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Abatement R&D, market imperfections, and environmental policy in an endogenous growth model

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ABSTRACT

We develop an endogenous growth model featuring environmental externalities, abatement R&D, and market imperfections. We compare the economic performances under three distinct regimes that encompass public abatement, private abatement without tax recycling, and private abatement with tax recycling. It is found that the benefit arising from private abatement will be larger if the degree of the firms' monopoly power is greater. With a reasonably high degree of monopoly power, a mixed abatement policy by which the government recycles environmental tax revenues to subsidize the private abatement R&D is a plausible way of reaching the highest growth rate and welfare.

1. Introduction

An important environmental problem policy-makers are facing concerns how to reconcile sustainable growth with limited pollution. On the one hand, endogenous growth theory requires that most economic factors grow unlimitedly. On the other hand, if pollution, an input or a by-product of output, were to grow to become infinitely large, any life or economic activities could hardly exist. To ensure sustainable growth, it is therefore essential for pollution to be abated within a survivable level in the long run. In the US, for example, the estimated total annual abatement expenditure represents between 1.5% and 2.5% of GDP (Berman and Bui, 2001).

Recent studies dealing with the relationship between pollution abatement and environmental growth, such as van Ewijk and van Wijnbergen (1995), Bovenberg and Smulders (1995, 1996) and Fullerton and Kim (2008), treat abatement as technology or knowledge that could be accumulated and developed in a separate sector (i.e., the environmental R&D sector).[1] Since knowledge is non-rival and has the characteristic of a public good, the costs associated with the use of abatement knowledge as an input are zero, while knowledge creation and accumulation, by contrast, require rival inputs

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[1] Alternatively, some studies treat abatement spending as a flow variable which cannot be accumulated. See Gradus and Smulders (1993), Ligthart and van der Ploeg (1994), Smulders and Gradus (1996), and Bovenberg and de Mooji (1997).

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and are costly.[2] This implies that, as stressed in Bovenberg and Smulders (1995), in a perfectly competitive market abatement R&D could *not* be rewarded so that no innovation in abatement technologies would be undertaken without the government's intervention. Therefore, this strand of the literature essentially assumes that abatement R&D activities are publicly conducted by the government.[3]

In reality, however, we often observe that private and public abatement activities coexist. Moreover, it is usually observed that abatement technologies are developed and produced in a private upstream sector, which then sells abatement equipment (or blueprints) to downstream polluting industries (OECD, 2000; Greaker and Rosendahl, 2008). In the US, the private abatement investment is even greater than the public abatement investment (OECD, 2007, Table 3).[4] Based on these observations, it is quite fair to say that a satisfactory model should be able to consider both possibilities of public and private abatement R&D. This is what we aim to do in this paper. To be more precise, we build up a theoretical framework which enables us to compare economic performance under the private and public abatement investment regimes.

Another key feature of our model is that we introduce imperfect competition in the intermediate good market. As mentioned above, private abatement R&D requires incentives, which are not available in a perfect market because, if they were, the competitive firms would not be left with any quasi-rent for abatement R&D. Hence, we should resort to a different market structure, such as an imperfectly competitive market. In the 1980s, several studies (e.g., Hart, 1982; Mankiw, 1985; Blanchard and Kiyotaki, 1987) noted that market power in the private sector plays a crucial role in the performance of government policy. More recently, Judd (2002) has also argued that imperfect competition is a key feature of dynamic modern economies. The empirical evidence, on the other hand, suggests that polluting industries are often equipped with monopoly power (Beccarello, 1996; Considine, 2001). To reflect the observed facts, a considerable body of studies have developed environmental economic models which take market imperfections into account (e.g., Fullerton and Metcalf, 2002; Greaker and Rosendahl, 2008; Chang et al., 2009).

Following in the footsteps of these studies, this paper develops an environmental endogenous-growth model that features market imperfections. More specifically, the market structure we consider is characterized by three vertically integrated sectors. Abatement technologies are developed in an upstream sector, which sells the abatement knowledge (ideas) to the intermediate sector. The intermediate sector, which generates pollution, can generate a positive profit by exhibiting monopoly power, but it has to pay fees to the upstream sector for the right to use the abatement knowledge. The perfectly competitive downstream sector produces a single final output by employing intermediate inputs. Under such a setting, we are able to deal with various regimes including public abatement (hereafter, GA), private abatement without tax recycling (PA), and private abatement with tax recycling (PAR) regimes. Moreover, we compare the relative superiority in terms of economic growth and social welfare among various regimes. In particular, we highlight whether market imperfections play an important role in determining the relative superiority.

An interesting issue in this paper is whether the private provision of abatement knowledge leads to a higher growth rate than public abatement. Our analysis shows that the answer crucially depends on two factors, namely the monopoly power of the polluting firms and the type of government spending. We find that the greater the degree of the firms' monopoly power, the larger will be the benefit arising from the private implementation of abatement. The reason for this result is that the incentive for the upstream sector to engage in R&D is precisely determined by the intermediate firms' profit. It is also found that growth will be enhanced if the government distributes its tax revenues to boost (or directly engage in) abatement R&D. This finding implies that if environmental tax revenues are used to provide public goods or other private services, a subsidy on private R&D abatement will possibly be a good choice to achieve higher economic growth and social welfare.

