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Economic Growth, Ecological Technology and Public Intervention

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Abstract

Seminal works on growth theory had mainly focused on exogenous technological change, where a certain given path of technological change was considered. At the end of the 1980s, a new growth theory emerged allowing for the endogeneity of technological change, where economic agents can affect the pace of technological change and where technology is essentially interpreted as "knowledge". The present paper aims to develop a simple endogenous growth model to study the effects of taxation on dirty intensive resources and the effects of subsidies on clean/ecological intensive resources. It also intends to analyse how exogenous environmental quality can affect the development of better quality (environmentally cleaner) inputs to production. For that, a dynamic general equilibrium growth model is considered based on the endogenous skill-biased technological change literature. It is shown that final-good sector bias is caused by the technological-knowledge bias, which is promoted by government intervention.

Keywords: economic growth, technological change, environment.
JEL codes: C61; O13; Q55; Q58

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1. Introduction

This paper aims to implement an analytical instrument capable of assessing the impact of clean and dirty technologies, as well as of energy/environmental policies on the production structure. It also intends to study how such policies can affect economic growth. For that, a dynamic general equilibrium growth model is considered based on the endogenous skill-biased technological change literature (e.g., Acemoglu, 2002).

Seminal works on growth theory had mainly focused on exogenous technological change, where a certain given path of technological change was considered. At the end of the 1980s, a new growth theory emerged allowing for the endogeneity of technological change, where economic agents can affect the pace of technological change and where technology is essentially interpreted as "knowledge" (e.g., Vollebergh et al., 2005).

Economic activities are mainly based on energy intensive sectors, but no power source is entirely impact-free. All energy sources give rise to some degree of pollution. The environmental impacts can, then, depend on how energy is produced and used, the fuel mix, the structure of the energy systems, the energy regulations and pricing structures.

One of the major challenges for policy-makers has been the definition and implementation of sustainable policy schemes. European Union programmes on technological change aim to stimulate not only innovation, in general, but also environmentally friendly technologies, in particular. These technologies are assumed to yield a double dividend, by stimulating economic growth and generating fewer emissions.

With the changing concepts of technology in economic theory together with their implications for sustainability, attention has shifted to the link between environmental policy and the bias of technological change. Indeed, over the last 10 years economists have been stressing the role of technological change in the analysis of energy, environmental and climate policy. One of the reasons, usually appointed for the disregard of the environment in models of endogenous growth is that incorporating environmental externalities and resource scarcity increases strongly their complexity. Thus, the early attempts have focused mostly on first generation models of endogenous innovation (e.g., Jones 1995), where growth is endogenous but technological knowledge progress is assumed exogenous. Thus, in that literature, environmental policy exerted only temporary effects on growth. However, the experience suggests that tighter environmental policies induce major technological-knowledge advances in abatement technologies. In an attempt to shed new light on these issues, around 1990 a large and growing number of new growth literature emerged, studying the traditional endogenous growth models in a framework where environment and non-renewable resources are present and where environmental taxation effects are considered, generating novel insights concerning the energy/environment-growth relation (e.g., Schou, 2000; Smulders and Nooij, 2003; Grimaud and Rougé, 2003).

Bovenberg and Smulders (1995, 1996), for instance, extended the model of Lucas (1988) by incorporating two "public" inputs to production: the environment and the abatement knowledge. The authors show that if environment acts mainly as a public consumption good, a reduced pollution level, to yield amenities, harms the productivity of man-made production factors, depressing growth. Conversely, if the environment acts mainly as a public input into production, the enhanced quality of the environment improves productivity, offsetting the adverse growth effect of lower pollution. Moreover, while the costs of a tighter environmental policy occur in the short run, the benefits arise only in the long-run since it takes time for nature to recover and for new abatement technologies to be developed.[1]

[1] Other models with nature as an input include Tahvonen and Kuuluvainen (1991), Gradus and Smulders (1993), Smulders and Gradus (1996), Elbasha and Roe (1996), Mohtadi (1996) and Xepapadeas (1997).

Peretto (2009), in turn, introduces the energy sector and studies the effects of a tax on energy use, but ignores the specific scarcity problems derived by the use of non-renewable resources. Under the assumption of no scale effects and that energy demand is inelastic, the author found that the tax has no effect on the steady-state growth rate, though it has important transitional effects. Bovenberg and Smulders (1995, 1996) consider a pollution tax, but not other distorting taxes. Bovenberg and de Mooij (1997), Greiner (2005) and Hettich (1998) consider both a pollution tax and distorting income tax, but not the two “public” capital stocks (environment and abatement knowledge).

Fullerton and Kim (2008), in turn, combine various elements from prior models to construct a single endogenous growth model with endogenous determination of pollution and environmental quality as well as accumulation of private capital and pollution abatement knowledge. They assume three assets in the economy: private capital (physical and human capital), public abatement knowledge (R&D) and the environmental quality (natural capital). They show that with abatement more effective than actual pollution, having higher pollution tax may mean lower growth, even with higher welfare. They also show the conditions under which it has the opposite effects (higher growth but lower welfare).

With the exception of Groth and Schou (2007), none of the aforementioned studies include the non-renewable resource in the “growth engine”. They use a simple general endogenous growth model where the resource enters the “growth engine” to study the effects of different forms of subsidies and taxation on capital and resources. Unlike the typical results from partial equilibrium analysis, they found that a tax on capital gains on a non-renewable resource stock is shown to be of rather importance for long-run growth. The same is true for a time-varying tax on resource use. These results also contrast with the general belief within endogenous growth literature that interest income taxes hamper growth, whereas investment subsidies promote growth. The authors show that this conventional view rests on the growth models where non-renewable natural resources are ignored, but does not go through when the non-renewable resource is an essential input in the sector generating long-run growth.[2]

The present paper aims to develop a simple endogenous growth model where both renewable and non-renewable resources enter in the "growth engine" to study the effects of taxation on dirty intensive resources and the effects of subsidies on clean/ecological intensive resources. It is also intended to analyse how exogenous environmental quality can affect the development of better quality (environmentally cleaner) inputs to production.

The remainder of the paper is organised as follows. Section 2 presents the model. Here, the final goods, the intermediate goods and the R&D sectors with government intervention are described, the individual's behaviour and the government balanced budget presented and the equilibrium characterised. Section 3 analyses the steady-state equilibrium and performs some comparative statics to study the impact of the economic policy tools on technological-knowledge bias and on final good sector bias, as well as on economic growth. Section 4 studies the transitional dynamics and proceeds to some sensitive analysis and section 5 concludes.

2. The Model

2.1 Overview

A standard economic structure with endogenous Shumpeterian R&D-growth theory (i.e., with vertical innovations) is considered. In line with Barro and Sala-i-Martin (2004, ch. 7) and Afonso (2008), it is considered an economy with three productive sectors: the final goods (FGs) sector, the intermediate goods (IGs) sector and the research and development (R&D) sector.

In the perfect competitive FGs sector ecological- and dirty-intensive goods are produced through one of two substitutable technologies: Ecological Technology (T_E) or Dirty Technology

[2] See Aghion et al. (1998), Brock et al. (2005), Smulders (2000, 2005) and Xepapadeas (2005) for recent reviews.

(T_D). The T_E is an environmentally friendly technology that contributes to reduce pollution (or energy/material waste). To produce with T_D, FG firms use dirty-specific IGs, such as non-renewable resources, namely fossil fuels. By contrary, to produce with T_E, FG firms use ecological-specific IGs, such as renewable resources. Composite (or aggregate) FG can be consumed, converted into quality adjusted IGs or directed to R&D activities.

The R&D activities, which are also developed in a competitive market, can be influenced by government policies, in order to develop new designs or successful research to enhance the environmental quality of both ecological and dirty-specific IGs, using the composite FG as the only input.

The IG firms, in contrast, have monopoly power over the sales of their environmental quality adjusted IG. Consequently, they can charge a price above marginal cost (*MC*), which can also be influenced by government policies. As there are always follower IGs firms performing R&D, at each time, the monopoly power is temporary and each leader firm is driven out of business by new successful research that eliminates its profit.

Individuals decide between working with ecological technology (T_E) and dirty technology (T_D) and between consumption and savings. For simplicity, we assume that individuals with high ability perform better using ecological technology (E), while those with lower ability perform better using dirty technology (D).

Since, this is a dynamic general equilibrium model, all markets clear throughout time.

2.2. Final-Goods Sector

Following Barro and Sala-i-Martin (2004, ch. 7), Afonso (2008) and Acemoglu and Zilibotti (2001), let's consider that each FG $n \in [0,1]$ can be produced by Dirty (T_D) or Ecological (T_E)

technology. The former (latter) uses D (E) skilled (unskilled) labour together with a continuum set of D(E)-specific IGs indexed by $j \in [0,J]$ $(j \in]J,1])$; i.e., $Y_n = f\left(D_n, IG_n^D; E_n, IG_n^E\right)$.

