficulty in introducing new environmental quality adjusted IGs and replacing old ones is proportional to the market size (measured by the respective labour), due to coordination among agents together with informational, organizational, transportation and marketing costs.

3. Technological Knowledge Dynamics with Ecological-Dirty countries trade in Intermediate-Goods

3.1 Overview

With the introduction of international trade in IGs,[8] the Dirty (Follower)-country has, now, access to the same technological knowledge as the Ecological (Leader)-country, either by imitation of the latest innovations, or by importing state-of-the-art IGs.[9] This improvement in the technological knowledge level of the *F*-country is a static benefit (or level effect) of international trade, with immediate effects both on the productivity level and on the prices of goods and factors, inducing some convergence between countries.

Under international trade, the *F*-country has got a marginal cost advantage in producing imitated *L*-country top-environmental-quality IGs, and so, it can under-price them. Consequently, with openness to international trade, the *L*-country IGs firms can loose their markets either due to the next *L*-country innovation or due to a lower-priced *F*-country imitation. The greater the probability of imitation, the faster the *L*-country firms will need to obtain the next successful innovation to capture the world market. Furthermore, as they produce IGs in less time, fewer *L*-country resources are spent in IGs production and more resources are available to R&D. Therefore, international trade of IGs induces a dynamic interaction between countries, which potentially drives to a higher steady-state world growth rate. Indeed, when the probability of successful imitation increases, due to the international trade of IGs (i.e., the speed of technological knowledge diffusion increases), it improves the ability of the *F*-country to benefit from innovations of the *L*-country and generates a better

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[8] IGs are assumed to be traded without any trade costs.

[9] However, *F*-country technological knowledge is not equalized with the *L*-country because at each moment in time not all innovations have been imitated yet. Hence, it is important to distinguish between the *F*-country technological knowledge, $Q_{M,F}$, and the available technological knowledge in the *F*-country, $Q_{M,L}$.

efficient allocation of production, since it becomes located in the *F*-country where *MC* is lower. However, the international trade of IGs forces the *F*-country IGs firms to support R&D imitative cost of state-of-the-art *L*-country IGs possibly several quality rungs above their own experience level. Therefore, they need to spend more resources in R&D imitative activity of a large number of quality grades.

Thus, international trade directly reflects the differences in technological knowledge between countries, due to their R&D activities. Based on the size of the technological knowledge gap and due to the static Bertrand price equilibrium, there will be three types of IGs firms in the world: IG firms of *L*-countries facing *L*-country competition, IG firms of *L*-countries facing *F*-country competition and IG firms of *F*-countries facing *L*-country competition.

From (1), IGs, used in the production of FG *n* in either country, can be produced by either the *L*-country, $x_n(k, j, t \mid M, L)$, after a successful innovation, or by the *F*-country, $x_n(k, j, t \mid M, F)$, after a lower priced successful imitation of the leading *L*-country quality level. Both countries use the state-of-the-art IGs in their FGs production, $k=k_L \geq k_F$, which can be produced domestically or not. In the latter case, countries immediately import the higher quality IG for domestic use.

3.2. Worldwide Limit Pricing, Intermediate-Goods demand and Final-Goods Supply

The composite final good of the *L*-country (2) cannot be the same as the *F*-country since the latter is assumed to be produced at a lower marginal cost, MC_F. Therefore, since under perfect competition, prices equalize marginal costs, the composite final good of the *F*-country will be:

$$Y_F(t) = MC_F \left\{ \exp \left[\int_0^1 \ln Y_n(t)\, dn \right] \right\} \qquad (16)$$

where $0<MC_F<MC_L=1$. This marginal cost advantage is transmitted to the production of IGs, influencing worldwide optimizing limit pricing (Grossman and Helpman, 1991, ch.12).

A *L*-country firm can capture the world market with a single quality level improvement over a *F*-country imitation, while a *F*-country firm can acquire the world market by a successful *L*-country imitation.

Assuming that (i) Φ_M and $(1-\Phi_M)$ are the proportion of ecological or dirty IGs produced in *L*-country and *F*-country respectively and (ii) Ψ_M and $(1-\Psi_M)$ are the proportion of IGs produced in the *L*-country that have, respectively, overcome imitator competition and innovator competition (i.e., that face imitator competition and those that do not), the production function (1) becomes:[10]

$$\begin{aligned} Y_n = \Big\{ & A_D \Big[\int_0^J \big[q^{k(j,t)} [\Phi_D (\Psi_D x_n(k,j,t) + (1-\Psi_D) x_n(k,j,t)) + (1-\Phi_D) x_n(k,j,t)] \big]^{1-\alpha} dj \Big] \, [(1-n) d \, D_n]^{\alpha} + \\ & + A_E \Big[\int_J^1 \big[q^{k(j,t)} [\Phi_E (\Psi_E x_n(k,j,t) + (1-\Psi_E) x_n(k,j,t)) + (1-\Phi_E) x_n(k,j,t)] \big]^{1-\alpha} dj \Big] \, [n \; e \; E_n]^{\alpha} \Big\} \end{aligned} \tag{17}$$

Since, there are three groups of IG firms, there will also be three possible sequences of successful R&D and three different limit prices for IGs as depicted in Table 1.

