

Cleaning the World Doing Maths

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Abstract

Pollution is introduced in a horizontal innovation framework with privately-performed multi-stage R&D process and research spillovers associated to each R&D component. R&D is performed by firms only and uniquely to get a new variety of good granting positive payoffs. New varieties of goods feed pollution which, in turn, acts as a negative externality on workers. However, within R&D, basic research, along with being the first necessary step for any R&D process, contributes to abate pollution unintentionally through generality and pervasiveness of its spillovers trajectories. A unique growth rate is determined which is not Pareto efficient. We tackle second-best environmental policy by taxing polluters and supporting pollution-abatement. Notably, in this set up, this matches with industrial policy. Support to basic research is second-best optimal as long as R&D performs little basic research. This finding shows that environmental care needs not necessarily to harm growth and that it can be pursued also by helping activities that contribute indirectly to abate pollution.

Keywords: basic research, endogenous growth, pollution, second-best environmental policy, spillovers

1 Introduction

”Tremendous opportunities are offered by research in order to optimize the life cycle of materials and products, and to break the link between environmental impact and economic growth. This is one of the major objectives of European research, which should be pursued for many years to come”. -Philippe Busquin, EU Research Commissioner-

In recent years there has been an increasing interest in extending endogenous growth models to incorporate environmental considerations. In particular, many attempts have focused on the idea that natural environment is indirectly a factor of production as higher quality of environment affects positively productivity of different factors of production, like in Smulders and Gradus (1996). Allowing for environmental issues inside the economy leads to concerns about pollution, which is, to date, widely acknowledged to be an inevitable by-product of economic activity and to be directly and negatively related to the level of environmental quality as assessed, among others, by Bovenberg and Smulders (1996).

Many contributions have explored the short and long run implications of

including pollution in an endogenous growth setting, and an increasing part of them has adopted frameworks where innovation plays a key role in abating pollution: among others: Barbier (1999) and Bovenberg and Smulders (1995). However, when environmental issues are embedded in R&D-based growth models or, more in general, when pollution is considered along with innovation, the focus is limited to R&D explicitly pursued to abate pollution. This perspective follows from the fact that privately-performed R&D is production-oriented, and pollution is a negative externality of production; therefore, it is assumed that being R&D carried on by firms for profits motivations, it aims at new product discoveries or cost reduction and, as long as environmental care does not generate profits, firms must be pushed towards pollution-abating R&D investment through Government deeds.

This vision, although widely popular, needs not to encompass all the pathways through which R&D, production and pollution are inter-related. In fact, even if it is undoubtedly true that firms do R&D to increase their profits, it may be the case that some of their R&D exerts some positive effects on pollution-abatement as an unintended by-product. This is indeed the case every time that an improvement in the frontier of knowledge following from R&D activity may also go through new ideas generated in production-

oriented activities, opening new and unexpected patterns and processes with positive effects on environmental care.

We claim that this mechanism takes place through the pervasiveness and the novelty of some R&D -namely basic research- and it is channelled through spillovers.

To support our claim we consider well-established economic works on R&D suggesting that the positive side-effects played by R&D spillovers change depending on the R&D activity considered. In particular, as analyzed by Auerswald (2001), Lichtemberg and Siegel (1991) and Salter and Martin (2001) basic research is the activity whose spillovers are the most significant and pervasive, whereas development spillovers are the weakest . Differences in spillovers strength and diffusion are mainly due to the degree of generality associated to R&D activities: basic research is the most general, therefore the outcomes of an investment in this activity are quite unpredictable and the same holds for the potential directions of its contributions to the stock of knowledge. Given all this, basic research is quite likely to be the best candidate to exert positive consequences on pollution abatement. To this respect, it is noteworthy that the US Environmental Protection Agency is currently monitoring R&D in nanofields (also privately performed), although

not environmental-oriented, to understand and evaluate the positive environmental side-effects as described in EPA White Paper on Nanotechnologies (2005). And nanofield R&D relies heavily on basic research.

Moreover, US data about R&D show that private agents perform multi-stage R&D processes in many industries, and both development and basic research are carried on. Figure 1 highlights the patterns of firms investments in basic research and development in United States between 1953 and 2003 following the National Science Foundation database¹

[INSERT FIGURE 1 HERE]

Figure 1. US Basic Research in Industry 1953:2003

The last element we provide to further strengthen our claim about the positive effects of basic research on pollution abatement even without being directly aimed at environmental targets, is a brief report of some anecdotal evidence about unintended pollution-reducing trajectories of privately performed basic-research-intensive activities. Ernest and Shetty (2005) and the National Center for Manufacturing Sciences have showed that in US and other countries, such as UK and Japan, nanotech companies are performing R&D processes where basic research has a key role. Then, several works about nanotechnology roadmapping, like Environmental Protection Agency

(2005) and Ernest and Shetty (2005), have highlighted important environmental side-effects of nanotech knowledge: from improved healthcare² to environmental care and energy savings. Other important sectors where R&D has generated fundamental trajectories towards environmental protection, though incidentally, are manufacturing and chemical industry. The former, as summarized by the Community Research of the European Commission (2002), has devoted significant R&D efforts in the plasma physics realm and the outcomes have been manifold: from plasma TV screen to lighter materials and technologies that improve the manufacturing process, mainly with respect to energy cost reduction. The US Aluminium Association together with the US Department of Energy (1999) have evaluated that R&D efforts towards materials in the chemistry industry has produced a bulk of knowledge and discoveries about some properties of some materials that allow, for instance, to replace steel with aluminium in vehicles production with a consequent reduction in car weight and fuel usage. The Environmental Protection Agency (2005) has estimated that the environmental trajectories of nanotech, chemical and manufacturing R&D lead to a potential energy savings for US close to 14.5% of total US energy consumption per year. The main environmental-friendly technological trajectories referring to our anec-

total evidence are summarized in Figure 2.