There is substitutability between technologies (T_E and T_D) and complementarity among inputs (between D_n and IG_n^D and between E_n and IG_n^E).[3] IGs are environmental quality adjusted. Thus, the expression for the n FG production function, at time t is:

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

A_D (A_E) is the exogenous productivity level that depends on the institutions, property rights, government services, cultural and geographical features, social conditions and polluted (clean) environmental quality. That is, A_D (A_E) is a negative (positive) externality of production resulted from a more polluted (cleaner) environmental quality. The integrals denote the contributions of the two types of IGs to the production. Each of the two IG terms includes an adjustment for the environmental quality, obtained with each successful research that is expressed by an exogenous constant $q>1$.[4] The term k represents the top environmental quality rung at time t and $k(j,t)$ expresses the j^{th} IG upgrade until t. In turn, $q^{k(j,t)} x_n^{(k,j,t)}$ denotes the used quantity of the IG j adjusted by environmental quality and the exponent (1-α) is its share in final good production. The "additive separability" of the IG means that they are perfect substitutes.[5]

[3] Unlike our model, Comolli (2006) proposes a two-sector neoclassical growth model with Cobb-Douglas technology in the intermediate sector and fixed-proportions technology in final good production, treating technological progress as exogenous. Additional references are Roseta-Palma et al. (2010) that use the traditional Cobb-Douglas production function, where all factors are essential but there are substitution possibilities, and England (2000) that emphasizes the complementarity of human-made and natural capital in production.

[4] Since the quality grades are perfect substitutes to production, in equilibrium only the highest environmental quality (the last upgrade) of IG is used because even though it is more expensive, the productive gains are larger. Thus, there is no need for using the sum function in (1).

[5] The discoveries of new ecological varieties of IG do not make any of the existing ones obsolete and no particular IG is totally essential to production.

Expressions with exponent $\alpha \in]0,1[$ represent the $D(E)$ type of labour share in production. It is also assumed that E skilled labour has an absolute productive advantage over D unskilled labour, guaranteed by $e>d\geq 1$. The relative productivity advantage of either type of labour is captured by n and $(1-n)$, which implies that $D(E)$ is relatively more productive in FGs indexed by smaller (larger) n. Consequently, the relative advantage of T_E increases with index n. Since $n \in [0,1]$, at each time t, there is a competitive equilibrium threshold final good $\bar{n}$, endogenously determined, where the switch from one technology to the other becomes advantageous.

The profit maximisation problem of the n^{th} FG producer, is as it follows:

$$\underset{x_n(k,j,t);D_n;E_n}{Max} \Pi_n = Max \left\{ p_n Y_n - \int_0^J p(k,j,t)\, x_n(k,j,t)\, dj - \int_J^1 p(k,j,t) x_n(k,j,t)\, dj - w_D D_n - w_E E_n \right\}, \tag{2}$$

Eq. (2) implies that the marginal product of each input must equal its price due to the presence of constant returns to scale. From the first order conditions (FOCs), we get for the case of $j \in [0,J]$ that:

$$x_n(k,j,t)_{|j \in [0,J]} = A_D^{1/\alpha}\, p_n^{1/\alpha} \left(\frac{1-\alpha}{p(k,j,t)} \right)^{1/\alpha} q^{k(j,t)\left(\frac{1-\alpha}{\alpha}\right)} [(1-n) d\, D_n] \tag{3}$$

Eq. (3) is the demand for dirty-specific IG j by the firm of the FG n produced with T_D. This equation implies that FG firms demand more dirty-specific IGs when their product price, p_n, is higher, when labour level, D_n, and the environmental quality of the IGs, $k(j,t)$, are greater and when dirty-specific IGs prices, $p(k,j,t)$, are lower. Substituting the IG demand functions for dirty and ecological-specific IG j into the production function, (1), after some algebra, we obtain the supply of the n^{th} FG:

$$Y_n(t) = p_n^{\frac{1-\alpha}{\alpha}} \left(\frac{1-\alpha}{p(k,j,t)} \right)^{\frac{1-\alpha}{\alpha}} \left[A_D^{1/\alpha} (1-n) d\, D_n\, Q_D(t) + A_E^{1/\alpha}\, n\, e\, E_n\, Q_E(t) \right] \tag{4}$$

$$Q_D(t) \equiv \int_0^J q^{k(j,t)\left(\frac{1-\alpha}{\alpha}\right)} dj \text{ and } Q_E(t) \equiv \int_J^1 q^{k(j,t)\left(\frac{1-\alpha}{\alpha}\right)} dj \tag{5}$$

where Q_D and Q_E are aggregate quality indexes that evaluate the technological knowledge in each range of IGs. Considering, now, the aggregate output of the economy, *Y*, it can be expressed by:

$$Y(t) = \int_0^1 p_n(t) Y_n(t) dn \; = \; exp\,[ln\,1]\; exp\left[\int_0^1 ln\,Y_n(t)\,dn\right] \; = \; exp\left[\int_0^1 ln\,Y_n(t)\,dn\right] \tag{6}$$

where, for simplicity, *Y* is assumed numeraire; i.e., its price is normalized at each *t* to one. All resources of the economy, i.e., the aggregate output, *Y*, can be used either in the production of intermediate goods, *X*, or in the R&D sector, *RS*, or in consumption, *C*; i.e.,

$$Y(t) = X(t) + RS(t) + C(t) \tag{7}$$

2.3. Intermediate-Goods Sector

The IG sector supplies to the FGs firms different environmental quality adjusted inputs. From (7), and for simplicity, *Y* will be input in the production of IGs. The IG firm can buy one unit of *Y* at its marginal cost (*MC*) of production, which is assumed to be one, convert it into a new quality adjusted IG at no cost, and then sell it back to FGs firms (Barro and Sala-i-Martin, 2004, ch. 7); i.e., the IG producer transforms *Y* into an IG with better environmental quality at no cost.

Like the FGs producers, the objective of the IGs firms is to maximize their profits. Following Romer (1990), the production of *j* requires a start-up cost of R&D, which can only be recovered if profits at each date are positive for a certain time in the future. This is assured by a system of intellectual property rights, known as patent law, which protects the leader firm's monopoly, while at the same time, almost without any costs, disseminates acquire technological knowledge to other firms. Consequently, the producer of the highest environmental quality of the j^{th} IG is a monopolistic competitor and his profit maximization problem is expressed by:

$$\underset{p(k,j,t)}{Max}\; \Pi(k,j,t) \; = \; [p(k,j,t) - 1]\; x(k,j,t) \tag{8}$$

Because the production function of IGs is assumed to be identical to the aggregate FG, the *MC* of an IG will be equal to the *MC* of *Y*. As the FGs firms are perfect competitors, their *MC* equals their price and so will the *MC* of IGs. That is, *MC*=1. Hence, the *MC* of producing an IG is independent of its quality level and it is identical across all *j*'s. Let's consider, for instance, the dirty-specific IG production, $j \in [0, J]$. Taking the first derivative of $\Pi(k, j, t)$ in respect to price, $p(k, j, t)$, and setting it equal to zero (FOCs), we have the following price:[6]

$$\frac{\partial \Pi_n}{\partial p(k,j,t)}_{|j \in [0,J]} = 0 \quad \Leftrightarrow \quad p(k,j,t) = p = \frac{1}{1-\alpha}\,, \tag{9}$$

The degradation of environmental quality is associated with pollution from the use of non-renewable resources, namely fossil fuels. Thus, these resources should be discouraged in favour of less polluted ones, such as the renewable resources. It is in this context that the environmental policy should act. 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 and hence, yield statically efficient outcomes (e.g., Baumol and Oates, 1994). In addition, 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 less of environmental commodity. Thus, it will be assumed the market-based instruments (taxes and subsidies) as the government policy.

Assuming, then, that the government can subsidise (tax) the ecological (dirty)-specific IG *j* by paying (charging) an ad-valorem fraction, s_x (τ_x), of each firm's cost, the after subsidy (tax) marginal cost of producing *j* is ($MC+\varphi_x$), that is, ($1+\varphi_x$), where φ_x denotes subsidies ($-s_x$) or taxes (τ_x).[7] Thus, the profit maximization price of the monopolistic IG firms, (9), yields $p = (1+\varphi_x)/(1-\alpha)$. Note that being $0<\alpha<1$ and $s_x<\alpha$, the monopoly pricing is always a mark-up on the after subsidy $MC=(1-s_x)$, since $p=(1+\varphi_x)/(1-\alpha) > MC=(1+\varphi_x)$. If there is no change in government intervention,

[6] For ecological-specific IG production, $j \in]J, 1]$, the price is the same.