The analysis of this paper is also related to recent studies on the effect of environmental taxation on economic growth. The conventional wisdom in the literature (e.g., Huang and Cai, 1994; Ligthart and van der Ploeg, 1994; Grimaud, 1999) is often that there is an unavoidable conflict between the economic growth and the conservation of the environment in the economy. However, in recent years a growing body of literature that proposes a positive growth effect of environmental taxation has accumulated. For example, in their frequently cited article, Bovenberg and Smulders (1995) find that environmental taxation has an ambiguous effect on economic growth by assuming that environmental quality is beneficial to input productivity.[5] In departing from this strand of the literature, our analysis assumes that the polluting inputs are purchased from abroad at a non-bargaining price. Accordingly, a higher environmental tax will reduce the pollution by way of an accumulation of abatement R&D, but the polluting inputs will remain unchanged. Since an environmental tax does not decrease the level of polluting inputs (and thereby the marginal productivities of other inputs), it undoubtedly spurs economic growth through the positive environmental productivity effect.

[2] See Smulders (1995) for a detailed discussion.

[3] One exception is van Ewijk and van Wijnbergen (1995), in which the accumulation of abatement capital is costless (a by-product of the accumulation of human capital); thus private abatement takes place even without policy intervention. As is evident, our model's structure is completely different from theirs. Furthermore, van Ewijk and van Wijnbergen (1995) do not deal with public abatement investment.

[4] See Hatzipanayotou et al. (2005) for more detailed discussions on private and public abatement in the US and the UK.

[5] Other justifications contributing to a positive (ambiguous) environmental tax effect on economic growth include a positive externality of abatement activities (Smulders and Gradus, 1996), an elastic labor supply (Hettich, 1998; Chen et al., 2003), the international accumulation of environmental assets (Ono, 2003), tax revenues recycled to subsidize intermediate goods R&D (van Zon and Yetkiner, 2003; Nakada, 2004), and the existence of an indeterminate equilibrium path (Itaya, 2008).

The remainder of this paper proceeds as follows. Section 2 describes the model and solves the firms' and households' optimization problems. Section 3 deals with three distinct regimes associated with different abatement policies. Section 4 presents our numerical results and compares the growth rates and the welfare levels among the three regimes. The final section presents some concluding remarks. Technical derivations are relegated to the Appendix.

2. The model

The economy we consider is composed of three parts: the households, the production sectors, and the government. The production sectors are characterized by a perfectly competitive market for final goods and a monopolistically competitive market for intermediate goods. Moreover, intermediate firms invest in abatement R&D to improve pollution reduction technology. In what follows, we in turn describe the structure of the economy.

2.1. Production sectors

In line with Benhabib and Farmer (1994) and Farmer and Guo (1994), the production side of the economy consists of two sectors: a perfectly competitive final good sector and a monopolistically competitive intermediate goods sector. There is a continuum of intermediate goods y_i, $i \in [0,\ 1]$, which are used by a single representative firm to produce a final good Y. Following Dixit and Stiglitz (1977), we specify that the production of the final good exhibits the following constant returns-to-scale technology:

$$Y = \left[\int_0^1 y_i^{1-\theta}\, di\right]^{1/(1-\theta)}, \quad \theta \in [0,\ 1) \tag{1}$$

As we will show later, θ indexes the degree of monopoly of the intermediate good firms.

Let π_Y denote the profit of the final good firm and q_i be the price of the ith intermediate good in terms of final output.[6] The maximization problem of the final good firm can be expressed as

$$\underset{y_i}{\text{Max}}\,\pi_Y = \left[\int_0^1 y_i^{1-\theta}\, di\right]^{1/(1-\theta)} - \int_0^1 q_i y_i\, di, \tag{2}$$

The first-order condition for this problem yields the demand function of the ith intermediate good:

$$y_i = (q_i)^{-(1/\theta)} Y. \tag{3}$$

It is quite clear from Eq. (3) that the demand function of the ith intermediate good has a constant price elasticity $1/\theta$. When $\theta=0$, intermediate goods are perfect substitutes in the production of the final good, implying that the intermediate goods sector is perfectly competitive. However, if $0<\theta<1$, intermediate good firms face a downward-sloping demand curve so that they can exert monopoly power. Since the main concern of our paper lies in the mutual interactions among environmental externalities, abatement R&D, and market imperfections, in the following analysis we focus our attention on the case in which $0<\theta<1$.

Based on the fact that the final market is perfectly competitive, substituting Eq. (3) into Eq. (2) and imposing the zero-profit condition yields

$$\int_0^1 q_i^{(\theta-1)/\theta}\, di = 1. \tag{4}$$

The technology for producing the ith intermediate good is given by[7]

$$y_i = A(N) k_i^{\alpha} e_i^{1-\alpha} l_{yi}^{\beta}, \quad A'(N) > 0, \tag{5}$$

where A is an environment-productivity function, N is the environmental quality, and k_i, l_{yi} and e_i are the capital, labor and emission inputs used by the ith intermediate firm, respectively. To reflect the positive production externality arising from the environmental quality, Eq. (5) specifies that the output level of the intermediate goods rises with a better natural environment. The profit function of the ith intermediate firm π_i can then be expressed as

$$\pi_i = q_i y_i - r k_i - m e_i - \omega\, l_{yi} - \tau_P p_i, \tag{6}$$

where r is the capital rental rate, ω is the real wage, m is the price of the polluting input, and τ_P denotes a tax (or price of permits) that the government levies on actual pollution p_i. We assume that this environmental tax evolves with the

[6] It should be noted that the final good is treated as the *numeraire* in this paper.