Table 1. Limit Pricing of each Intermediate-Good

t-dt	*t*	Share in IGs production at *t*	*p(j)*
L produces and exports quality *k*	*L* produces and exports quality *k*+1	$\Phi_M(1-\Psi_M)$	$p_{M,L\text{-}L}(j) = q(1+\varphi_x)$
L produces and exports quality *k*	*F* produces and exports quality *k*	$1-\Phi_M$	$p_{M,F\text{-}L}(j) = (1+\varphi_x)$
F produces and exports quality *k*	*L* produces and exports quality *k*+1	$\Phi_M\Psi_M$	$p_{M,L\text{-}F}(j) = q(MC_F+\varphi_x)$

[10] The specification of these proportions as functions of the probabilities of successful R&D, necessary for transitional dynamics, has been performed in such a way that, as in Dinopoulos and Segerstrom (2004), the proportion of IGs produced in the *L*-country increases (decreases) with the probability of innovation (imitation).

L-country entrants with better environmental quality compete either with L-country incumbents at the same MC, capturing the whole market by selling at any price slightly below $q(1+\varphi_x)$, or with F-country incumbents with lower MC, capturing the entire market by selling at any price slightly below $q(MC_F+\varphi_x)$. Furthermore, F-country entrants with lower MC compete on the same environmental quality rung with a L-country incumbent, capturing the whole market by selling at any price below $(1+\varphi_x)$. Therefore, $q(1+\varphi_x)>(1+\varphi_x)$, $q(MC_F+\varphi_x)>(1+\varphi_x)$ and $(1+\varphi_x)>(MC_F+\varphi_x)$.

The price index for the M-type IGs, as a weighted average of the limit prices defined in Table 1, is at each t expressed by the following expression:

$$\overline{p}_M = (1+\varphi_x) + \Phi_M (1+\varphi_x)(q-1) - \Phi_M \, \Psi_M \, q \, [(1+\varphi_x)-(MC_F+\varphi_x)] \tag{18}$$

3.3. Level Effects in the Dirty Country

By allowing international access to the state-of-the-art IGs, international trade affects the structure of FGs production in the F-country, through the ratio $Q_{E,L}/Q_{D,L}$:

$$\overline{n}_F = \left\{ \left[\left(\frac{A_{E,F}}{A_{D,F}} \right)^{1/\alpha} \frac{e}{d} \, \frac{E_F}{D_F} \, \frac{Q_{E,L}}{Q_{D,L}} \right]^{1/2} + 1 \right\}^{-1} \tag{19}$$

Since the TK gap is always favourable to the L-country in either specific knowledge – $Q_{M,L} > Q_{M,F}$ - (the Dirty country always lags behind), the F-country enjoys an immediate absolute and relative advantage in terms of aggregate product,[11] apparent in (10).

Considering that the L-country has got cleaner environmental quality levels and more abundant ecological labour, i.e., $(A_{E,L}/A_{D,L})>(A_{E,F}/A_{D,F})$ and $(E_L/D_L)>(E_F/D_F)$ respectively, comparing (19) with (8) we get that $\overline{n}_F > \overline{n}_L$, i.e., the L-country always produces more FG with ecological technology and ecological labour than the F-country. Since both countries

[11] Indeed, the level of the composite FG increases with $Q_{M,L}$.

have access to the same state-of-the-art IGs, differences in the structure of the FGs production are determined exclusively by differences in domestic environmental quality levels and domestic labour endowments.[12] Therefore, despite the immediate convergence in productivity and prices of FGs in *F*-country, the structure of FGs' production and prices remain different between countries.

It is worthmention that due to the FGs price channel, (19) is larger than in pre-trade because labour endowment influences the direction of R&D. There are stronger incentives to improve technological knowledge that saves the relatively scarce labour type. As *F*-country is *E*-labour scarce, its pre-trade technological-knowledge bias is $\left(Q_{E,F}/Q_{D,F}\right)>\left(Q_{E,L}/Q_{D,L}\right)$.