[7] Since subsidy and tax rates are relatively stable over *t*, we consider that they are stationary and exogenously given.

this price is a constant mark-up over t, across j and for all quality grades k. The closer α is to zero, the smaller is the mark-up, meaning that there is less room for monopoly pricing.[8]

Each unit of the best environmental quality good is equivalent to q units of the following best environmental quality good. If the top environmental quality grade is priced at $(1+\varphi_x)/(1-\alpha)$, then a good of the next top environmental quality grade could be sold at most at $(1+\varphi_x)/q(1-\alpha)$. If $(1+\varphi_x)/q(1-\alpha) < (1+\varphi_x)$, the next best environmental quality producer (and all lower environmental quality producers) cannot compete against the leader's monopoly price and the monopoly pricing will prevail. However, if $(1+\varphi_x)/q(1-\alpha) \geq (1+\varphi_x)$, the providers of IGs can engage in Bertrand competition (Grossman and Helpman, 1991, chap.4). In this case, the environmental quality leader employs a limit price strategy, a price that is sufficiently below the monopoly price so as to make it just barely unprofitable for the next best environmental quality to be produced; This limit pricing is:

$$p = q(1+\varphi_x), \text{ where } (1+\varphi_x) < q(1+\varphi_x) \leq \frac{1+\varphi_x}{1-\alpha} \tag{10}$$

If the leader prices at a price slightly below $q(1+\varphi_x)$, for example $q(1+\varphi_x)-\varepsilon$, then the closest follower can charge at most $(1+\varphi_x)-\varepsilon/q$, a price that results in negative profit and the lower environmental quality goods are again driven out of the market. Thus, if $(1+\varphi_x)/q(1-\alpha) \geq (1+\varphi_x)$, the limit pricing will prevail, so that the leader can successfully capture the whole market.[9] Plugging (10) and (5) into the demand functions for dirty and ecological-specific IGs, it follows that their aggregate explicit demand functions become:

[8] Indeed, when α=0, monopoly pricing is not viable, since price becomes equal to MC (typical of perfect competition).

[9] It is worth noting that regardless of the strategy (monopoly or limit pricing), the price of IGs is taken as given by the FGs producers, who are price takers.

$$X_n(k,j,t)_{|j\in[0,1]} = p_n^{1/\alpha}\left(\frac{1-\alpha}{q(1+\varphi_x)}\right)^{1/\alpha}\left[A_D^{1/\alpha}(1-n)d\,D_n\,Q_D(t)\right]+\left[A_E^{1/\alpha}\,n\,e\,E_n\,Q_E(t)\right] \tag{11}$$

Accordingly, substituting (10) into (4), the production function of FG n turns out to be:

$$Y_n(t) = p_n^{\frac{1-\alpha}{\alpha}}\left(\frac{1-\alpha}{q(1+\varphi_x)}\right)^{\frac{1-\alpha}{\alpha}}\left[A_D^{1/\alpha}(1-n)d\;D_n\;Q_D(t)\;+\;A_E^{1/\alpha}\;n\;e\;E_n\;Q_E(t)\right] \tag{12}$$

Like (4), (12) emphasises that the FGs production growth relies on the improvements on the available technological knowledge, Q_D and Q_E, on labour, D_n and E_n and on the exogenous environmental quality A_D and A_E.

2.4. Equilibrium for a given aggregate quality indexes

Generically, in equilibrium, only one technology, T_D or T_E will be used to produce each FG. Hence, there will be a threshold FG $\bar{n}\in[0,1]$, such that only T_D, D_n and dirty-specific IG are used to produce FGs indexed by $0\leq n\leq\bar{n}$ ($E_n=x_n|_{j\in]J,1]}=0$, $\forall\ 0\leq n\leq\bar{n}$) and only T_E, E_n and ecological-specific IG are used to produce FGs indexed by $\bar{n}<n\leq 1$ ($D_n = x_n|_{j\in[0,J]} = 0$, $\forall\ \bar{n}<n\leq 1$).[10]

In equilibrium, each labour type must be paid its marginal productivity, w_D and w_E, that must be equalised across all $n\in[0,\bar{n}]$ ($n\in]\bar{n},1]$).

Nevertheless, w_D and w_E will only occur for all $n\in[0,\bar{n}]$ and for all $n\in]\bar{n},1]$, respectively, if $p_n^{1/\alpha}(1-n)$ and $p_n^{1/\alpha}\,n$ are constants (independent of n). Defining $p_D^{1/\alpha}$ as $p_n^{1/\alpha}(1-n)$ and $p_E^{1/\alpha}$ as $p_n^{1/\alpha}\,n$, $\bar{n}$ can be expressed in terms of price indexes of FGs:

$$p_n = p_D(1-n)^{-\alpha} \text{ and } p_n = p_E\; n^{-\alpha} \tag{13}$$

Given the constructed indexes, when $n=\bar{n}$ holds (i.e., when both a firm using T_D and a firm using T_E breakeven), the price indexes ratio of FGs produced with both technologies is:

[10] In final goods with $n\leq\bar{n}$ ($n>\bar{n}$), firms using T_D (T_E) obtain zero profits, while a firm using T_E (T_D) would obtain negative profits. Thus, there is a threshold final good $\bar{n}\in[0,1]$, where the switch from T_D to T_E is advantageous.

$$p(t) = \frac{p_E(t)}{p_D(t)} = \left(\frac{\bar{n}(t)}{1-\bar{n}(t)}\right)^{\alpha} \tag{14}$$

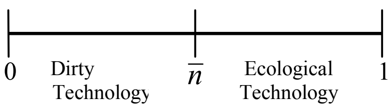
From (14) and since $0<\alpha<1$, it is clear that there are stronger incentives to develop technologies when the FGs produced by these technologies have higher prices.

Given the supply of labour and the current state of technological knowledge, after some algebra, we find the threshold FG $\bar{n}$ that arises from the profit maximization of both perfectly competitive FG producers and monopolistic IG firms as well as from the full-employment equilibrium in factor markets,:

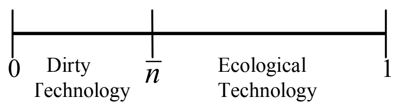
$$\bar{n} = \left\{ \left[\left(\frac{A_E}{A_D}\right)^{1/\alpha} \frac{e}{d}\, \frac{E}{D}\, \frac{Q_E}{Q_D} \right]^{1/2} + 1 \right\}^{-1} \tag{15}$$

This competitive equilibrium of $\bar{n}$ relies on the determinants of economic viability of both technologies; i.e., it relies on both the relative productivity, (e/d), and prices of E and D labour type, as well as of IGs, due to the complementarity among inputs in production and it also relies on the relative exogenous environmental quality, $(A_E/A_D)^{1/\alpha}$. The determinants for the relative productivity and prices of IGs are summarized in the aggregate quality indexes Q_D and Q_E. The ratio $B \equiv Q_E/Q_D$ measures the (ecological) technological-knowledge bias. Thus, with $\bar{n} \in [0,1]$:

(i) When Q_E=Q_D, then:



(ii) When $B\uparrow$, then:



Eq. (18) shows that when either a highly E-biased technology, high (Q_E/Q_D), or when there is a relative large supply of E labour, high (E/D), or even when there is a large productivity advantage of E over D, high e/d, or when there is a large productivity advantage of the ecological exogenous environmental quality over the polluted one (A_E/A_D), the fraction of FGs employing E

and using T_E is large and $\bar{n}$ is small. Thus, $\bar{n}$ can be interpreted as a FG sector bias or a technology margin. From the previous statements, the price indexes can also be expressed in function of their determinants; indeed, since by definition, $\exp\int_0^1 \ln p_n \, d_n = 1$, and considering (13) and (14), we get, after some algebra, that:

$$p_E = \exp(-\alpha)\,(1-\bar{n})^{-\alpha} \text{ and } p_D = \exp(-\alpha)\,\bar{n}^{-\alpha} \tag{16}$$

Through (15), (16) can be rewritten in function of their determinants rather than in function of the threshold $\bar{n}$, and so can the price index ratio, (14):

$$\frac{p_E}{p_D} = \left(\frac{\bar{n}}{1-\bar{n}}\right)^{\alpha} = \left(\frac{A_D^{1/\alpha}}{A_E^{1/\alpha}}\,\frac{d}{e}\,\frac{D}{E}\,\frac{Q_D}{Q_E}\right)^{\alpha/2} \tag{17}$$

From (17), small $\bar{n}$ implies a small relative price of FGs produced with T_E. As a result, the demand for E-specific IGs is low, discouraging R&D activities aimed at improving their environmental quality. Thus, labour and exogenous environmental quality levels affect the direction of R&D (technological progress) through the FG price channel (e.g., Acemoglu, 2002).