[7] It is worth noting that in a monopolistically competitive market, although the production function is in an increasing-returns-to-scale form, this does not necessarily imply negative profits as long as the monopoly power θ is large enough (see, e.g., Benhabib and Farmer, 1994). In fact, as will be seen later in our numerical example, the profit–output ratio of an intermediate firm is around 2.8%.

aggregate capital, i.e., $\tau_P = \tau K$, where τ is a (constant) policy parameter.[8] It is also assumed that the intermediate firm purchases polluting input e_i from abroad so that the input price m is treated as exogenous throughout the paper (e.g., the polluting input can be thought of as if it were petroleum).

2.2. Environmental quality

The pollution generated in the production process of the ith intermediate firm is of the form

$$p_i = \left(\frac{e_i}{H}\right)^{1/\varepsilon}, \tag{7}$$

where H is the stock of abatement knowledge, and $1/\varepsilon$ ($\varepsilon > 0$) is the elasticity of pollution production with respect to "abated polluting inputs". In Eq. (7), pollution is specified to be positively related to polluting input e_i and negatively related to abatement knowledge H. Accordingly, the total pollution P in the economy is the sum of polluting emissions generated by all intermediate firms:

$$P = \int_0^1 p_i \, di. \tag{8}$$

Following Tahvonen and Kuuluvainen (1991), Bovenberg and Smulders (1995) and Fullerton and Kim (2008), the natural environment is treated as a renewable resource, and can hence be specified to grow and deplete in the following manner:

$$\dot{N} = bN(1-N) - P, \tag{9}$$

where a dot denotes the rate of change with respect to time, b is a parameter that captures the degree of ecological regeneration, and the term $bN(1-N)$ reflects the regeneration capacity of the environment, which might initially increase with a larger N but will eventually decline when N exceeds a threshold value. Eq. (9) indicates that a rise in the level of pollution is associated with a decline in environmental quality in the next period. In the steady state, the environmental quality remains constant over time since pollution equals the regeneration capacity of the environment ($P = bN(1-N)$).

We restrict our analysis to a symmetric equilibrium in which $k_i = k$, $e_i = e$, $l_{yi} = l_y$, $p_i = p$, $\pi_i = \pi$, $y_i = y$, and $q_i = q$ for all i. As a result, from Eq. (1) we have $Y = \left[\int_0^1 {y_i}^{1-\theta} di\right]^{1/(1-\theta)} = y$. With $y = y_i$ and $q_i = q$, the profit of the final good firm stated in Eq. (2) can then be expressed by $\pi_Y = (1-q)y$. Given that the final good sector is perfectly competitive, the representative final good firm earns zero profit (i.e., $\pi_Y = 0$) in equilibrium. Accordingly, the zero-profit condition in the final good sector $\pi_Y = 0$ requires that $q = 1$. Furthermore, let K, E, and L_y denote the aggregate capital stock, aggregate emission, and aggregate labor hired by the intermediate firms. Then, we have $K = \int_0^1 k_i \, di = k$, $E = \int_0^1 e_i \, di = e$, $L_y = \int_0^1 l_{yi} \, di = l_y$. As a consequence, the intermediate firms' first-order conditions can be arranged as

$$(1-\theta)\alpha \frac{Y}{K} = r, \tag{10}$$

$$(1-\theta)(1-\alpha)\varepsilon \frac{Y}{P} = \tau_P + m\varepsilon H P^{\varepsilon - 1}, \tag{11}$$

$$(1-\theta)\beta \frac{Y}{L_y} = \omega. \tag{12}$$

Eqs. (10)–(12) indicate that, given the environmental quality and abatement knowledge, firms equate the marginal revenue of the capital, pollution and labor to their respective marginal cost. Of particular note, the right-hand side of Eq. (11) represents the marginal cost of pollution, and contains two parts. The first part is the environmental tax implemented by the government τ_p. The second part means that, in addition to the taxation, in raising one unit of pollution the firm needs to purchase $\varepsilon H P^{\varepsilon-1}$ units of the dirty input, and thus pay the cost $m\varepsilon H P^{\varepsilon-1}$. It follows from Eq. (11) that a larger abatement knowledge raises the marginal cost of pollution; thereby reducing the use of it.[9]

2.3. Households

There is a continuum of identical infinitely lived households, each of which derives positive utility from both consumption C and environmental quality N. Population is stationary and normalized to unity for simplicity. The

[8] To prevent the aggregate pollution from growing to infinity (in which case nothing could survive), we have to assume that the environmental tax grows over time. This is a commonly used assumption in the literature on environmental and endogenous growth (see, e.g., Bovenberg and Smulders, 1995; Nielsen et al., 1995; Ono, 2007; Fullerton and Kim, 2008). Smulders (1995) provides a detailed discussion on this point. As for the realistic concern, the effective tax rates on fuel oil, coal and gas increased gradually during the period 1988–2006 in many European countries (Andersen and Ekins, 2009).