3.4. R&D Sector Equilibrium

The instantaneous probability of the successful imitation of the current IG *j* higher environmental quality *k(j,t)* that transfers the IGs production to the *F*-country, is given by:[13]

$$pb_F(k,j,t) = rs_F(k,j,t)\cdot \beta_F\, q^{k_F(j,t)}\cdot \xi_F^{\;-1} q^{-(1/\alpha)\,k_F(j,t)}\cdot M_F^{\;-\zeta_F}\cdot \\ \cdot B_N(j,t)\cdot B_T(j,t)\cdot f\left(\tilde{Q}_M(t),b\right)^{-\sigma+\tilde{Q}_M(t)} \tag{20}$$

(i) $0<\beta_F<\beta_L$, i.e., it is considered that learning by past innovations should have greater effects than learning by past imitations; (ii) $k_F \le k_L$, i.e., the *F*-country imitator need only to imitate technologies one quality level above the current *F*-country quality level, since they are only selling the domestically imitated IGs; (iii) $\xi_L>\xi_F>0$, i.e., it is assumed that the complexity cost of imitation is lower than the innovation, as new ideas are progressively

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[12] The countries growth rates depend on their respective labour endowments and on the *L*-country technological progress.

[13] The probability of successful imitation in IG*j* is assumed to be dependent on all past successful research in all IGs in both countries. By contrast, the probability of successful innovation is assumed to be dependent only on past successful research in IG*j* in the Ecological country.

more complex to implement; (iv) ζ_F>0, i.e., the adverse effect of market size is assumed to be the same in both country types; (v) $B_N(j,t)\cdot B_T(j,t)\cdot f\left(\tilde{Q}_M(t),b\right)^{-\sigma+\tilde{Q}_M(t)}$, with 0<$\tilde{Q}_M(t)$<1 and σ>0, is a catching-up term, specific to the Dirty country. Terms $B_N(j,t)$ and $B_T(j,t)$ are exogenous variables that capture positive effects of imitation capacity. The former embodies the imitation productivity level dependent on national causes, including domestic policies promoting R&D. The latter represents the imitation productivity level dependent on external causes, comprising the degree of openness to international trade and other international trade policies, namely international integration, as well as the Dirty country's relative labour level.[14] Thus, it is assumed that labour enhances the imitation capacity, speeding up convergence with the Ecological country (Aghion et al., 2004). For simplicity, $B_N(j,t)$ and $B_T(j,t)$ are not specific to each IG. The term $f\left(\tilde{Q}_M(t),b\right)$ is a quadratic imitation function that captures the backwardness advantage, as in Papageorgiou (2002):

$$f\left(\tilde{Q}_M(t),b\right)=\begin{cases}0 & ,\ 0<\tilde{Q}_M(t)\le b\\ -\tilde{Q}_M(t)^2+(1+b)\,\tilde{Q}_M(t)-b & ,\ b<\tilde{Q}_M(t)<1\end{cases} \tag{21}$$

Where $\tilde{Q}_M(t)\equiv\left(Q_{M,F}(t)/Q_{M,L}(t)\right)$ is the relative TK level of the Dirty-country *M*-specific IGs and $b\in(0,1)$ is the TK threshold that dictates whether the *F*-country can imitate or not.[15] Due to the quadratic function, the *F*-country can imitate existing TK and grow rapidly only when it is sufficiently closed to the technological knowledge frontier. The notion that the larger the

[14] The instantaneous probability of successful research is high when both the flow of resources devoted to R&D and the coefficient on past research experience are high. The instantaneous probability of successful research is low when the fixed cost of research, the effectiveness of all costs that capture the adverse effect of market size and the complexity of research are higher. The probability of successful imitation is higher when the imitative capacity of the country is good, which increases with openness.

[15] The smaller the value of *b*, the greater the probability of successful imitation, the TK imitation and the *F*-country growth in transition. In such cases, the speed of convergence to the steady-state growth decreases.

initial technological knowledge gap, the higher the catching-up is not applied unconditionally. There are limits to the advantages of backwardness, since there is a threshold distance beyond which the cost of imitation is infinite. Therefore, if the gap is smaller than the threshold (is not large), i.e., when $\tilde{Q}_M(t)$ is above threshold *b*, then *F*-countries can benefit from the backwardness advantage (they find it easier to imitate, grow faster and converge to the *L*-country's income level). If the gap is greater than the threshold (is wider), i.e., when $\tilde{Q}_M(t)$ is below threshold *b*, then backwardness is no longer an advantage and *F*-countries show no potential to imitate and grow rapidly.