Finally, we can determine X and Y either in function of both their determinants or in function of the threshold $\bar{n}$. By definition, $X = \int_0^J X(k,j,t)dj + \int_J^1 X(k,j,t)dj$, then through (11), (13) and (15)-(16), the equilibrium of X in function of its determinants is given by:

$$X = \exp(-1)\left(\frac{1-\alpha}{q(1+\varphi_x)}\right)^{1/\alpha}\left[\left(A_D^{1/\alpha} Q_D\, d\, D_n\right)^{1/2} + \left(A_E^{1/\alpha} Q_E\, e\, E_n\right)^{1/2}\right]^2 \tag{18}$$

Accordingly, the equilibrium of the aggregate output, Y, in function of the threshold $\bar{n}$ or in function of its determinants, is given by:

$$Y = \left(\frac{1-\alpha}{q(1+\varphi_x)}\right)^{-1} X \tag{19}$$

2.5. R&D sector

The incentive for follower firms to support R&D depends on the value of a patent, $V(k,j,t)$, (the expected present value of the profits flow to the monopolist producer of IG j). This, in turn, depends on the given equilibrium interest rate, r, on the profits yielded at each time, $\Pi(k,j,t)$, and on the expected duration of the flow, which depends on the expected duration of the monopoly power. This duration, in turn, depends on the probability of a new successful research, $pb(k,j,t)$.

In Schumpeter models with vertical innovation, the outcomes of R&D improve the quality of IGs and, consequently, the indexes quality in (5), while creatively destroying the profits from the previous improvement. Following Aghion and Howitt (1992), for a firm engaged in R&D, the instantaneous probability at t,[11] – or the Poisson probability distribution with an arrival rate $pb(k,j,t)$ –, of successful innovation in the next higher quality of IG j, $k(j,t)+1$, is:

$$pb(k,j,t) = rs(k,j,t)\,\beta\, q^{k(j,t)}\,\xi^{-1} q^{-\frac{1}{\alpha}k(j,t)} M^{-1}\, h(j) \tag{20}$$

where: $rs(k,j,t)$ is the flow of aggregate FG resources devoted to R&D in IG j at t and $\beta q^{k(j,t)}$, with $\beta>0$, is the positive learning effect of accumulated public technological knowledge from past successful R&D in the IG j.[12] Thus, a greater β depicts a better innovation capacity (makes future learning easier) and $q^{k(j,t)}$ denotes the higher quality level attained through innovation.

Term $\xi^{-1} q^{-\frac{1}{\alpha}k(j,t)}$, where $\xi>0$, is the adverse effect caused by the increasing complexity of quality improvements in j. As quality adjusted IGs become more complex, R&D is progressively more difficult, implying a lower instantaneous probability of success, which, *ceteris paribus*,

[11] The instantaneous probability means that $pb(k,j,t)dt$ is the probability that a certain firm will innovate during the time interval from t to $t+dt$, where dt is an infinitesimal increment of time.

[12] While this learning effect is a process of quality improvement by past successful R&D, the conventional learning-by-doing is usually formulated as the decline of production costs induced by cumulative experience of production.

increases the cost of R&D. Hence, ξ represents the fixed cost of R&D, where higher values of ξ are associated with a higher level of R&D difficulty.

Since $M=D$ if $0\leq j\leq J$ and $M=E$ if $J<j\leq 1$, M^{-1} is the adverse effect of market size. The difficulty in introducing new quality adjusted IGs and replacing old ones is proportional to the market size, due to coordination among agents, processing of ideas and informational, organizational, transportation and marketing costs. As rents of leader firms are proportional to the market size, we assume that leader firms try to protect their economic rents by extending the expected duration of their monopoly power, that is, by making the probability of the next successful R&D more difficult (for example, through technical barriers).

Term $h(j)$ can be called a technological-knowledge absorption effect. It captures an absolute advantage of less polluted natural environment over more polluted natural environment in implementing advanced technological knowledge. Cleaner air improves health and productivity of workers, and thus their capacity to adapt to new technological knowledge. The proposed specification for $h(j)$ is:

$$h(j)=\begin{cases} 1 & , if\ 0\leq j\leq J \\ \left(1+\dfrac{A_E}{A_E+A_D}\right)^{\sigma} & , if\ J<j\leq 1 \end{cases} \qquad \text{where: } \sigma = 1+\frac{A_E}{A_D} \tag{21}$$

Profits at t for a j IG monopolist using a successful R&D of quality k relies on the mark-up (after subsidies/taxes marginal cost) and on the demand for j by the FG producers. Formally, this occurs by solving (8) considering (11) and (13):

$$\Pi(k,j,t)=m\ M\left[(q-1)\left(1+\varphi_{x,M}\right)\right]\left(\frac{p_M\ A_M\ (1-\alpha)}{q\left(1+\varphi_{x,M}\right)}\right)^{1/\alpha} q^{k(j,t)\left(\frac{1-\alpha}{\alpha}\right)} \tag{22a}$$

$$\Pi(k,j,t)=m\ M\left[(q-1)\left(1+\varphi_{x,M}\right)\right]\left(\frac{p_M\ A_M\ (1-\alpha)}{q\left(1+\varphi_{x,M}\right)}\right)^{1/\alpha} q^{k(j,t)\left(\frac{1-\alpha}{\alpha}\right)}\left[(q+1)\,q^{-1/\alpha}-q^{\frac{\alpha-1}{\alpha}}\right] \tag{22b}$$

m=e for M=E and m=d for M=D. Thus, the limit pricing of monopolistic firms can be M-specific, i.e., $p(D)=q(1+\tau_{x,D})$ for $0 \leq j \leq J$ and $p(E) = q(1-s_{x,E})$ for $J < j \leq 1$.

Eq. (26a) gives the incremental profits of follower firms taking over the leader position, while (26b) provides the incremental profits of leader firms replacing themselves. Comparing (26a) with (26b), the gain to a follower firm is greater, which is guaranteed by the assumption that q>1 and 0<α<1. It is worth noting that: (i) when the follower firm takes over the leader position, it goes from having no profits to having profits; (ii) due to complementarity in (1) the size of the market for ecological and dirty-specific IGs is the employed E and D labour type. Thus, the scale effect, M, is apparent in the size of the profits in (26a).

However, the most relevant factor is not instantaneous profits, but instead the expected present value of profits flow:

$$V(k,j,t) = \frac{\Pi(k,j,t)}{r(t) + pb(j,k,t)} \tag{23}$$

This expression states that, the expected income generated by the successful research on rung k^{th} at time t, $V(k,j,t)\, r(t)$, equals the profit flow, $\Pi(k,j,t)$, minus the expected capital loss, $V(k,j,t)\, pb(j,k,t)$, that will occur when the k^{th} rung is replaced by a new one. The denominator is the effective discount rate at the time of the successful research of rung k. It is equal to the interest rate, $r(t)$, plus the rate of Schumpeter's creative destruction. The more research is expected to take place, the shorter the duration of the monopoly profits that will be enjoyed by the creator of the next successful research and, therefore, the smaller the pay-off to innovating.

Under free entry R&D equilibrium, $\Pi(k,j,t)$=0 must hold and the expected returns must equal the spent resources. That is, at each time t, the expected reward for pursuing the $(k+1)^{th}$ successful research, must equal the after subsidy cost of research. Hence,

$$pb(j,k,t)\, V(k+1,j,t) = (1-s_r)\, rs(k,j,t) \tag{24}$$

s_r is a governmental ad-valorem subsidy to R&D, which results in a reduction of R&D costs and can be M-specific.[13] In this setting, the government can allocate its expenditures on R&D using a continuum of different policy rules, from the extreme symmetric rule (each M-specific R&D activity gets the same) to the extreme asymmetric rule (only E or D-specific R&D activity gets the subsidy). Thus, the limit pricing of the monopolistic firms 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 $J<j\leq 1$.

From (20), (22a) and (23), the equilibrium M-specific probability of successful R&D is:

$$pb(j,k,t) = \frac{\beta}{\xi} \frac{(1+\varphi_{x,M})}{(1-s_{r,M})} \frac{(q-1)}{q} \left(\frac{p_M \, A_M \, (1-\alpha)}{(1+\varphi_{x,M})} \right)^{1/\alpha} m \, h(j) - r(t) \equiv pb(t) \tag{25}$$

Given the interest rate, r, and the FGs' price indexes, p_M, (25) turns out to be independent of IG j and quality rung k, due to the removal of scale of technological knowledge effects. That is, the positive influence of the quality rung on profits, see (22a), and on the learning effect, see (20), is exactly offset by its negative effect on the complexity cost, see (20).