[9] It is equivalent if the firm chooses the dirty input e instead of pollution p. In this case, Eq. (11) should be rewritten as $(1-\theta)(1-\alpha)Y/E = \tau_P P^{1-\varepsilon}/\varepsilon H + m$. Then, by imposing $E = P^{\varepsilon} H$ we can obtain the same result as reported in Eq. (11).

representative household utility is given by

$$W=\int_0^\infty \frac{(CN^\eta)^{1-\sigma}-1}{1-\sigma}\exp[-\rho t]\,dt, \tag{13}$$

where W is the discounted lifetime utility of the representative household, ρ is the subjective time preference rate, σ is the intertemporal substitution elasticity, and η denotes the weight in terms of the utility attached to the environment or, as proposed by Fullerton and Kim (2008), the "consumption externality" in relation to the environment.

Each household is endowed with a fixed amount of labor $\overline{L}$, which is allocated to production between the intermediate goods (L_y) and research (L_H). We assume that labor is homogeneous and perfectly mobile across sectors. A unique wage rate must, as a result, hold. The representative household receives income by supplying labor and capital services to firms. In addition, it receives profits π (in the form of dividends) and lump-sum transfers G from the government. Finally, a capital income tax rate τ_K is levied on the capital rentals. Accordingly, the budget constraint faced by the representative household can be expressed as

$$\dot{K}=(1-\tau_K)rK+\omega\overline{L}+\pi+G-C. \tag{14}$$

The optimum conditions for the representative household with respect to consumption and physical capital are

$$C^{-\sigma}N^{\eta(1-\sigma)}=\lambda, \tag{15}$$

$$\dot{\lambda}/\lambda=\rho-(1-\tau_K)r, \tag{16}$$

where λ is the shadow price of the private capital stock.

2.4. Abatement R&D activity

As noted earlier, pollution abatement technologies are regarded as knowledge and can thus be accumulated over time. The creation of knowledge requires efforts and time so that innovation and invention are acts of investment (Smulders, 1995). In line with Romer (1990) and Jones (1995), we assume that new ideas are developed by the labor input and the existing stock of ideas. To be more precise, abatement knowledge H is specified to be created in the following manner:

$$\dot{H}=\delta L_H H, \tag{17}$$

where δ is a productivity parameter and L_H denotes the labor input for R&D activities.

In our model, for long-run growth to be feasible and sustainable, the balanced growth path (BGP) in the steady state is characterized by

$$\frac{\dot{Y}}{Y}=\frac{\dot{C}}{C}=\frac{\dot{K}}{K}=\frac{\dot{H}}{H}=\frac{\dot{E}}{E}=g,\quad \dot{N}=\dot{P}=0, \tag{18}$$

where environmental quality and pollution are limited in a physical sense, and all other economic variables grow at a common constant endogenous growth rate g.

3. Public versus private abatement

Two possible facts concerning the R&D activities and the government budget constraint are considered in this section. First, the R&D activities can be conducted by either private firms or the government. Second, if the R&D activities are engaged in by private firms, the government may or may not subsidize the R&D activities. Based on these two kinds of possibility, our analysis can be classified into three different regimes: public abatement (GA), private abatement without tax recycling (PA), and private abatement with tax recycling (PAR). Since the government budget constraint varies with each of the three regimes, the BGP may display quite contrasting results among these three regimes. In what follows, we discuss three types of regimes in turn.

3.1. Public abatement

Under the GA regime, the R&D activities are engaged in by the government. Under such a situation, the balanced budget constraint faced by the government can be expressed as follows:

$$G+q_H\dot{H}=\tau_K rK+\tau_P P, \tag{19}$$

where new abatement knowledge $\dot{H}$ is produced according to Eq. (17), and q_H is the price of abatement knowledge relative to final goods. Eq. (19) states that the government receives its revenues in the form of capital taxes $\tau_K rK$ and pollution taxes $\tau_P P$ to finance its provision of lump-sum transfer payments to the household G and public abatement investment $q_H\dot{H}$.

Eq. (19) is consistent with the Fullerton and Kim (2008) specification, in which abatement knowledge is regarded as a public good and can be used freely by firms. Notice that since labor is perfectly mobile, the marginal revenue product of labor should be the same between two sectors. That is

$$(1-\theta)\beta\frac{Y}{L_y}=q_H\frac{\partial\dot{H}}{\partial L_H}. \tag{20}$$

Using Eqs. (17), (19), and (20) together with the household budget constraint yields the resource constraint of the economy:

$$\dot{K}=Y-C-mE. \tag{21}$$

Imposing the conditions for a BGP and defining the following transformed variables: $h=H/K$, $c=C/K$, $w=\omega/K$, and $\phi=G/K$, the macroeconomy along the BGP equilibrium can then be described by the following set of equations:

$$g^*=\frac{1}{\sigma}\left[(1-\tau_K)(1-\theta)\alpha A(N^*)P^{*(1-\alpha)\varepsilon}h^{*1-\alpha}L_y^{*\beta}-\rho\right], \tag{22}$$

$$g^*=\delta(\overline{L}-L_y^*), \tag{23}$$

$$(1-\theta)(1-\alpha)\varepsilon A(N^*)P^{*(1-\alpha)\varepsilon}h^{*1-\alpha}L_y^{*\beta}=\tau P^*+\varepsilon m h^* P^{*\varepsilon}, \tag{24}$$

$$(1-\theta)\beta A(N^*)P^{*(1-\alpha)\varepsilon}h^{*1-\alpha}L_y^{*\beta}=w^*L_y^*, \tag{25}$$

$$c^*=A(N^*)P^{*(1-\alpha)\varepsilon}h^{*1-\alpha}L_y^{*\beta}-g^*-mh^*P^{*\varepsilon}, \tag{26}$$

$$P^*=bN^*(1-N^*), \tag{27}$$

$$\tau_K(1-\theta)\alpha A(N^*)P^{*(1-\alpha)\varepsilon}h^{*1-\alpha}L_y^{*\beta}+\tau P^*=\phi+w^*(\overline{L}-L_y^*), \tag{28}$$

where the superscript "$_*$" denotes the steady-state value.