Once affected by the exponent function $\sigma(\tilde{Q}_M, t) = -\sigma + \tilde{Q}_M(t)$ in (20), $f(\cdot)$ yields an increasing advantage of backwardness.[16]

The level effect of international trade also involves immediate changes in the allocation of resources. The amount of the *F*-country resources devoted to R&D increases for two reasons. First, the incentives to imitation increase owing to the positive effect of openness on the probability of successful imitation (20-v). Second, the access to enlarged markets requires more resources due to the adverse effect of market size on the probability of successful imitation (20-iv).[17]

The *F*-country IG leader uses an imitation of quality *k*, whose profits rely on the marginal cost, the mark-up and on the world demand for IG by the FG producers:

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16 Where the size of σ affects how quickly the probability of successful imitation falls as technological knowledge gap narrows. $\sigma(\cdot)$ can be interpreted as a variable elasticity of the probability of successful imitation with respect to $f(\cdot)$. Given the small positive value of $f(\cdot)$, $\sigma(\cdot)$ must be negative to guarantee that the *F*-country can benefit from the relative backwardness.

[17] Resources devoted to R&D also increases immediately in the *L*-country, but only for the second reason. *L*-country resources are reallocated at the expense of current consumption, contrary to the *F*-country, where consumption increases with the immediate increase in aggregate income.

$$\Pi_{M,F}(k,j,t)=m\,(1-\alpha)^{1/\alpha}q^{k(j,t)\,(1-\alpha)/\alpha}\{(1-MC_F)\,[M_F(p_{M,F}A_{M,F}/(1+\varphi_{x,M,F}))^{1/\alpha}+M_L(p_{M,L}A_{M,L}/(1+\varphi_{x,M,F}))^{1/\alpha}]\} \quad (22)$$

$m{=}e$ for $M{=}E$ and $m{=}d$ for $M{=}D$. Thus, the limit pricing of IGs firms can be M-specific, i.e., $p(D)=(1+\tau_{x,D})$ for $0\leq j\leq J$ and $p(E)=(1-s_{x,E})$ for $J<j\leq 1$. Eq. (22) gives the incremental profits of follower firms taking over the leader position.

The L-country IG leader, in turn, uses either an innovation of quality (k+1) or an imitation of quality k. Thus, the L-country firms aggregate expression for the profits flow is obtained by:

$$\begin{aligned}\Pi_{M,L}(k,j,t) &= m\,(1-\alpha)^{1/\alpha}q^{k(j,t)\,(1-\alpha)/\alpha}\cdot\\ &\cdot\Big\{\Psi_M\,[q\,(MC_F+\varphi_{x,M,L})-(1+\varphi_{x,M,L})]\,\Big[M_F\left(\frac{p_{M,F}A_{M,F}}{q(MC_F+\varphi_{x,M,L})}\right)^{1/\alpha}+M_L\left(\frac{p_{M,L}A_{M,L}}{q(MC_F+\varphi_{x,M,L})}\right)^{1/\alpha}\Big]+\\ &+(1-\Psi_M)\,[q\,(1+\varphi_{x,M,L})-(1+\varphi_{x,M,L})]\,\Big[M_F\left(\frac{p_{M,F}A_{M,F}}{q(1+\varphi_{x,M,L})}\right)^{1/\alpha}+M_L\left(\frac{p_{M,L}A_{M,L}}{q(1+\varphi_{x,M,L})}\right)^{1/\alpha}\Big]\Big\}\end{aligned} \quad (23)$$

Eq. (22) and (23) show that profits depend negatively on the national after subsidy/tax MC of the respective IG, but positively on the price of the respective IGs, on the quality rung, k, on the productivity parameters, $A_{M,F}$ and $A_{M,L}$, on the price indexes, $P_{M,F}$ and $P_{M,L}$, and on the market size, M_F and M_L.

Due to technological complementarity in (1) the market size for M-specific IGs is the employed M-labour type. Thus, the scale effect, M, is apparent in (22) and (23).

It is worthnoting that, while the monopoly duration of the F-country IG firm (22) ends with the next innovation, which can only be driven by some L-country firm, the monopoly duration of the L-country IG firm (23) ends with its imitation or the next innovation.