From (25), it is clear that R&D equilibrium rates respond negatively to the interest rate and to an increase in the exogenous given tax rate of D-specific IGs, $\tau_{x,D}$. Conversely, they are encouraged both by an increase in the exogenous given subsidy rates of M-specific R&D, $s_{r,M}$, and of E-specific IGs, $s_{x,E}$. They also respond positively to the exogenous environmental quality, A_M, and to the FGs' price indexes, p_M. Indeed, computing pb_E-pb_D, it can be observed a dynamic price effect, which indicates that there will be stronger incentives to improve different types of technology when the goods produced by these technologies command higher prices. Thus, the

[13] In our model, it is assumed that a subsidy to D-R&D, fosters environmental improvement of dirty IGs converting them into less polluted IGs.

direction taken by technological-knowledge progress is driven by the price channel and can be affected by the structure of government intervention.[14]

The first term on the right-hand side of (25) is the rate of return from R&D. This rate of return must cover the ordinary rate of return, r, plus the premium for the probability per unit of time that a competitor will succeed, $pb(k,j,t)$, and thereby drive the incumbent out of the business. Thus, if r is constant over t, then $pb(k,j,t)$ is also constant, and so are all IGs of each M-type. From (20) and (25), the equilibrium amount of resources devoted to the aggregate of R&D in each type of IGs, for each t, is

$$RS(k,j,t) = \int_0^1 pb_M \frac{\xi}{\beta} M\, q^{k(j,t)\left(\frac{1-\alpha}{\alpha}\right)} dj \;\Leftrightarrow\; RS(k,j,t) = \frac{\xi}{\beta}\left[Q_D\, D\, pb_D + Q_E\, E\, pb_E\right] \tag{26}$$

Eq. (26) shows that the aggregate resources devoted to R&D depend positively on the aggregate quality indexes, Q_D and Q_E, and on market profitability, that is, on market-size effect in R&D captured by M-labour. Conversely, they depend negatively on both the interest rate, r, and on the experience-adjusted cost of innovation. Since in equilibrium, the probability of successful research for all IGs of each M-type, see (25), determines the speed of technological knowledge, it can be translated into the path of M-type technological knowledge. Thus, the equilibrium M-specific growth rate of technological progress, Q_M, at each t, is given by:

$$E\left(\frac{\Delta Q_M}{Q_M}\right) = \frac{\dot{Q}_M}{Q_M} = pb_M\left[q^{\left(\frac{1-\alpha}{\alpha}\right)} - 1\right], \tag{27}$$

where $[q^{((1-\alpha)/\alpha)}-1]$ is the impact of each vertical successful R&D on the technological progress.

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[14] This result is different from the skill biased technological change literature, which does not take into account the endogenous accumulation of human capital and which does not remove the scale effects. In contrast to what happens in our study, in this literature, the direction of technological knowledge progress is related with the exogenous increase in the skills supply, which induces faster upgrading of skill complementary technologies because under substitutability the market size effect dominates the price channel.

2.6. Consumption

The economy is assumed to have a time invariant number of heterogeneous individuals, continuously indexed by $a \in [0, 1]$, who decide the allocation of income between consumption of the aggregate FG and savings (lending in return for future interest). For simplicity, an exogenous threshold individual $\bar{a}$ is considered, such that individuals with high ability $a > \bar{a}$ are Ecological skilled, whereas individuals with lower ability $a \leq \bar{a}$ are Dirty skilled (i.e, unskilled).[15]

It is assumed a continuous time approximation of an overlapping generations model (e.g., Barro and Sala-i-Martin, 2004). The individual skills acquired rely on the family background, where it is assumed that parents are altruistic and leave everything to their children, including their knowledge. Thus, each individual with ability *a*, will seek to maximize the following infinite horizon lifetime utility or felicity function with constant elasticity of substitution:

$$U(a,t) = \int_0^{\infty} \left[\frac{c(a,t)^{1-\theta} - 1}{1-\theta} \right] \exp(-\rho t)\, dt \text{, where:} \tag{28}$$

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

The intertemporal budget constraint of individual *a*, for all $t \geq 0$, is given by:

$$\dot{K}(a,t) = (1-\tau_k)\, r(t)\, K(a,t) \;+\; (1-\tau_{w,M})\, w_M(t)\, M(a) \;-\; c(a,t), \text{ where:} \tag{29}$$

(i) $\dot{K}(a,t)$ is the individual a savings, at t; (ii) τ_k and $\tau_{w,M}$ are per-unit taxes on assets and wages respectively; (iii) $K(a,t)$ is the total asset holdings of individual a, at t, with return r. They are in the form of ownership of firms that produce IGs (and not in the form of public debt owned by individuals, as it is assumed that the government budget is balanced at every time); (iv) $M=E$ if

[15] The ability *a*, specific to each individual, can be viewed as the talent, the intelligence or the learning capacity this individual was born with and that can be developed during his/her life. It also defines implicitly his/her skilled type.

$a > \overline{a}$ and $M=D$ if $a \leq \overline{a}$; (v) Due to the arbitrage in the assets market, r (the premium for postponing the consumption) depends only on t; (vi) w_M is the wage per unit of M-type labour.

Each individual seeks to solve an optimal control problem of maximization of the lifetime utility (28), subject to the budget constraint (29). The FOCs for both the control and the state variable must satisfy (29) together with the transversality condition, which guarantees that the limit value of the assets is zero. The obtained solution for the individual's consumption path is:

$$\frac{\dot{c}(a,t)}{c(a,t)} = \frac{\dot{c}(t)}{c(t)} = \frac{\dot{C}(t)}{C(t)} = \frac{1}{\theta}\left[(1-\tau_k)\, r(t) - \rho\right] \tag{30}$$

This solution is the standard Euler equation, where $\dot{c}(t)/c(t)$ yields the growth rate of consumption for all individuals (independent of their ability). In the same way, $C(t)$ stands for the aggregate consumption and $\dot{C}(t)/C(t)$ for its growth rate, assuming that population does not grow. Consumption growth rate relies on the difference between the interest rate after assets income tax, $(1-\tau_k)\, r(t)$, and the rate of time preference, ρ, as well as on the intertemporal elasticity of substitution, $1/\theta$ (the preference for substituting intertemporally). Low values of θ imply higher willingness to substitute temporally and thus, a bigger response of the consumption growth rate to the gap between $(1-\tau_k)\, r(t)$ and ρ. This gap determines whether individuals choose a consumption pattern that rises, stays constant or falls over time. It is expected that $(1-\tau_k)\, r(t) > \rho$, and so that individuals choose a pattern of consumption that rises over time. That is, higher market interest rates induce individuals to save more at the present and spend more in the future.

2.7. Government budget and aggregate resource constraints

We assume that the government budget is balanced at each time, that is:

$$\tau_k r(t)\int_0^1 K(a,t)\,da + \tau_M w_M(t)\int_0^1 \left[u_w(a,t) M(a,t)\right] da + \tau_{x,D} X(t) = s_{x,E} X(t) + s_{r,M} RS(t) \tag{31}$$

The left-hand side of (31) is government tax revenue from assets income, $\tau_k r(t)K(t)$, from labour income, $\tau_M\,[w_E(t)E(t)+w_D(t)D(t)]$, and from an environmental tax on IGs that use dirty technology, $\tau_{x,D}X(t)$. The right-hand side is government expenditures on environmental subsidies for clean IGs (renewable resources) used by clean technology, $s_{x,E}X(t)$, and for R&D to enhance the environmental quality of both clean and dirty-specific IGs, $s_{r,M}RS(t)$.

Solving the budget constraint (7) for the aggregate consumption, *C*, and substituting *Y*, *X* and *RS* by (19), (18) and (26), respectively, we get that *C* is also a constant multiple of the aggregate quality indexes and labour levels, $Q_D D$ and $Q_E E$; i.e., $C=f(Q_D,Q_E)$. Hence, in equilibrium, *Y*, *C*, *X* and *RS* are all constant multiples of the same variables.

3. The Steady State Equilibrium

The steady state equilibrium is a path where all variables either grow at a constant rate over time or are time invariant, such that each individual maximizes the lifetime utility, each FG, IG and R&D firm maximizes its profits, and all the markets clear. The dynamic equilibrium can be described by the path of the state of the two aggregate quality indexes towards the steady state.

Since, in equilibrium *Y*, *X*, *RS* and *C* are all constant multiples of Q_E and Q_D, the stable and unique steady-state endogenous growth rate, designated by $g^*\left(\equiv g_D^* \equiv g_E^*\right)$, is:

$$g^*=\left(\frac{\dot{Y}}{Y}\right)^*=\left(\frac{\dot{X}}{X}\right)^*=\left(\frac{\dot{RS}}{RS}\right)^*=\left(\frac{\dot{Q}_D}{Q_D}\right)^*=\left(\frac{\dot{Q}_E}{Q_E}\right)^*=\left(\frac{\dot{C}}{C}\right)^*=\left(\frac{\dot{c}}{c}\right)^*=\frac{1}{\theta}\left[(1-\tau_K)r^*-\rho\right]\Rightarrow\left(\frac{\dot{p}_E}{p_E}\right)^*=\left(\frac{\dot{p}_D}{p_D}\right)^*=\left(\frac{\dot{\bar{n}}}{\bar{n}}\right)^*=0 \tag{32}$$

Eq. (32) implies a constant steady-state interest rate, $r^*\left(\equiv r_D^* \equiv r_E^*\right)$, obtained by setting the consumption growth rate (30) equal to technological-knowledge growth rate (27). Then, g^* arises from plugging r^* into (32). Also from (32), the steady-state technological-knowledge bias,

B^*, remains stable, that is, $\left(\dot{Q}_D/Q_D\right)^* - \left(\dot{Q}_E/Q_E\right)^* = 0$. By equaling the steady-state growth rates of Q_E and Q_D, it can also be found p_M^* and $\bar{n}^*$.