The macroeconomic model expressed in the above seven equations determines seven unknowns, i.e., h^*, c^*, P^*, N^*, L_y^*, w^*, and g^*. Since the system is in a nonlinear form and is too complicated to enable a closed-form solution to be obtained, we present our results via numerical analysis.

3.2. Private abatement R&D

This subsection deals with both the PA and PAR regimes. Under these two regimes, the R&D activities are undertaken by private firms. Accordingly, we first need to formulate how abatement knowledge is produced in the R&D sector. To achieve this purpose, in line with the standard R&D literature including Romer (1990) and Jones (1995), we assume that there are three vertically integrated sectors in this economy. The abatement technology is developed and produced in an upstream R&D sector, which hires labor to engage in innovation activity and then sell the abatement technology (blueprints) to the midstream intermediate (polluting) sector. The downstream final good sector produces a single final output by employing a set of intermediate inputs.

There are many identical firms (and also potential entrants) operating in the R&D sector, but at each moment in time only one of these firms achieves a technological breakthrough and thus makes the latest development, namely the state-of-the-art technology for H.[10] Therefore, it is the only firm that is able to sell the respective blueprint for the right to use the abatement technology.[11] Since all firms are identical, the model can be solved as if there is a representative R&D firm. This representative R&D firm hires labor L_H to develop the abatement technology according to the production function reported in Eq. (17). The profit function of the R&D firm is[12]

$$\pi_H=q_H\dot{H}-(1-s)\omega\, L_H, \tag{29}$$

where s is the subsidy rate for the labor employment of the R&D sector.

Following the literature on R&D-based endogenous growth models (Grossman and Helpman, 1991; Barro and Sala-i-Martin, 2004), two important assumptions are made. First, there is free entry into the R&D sector so that the R&D firm earns

[10] This implies that each firm has a fixed probability of developing a technological improvement, as in a quality ladder model of innovation.

[11] In the vast literature on R&D-based growth models, the products of R&D (knowledge or blueprint) are not homogeneous but sector-specific. A blueprint may relate to a new variety or a better quality of a given variety, but in any case it will be used by a unique monopolist. This implies that there are many firms in the R&D sector and the number of firms is determined by the zero profit condition. In the present paper, however, the abatement technology is a homogeneous good. Hence, for the R&D sector to be able to extract all the profits of the intermediate firms (as will be assumed below), it must be the case that at each moment there is only one firm that sells the abatement technology. We would like to thank an anonymous referee for bringing this point to our attention.

[12] Since the technology is non-rival, the marginal cost of supplying $\dot{H}$ to one more intermediate firm is zero. This means that the R&D sector will sell its product to each and all the intermediate firms. Therefore, in Eq. (29) the revenues of the R&D sector should be $x\, q_H\dot{H}$ where x denotes the number of the intermediate firms. Notice that we have assumed $x=1$ and thus x is ignored in Eq. (29).

zero profit.[13] Second, the R&D sector has pricing power; it charges a price for its product (blueprint) at which the intermediate firms are indifferent between buying the blueprint (to produce the intermediate product) and not buying it (to leave the market). An intermediate firm that pays for the blueprint has the right to use that technology forever, but for the next period it has to pay another fee for the right to use the latest-generated technology. That is to say, in each period the firms pay for new technology ($\dot{H}$), but use the whole existing stock of technology (H) in order to abate pollution. Accordingly, in each period the price of technology q_H must be set to the level at which the technology generated in the R&D sector extracts all the profit of the intermediate firms, which can be expressed by[14]

$$q_H \dot{H} = \int_0^1 \pi_i \, di = \pi. \tag{30}$$

Eq. (30) says that the *license fee* for new abatement knowledge must be equal to the net profit that a monopolistic firm can earn.[15] Notice that because we have a continuum of intermediate firms in the interval (0,1), the total payment to the R&D sector is the sum of all intermediate firms' profits.

Under the PA regime, the government does not subsidize R&D activities, and hence this regime corresponds to $s=0$ in Eq. (29). Alternatively, under the PAR regime, the government provides R&D subsidies, and hence this regime is associated with $s>0$ in Eq. (29). We now deal with these two regimes in turn.