The expected present value of the profits flow of both F-country and L-country IG producer are, respectively:

$$V_F(k,j,t)=\Pi_F(k,j,t)/[r_F(t)+pb_L(j,k,t)] \quad (24.a)$$

$$V_L(k,j,t)=\frac{\Pi_L(k,j,t)}{r_L(t)+pb_L(j,k,t)+pb_F(j,k,t)-pb_L(j,k,t)pb_F(j,k,t)} \quad (24.b)$$

These expressions state the expected reward from carrying out the successful imitative and innovative research, $V(k, j, t)$. This domestic patent depends positively on the amount of profits yield, $\Pi_F(k, j, t)$ and $\Pi_L(k, j, t)$, and negatively on the effective discount rate at *t*.[18] The duration of an imitation patent depends on the probability of the *(k+1)*th successful innovation in the *L*-country, $pb_L(j, k, t)$, as shown in the third case in Table 1, whereas the duration of an innovation patent comes from both the *(k+1)*th innovation and the k^{th} imitation, $pb_L(j,k,t)+pb_F(j,k,t)-pb_L(j,k,t)pb_F(j,k,t)$, as shown in the first and second cases in Table 1. The feedback effect between countries is clear in both $V_F(k, j, t)$ and $V_L(k, j, t)$ since the former depends on $pb_L(j,k,t)$ and the latter on $pb_F(j,k,t)$.

Given the functional forms (12) and (20) of the success probabilities in R&D, under free entry R&D equilibrium, the expected revenues must equal the spent resources:

$$pb_F(k, j, t)\, V_F(k, j, t) = \left(1 - s_{r,F}\right) rs_F(k, j, t) \tag{25.a}$$

$$pb_L(k, j, t)\, V_L(k+1, j, t) = \left(1 - s_{r,L}\right) rs_L(k, j, t) \tag{25.b}$$

$s_{r,F}$ and $s_{r,L}$ are governmental ad-valorem subsidies to R&D that result in a reduction of R&D costs and can be *M*-specific.[19] The government can use a continuum of different policy rules, from the extreme symmetric rule (each *M*-R&D activity gets the same) to the extreme asymmetric rule (only *E* or *D*-R&D activity gets the subsidy). Thus, the limit pricing can be *M*-specific, i.e, with $s_{r,D} \neq s_{r,E}$: $p(D)=q(1-s_{r,D})$ for $0 \leq j \leq J$ and $p(E)=q(1-s_{r,E})$ for $J<j \leq 1$.

Plugging (20) with $\varsigma_F = 1$ and (24.a) into (25.a), and solving for pb_L, the equilibrium probability of successful innovation in a *M*-specific IG is:

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[18] The effective discount rate is given by the interest rates, $r_F(t)$ and $r_L(t)$ and by the expected duration of the flow or the rate of Schumpeter creative destruction.

[19] A *D*-R&D subsidy is assumed to foster environmental advances of *D*-IGs altering them into less polluted IGs.

$$pb_L(j,k,t) = \frac{\beta_F}{\xi_F}\, B_D\, B_T\, f\left(\tilde{Q}_M(t), d\right)^{-\sigma+\tilde{Q}_M(t)} \tilde{Q}_M(t)\, (1-\alpha)^{1/\alpha}\, \frac{(1-MC_F)}{(1-s_{r,M,F})}\, m\, Z_M(t) - r_F(t) \tag{26}$$

Where:

$$Z_M(t) = \frac{M_F}{M_F+M_L}\left(\frac{p_{M,F}\, A_{M,F}}{(1+\varphi_{x,M,F})}\right)^{1/\alpha} + \frac{M_L}{M_F+M_L}\left(\frac{p_{M,L}\, A_{M,L}\,(1-\alpha)}{(1+\varphi_{x,M,F})}\right)^{1/\alpha} \tag{27}$$

Eq. (26) indicates that the equilibrium *M*-specific, pb_L, for a new quality of IG *j* is higher when profits from sales, Z_M, are higher. In turn, the profits will be higher when the price indexes, p_M, are higher. It also follows that given the interest rate, *r*, and the FGs' price indexes, p_M, (26) is independent of IG *j* and quality rung *k*, for two reasons. The first and most substantial reason is the scale removal of TK effects. Indeed, the positive influence of the quality rung on profits – exponents of *q* in (22) -, and on the learning effect, (20)-(ii), is exactly offset by its negative effect on the complexity cost, (20)-(iii). The other reason is the simplifying assumption that the determinants of imitation capacity, B_D and B_T, (20)-(v), are not specific to each IG. The adverse effect of market size, due to the scale-proportional difficulty of introducing new quality IGs, see (12)-(iv) and (20)-(iv), is designed to offset the scale effect on profits, (20)-(v). Indeed, with ζ=1, the influence of market size becomes negligible, as is apparent in expression Z_M in (27). Eq. (26) also shows that, now, pb_L is affected by the imitation activity due to the feedback effect between countries.