By $s_{x,E}$ and $s_{r,M}$ government intervention positively affects r^* and hence g^*. In fact, while $s_{x,E}$ increases the monopolistic profits, see (22a), acting as an incentive to R&D, $s_{r,M}$ falls the cost of R&D, see (24), increasing pb_M, (27). Conversely, by $\tau_{x,D}$ and τ_K, government intervention negatively affects r^* and thus g^*. Indeed, $\tau_{x,D}$ decreases the monopolistic profits, acting as a disincentive to R&D and τ_K decreases investment in R&D, due to the smaller expected marginal benefit. Since τ_w is absent in equilibrium conditions, it does not directly affect g^*.

4. Transitional Dynamics and Sensitivity Analysis

We solve the model numerically to illustrate the effect of both government intervention and an increase in the positive externality of production derived from a cleaner environmental quality on the direction of technological knowledge and on the threshold FG. Using (27) and given that the interest rate, r, is always unique, the stability of the technological-knowledge bias, B, is given by:

$$\frac{\dot{B}}{B} = \frac{\dot{Q}_E}{Q_E} - \frac{\dot{Q}_D}{Q_D} = \frac{\beta}{\xi}\left(\frac{q-1}{q}\right)(1-\alpha)^{1/\alpha}\exp(-\alpha)\left\{ e\left(1+\frac{A_E}{A_E+A_D}\right)^{\sigma}\left(\frac{1-s_{x,E}}{1-s_{r,E}}\right)\left(\frac{A_E}{1-s_{x.E}}\right)^{1/\alpha} \left[1+\left(\frac{Q_E}{Q_D}\frac{e}{d}\frac{E}{D}\right)^{-1/2}\right]^{\alpha} - d\left(\frac{1+\tau_{x,D}}{1-s_{r,D}}\right)\left(\frac{A_D}{1+\tau_{x.D}}\right)^{1/\alpha}\left[1+\left(\frac{Q_E}{Q_D}\frac{e}{d}\frac{E}{D}\right)^{1/2}\right]^{\alpha}\right\} \tag{33}$$

Using the *Matlab* software to solve (33) and bearing in mind the baseline parameter values in Table 1, the technological-knowledge's time path, B, is displayed in Fig.1a and the threshold final good's time path, $\bar{n}$, is displayed in Fig. 2a.

Table 1. Baseline parameter values

Parameter	Value	Parameter	Value
A_E	1.50	α	0.70
A_D	1.50	β	1.60
e	1.20	θ	1.50
d	1.00	ρ	0.02
E	0.70	σ	2.00
D	1.00	ξ	4.00
q	3.33	$s_{x,E}$, $s_{r,E}$, $s_{r,D}$ $\tau_{x,D}$	0.00

Source: Authors' assumptions based on theoretical framework and on the literature.

For simplicity, in our model, public policies towards ecological technological knowledge are captured by both the subsidies $s_{r,E}$ and $s_{x,E}$ and the tax $\tau_{x,D}$. This means that government intervention can produce both a reduction of E-R&D costs – through $s_{r,E}$, see (24), and an increase of the profitability of producers of E-type intermediate goods – through $s_{x,E}$, see (22a), stimulating investment in E-R&D. On the other hand, $\tau_{x,D}$ discourages investment in D-R&D in favour of E-R&D by decreasing the profitability of producers of D-type intermediate goods.

Nine different cases are depicted: (i) $s_{x,E}$, $s_{r,E}$ and $\tau_{x,D}$ increase to $s_{x,E}$=$s_{r,E}$=$\tau_{x,D}$=0.2 (case 1); (ii) $s_{r,E}$ increases to $s_{r,E}$=0.2 (case 2); (iii) $s_{x,E}$ increases to $s_{x,E}$=0.2 (case 3); (iv) $\tau_{x,D}$ increases to $\tau_{x,D}$=0.2 (case 4); (v) A_E increases to A_E=2.10 (case 5); (vi) $s_{x,E}$, $s_{r,E}$ and $\tau_{x,D}$ increase to $s_{x,E}$=$s_{r,E}$=$\tau_{x,D}$=0.2 and A_E increases to A_E=2.10 (case 6); (vii) $s_{r,E}$ increases to $s_{r,E}$=0.2 and A_E increases to A_E=2.10 (case 7); (viii) $s_{x,E}$ increases to $s_{x,E}$=0.2 and A_E increases to A_E=2.10 (case 8); (ix) $\tau_{x,D}$ increases to $\tau_{x,D}$=0.2 and A_E increases to A_E=2.10 (case 9).

Figure 1*a*

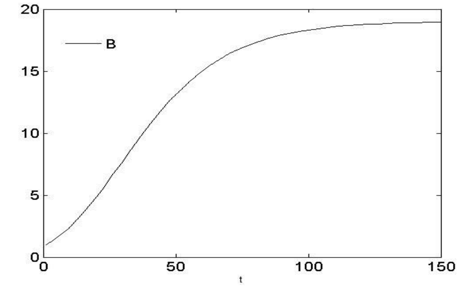


Figure 1*b*

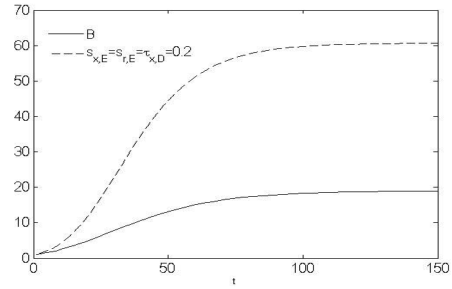


Figure 1*c*

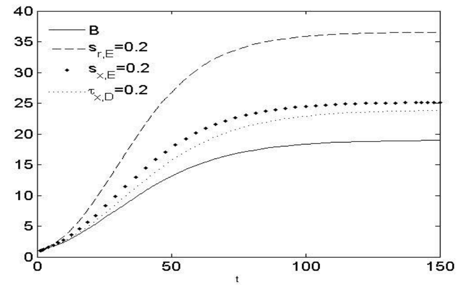


Figure 1*d*

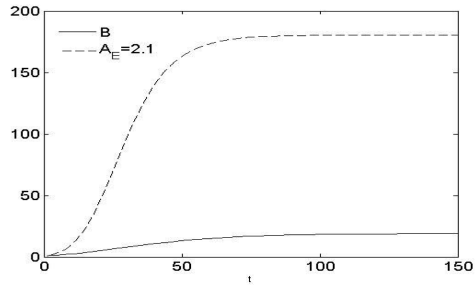


Figure 1*e*

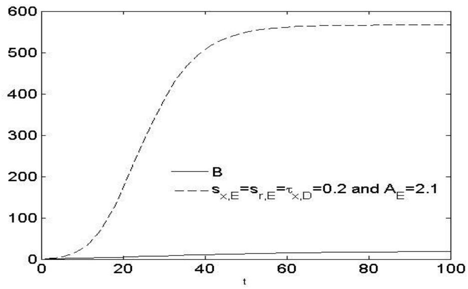
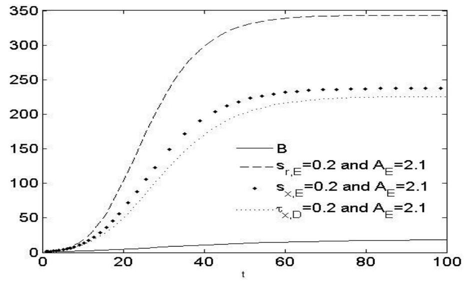


Figure 1*f*



Note: Transitional dynamics of: (*a-c*) the technological-knowledge bias, *B*, without exogenous increase in A_E and (*d-f*) the technological-knowledge bias with exogenous increase in A_E.