3.2.1. *Private abatement R&D without tax recycling*

Under the PA regime, the government neither invests in R&D nor subsidizes it (i.e., $s=0$). Hence, the government budget constraint is given by

$$G = \tau_K rK + \tau_P P. \tag{31}$$

Since the profit of the intermediate firms is allocated to pay for the use of abatement knowledge, no dividends are distributed to the households. Accordingly, the household budget constraint can be rewritten as

$$\dot{K} = (1-\tau_K) rK + \omega \overline{L} + G - C. \tag{32}$$

Based on the above conditions, it can be shown that the resource constraint reported in Eq. (21) still holds in the PA regime. At the BGP equilibrium, the economy is described by Eqs. (22)–(27) together with the following condition (mathematical derivations are provided in Appendix A):

$$g^* = \frac{\delta[1-(1-\theta)(\alpha+\beta)-(1-\theta)(1-\alpha)\varepsilon]}{(1-\theta)\beta} L_y^* - \frac{\delta(1-\varepsilon) m h^* P^{*\varepsilon}}{w^*}. \tag{33}$$

3.2.2. *Private abatement R&D with tax recycling*

Under the PAR regime, the government subsidizes the private abatement R&D instead of directly conducting the R&D activities. Hence, the government budget constraint becomes

$$G + s\omega L_H = \tau_K rK + \tau_P P. \tag{34}$$

After some manipulations, Eqs. (33) and (34) can be modified as

$$g^* = \frac{\delta[1-(1-\theta)(\alpha+\beta)-(1-\theta)(1-\alpha)\varepsilon]}{(1-s^*)(1-\theta)\beta} L_y^* - \frac{\delta(1-\varepsilon) m h^* P^{*\varepsilon}}{(1-s^*) w^*}, \tag{35}$$

$$\tau_K (1-\theta)\alpha A(N^*) P^{*(1-\alpha)\varepsilon} h^{*1-\alpha} L_y^{*\beta} + \tau P^* = \phi + s^* w^* (\overline{L} - L_y^*). \tag{36}$$

The BGP economy can then be described by Eqs. (22)–(27), (35), and (36), where eight unknowns h^*, c^*, P^*, N^*, L_y^*, w^*, g^*, and s^* are solved in eight equations.

4. Quantitative results

A numerical analysis is presented in this section to trace how the growth rate and welfare level will react following a change in an environmental policy under the three regimes. To construct an illustrative example, we choose benchmark

[13] As pointed out in Grossman and Helpman (1991), this assumption implicitly supposes that potential entrants or outsiders can, via inspection of the goods in the market, completely learn about the state of knowledge (due to the public-good characteristics of knowledge) to mount their own research efforts and then replace the existing R&D firm.

[14] In the standard R&D-based endogenous models, the intermediate firms make a one-off payment to the R&D sector for the right to use the knowledge forever after. However, in our model the intermediate firms need to make flow payments to use the abatement knowledge in every period. In Section 5.1 we will discuss this point more in detail.

[15] According to Kamien and Tauman (1986), a patentee can license her invention to an oligopolistic industry by means of a fixed fee or a per unit royalty. It should be noted that in this paper the price of abatement knowledge can be regarded as a fixed license fee that an intermediate firm should pay to the R&D sector in exchange for the right to use abatement knowledge.

Table 1
Baseline parameters.

Parameter	Value	Parameter	Value
α	0.24	β	0.67
σ	1.5	ρ	0.05
ε	0.6	η	0.7
γ	0.77	θ	0.35
τ_K	0.16	ϕ	0.06
τ	30	δ	0.01
m	1.8	$\overline{L}$	15
b	0.04		

parameter values that are within the plausible ranges used in the literature. Table 1 lists the benchmark parameter values, and some interpretations concerning these parameter configurations should be provided here. First, in line with Fullerton and Kim (2008), we specify the environmental productivity function as being of the form $A(N)=N^{\gamma}$ and set the following parameters: $\gamma=0.77$, $\alpha=0.24$, $b=0.04$, $\eta=0.7$. Second, the values $\sigma=1.5$, $\beta=0.67$, and $\rho=0.05$ are based on the calibration exercises in Lucas (1990) and Stokey and Rebelo (1995). The monopoly power index $\theta=0.35$ is calibrated such that the resulting profit ratio in our economy is 2.8%, and conforms to the profit ratio of a typical US industry; see, e.g., Basu and Fernald (1997) and Guo and Lansing (1999).[16]

Third, to reflect the model's plausibility we choose $\tau_K=0.16$ (based on the estimate reported by Auerbach, 1996) and $\phi=0.06$ as policy parameters. This in turn implies that the government's spending as a proportion of output is around 8%, and hence this numerical value lies within the reasonable interval in the literature (see e.g., Galí, 1994). Fourth, the pollution tax relative to the capital stock $\tau=\tau_P/K$ is 30 so that the ratio between the tax revenues and the output is about 17%.[17] Fifth, as for the pollution conversion parameter, while Bovenberg and Smulders (1995) simply assume that ε is equal to 1, Fullerton and Kim (2008), however, relax this assumption and allow ε to vary from 0.6 to 0.9. A relatively low value of ε means that the elasticity of pollution production with respect to "abated polluting inputs" is high. That is, raising the level of polluting inputs will not only increase pollution, but will also accelerate the generation process. More specifically, the investment in abatement knowledge will be more important if the elasticity is higher. To highlight the role of abatement investment, we set $\varepsilon=0.6$ as our parameter value. Finally, the values of $(m,\delta,\overline{L})$ are calibrated so that the balanced growth rate is 3.12%, which is close to the average growth rate for the past 30 years in the US.