[INSERT FIGURE 2 HERE]

Figure 2. Environmental Trajectories of Basic-Research-Intensive Privately Performed R&D

A discussion on the relevant distinctions between basic research and the other R&D components starts from the definition of each activity following what has been established by the National Science Foundation of United States (2003) and subsequently adopted in the literature on R&D. Basic research is defined as a "systematic study directed towards greater knowledge or understanding of the fundamental aspects of phenomena and of observable facts without specific application towards procedures and products in mind". Development is defined as "a systematic application of knowledge towards the production of useful materials, devices, systems and methods, to meet specific requirements". The focus on basic research and development may appear to neglect the existence of another step, applied research, but in fact, this is not the case, as applied research is embedded with characteristics of both basic research and development without any strong peculiarity.

Economic literature has investigated the economic effects of basic research: among others, Audrestch et al (2002), Kesteloot and Veugelers (1995),

Link and Long (1981), Nelson (1959) identify several specific features: creation of breakthrough innovations; highest generality and pervasiveness of spillovers; need of further research effort to deliver economically exploitable design. These typifying elements have to be embedded in a discussion about the economic effects of basic research.

All these considerations seem to provide enough support to our claim; therefore we develop a framework accounting for the possible unintended effects of privately-performed R&D on pollution, driven by basic research spillovers, to check the consequences in terms of growth and policy-making.

Our perspective may give some interesting insights also with respect to the linkage between R&D and environmental policy. In environmental literature, R&D policy is generally needed to push private firms to perform the socially optimal amount of pollution-abating R&D. However, evidence on federal support to R&D in US shows that different fiscal incentives are used depending on R&D composition and that federal support is mainly directed towards basic research activity. Therefore, by constructing a set up where basic research is disentangled from development and contributes accidentally to environmental preservation, it is possible to check whether the observed differences in fiscal incentives play some effects also on environmental care.

The consequences of this exercise may be particularly interesting considering that, notwithstanding well established results on the damages created by pollution, environmental policy gets enforced quite slowly, since efforts towards environmental improvements may be overshadowed by the fear that environmental policy damages the economy through a reduction in production and in economic growth. In fact, there is an active debate between those who argue that, being pollution an inevitable side-product of production, economic growth cannot be ecologically sustainable and those who replicate that a growing economy can produce a growing amount of abatement devices so that pollution is offset. Empirical evidence for developed countries seems to support the latter point of view, as there exists substantial evidence that developed countries experience economic growth associated to improvement in environmental quality and that this is achieved through policy enforcement, as it has been demonstrated by Grossman and Krueger (1995) and Stokey (1998).

So, if environmental policy matches with R&D policy and R&D policy helps firms in their production oriented R&D investments, then it may be that support to pollution abatement gets enforced through support to privately-performed and growth-promoting R&D. In this way we make a

point in favour of the optimistic point of view supporting sustainable growth.

To address the issues outlined above, we explicitly model the distinction between basic research and development in a set up where R&D determines growth and basic research, although incidentally, also helps reducing pollution. The framework builds on horizontal innovation literature, with the introduction of the distinction between basic research and development according to both literature and the data.

One of the main result of the model refers to the effects of productivity of research activities on growth and pollution. An increase in basic research productivity helps reducing pollution, whereas an increase in development productivity plays the opposite effect, by reducing the amount of basic research that each innovator needs to have to get a new variety of good, thus reducing pollution abating activities. Overall, the effects on growth are positive, meaning that the positive effect of development productivity in reducing the R&D cost that firms must bear to start producing offsets the negative effect played by the same productivity through pollution.

Failure to internalize both negative externality from pollution and positive spillovers from R&D implies that private agents fail to reach the first best. Therefore, there is room for policy design and welfare discussions with

respect to growth, R&D and pollution. To this respect, we will not address the issue of policy-design to reach the first best allocation since we follow Barro and Sala-I-Martin (2004) by acknowledging that the successful execution of first best policies appears to be difficult. Thus, we will tackle more realistic policy-making through the introduction and the analysis of second-best R&D and environmental policy. We consider a specific environmental R&D policy which is consistent with existing literature on pollution and on R&D (Smulders and Gradus, 1996): taxes are levied on polluters and revenues are devoted to pollution-abating activities. In this set up, the latter activities correspond to R&D effort, so supporting pollution-reducing activities equals supporting production oriented R&D, a kind of policy which is generally advocated in horizontal-innovation literature. Given this policy structure, second-best optimal fiscal policy shows that the Government must pursue support to basic research as long as applied R&D technology is using basic research at a low level relative to other inputs. This result is deeply related to environmental policy considerations: pollution increases as applied knowledge accumulates, since new final designs correspond to new varieties of intermediate goods, but basic research partly offsets this negative side-effect. So, the optimal fiscal policy result is driven by the fact that any increase in

the size of intermediate goods which is not determined by a sufficient employment of pollution-abating basic research does not allow the economy to reach the second best unless the Government intervenes to subsidize basic research usage. Referring to existing literature on growth and pollution, this contribution suggests that supporting privately-performed basic research benefits an economy affected by pollution, even if basic research, and R&D in general, are not specifically aimed at pollution-abatement.

The paper is organized as follows: Section 2 describes the economy; Section 3 presents the decentralized solution; Section 4 discusses the dynamic optimal taxation problem. Section 5 concludes.

2 The Economy

In modelling the different R&D components, both literature and evidence suggest that we have to distinguish basic research from development along the following lines: *(i)* basic research is the preliminary step of a multi-stage research process where development is the last one; *(ii)* basic research generates positive spillovers affecting the economy across sectors; *(iii)* spillovers associated to development activity are weak and do not spur across differ-

ent sectors; *(iv)* R&D processes performing basic research are more likely to deliver breakthrough innovations, which translates into designs granting long-lasting profits.