Figure 2*a*

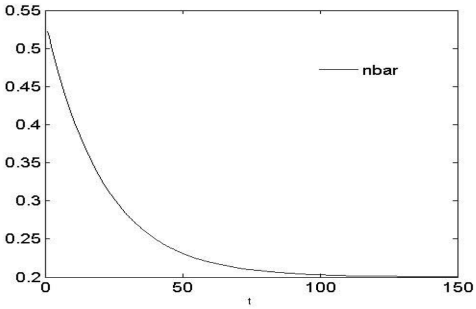


Figure 2*b*

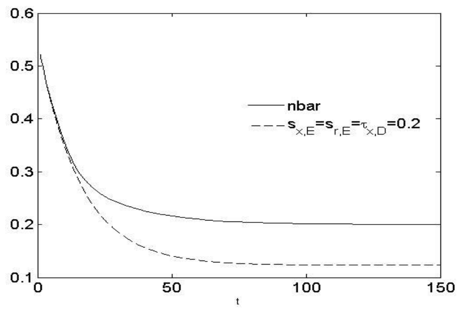


Figure 2*c*

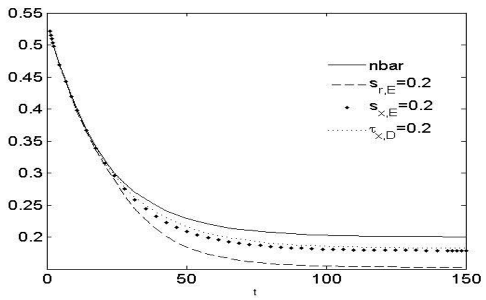


Figure 2*d*

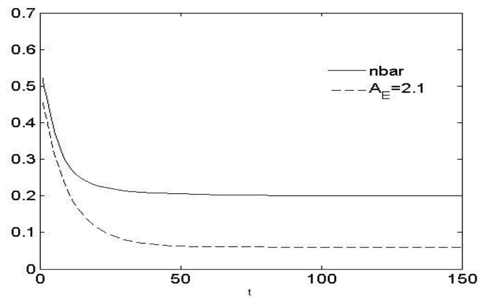


Figure 2*e*

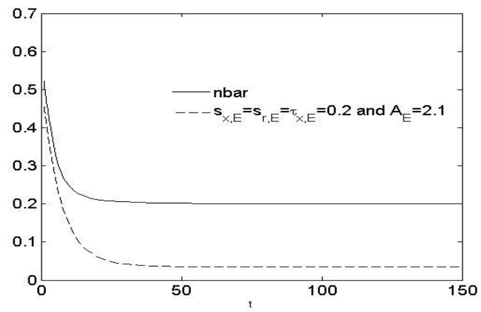
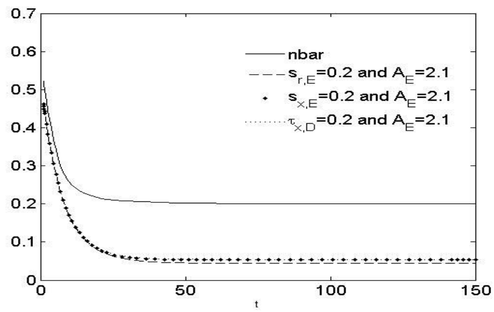


Figure 2*f*



Note: Transitional dynamics of: (*a-c*) the threshold final good, $\overline{n}$, without exogenous increase in A_E and (*d-f*) the threshold final good with exogenous increase in A_E.

Table 2 compares initial and steady-state values of B and $\overline{n}$ under the aforesaid nine cases.

Table 2. Comparing initial and steady-state values of B and $\overline{n}$.

Variable	Initial Value [j]	Steady state value	Steady-state values of B and $\overline{n}$ under 9 different cases								
			Case1[a]	Case2[b]	Case3[c]	Case 4[d]	Case5[e]	Case6[f]	Case7[g]	Case8[h]	Case 9[i]
B	1	18.96	60.64	36.53	25.13	23.82	180.37	566.44	343.44	237.75	226.04
$\overline{n}$	0.52	0.20	0.12	0.15	0.178	0.18	0.06	0.03	0.04	0.052	0.054

Note 1: [a] Case 1: $s_{x,E}=s_{r,E}=\tau_{x,D}=0.2$ and $s_{x,D}=s_{r,D}=\tau_{x,E}=0.0$; [b] Case 2: $s_{r,E}=0.2$ and $s_{x,E}=s_{x,D}=s_{r,D}=\tau_{x,E}=\tau_{x,D}=0.0$; [c] Case 3: $s_{x,E}=0.2$ and $s_{x,D}=s_{r,E}=s_{r,D}=\tau_{x,E}=\tau_{x,D}=0.0$; [d] Case 4: $\tau_{x,D}=0.2$ and $s_{x,E}=s_{x,D}=s_{r,E}=s_{r,D}=\tau_{x,E}=0.0$; [e] Case 5: $s_{x,E}=s_{x,D}=s_{r,E}=s_{r,D}=\tau_{x,E}\tau_{x,D}=0.0$ and $A_E=2.10$; [f] Case 6: $s_{x,E}=s_{r,E}=\tau_{x,D}=0.2$ and $s_{x,D}=s_{r,D}=\tau_{x,E}=0.0$ and $A_E=2.10$; [g] Case 7: $s_{r,E}=0.2$ and $s_{x,E}=s_{x,D}=s_{r,D}=\tau_{x,E}=\tau_{x,D}=0.0$ and $A_E=2.10$; [h] Case 8: $s_{x,E}=0.2$ and $s_{x,D}=s_{r,E}=s_{r,D}=\tau_{x,E}=\tau_{x,D}=0.0$ and $A_E=2.10$; [i] Case 9: $\tau_{x,D}=0.2$ and $s_{x,E}=s_{x,D}=s_{r,E}=s_{r,D}=\tau_{x,E}=0.0$ and $A_E=2.10$.

Note 2: [j] Initial values of B and $\overline{n}$ are the baseline steady-state values of B and $\overline{n}$ under no government intervention and with no increase in positive externality of production derived from a cleaner environmental quality. Nevertheless, unlike B, the initial value of $\overline{n}$ becomes 0.46 instead of 0.52 when an increase in positive externality of production derived from a cleaner environmental quality takes place. Thus, the initial value of $\overline{n}$ is 0.52 in cases (1-4) and 0.46 in cases (5-9).

Fig. 1*a* and Fig. 2*a* show the baseline steady-state values of, respectively B and $\bar{n}$, under no government intervention and with no increase in positive externality of production.

Fig. 1*b* and Fig. 2*b* show that an exogenous increase at t=0 in $s_{x,E}$ together with $s_{r,E}$ and $\tau_{x,D}$ accentuates, respectively the technological-knowledge bias, B, and the final good sector bias, $\bar{n}$. Indeed, since greater $s_{x,E}$ increases the size of profits that accrue to the producers of E-type IGs, and greater $s_{r,E}$ decreases the cost of E-R&D, then an increase in $s_{x,E}$ and $s_{r,E}$ boosts the incentives to perform E-R&D, thereby increasing the growth rate of the E-specific technological knowledge. Furthermore, since greater $\tau_{x,D}$ decreases the size of profits that accrue to the producers of D-type IGs, then an increase in $\tau_{x,D}$ discourages D-R&D. Thus, until the new steady-state, such bias increases the supply of E-type IGs, increasing the number of FGs produced with E-technology and decreasing $\bar{n}$, see (15). In turn, the relative price of E-FG, see (14), lowers continuously towards the stable new steady-state level. This implies that B is increasing, but at a falling rate until it reaches its new higher steady-state, B^*=60.64 (from $B^*_{Baseline}$=B(t=0)=18.86), and that $\bar{n}$ is decreasing, but at a falling rate until it reaches its new lower steady-state, $\bar{n}^*$=0.12 (from $\bar{n}^*_{Baseline}$=$\bar{n}$ (t=0)=0.20), as depicted in Table 2.

Fig. 1*c* and 2*c* compare the baseline steady-state values of B and $\bar{n}$, respectively with the increase of each type of subsidies and tax ($s_{x,E}$, $s_{r,E}$ and $\tau_{x,D}$). It is clear that $s_{r,E}$ is, by far, the one that most contributes to accentuate both technological-knowledge bias, B, and final good sector bias, $\bar{n}$. By contrary, $\tau_{x,D}$, is the lesser contributor.

Fig. 1*d* shows that the increase in the exogenous ecological productivity (A_E), clearly heightens the technological-knowledge bias in favour of E-IGs. Indeed, the technological-knowledge-absorption effect is greater than in the baseline scenario. In (21), $h(j)$ jumps immediately from 2.25 to 3.01 as a result of a move from A_E=1.50 to A_E=2.10. Thus, as with government intervention, but in this case with notably stronger magnitude, such bias increases the supply of E-type IGs, thereby increasing the number of FGs produced with E-technology and lowering their relative price. Thus, relative prices of FGs produced with E-technology drop continuously towards the stable new steady-state level, which implies that B is increasing, but at a falling rate until it reaches its new higher steady-state, $B^* = 180.37$, as depicted in Table 2.

In turn, Fig. 2d shows that an increase in A_E heightens the FG sector bias in favour of E-FGs. However, an increase in A_E also causes an instantly drop in $\bar{n}$ at time t=0, from $\bar{n}_{\text{Baseline}}$= 0.52 to $\bar{n}$=0.46. This immediate fall is due to the rise in the supply of A_E without new endogenous technological-knowledge progress and thus without change in technological-knowledge bias. Like in Fig. 1d, the increase in A_E implies an increase in the number of FGs produced with E-technology ($\bar{n}$ diminishes) and consequently a decrease of the relative prices of those FGs. Nevertheless, these lower prices disincentive the development of E-technologies which implies that $\bar{n}$ is decreasing, but at a falling rate until it reaches its new lower steady-state, $\bar{n}^*$=0.06 (see Table 2). Once in steady-state, with a constant technological-knowledge bias, $\bar{n}^*$ remains constant. With a sufficiently strong technological-knowledge-absorption effect, as in the present case, the steady-state $\bar{n}^*$ is smaller than under the baseline scenario, with no increase in A_E, $\bar{n}^*$=0.06<$\bar{n}^*_{\text{Baseline}}$=0.20 (Table 2).