4.1. Comparison of three regimes

Table 2 presents the key endogenous variables in the benchmark case. Our goal is to compare the steady state growth rate and the welfare level under the three regimes. As shown in Table 2, in the GA regime, the steady state growth rate is about 3.12%. In the PA regime, the government switches the abatement spending to a lump-sum transfer, and the intermediate firms are forced to purchase the license fee for abatement knowledge from the R&D firms. Under such an arrangement, the growth rate declines to 1.43% in response. However, if the tax revenues are recycled to subsidize the R&D sector, the growth rate of 3.55% is ranked the highest among the three regimes. In addition, as shown in Table 2, the rank of the abatement knowledge among the three regimes is the same as that of the balanced growth rate. The intuition behind this coincident ranking follows from the fact that, as indicated in Eq. (17), an accumulation of abatement knowledge unambiguously enhances economic growth.

However, by comparing the value of pollution under the three regimes, it may be somewhat surprising that a higher abatement investment to capital ratio (i.e., a higher h^*) is associated with more pollution. The economic intuition behind this result can be explained as follows. Other things being equal, a better environment (less pollution) should be achieved if the firm has access to more abatement knowledge. However, once the government directly provides or indirectly subsidizes abatement knowledge, the cost of pollution-reducing activities will decline. Cheaper abatement knowledge gives the firms an incentive to use more polluting inputs, which worsen the environmental quality. In our model, it seems that the latter effect dominates the former, and thus abatement knowledge and pollution receive the same ranking among the three regimes.

We now turn to compare the level of welfare under the three regimes. We focus on the welfare along the BGP, denoted by W^*, which is calculated by using Eqs. (13) and (26)

$$W^*=\frac{1}{1-\sigma}\left\{\frac{-1}{(1-\sigma)g^*-\rho}C_0{}^{1-\sigma}N^{*\eta(1-\sigma)}-\frac{1}{\rho}\right\}, \tag{37}$$

[16] We choose the GA regime as our baseline economy when calibrating.

[17] Supposing that $K=1$, in the steady state we have $P=0.0042$ and $Y=0.7383$. Accordingly, the ratio of pollution tax revenues to output is (30)(0.0042)/0.7383 = 17%, which is in line with the value 17.8% in Fullerton and Kim (2008).

Table 2
Comparison of three regimes.

Regimes	N^*	P^*	h^*	$g^*(\%)$	W^*
GA	0.8809	0.00420	2.2964	3.116	−1.0372
PA	0.9007	0.00358	1.4722	1.427	−14.7173
PAR	0.8779	0.00429	2.5635	3.554	−0.6392

where $C_0 = [A(N^*)P^{*(1-\alpha)\varepsilon}h^{*1-\alpha}L_y^{*\beta} - g^* - mh^*P^{*\varepsilon}]K_0$ is the endogenously determined level of consumption on the BGP, and K_0 is the initial (predetermined) capital stock. Without loss of generality, we set $K_0 = 1$ in our numerical model. We follow Barro (1990) to assume that the economy jumps to the BGP right from the beginning, which means that given a predetermined initial amount of capital K_0, the levels of all endogenous variables (including C_0) are simultaneously determined. This assumption implies that the level of welfare expressed in Eq. (37) does not consider the transition dynamics and thus our quantitative results only apply to the BGP.

The numerical values of social welfare under the three regimes are reported in the last column of Table 2. It is clear that the ranking of the level of welfare among the three regimes is the PAR regime, the GA regime and the PA regime in that order. The policy implication is that, given the baseline parameter values, the growth rate and welfare are the lowest if abatement activities are conducted privately without government intervention. Nevertheless, they could be both enhanced once the government engages in public abatement or provides incentives for private abatement R&D. If the latter is the case, the growth rate and welfare could achieve the highest levels.

4.2. Parameters with policy implications

It should be noted that the numerical results regarding the growth rate and welfare are examined only under the baseline parameter values. An interesting concern is how our numerical results are related to the values of the parameters. To this end, in what follows we propose three relevant parameters that need to be considered by the policy-makers.

4.2.1. Market imperfection

An early but insightful point of view by Schumpeter (1942) is that more competition would erode the monopolistic rents, and thus reduce the incentive to undertake R&D activities. We stand in line with this perspective and extend it to an economy in which R&D investment is used to control the pollution. To be more specific, in our model the decentralized economy suffers from two market failures. The first concerns the environmental externality. Pollution harms human health and productivity, but is not accounted for by the polluting firms. The second has to do with the market imperfections regarding the supply of intermediate goods. However, these imperfections can become the motivation for people to engage in R&D in the case where the polluting firms need to pay a license fee to use abatement technologies, but not in the case where there is public provision of free abatement knowledge. In other words, only in the regime of private abatement (PA and PAR) can the second market failure (imperfect competition) remedy the first market failure (the environmental externality). Based on this observation, market imperfections play a critical role when integrating abatement investment with private incentives.

Fig. 1 exhibits the effects of varying the monopoly power parameter (θ). A rise in θ is associated with an increase in both the balanced growth rate and the level of welfare under both the PA and PAR regimes. To explain this result, by using Eqs. (29) and (30) and $\pi_H = 0$ we obtain $\pi = (1-s)\omega L_H$, where a higher profit implies more employment of research workers. As noted previously, the R&D firms can price their ideas exactly to extract all the profit of the intermediate firms. For this reason, a higher θ (as well as the profit of the intermediate firms) means that more resources are contributed to hire labor in the R&D sector, thereby stimulating the balanced growth rate.