Points *(i)* to *(iv)* affect the economy in many ways: by changing the structure of payoffs from R&D efforts with respect to standard horizontal innovation literature, by exerting spillovers effects on technology of good production and by changing the structure of the research process. The new elements are introduced inside an horizontal innovation framework. Referring to point *(iv)*, we take this feature to the extreme and we assume that designs generated by multi-stage R&D processes with basic research give perpetual monopolistic payoffs to innovators.

The economy is characterized by a unique multi-stage R&D sector: first, firms perform basic research, then basic research output is employed in the second research activity to produce an applied design for a new variety of intermediate good. Intermediate goods are used in the production of the final good forever. Research activities generates spillovers: basic research exerts an inter-sector effect on final good production, whereas development reaches R&D activities, only. The latter assumption comes from the so called "dynamic paradigm" developed by Stokes (1997), which states that certain

basic research processes benefit from feedbacks from applied research and development activities.

Pollution is modelled as a side product of economic activity and it affects the economy as a negative externality on final good production. However, basic research, through its strong and pervasive positive spillover effects, helps reducing the negative effects. The structure of the economy is summarized in Figure 3³.

[INSERT FIGURE 3 HERE]

Figure 3. Structure of the Economy

2.1 The model

Final good sector. Producers of final good have access to a production technology combining a number of intermediate inputs to produce final output, which is then sold in the market at unit price. Formally,

$$Y = (E_P L_Y)^{1-\alpha} \int_0^N x_j^\alpha dj, \quad (1)$$

where $0 < \alpha < 1$. Final good sector uses a continuum of intermediate goods, x_j , and labour, L_Y , as costly inputs and it is affected by an externality, E_P .

x_j is the employment of the j th type of intermediate good and N is the total number of varieties of intermediates in the economy. N corresponds also to the total stock of applied designs produced.

Final good is used for consumption and input for the production of intermediate goods. We take the price of Y as the numeraire.

The externality affecting final good production is determined by pollution, exerting a negative effect on workers,

$$E_P = P^{-1} \tag{2}$$

Pollution. Following well-established results in economic literature, we assume that natural environment is indirectly a factor of production. Then, natural environment is negatively and directly related to pollution. Therefore, we will use the latter as a proxy for natural environment. We adopt the idea that pollution is a side product of economic activity, therefore, we assume that it depends positively on the size of the economy, which we proxy by $\int_0^N x_j^\alpha dj$. Then, hinging both on empirical and anecdotal evidence, we also claim that innovation helps reducing pollution and that the strongest contribution to pollution-abatement comes from basic research, being devoted

towards general knowledge and not simply focused on new firms creation as development is. Therefore, pollution is determined by the following expression

$$P = \frac{Nx}{Q}, \quad (3)$$

where Q represents aggregate basic research ideas and we have assumed symmetry across intermediate goods.

Intermediate good sector. Each intermediate good producer holds a patent which grants the exclusive right to produce a specific variety of intermediate good. Every patent allowing for a new variety grants perpetual monopolistic profits to producer. We assume that an intermediate good, once invented, costs one unit of Y to produce and it benefits from applied knowledge. Then, as eq.(1) shows, it is used in the production of final good forever.

Research firms. New firms wishing to enter intermediate good production must invest in research first. An entrant has to invest in basic research first and then to use its output as an input to try to get a useful design. This two-stage research process captures both the idea that a basic research design leads to production of goods only if some applied research activity is performed afterwards and that creating breakthrough innovation is not as

easy as innovating along existing knowledge.

Firms face the two stage decision process typical of standard models of horizontal innovation. First, they decide whether to enter or not. Entrants will invest in R&D if the market value of the firm producing the new variety of intermediate good is at least as large as the R&D expenditure they have to bear to start the firm. Then, they decide the optimal price at which to sell their new intermediate goods to final good sector firms. This price determines the demand they face and, as a consequence, the expected future profits. We solve the two stage problem backward. by deriving the optimal price for new intermediate good, assuming that a new design which translates into a new good has already been invented. Then, we find the value of the firm and compare it to the R&D cost. Since we assume that there is free entry into the business of being an inventor, we will deal with a free entry condition that holds in equilibrium such that entry occurs when the market value of the firm equals the R&D cost. The market value of a new intermediate good firm is given by $V = \int_t^\infty e^{-\int_t^s r(\tau)d\tau} \pi(s) ds$, where π are the instantaneous profits from intermediate good production. An intermediate good costs one unit of Y to produce, therefore, profits accruing to firm producing variety j are given by $\pi_j = (\tilde{p}_j - 1)x_j$, where \tilde{p}_j is determined by profit maximization

in the final good sector. The market values for a new intermediate good firm is given by

$$V = \frac{\pi}{r}. \quad (4)$$

We assume a R&D cost determined by R&D firms profit maximization problems. The R&D cost that entrants must pay corresponds to the price of a new patent. This price is determined by R&D firms considering their two-step technology. A representative firm i generates a new blueprint according to

$$\frac{1}{\eta_N} (NL_{Ni})^\beta q_i^{1-\beta}, \quad (5)$$

where $\frac{1}{\eta_N}$ is an exogenous productivity parameter, L_{Ni} is labour devoted to development activity, q_i is basic research and N is a positive intra-sector spillover effect played by existing applied knowledge. Then, $0 < \beta < 1$.

The same firm i produces basic research, q_i , according to

$$q_i = \frac{1}{\eta_Q} L_{Qi} N \quad (6)$$

where η_Q is an exogenous productivity parameter, L_{Qi} is labour force devoted to basic research. We are assuming that the stock of applied knowledge exerts

a positive externality effect on basic research activity, through feedbacks, following the "dynamic paradigm" described above. At each point in time, there are \dot{N} innovators, which we assume to be all equal. Therefore, at the aggregate level, applied knowledge accumulates following $\dot{N} = \frac{1}{\eta_Q^{1-\beta}\eta_N} L_N^\beta L_Q^{1-\beta} N$. Analogously, basic research accumulates according to $\dot{Q} = \frac{1}{\eta_Q} L_Q N$.