Fig. 1(e-f) and Fig. 2(e-f) present the same behaviour as Fig. 1(b-c) and Fig. 2(b-c), respectively, but with stronger magnitude.

As a result of the price channel, the path of B in Fig. 1(a-c) and the path of $\bar{n}$ in Fig. 2(a-c) are strongly smoothed compared with the path of B and $\bar{n}$ in Fig. 1(d-f) and Fig. 2(d-f), respectively. In fact, *ceteris paribus*, the exogenous increase of A_E immediately increases the profits of the monopolistic producers of E-specific IGs, (22), and thus, the demand for E-R&D.

5. 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, government intervention and environmental-quality bias. The essential idea is that the same economic forces that affect the technological-knowledge progress will also shape its respective bias and the final-good sector bias. The technological-knowledge bias and the final-good sector bias are produced by the price channel, induced by government policy and by an increase in the positive externality of production derived from a cleaner environmental quality.

As far as technological-knowledge bias is concerned, it is only with the presence of the price channel that an increase in a subsidy to the production of *E*-type intermediate goods and/or in a subsidy to *E*-type R&D and/or in a tax to *D*-type intermediate goods can strongly re-direct R&D towards quality improvement of *E*-type intermediate goods. In the same way, only with the price channel can an increase in positive externality productivity expand the technological-knowledge-absorption effect, which, in turn, strongly fosters R&D towards quality improvement of *E*-type intermediate goods. This increases the productivity of these intermediate goods, which diminishes the perfectly competitive domestic relative prices of final goods produced with the *E*-technology. Thus, through the price channel, the technological-knowledge bias is increasing but at a decreasing rate until it reaches its new higher steady state.

Regarding the final-good sector bias, the path of technological-knowledge bias stimulates the relative number of *E*-final goods, thereby decreasing the threshold final good. For the same reasons as for technological-knowledge bias, final-good sector bias is also accentuated by the price channel, induced by government intervention. It was found that an exogenous increase in positive environmental quality causes an instant drop in final-good sector bias due to the unchanged technological-knowledge bias. From then onwards the transitional dynamics towards the constant steady-state is decreasing, but at a falling rate, since the lower prices of the ecological intensive final goods, derived by the increase in the number of final goods produced with *E*-technology, disincentive the development of *E*-technologies and thus the number of *E*-FG, Furthermore, with a sufficiently strong technological-knowledge-absorption effect, the steady-state of the final goods sector bias is smaller than the previous one.

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References

Acemoglu, Daron (2002), "Directed Technical Change." *Review of Economic Studies*, 69, pp. 781-810.

Acemoglu, Daron and Fabrizio Zilibotti (2001), "Productivity differences." *Quarterly Journal of Economics*, 116(2), pp. 563-606.

Afonso, Óscar (2008), "The impact of government intervention on wage inequality without scale effects", *Economic Modelling*, 25(2), pp. 351-362.

Aghion, Philippe and Peter Howitt (1998), *Endogenous growth theory*, MIT Press Cambridge, MA.

Aghion, Philippe and Peter Howitt (1992), "A model of growth through creative destruction." *Econometrica*, 60(2), pp. 323-352.

Barro, Robert and Xavier Sala-i-Martin (2004), *Economic Growth*. 2nd Edt. Cambridge, Massachusetts: MIT Press [1st Edt.: New York: McGraw-Hill, Inc., 1995].

Baumol, William J. and Oates, Wallace E. (1994). *The Theory of Environmental Policy*, 3rd ed., Cambridge University Press, Cambridge, MA.

Bovenberg, Ary L. and Ruud De Mooij (1997), "Environmental tax reform and endogenous growth." *Journal of Public Economics*, 63(2), pp.207-237.

Bovenberg, Ary L. and Sjak Smulders (1996), "Transitional impacts of environmental policy in an endogenous growth model." *International Economics Review*, 37(4), pp.861-893.

Bovenberg, Ary L. and Sjak Smulders (1995). "Environmental quality and pollution-augmenting technical change in a two-sector endogenous growth model." *Journal of Public Economics*, 57(3), pp.369-391.

Brock, William A. and Michael S. Taylor (2005), "Economic growth and the environment: a review of theory and empirics." In *Handbook of Economic Growth*, P. Aghion and S. Durlauf (Eds.), North-Holland, Amsterdam.

Comolli, Paul (2006), "Sustainability and growth when manufactured capital and natural capital are not substitutable." *Ecological Economics*, 60(1), pp. 157-167.

Elbasha, Ellamin H. and Terry L. Roe (1996), "On endogenous growth: the implications of environmental externalities." *Journal of Environmental Economics and Management*, 31(2), pp. 123-146.

England, Richard W. (2000), "Natural capital and the theory of economic growth." *Ecological Economics*, 34(3), pp. 425-431.

Fullerton, Don and Seung-Rae Kim (2008), "Environmental investment and policy with distortionary taxes, and endogenous growth." *Journal of Environmental Economics and Management*, 56(2), pp. 141-154.

Gradus, Raymond and Sjak Smulders (1993), "The trade-off between environmental care and long-term growth-pollution in three prototype growth models." *Journal of Economics*, 58(1), pp. 25-51.

Greiner, Alfred (2005), "Fiscal policy in an endogenous growth model with public capital and pollution." *Japanese Economic Review*, 56(1), pp. 67-84.

Grimaud, André and Luc Rougé (2003), "Non-renewable resources and growth with vertical innovations: optimum, equilibrium and economic policies." *Journal of Environmental Economics and Management*, 45 (2, supplement 1), pp. 433-453.

Grossman, Gene M. and Elhanan Helpman (1995), *Innovation and growth in the global economy*. Cambridge, Massachusetts: MIT Press.

Groth, Christian and Poul Schou (2007), "Growth and non-renewable resources: The different roles of capital and resource taxes." *Journal of Environmental Economics and Management*, 53(1), pp. 80-98.

Hettich, Frank (1998), "Growth effects of a revenue-neutral environmental tax reform." *Journal of Econom*ics, 67(3), pp. 287-316.

Jones, Charles I. (1995), "R&D-based models of economic growth." *Journal of Political Economy*, 103(4), pp. 759-784.

Lucas, Robert E. (1988), "On the mechanics of economic development." *Journal of Monetary Economics*, 22(1), pp. 3-42.

Mohtadi, Hamid (1996), "Environment, growth and optimal policy design." *Journal of Public Economics*, 63(1), pp.119-140.

Peretto, Pietro F. (2009), "Energy taxes and endogenous technological change." *Journal of Environmental Economics and Management*, 57(3), pp. 269-283.

Romer, Paul M. (1990), "Endogenous technological change." *Journal of Political Economy*, 98(5), pp. S71-S102.

Roseta-Palma, Catarina, Alexandra Ferreira-Lopes and Tiago Neves Sequeira (2010), "Externalities in an endogenous growth model with social and natural capital." *Ecological Economics*, 69(3), pp. 603-612.

Schou, Poul (2000), "Polluting non-renewable resources and growth." *Environmental and Resource Economics*, 16(2), pp. 211-227.

Smulders, Sjak (2005), "Endogenous technological change, natural resources and growth." In *Scarcity and Growth Revisited: Natural Resources and the Environment in the New Millenium*, R.David Simpson, Michael A. Toman, Robert U. Ayres (Eds.), The Johns Hopkins University Press for Resources for the Future press, chapter 8.

Smulders, Sjak (2000), "Economic growth and environmental quality." In *Principles of Environmental and Resource Economics: A Guide for Students and Decision-makers*, H. Folmer and H.L. Gabel (Eds.), Edward Elgar Publishers, second ed., Celtenham, UK.

Smulders, Sjak and Raymond Gradus (1996), "Pollution abatement and long-term growth." *European Journal of Political Economics*, 12(3), pp.505-532.

Smulders, Sjak and Michiel de Nooij (2003), "The impact of energy conservation on technology and economic growth." *Resource Energy Economics*, 25, pp. 59-79.

Tahvonen, Olli and Jari Kuuluvainen (1991), "Optimal growth with renewable resources and pollution." *European Economic Review*, 35(2-3), pp. 650-661.

Xepapadeas, Anastasios (2005), "Economic growth and the Environment." In *Handbook of Environmental Economics*, K. Maler and J. Vinvent (Eds.), vol. 3, North-Holland, Amsterdam.

Xepapadeas, Anastasios (1997), "Economic development and environmental pollution: traps and growth." *Structural Change and Economic Dynamics*, 8(3), pp. 327-350.

Vollebergh, Herman R.J. and Claudia Kemfert (2005), "The role of technological change for a sustainable development." *Ecological Economics*, 54(2-3), pp. 133-147.

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