From (26) and (27), it is clear that R&D equilibrium rates respond negatively to the interest rate and to a raise in the exogenous tax rate of *D*-IGs, $\tau_{x,D}$. Conversely, they are encouraged by an increase in the exogenous ad-valorem subsidy rates of *M*-R&D, $s_{r,M}$, and *E*-IGs, $s_{x,E}$, and on the exogenous environmental quality, A_M, and FGs' price indexes, p_M. Thus, the direction taken by technological-knowledge is driven by the price channel and can be affected by the structure of government intervention.[20]

[20] This result is different from the skill biased technological change literature that omits the endogenous accumulation of human capital and highlights the scale effects. In this literature, the technological knowledge

Given that the probability of successful innovation for all IGs of each *M*-type – as a Poisson arrival rate – determines the speed of TK progress, see (26), the equilibrium can be translated into the path of the *L*-country *M*-type of TK. Due to the free trade in IGs, the *F*-country is also allowed to benefit from it. Thus, the equilibrium growth rate of *M*-specific technological progress, Q_M, at *t*, is given by:

$$E\left(\Delta Q_{M,L}/Q_{M,L}\right)= \dot{Q}_{M,L}/Q_{M,L} = pb_{M,L}\left[q^{(1-\alpha)/\alpha}-1\right], \qquad (28)$$

where $[q^{((1-\alpha)/\alpha)}-1]$ is the impact of each successful innovation on the technological progress. From (28) it is clear that there are international trade feedback effects with IT of IGs. The positive level effect from the innovator to the imitator feeds back into the innovator, affecting the *L*-country technological knowledge through creative destruction. Indeed, dirty-country benefits from innovations through the access to the state-of-the-art IGs allowing to increase production and, consequently the available resources to R&D imitation Therefore, the imitation shifts IGs production from the Ecological to the Dirty-country, where production is more efficient due to the lower MC. This induces the Ecological-country to devote fewer resources to IGs production and more resources to R&D.

3.5. The Steady State Equilibrium

By assumption, through free IGs trade, both countries have access to the same state-of-the-art IGs and the same FGs technology of production, except environmental quality, *A*, and labour, *M*, levels, which are country specific. This implies differences in levels but not in growth rates. Thus, the steady-state growth rate must be the same for both countries.[21] Through the

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bias is related with the exogenous increase in the skills supply, which induces faster upgrading of skill-labour complementary since under technological substitutability the market size effect dominates the price channel.

[21] The steady-state equilibrium is a path where all variables either grow at a constant rate (not necessarily the same) or are time invariant.

Euler equation (15), this entails that, in steady-state, the interest rates are also equalized between countries.

All resources of the economy, i.e., the aggregate FG, Y, can be allocated between consumption, C, production of IGs, X, and R&D, RS. In the case of the F-country, this is:

$$Y_F(t) = C_F(t) + X_F(t) + RS_F(t) \tag{29}$$

Since, in equilibrium Y, X, RS and C are all constant multiples of the L-country TK levels (Q_E and Q_D) and the domestic levels of labour, M, the stable and unique steady-state endogenous growth rate, $g^*\left(\equiv g_D^* \equiv g_E^*\right)$, common to both countries, is:

$$g^* = \left(\frac{\dot{Y}}{Y}\right)^* = \left(\frac{\dot{X}}{X}\right)^* = \left(\frac{\dot{RS}}{RS}\right)^* = \left(\frac{\dot{Q}_{D,L}}{Q_{D,L}}\right)^* = \left(\frac{\dot{Q}_{E,L}}{Q_{E,L}}\right)^* = \left(\frac{\dot{C}}{C}\right)^* = \left(\frac{\dot{c}}{c}\right)^* = \frac{1}{\theta}\left[(1-\tau_K)r^* - \rho\right] \Rightarrow \left(\frac{\dot{p}_E}{p_E}\right)^* = \left(\frac{\dot{p}_D}{p_D}\right)^* = \left(\frac{\dot{\bar{n}}}{\bar{n}}\right)^* \tag{30}$$

Eq. (30) shows that steady-state growth is driven by the L-country TK growth rate, although it is affected by both F-country imitation and F-country demand for IGs which depends on the F-country levels of labour at work. Therefore, (30) implies steady levels of threshold FGs, as well as of final and intermediate goods, price indexes and steady-state gaps in both types of technological knowledge.[22] From (30) it is also patent that by $s_{x,E}$ and $s_{r,M}$, government intervention positively affects r^* and hence g^*.[23] Indeed, while $s_{x,E}$ increases the monopolistic profits, see (22)-(23), acting as an incentive to E-R&D, $s_{r,M}$ decreases the cost of R&D, see (25), increasing the equilibrium probability of successful research, pb_M, (26). Conversely, by $\tau_{x,D}$ and τ_K, government intervention negatively affects r^* and thus g^*. $\tau_{x,D}$ decreases the monopolistic profits, discouraging D-R&D and τ_K decreases investment in R&D, due to its smaller expected marginal benefit. Since τ_w is absent in equilibrium conditions, it does not directly affect g^*.