Households. Households maximize utility over an infinite horizon. They are endowed with constant aggregate flows of labour which they supply inelastically,

$$\bar{L} = L_Y + L_N + L_Q \quad (7)$$

Their objective function is given by

$$U(C) = \int_0^\infty \ln C e^{-\rho t} dt \quad (8)$$

Households own shares of intermediate goods firms and receive a wage rate on labour. They discount the future at rate ρ . In a closed economy, the total of households' assets equals the market value of firms and they have to choose between consuming now or accumulating new patents in the two

sectors. Their budget constraint is given by

$$C + \dot{a} = w_Q L_Q + w_N L_N + w_Y L_Y + r a,$$

where a stands for assets. The consumption plan they set when maximizing utility subject to the constraints satisfies standard Euler equation

$$\frac{\dot{C}}{C} = r - \rho \tag{9}$$

3 Decentralized equilibrium and BGP

3.1 BGP

Proposition 1 *As long as all R&D activities grow at the same rate, that is $\frac{\dot{N}}{N} = \frac{\dot{Q}}{Q}$, then all variables in the economy, including P , will grow at the same rate given by*

$$\frac{\dot{N}}{N} = \frac{1}{\eta_Q^{1-\beta} \eta_N} L_N^\beta L_Q^{1-\beta} \tag{10}$$

Proof. See Appendix A. ■

Now, we need to find the equilibrium expression for this growth rate, therefore, we need to solve for the decentralized equilibrium.

3.2 Decentralized equilibrium

Profits from final good production are given by

$$\max_{\{x\}_{j=0}^{lN}, L_Y} (E_P L_Y)^{1-\alpha} \int_0^{lN} x_j^\alpha dj, - \int_0^{lN} \tilde{p}_j x_j dj - w_Y L_Y$$

where \tilde{p}_j , is the price of the j th monopolized intermediate good. Final good sector is competitive, therefore input prices are taken as given. Also pollution, being an externality, is take as given by firms. Instantaneous profit maximization gives the following first order conditions, once symmetry has been imposed

$$\tilde{p} = \left(\frac{L_Y}{P} \right)^{1-\alpha} \alpha x^{\alpha-1}, \quad (11)$$

$$w_Y = (1 - \alpha) lN x^\alpha P^{\alpha-1} L_Y^{-\alpha} \quad (12)$$

where we have substituted for E_P using eq.(2). Eq.(11) is the inverse demand function faced by intermediate good producers. Recall that we assume that an intermediate good, no matter its type, once invented, costs one unit of Y to produce; this assumption together with the demand functions allow us to write the profit flows for intermediate goods. If we deal with the j th monopolized intermediate good, the profit flow is given by $\pi_j = (\tilde{p} - 1) x_j$,

where \tilde{p} is given by eq.(11). Since monopolists set marginal revenues equal to marginal cost, we get that $\tilde{p} = \frac{1}{\alpha}$, $x = \alpha^{\frac{2}{1-\alpha}} P^{-1} L_Y$. Therefore, symmetry across all the monopolized intermediate goods implies that

$$\pi_j = \pi = \left(\frac{1 - \alpha}{\alpha} \right) \alpha^{\frac{2}{1-\alpha}} P^{-1} L_Y \quad (13)$$

Monopolistic profits represent the positive payoffs from R&D investment, thus providing the right incentive to innovate. Innovation is a costly activity and its cost affects entry decision. This cost has to be determined. R&D evolves following two stages: we may think that the R&D process is carried on by a vertically integrated firm performing both stages. The problem of the typical firm is to maximize instantaneous profits from development activity subject to the technological constraint represented by basic research technology, eq.(6),

$$\max_{L_{Ni}, L_{Qi}} \frac{\hat{p}}{\eta_N \eta_Q^{1-\beta}} L_{Ni}^\beta L_{Qi}^{1-\beta} N - w_N L_{Ni} - w_Q L_{Qi}$$

where \hat{p} is the price for a new useful design and w_h , $h = N, Q$ is the wage rate for labour devoted to development and basic research respectively. First

order conditions and no arbitrage in the labour market imply

$$w_N = \frac{\hat{p}^\beta}{\eta_N \eta_Q^{1-\beta}} \left(\frac{L_Q}{L_N} \right)^{1-\beta} N, \quad (14)$$

$$w_Q = \frac{\hat{p}(1-\beta)}{\eta_N \eta_Q^{1-\beta}} \left(\frac{L_Q}{L_N} \right)^{-\beta} N, \quad (15)$$

$$L_Q = \frac{(1-\beta)}{\beta} L_N. \quad (16)$$

where we have assumed that all R&D firms are identical, implying $L_{Qi} = \frac{L_Q}{N}$ and $L_{Ni} = \frac{L_N}{N}$. Non arbitrage applies also with respect to final good labour market, therefore, we set eq.(12), after having substituted for x , equal to eq.(14) after having substituted for $\frac{L_Q}{L_N}$ through eq.(16) and we solve for the price of a new blueprint

$$\hat{p} = \frac{l(1-\alpha) \alpha^{\frac{2\alpha}{1-\alpha}} \eta_N \eta_Q^{1-\beta}}{(1-\beta)^{(1-\beta)} \beta^\beta} P^{-1} \quad (17)$$

Eq.(17) can be used inside the free entry condition in intermediate good production, $r_{entry} = \frac{\pi}{V_N} + \frac{\dot{V}_N}{V_N}$, with π given by eq.(13) and $V_N = \hat{p}$ from free entry. Thanks to the BGP assumption, $\dot{V}_N = 0$. Using eq.(7), (16) and

eq.(17), r_{entry} can be rewritten as

$$r_{entry} = \frac{\alpha (1 - \beta)^{(1-\beta)} \beta^\beta}{\eta_N \eta_Q^{1-\beta}} \left(\bar{L} - \frac{L_N}{\beta} \right). \quad (18)$$

Then, since there is a unique BGP growth rate, the Euler equation generates another expression for the interest rate

$$r_{savings} = \frac{1}{\eta_N \eta_Q^{1-\beta}} L_N^\beta L_Q^{1-\beta} + \rho. \quad (19)$$

Non arbitrage in asset market implies that rates of returns must be equal, therefore eq.(18) must equal eq.(19). Solving for L_N we find

$$L_N = \left[\frac{\alpha (1 - \beta)^{(1-\beta)} \beta^\beta \bar{L} - \rho \eta_N \eta_Q^{1-\beta}}{1 + \alpha} \right] \left(\frac{\beta}{1 - \beta} \right)^{1-\beta}. \quad (20)$$

Finally, we substitute the equilibrium expression for L_N inside eq.(10) and we find the equilibrium value for the BGP growth rate

$$\gamma = \frac{\alpha (1 - \beta)^{(1-\beta)} \beta^\beta \bar{L} - \rho \eta_N \eta_Q^{1-\beta}}{(1 + \alpha) \eta_N \eta_Q^{1-\beta}}, \quad (21)$$

and for pollution

$$P = \left[\frac{\alpha^{\frac{2}{1-\alpha}} \eta_Q^\beta}{\eta_N} \left(\frac{1-\beta}{\beta} \right)^\beta \left(\bar{L} - \frac{L_N}{\beta} \right) \right]^{\frac{1}{2}} \quad (22)$$

With respect to eq.(21), the following Proposition holds:

Proposition 2 *The decentralized outcome given by eq.(21) is not Pareto Optimal.*

Proof. See Appendix B. ■

3.3 Comparative Statics

Note that the expression for the growth rate is positively affected by the size of population. Then, productivity of basic research plays a positive effect on growth, as well as productivity of development, by increasing returns from R&D investment. With respect to pollution, eq.(22) shows that an increase in basic research productivity helps reducing pollution, whereas an increase in development productivity increases pollution, by reducing the amount of basic research that each innovator needs to get a new variety of good, thus lowering the aggregate level of basic research available to abate pollution. Thus, increasing basic research productivity exerts positive effects both on

returns from R&D and on pollution abatement, whereas increasing development productivity benefits returns from R&D, but increases also pollution. However, since private agents are not able to internalize negative spillovers from pollution, they cannot capture the effects played by R&D components on pollution.

4 Environmental Policy

We introduce a Government whose goal is reducing pollution by taxing intermediate good producers and devoting the resulting revenues to basic research support. This policy is consistent to the fact that pollution depends positively on the size of the intermediate good sector and negatively on basic research and also to existing literature on environmental policy and growth, as described and developed by the US Environmental Protection Agency (2005) and economists such as Stokey (1998).

Formally, let τ_x be the tax rate on monopolistic profit in intermediate good production and θ_Q be the subsidy rate on basic research. Then, we assume that the Government is constrained to run a balanced budget, which

writes as follows

$$\tau_x l N \pi = \theta_Q w_Q L_Q, \quad (23)$$

where $0 < \theta_Q < 1$ and $1 > \tau_x > 0$. First, we find the decentralized equilibrium once environmental policy has been adopted and we compare it with to the decentralized outcome without any fiscal policy. In this first exercise, fiscal tools are exogenously given. Then we deal with second-best environmental policy to determined the optimal value for both the tax and the subsidy rate.

4.1 Decentralized Equilibrium

Introducing the environmental policy characterized by the Government balanced budget described in eq.(23) in the economy described in Section 2 causes the following changes: monopolistic profits from intermediate good production are taxed, therefore the value of a new firm in the sector is now given by $V_N = \frac{(1-\tau_x)(\tilde{p}-1)x}{r_{entry}}$, where \tilde{p} is still given by eq.(11). Then, the Government uses revenues from taxation to help basic research production; as a

consequence profit maximization for the i -th R&D firm becomes

$$\max_{L_{Ni}, L_{Qi}} \frac{\hat{P}}{\eta_N \eta_Q^{1-\beta}} L_{Ni}^\beta L_{Qi}^{1-\beta} N - w_N L_{Ni} - (1 - \theta_Q) w_Z L_{Qi}, \quad (24)$$

where we have substituted for q_i in development technology using eq.(6). As there are no fiscal tool affecting households, then Euler equation is still given by eq.(9).

By going through the same steps highlighted in Section 3, we find the decentralized equilibrium and the corresponding BGP growth rate when environmental policy is enforced

$$L_N = \left[\frac{\alpha (1 - \beta)^{(1-\beta)} \beta^\beta \bar{L} - \rho \eta_N \eta_Q^{1-\beta} (1 - \theta_Q)^\beta}{(1 - \beta \theta_Q) (1 + \alpha)} \right] \frac{(1 - \theta_Q) \beta^{1-\beta}}{(1 - \beta)^{1-\beta}}, \quad (25)$$

$$\gamma_E = \frac{(1 - \theta_Q)^\beta \left[\alpha (1 - \beta)^{(1-\beta)} \beta^\beta \bar{L} - \rho \eta_N \eta_Q^{1-\beta} (1 - \theta_Q)^\beta \right]}{(1 - \beta \theta_Q) (1 + \alpha) \eta_N \eta_Q^{1-\beta}} \quad (26)$$

By comparing eq.(25)-(26) to eq.(20)-(21), we can conclude that the introduction of the environmental policy has two opposite effects on growth: on the one hand, by diminishing profits from intermediate good production, it reduces the incentive to enter; on the other hand, by subsidizing basic research, it helps pollution abatement and, consequently, benefits profits from

intermediate good production. Both effects are present in eq.(26).

However, as the positive effect from basic research support is not internalized by private agents, as it affects an externality, we decide to introduce welfare considerations to understand more deeply the consequences of environmental policy. So, θ_Q has to be endogenously determined.