[22] Indeed, while complete convergence in available technological knowledge is instantaneous with international trade (level effect), domestic levels may not converge completely, that is, $\tilde{Q}_E$ and $\tilde{Q}_D$ may remain below one.

[23] $s_{x,E}$ and $s_{r,M}$ promote TK progress, which leads to an increase in the long run growth rate.

Thus, it is clear that R&D drives steady-state endogenous growth. A higher steady-state interest rate induces a strong R&D activity that shortens the duration of monopolist positions, i.e., there is a strong process of creative destruction. However, this feature is not specific to international trade. To look at the steady-state effects of international trade, we have to analyse the *F*-country growth imitation. Since in steady-state there is a world growth rate common to both countries, we must compare the world steady-state interest rate, $r^*\left(\equiv r_F^* \equiv r_L^*\right)$, obtained by setting the consumption growth rate (15) equal to the *L*-country technological-knowledge growth rate (28), to the one that would prevail in the *F*-country under a pre-trade steady-state (without IT).[24]

$$r^* = \left\{\left[q^{(1-\alpha)/\alpha} - 1\right]\theta + (1-\tau_k)\right\}^{-1} \left\{\frac{\beta_F}{\xi_F}\, B_D\, B_T\, f\left(\tilde{Q}^*{}_M(t), d\right)^{-\sigma+\tilde{Q}^*{}_M(t)} \tilde{Q}^*{}_M(t)\,(1-\alpha)^{1/\alpha}\,\frac{(1-MC_F)}{\left(1-s_{r,M,F}\right)}\cdot \right. \\ \left. \cdot\, m\, Z^*{}_M(t)\left[q^{(1-\alpha)/\alpha} - 1\right]\theta + \rho\right\} \tag{31}$$

Given that goods, assets and technological knowledge do not flow internationally in autarky, the advantage of backwardness and openness disappear from the probability of successful imitation (20). Therefore, from autarky to trade in IGs, the increment in the steady-state interest rate depends on the following difference:

$$H_T\, f\left(\tilde{Q}^*{}_M(t), h\right)^{-\sigma+\tilde{Q}^*{}_M(t)} \tilde{Q}^*{}_M(t)\,(1-MC_F)\, Z^*{}_M - \left(\frac{q-1}{q}\right)\left[A_{M,F}\, p^*{}_{M,F}\Big|_{pre-trade}\right]^{1/\alpha}\left(MC_F + \varphi_{X,M,F}\right)^{(\alpha-1)/\alpha} \tag{32}$$

The evaluation of (32) requires solving for transitional dynamics through calibration and simulation. Nevertheless, besides level effects, international trade of IGs also influences steady-state growth in four opposite directions.

The first is the positive catching-up effect on the probability of successful imitation. Imitation capacity increases with the openness degree, captured by H_T, and the advantages of backwardness are only acquired in the presence of international trade. Through the feedback

[24] The steady-state growth rates, g^*, result from plugging the steady-state interest rate, r^*, into the growth rate of consumption (15). Thus, the determinants of r^* are also the determinants of g^*.

effect, the probability of successful innovation and, hence, the steady-state growth rate are also positively affected, see (26) and (28).

The second is the positive spillovers from Ecological to Dirty-country. Each innovation in the *L*-country tends to lower the cost of *F*-country imitation because backward advantage is strengthened with each improvement of the technological knowledge frontier.

The third (counteracting way) is the monopolistic competition mark-up. Ignoring the subsidy or tax, φ_x, the *F*-country's mark-up under international trade is $(1-MC_F)$, clearly less than the mark-up in the *F*-country under pre-trade, which is $(q-MC_F)$. This profit loss also happens to the *L*-country monopolist. Indeed, considering the after subsidy/tax *MC*, which is $(1+\varphi_{x,M,L})$, the average mark-up between the first $(q-1)(1+\varphi_{x,M,L})$ and the third $q(MC_F+\varphi_{x,M,L})-(1+\varphi_{x,M,L})$ situation in Table 1 is smaller than $(q-1)(1+\varphi_{x,M,L})$, which is the mark-up under pre-trade. This occurs because, in pre-trade, successful researches are protected from international competition. Once engaged in international trade, and once imitation has become profitable (provided that the TK threshold *h* is overcome),[25] profit margins in both countries are reduced, discouraging R&D.[26]

The fourth (counteracting way) is that *F*-country firms have to support R&D imitative costs of state-of-the-art *L*-country IGs, possibly several quality rungs above their own experience level in pre-trade (and thus more complex). This is reflected in the presence of the technological knowledge gap, $\tilde{Q}^*_M$, in (32).