4.2 Second-Best Environmental Policy

We have showed that this economy presents a decentralized solution which differs from the first best. Therefore, there is room for fiscal policy. Instead of looking for a fiscal menu pushing the economy towards the first best, here we decide to focus on second-best optimal fiscal policy. This choice hinges on the awareness that successful execution of first best policies appears to be difficult as it generally implies non distortionary tools and the disposal of huge amount of information by policy-makers.

We consider a benevolent Government fixing its distorting environmental policy by taking into account the decentralized competitive equilibrium. In doing so, the Government attempts to internalize both basic research and pollution externalities. To set the second-best environmental policy, the Government chooses θ_Q to maximize eq.(8) subject to the decentralized

competitive equilibrium. Following Park and Philippopoulos (2004, 2002), we shall find it useful to rewrite the problem in terms of variables which will be constant in equilibrium, following well-established contributions to the second-best optimal taxation theory, therefore, we introduce $\hat{C} \equiv \frac{C}{N}$. The introduction of this variable makes the decentralized equilibrium conditions change as follows

$$\gamma_{\hat{C}} = \frac{\dot{C}}{C} - \frac{\dot{N}}{N} = \frac{\hat{C}}{\hat{p}} - \frac{w\bar{L}}{\hat{p}N} - \rho,$$

where $\frac{\dot{C}}{C} = r - \rho$, with r given by eq.(25) and $\frac{\dot{N}}{N} = r + \frac{w\bar{L}}{\hat{p}N} - \frac{\hat{C}}{\hat{p}}$, with w given by eq.(12) and \hat{p} given by eq.(17). After some substitutions, we get that

$$\gamma_{\hat{C}} = \chi \left[\frac{\zeta - \rho \eta_N \eta_Q^{1-\beta} (1 - \theta_Q)^{1-\beta}}{(1 + \alpha) (1 - \beta)^{(1-\beta)} \beta^\beta} \right]^{\frac{1}{2}} (1 - \theta_Q)^{\frac{\beta}{2} + \beta - 1} \hat{C} - \frac{\phi}{(1 - \theta_Q)^{1-\beta}} - \rho, \quad (27)$$

where χ , ζ and ϕ are a functions of parameters⁴.

Then, the Government has to maximize eq.(8) subject to eq.(27). The

⁴ $\chi = \frac{(1-\beta)^{(1-\beta)} \beta^\beta}{(1-\alpha) \alpha^{\frac{2\alpha}{1-\alpha}} \eta_N \eta_Q^{1-\beta}} \left(\frac{\eta_N}{l \eta_Q^\beta \alpha^{\frac{2}{1-\alpha}}} \right)^{\frac{1}{2}}$
 $\zeta = (1 - \beta)^{(1-\beta)} \beta^\beta \bar{L}$
 $\phi = \frac{\zeta}{\eta_N \eta_Q^{1-\beta}}$

current-value Hamiltonian for this problem is

$$H = \ln \hat{C} + \lambda \left\{ \frac{\chi \hat{C}}{(1 - \theta_Q)^{1 - \frac{\beta}{2} - \beta}} \left[\frac{\zeta - \rho \eta_N \eta_Q^{1-\beta} (1 - \theta_Q)^{1-\beta}}{(1 + \alpha) (1 - \beta)^{(1-\beta)} \beta^\beta} \right]^{\frac{1}{2}} - \frac{\phi}{(1 - \theta_Q)^{1-\beta}} - \rho \right\} \hat{C}$$

There is a unique control variable, θ_Q and a unique state variable, \hat{C} . First order conditions for this problem are

$$\begin{aligned} \frac{1}{\hat{C}\lambda} + \frac{2\chi\hat{C}}{(1 - \theta_Q)^{1 - \frac{\beta}{2} - \beta}} \left[\frac{\zeta - \rho \eta_N \eta_Q^{1-\beta} (1 - \theta_Q)^{1-\beta}}{(1 + \alpha)\zeta} \right]^{\frac{1}{2}} - \frac{\phi}{(1 - \theta_Q)^{1-\beta}} - \rho &= -\frac{\dot{\lambda}}{\lambda} + \rho, \\ \frac{2(1 - \beta)\phi\bar{L}}{\chi(1 - \theta_Q)^{2-\beta}} &= \frac{\left[\frac{(2\beta-1)\rho\eta_N\eta_Q^{1-\beta}(1-\theta_Q)^{2\beta-2} - (3\beta-2)\zeta(1-\theta_Q)^{3\beta-3}}{(1+\alpha)\zeta} \right] \hat{C}}{\left[\frac{\zeta(1-\theta_Q)^{3\beta-2} - \rho\eta_N\eta_Q^{1-\beta}(1-\theta_Q)^{2\beta-1}}{(1+\alpha)\zeta} \right]^{\frac{1}{2}}} \end{aligned} \quad (28)$$

$$\gamma_{\hat{C}} = \chi \left[\frac{\zeta - \rho \eta_N \eta_Q^{1-\beta} (1 - \theta_Q)^{1-\beta}}{(1 + \alpha)\zeta} \right]^{\frac{1}{2}} (1 - \theta_Q)^{\frac{\beta}{2} + \beta - 1} \hat{C} - \frac{\phi}{(1 - \theta_Q)^{1-\beta}} - \rho. \quad (29)$$

Then, Proposition 1 states that, in equilibrium, all variables grow at the same rate. This finding, together with the definition for \hat{C} implies $\gamma_{\hat{C}} = 0$. Using this result inside eq.(29) gives the steady state value for \hat{C} , which we

use inside eq.(28) to determine the equilibrium expression for θ_Q ⁵

$$1 - \Upsilon^{\beta-1} = \theta_Q. \quad (30)$$

Then, with respect to eq.(30), the following Lemma is verified.

Lemma 3 *In an economy described by eq.(9)-(17), where the Government enforces an environmental policy summarized by eq.(23), the second-best policy states that basic research is affected by a fiscal tool given by eq.(30) which is positive as long as the amount of basic research employed in the R&D process is below a threshold level.*

Proof. Eq.(30) implies that θ_Q is positive as long as $\beta > 3/5$. Maximization of eq.(24) and non arbitrage in the labour market implies the following relationship for labour allocation

$$\frac{L_Q}{L_N} = \frac{(1 - \beta)}{\beta(1 - \theta_Q)},$$

which shows that, for high value for β , the amount of labour devoted to

⁵ $\Upsilon = \frac{-\Sigma + \sqrt{\Sigma^2 + 4\Gamma(1-3\beta)\zeta\rho}}{2\Gamma}$
 where $\Sigma = \left[(1 - 3\beta)\zeta\phi + (1 - 2\beta) - \eta_N\eta_Q^{1-\beta}\rho^2 - 2(1 - \beta)\phi\eta_N\eta_Q^{1-\beta}\rho \right]$
 and $\Gamma = \left[2(1 - \beta)\phi\zeta + (1 - 2\beta)\eta_N\eta_Q^{1-\beta}\rho\phi \right]$

basic research is low relative to labour devoted to development. Then, according to eq.(6), if L_Q is low, then basic research produced is lower and, as a consequence, new designs are produced employing relatively less basic research. Recalling eq.(3), we can conclude that any increase in Nx , which is not determined by a sufficient employment of basic research, is not optimal in terms of welfare. ■

Our findings states that environmental policy in this type of economy benefits welfare as long as the R&D process does rely heavily on development activity. In fact, whenever this is the case, as applied knowledge accumulates pollution increases, since new final designs correspond to new varieties of intermediate goods while the low employment of basic research does not offset the increase in pollution.

We can conclude that any increase in the size of intermediate goods which is not determined by a sufficient employment of pollution-abating basic research does not allow the economy to reach the second best unless the Government intervenes to subsidize basic research usage.

Looking at US data on privately performed R&D from the National Science Foundation (2003) we find interesting suggestions in temrs of policy advice. The share of basic research on total privately performed R&D ranges

around 4%, reaching 15% if we assume that a half of applied research is really close to basic research and 23% if we assume that all applied research can be labelled basic research. In any case, being the share of fundamental research quite small compared to development, our model allows to argue that it would be second-best optimal for US Government to enforce basic research support also with respect to environmental care.

5 Conclusion

The debate on the role of pollution on economic growth has, thus far, analyzed the effects of R&D explicitly aimed at environmental care, but little consideration has been given to the effects of the different R&D components. However, basic research is endowed with some peculiarities that may help pollution-abatement even if the R&D process embedding basic research as its preliminary step is not directly aimed at environment preservation. Basic research is, by definition, "a systematic study directed towards greater knowledge or understanding of the fundamental aspects of phenomena and of observable facts without specific application towards procedures and products in mind"; the generality inherent to basic research is such that its output may

exert positive effects towards other economic activities through spillovers, which are endowed with the largest span on possible trajectories. Anecdotal evidence has indeed pointed out several trajectories through which basic research discoveries made in some industries such as microelectronics, chemical and manufacturing, have been playing some accidental effects on pollution management. Finally, data on US shows a positive magnitude of basic research performed by private agents. All these observations boost to analyze which might be the outcomes of introducing these linkages between R&D, pollution and growth within a growth model.

This paper addresses this issue from a theoretical perspective, by developing an R&D based endogenous-growth model in which pollution is a by-product of economic activity playing a negative effect on final good production, which is partly offset by a positive externality played by basic research. Basic research belongs to a multi-stage research process carried on by private firms for profit reasons, therefore it is not part of pollution-abating R&D.

Within this set up, a unique decentralized equilibrium is found. The decentralized outcome displays different effects of R&D activities: basic research productivity exerts positive influences on growth and pollution, by

reducing negative externalities and by increasing private returns from R&D investments; development productivity has more complicated effects, as, on the one hand, it increases the level of pollution in the economy by increasing the amount of goods produced (and therefore pollution) for a given amount of pollution-abating basic research, whereas on the other hand it increases private returns from R&D investment, thus promoting growth.

In terms of welfare and policy design, we find that the decentralized equilibrium is not Pareto optimal: pollution, R&D spillovers and monopolistic competition constitute sources for market failure that private agents fail to internalize. To this respect, instead of focusing on optimal fiscal policy to reach the first best, we decide to tackle second-best optimal fiscal policy to deal with fiscal tools which may be more realistically enforced by Governments. The policy we choose to study is both an R&D and an environmental policy, since it provides support to basic research, being an R&D activity generating positive externalities and, at the same time, it helps basic research because it abates pollution. Aid to privately performed basic research comes from taxation to intermediate good producers, as each of them contributes positively to deteriorating environmental quality. Support to basic research is optimal only when the R&D technology usage of basic research relative to

other development-specific inputs is below a threshold level. As long as the R&D process does rely heavily on development activity, as applied knowledge accumulates pollution increases, since new final designs correspond to new varieties of intermediate goods, and the low employment of basic research does not offset the increase in pollution. Then, any increase in the size of intermediate goods which is not determined by a sufficient employment of pollution-abating basic research does not allow the economy to reach the second best unless the Government intervenes to subsidize basic research usage.

US data on the composition of privately performed R&D shows that the share of basic research on total privately performed R&D is quite small, therefore, we can conclude that it would be second-best optimal for US Government to enforce basic research support also with respect to environmental care.

Solution to second-best environmental policy helps to shed some light on the current debate about the effect of pollution concern on economic growth. In fact, our findings states that, if we acknowledge that R&D drives growth and that firms perform basic research, then an environmental policy supporting pollution-abating activities, even if accidentally, and taxing polluters

exerts a positive effect on GDP growth as long as basic research activity is relatively smaller than other R&D activities. This result supports the idea that sustainable growth is possible and it is also consistent with empirical evidence on developed countries, where environmental care pursued through policy design does not harm economic growth.