From (32), if the impact of the openness, H_T, is strong and if MC_F is low, then the steady-state growth tends to be higher under IT of IGs than with TK diffusion without IT.

The effect of IT on the steady-state growth rate is, thus, ambiguous.

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[25] If the TK threshold *b* is not overcome when countries open up to IT, the *F*-country firms will not support imitation since the imitation costs will be strongly higher.

[26] The reduction of margins is not offset by market enlargement, since the scale effect was removed.

This world growth rate is affected by the levels of both exogenous variables and parameters, as expected in an endogenous growth model. In particular, in both countries the levels of environmental quality ($A_{M,L}$ and $A_{M,F}$) and of the R&D technology parameters (β, H_D and H_T) improve the common growth rate through their positive effect on the R&D profitability, (23) and (26). Indeed, a better environmental quality affects positively the level of domestic output and the world growth rate as well. Thus, IT emphasises the importance of domestic environmental quality improvements in both countries, since they become significant not only at home but also abroad. In turn, β, H_D and H_T enhance imitation activity and, consequently, increase the probability of successful innovation as well as the steady-state world growth rate and each innovation lowers the cost of imitation meaning that positive spillovers from innovation to imitation occur. The labour share in the production function, α, the discount rate, ρ, the inverse of the intertemporal elasticity of substitution, θ, the exogenous subsidies, s_x and s_r, the assets income tax, τ_k, and the labour income tax, τ_w, have the same influence on the world steady state growth rate as with no IT of IGs and for the same reasons. The impact of both MC_L and MC_F on steady-state growth results from the combination of typical Schumpeterian-R&D effects. A higher MC_L leads to a higher mark-up for monopolist producers in the *F*-country, whereas a higher MC_F implies a smaller mark-up. Thus, a higher MC_L provides an incentive to imitation activity, which affects positively the equilibrium probability of successful innovation and thereby world growth, while the inverse holds when MC_F is higher.

4. Conclusion

In line with Schumpeterian growth literature, this paper provides an endogenous non-scale mechanism to link technological-knowledge progress, technological-knowledge bias, final-good sector bias and government intervention under international trade of intermediate goods.

Two countries, the Ecological (*L*-country) and the Dirty (*F*-country), with different environmental quality levels and available technological knowledge, are considered and both are capable of conducting R&D. The *L*-country devote innovative R&D activities to increase the IGs environmental quality, while the *F*-country mimics the R&D process of the Ecological (Leader) country's current best qualities. Under international trade, IGs can flow from Ecological to Dirty and from Dirty to Ecological country.

With this paper, we have concluded that if improvements in the probability of successful imitation, due to the IT of IGs, are sufficiently strong, both countries grow more quickly under the IT of IGs because once the innovations are imitated, Ecological-country IGs firms can only capture the world market by supporting the next innovation. Consequently, a higher probability of successful imitation increases the speed of TK transfer, which improves the Dirty-country ability to benefit from Ecological-country innovations inducing an efficient allocation of production in the Dirty-country where *MC* is lower[27]. This, together with the initial level effect induced by the IT of IGs, feeds back into the *L*-country, affecting its TK through creative destruction and so, the steady-state world growth rate (common to both countries), that tends to be greater.

Concerning the effects of both IGs and R&D subsidies, when they are equal in both countries, a rise in their rates leads to a permanent increase in the long-run world steady-state, since they promote TK progress, regardless of the IT regime. Conversely, when these subsidies are different between countries, then when they increase in the Dirty-country without IT, the steady-state world growth rate is not affected, but the TK gap decreases. However, when they increase in the Dirty-country with IT of IGs a permanent increase in the world steady-state occurs.

[27] By assumption, *MCs* are different in the *F*-country under the two IT regimes.

Therefore, we can conclude that IT of IGs induces a greater Ecological-biased TK change and the same economic forces that affect the TK progress will also shape its respective bias and the final-good sector bias. These biases result from the direction of TK induced by the price channel under international trade, which is stimulated by government policy. As soon as openness takes place, the price channel yields an increase in the *E*-technological bias, i.e., TK becomes relatively more endogenously biased towards *E*-technology than without IT.

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