6 Appendix

Appendix A: Proof of Proposition 1

Eq.(1) shows that $\frac{\dot{Y}}{Y} = \frac{\dot{N}}{N}$. Then, we need to show that also consumption and pollution grow at the same rate. We take the economy-wide resource constraint, given by $Y = C + lNx$, and we take the derivative with respect to time. We see that $\frac{\dot{C}}{C} = \frac{\dot{Y}}{Y} = \frac{\dot{N}}{N}$. Then, recall that pollution is given by $P = \frac{lNx}{Q}$, implying $P = \frac{lNx}{q}$, where $q = \frac{1}{\eta_Q} \left(\frac{L_Q}{N} \right) N$. So, q will be constant along the BGP. Then, as long as x is constant, as it turns to be in equilibrium, then $\frac{\dot{P}}{P} = \frac{\dot{N}}{N}$. Finally, we can conclude that all the variables in the economy grow at the same rate, given by $\frac{\dot{N}}{N} = \frac{1}{\eta_N \eta_Q^{1-\beta}} L_N^\beta L_Q^{1-\beta}$.

Appendix B: Proof of Proposition 2

Proof to Proposition 2 is given by the solution of the Social Planner

problem. The Planner maximizes the utility of the representative household taking into consideration the economy-wide resource constraint and the law of motion for the state variables:

$$\max_{C,x,P,L_Z,L_N} \int_0^{\infty} (\ln C) e^{-\rho t} dt,$$

$$s.t. \quad \dot{N} = \frac{1}{\eta_N \eta_Q^{1-\beta}} L_Q^{1-\beta} L_N^\beta N$$

$$Y = C + lNx$$

$$Y = \left(\frac{L_Y}{P} \right)^{1-\alpha} lNx^\alpha$$

$$\bar{L} = L_Q + L_N + L_Y$$

$$P = \frac{lNx}{Q}$$

and N_0 is the initial value for N . We write the current value Hamiltonian for this problem as

$$H = \ln C + \mu \frac{L_Q^{1-\beta} L_N^\beta N}{\eta_N \eta_Q^{1-\beta}} + \lambda \left[(\bar{L} - L_Q - L_N)^{1-\alpha} lNx^\alpha \left(\frac{1}{\eta_Q^\beta \eta_N l x} \right)^{1-\alpha} \left(\frac{L_Q}{L_N} \right)^{\beta(1-\alpha)} - C - lNx \right]$$

The relevant FOCs for this problem are

$$C^{-1} = \lambda \quad (31)$$

$$\frac{(2\alpha - 1)^{\frac{1}{(1-\alpha)^2}} \left(\frac{L_Q}{L_N}\right)^{\frac{\beta}{2}} (\bar{L} - L_Q - L_N)^{\frac{1}{2}}}{\left(\eta_Q^\beta \eta_N l\right)^{\frac{1}{2}}} = x \quad (32)$$

$$\lambda \frac{x^{2\alpha-1} (\bar{L} - L_Q - L_N)^{-\alpha}}{\left(\eta_Q^\beta \eta_N\right)^{1-\alpha}} \left(\frac{L_N}{L_Q}\right)^{\beta\alpha} \left[1 - \beta \frac{(\bar{L} - L_Q - L_N)}{L_Q}\right] = \mu \frac{\beta l^{1-\alpha}}{l \eta_N \eta_Q^{1-\beta} (1-\alpha)} \left(\frac{L_Q}{L_N}\right) \quad (33)$$

$$\lambda \frac{x^{2\alpha-1} (\bar{L} - L_Q - L_N)^{-\alpha}}{\left(\eta_Q^\beta \eta_N\right)^{1-\alpha}} \left(\frac{L_N}{L_Q}\right)^{\beta\alpha} \left[1 + \beta \frac{(\bar{L} - L_Q - L_N)}{L_N}\right] = \mu \frac{\beta l^{1-\alpha}}{l \eta_N \eta_Q^{1-\beta} (1-\alpha)} \quad (34)$$

$$\frac{\lambda}{\mu} \left[\left(\frac{L_Q}{L_N}\right)^{\beta(1-\alpha)} \frac{l x^{2\alpha-1} (\bar{L} - L_Q - L_N)^{1-\alpha}}{\left(\eta_Q^\beta \eta_N\right)^{1-\alpha}} - l x \right] + \frac{L_Q^{1-\beta} L_N^\beta}{\eta_N \eta_Q^{1-\beta}} = -\frac{\dot{\mu}}{\mu} + \rho \quad (35)$$

First, eq.(33) implies that $\frac{\dot{\lambda}}{\lambda} = \frac{\dot{\mu}}{\mu}$. Then, using eq.(32) inside eq.(33) and eq.(34) and setting the resulting expressions equal, we get

$$L_Q = L_N$$

which differs from labour allocation in the R&D sector determined by private

agents. By substituting this value for labour inside eq.(34) and eq.(35) and using the resulting expression for eq.(34) inside eq.(35) we get the equilibrium expression for labour

$$\left[\frac{2\beta\rho\bar{L}}{\eta_Q^\beta\eta_N^\alpha(2\alpha-1)} - 1 - 2\beta \right] L_N - \frac{4\beta\rho\bar{L}}{\eta_Q^\beta\eta_N^\alpha(2\alpha-1)} L_N^2 + \beta\bar{L} = 0$$

This second degree equation in L_N shows that the equilibrium value for labour is unique and different from the decentralized result. We can conclude that the decentralized equilibrium does not match the first best outcomes and that, as a consequence, the growth rate determined by private agents is not Pareto optimal.

7 Notes

1. Data are in millions of constant 1996 dollars.
2. It is widely acknowledged that pollution has a positive and significant effect on cancer proliferation and on reducing the quality of life. For an update of results on this linkage see Arden (2002).
3. Upward pointing white arrows show the sequence of processes needed

to produce final output. Gray arrows highlight the different purposes of final output. Dotted arrows show the direction of both positive and negative externalities.

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