In the GA regime, on the contrary, the effects of θ on the long-term growth rate and welfare are almost negligible. The reason for this result stems from the fact that in the GA regime abatement investment is undertaken only by the government, and thus has no direct relationship with the firms' profit. More specifically, the numerical results depicted in Fig. 1 indicate that, under both the PA and PAR regimes, the greater the degree of imperfect competition, the larger the benefit of private abatement will become. When θ is large enough, both the balanced growth rate and the social welfare for the PA regime may possibly exceed those for the GA regime. Moreover, if the government can recycle its tax revenues to provide incentives for private abatement R&D, both economic growth and welfare will be further enhanced.

4.2.2. The type of government spending

We now discuss the parameter related to the public sector. In their recent study, Fullerton and Kim (2008) show that government spending on transfer payments (ϕ) is a non-environmental parameter with important implications for environmental policy. The effect of changing ϕ is depicted in Fig. 2. It is shown that, in response to an increase in ϕ, the growth rate and social welfare decline in both the PAR and GA regimes but remain unchanged in the PA regime. The intuition for this result is straightforward. In the PA regime all tax revenues are returned to the households. The abatement investment which stirs up economic growth comes only from the monopolistic rents so that ϕ has no role in economic activities.

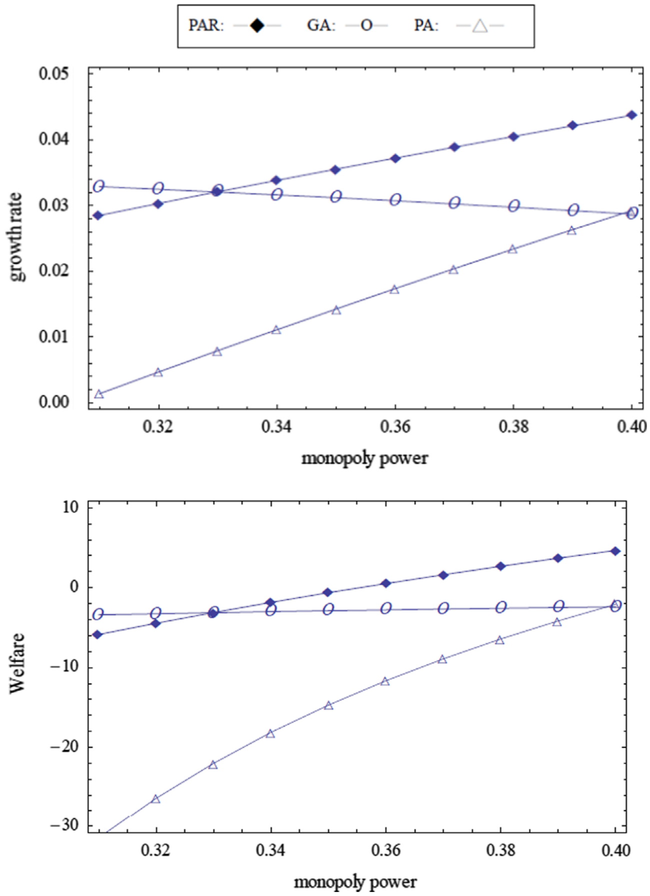

Fig. 1. The effect of monopoly power.

However, under both the PAR and GA regimes, economic growth becomes closely related to ϕ since the government uses its tax revenues to stimulate (or directly conduct) abatement R&D. A positive value of ϕ indicates that a part of the revenues from the environmental tax must be spent on transfer payments. The greater need for transfer payments implies that less tax revenue will be used in abatement R&D, and hence will lead to a deterioration in the balanced growth rate. As is evident, our results indicate that the conclusion in Fullerton and Kim (2008) is valid under both the PAR and GA regimes but invalid under the PA regime.

4.2.3. The effect of an environmental tax

We now turn to investigate the effect of an environmental tax policy. It is shown in Fig. 3 that raising an environmental tax can stimulate economic growth as well as reduce the level of pollution. Bovenberg and Smulders (1995) have clearly pointed out the two opposing forces whereby the environmental policy affects the long-term growth rate. First, a lower level of polluting inputs decreases the productivity of reproducible inputs, thereby lowering economic growth. Second, a reduction in pollution improves the environmental quality, which benefits productivity and economic growth. As a result, Bovenberg and Smulders (1995) suggest that the environmental tax has an ambiguous effect on economic growth.

In our model, however, by referring to Eq. (6), the pollution inputs are purchased from abroad at a given price so that a higher environmental tax can simultaneously reduce the pollution p $(=p_i)$ but keep the polluting inputs e $(=e_i)$ unchanged. Under such a situation, a tighter environmental policy no longer decreases the productivity of capital and labor, because a lower level of pollution in production is offset by more abatement knowledge. Hence, our model only presents the second environmental quality effect.

To highlight the importance of this environmental quality effect, we consider the alternative value $\gamma=0$ to indicate that production gains no extra benefit from a better environmental quality.[18] The numerical results are depicted in Fig. 4. It can be seen that, in the absence of an environmental externality, raising an environmental tax has no effect on the long-term

[18] It should be noted that $\gamma=0$ only removes the environmental externality in relation to production; nonetheless the externality in regard to the households' utility is always present.

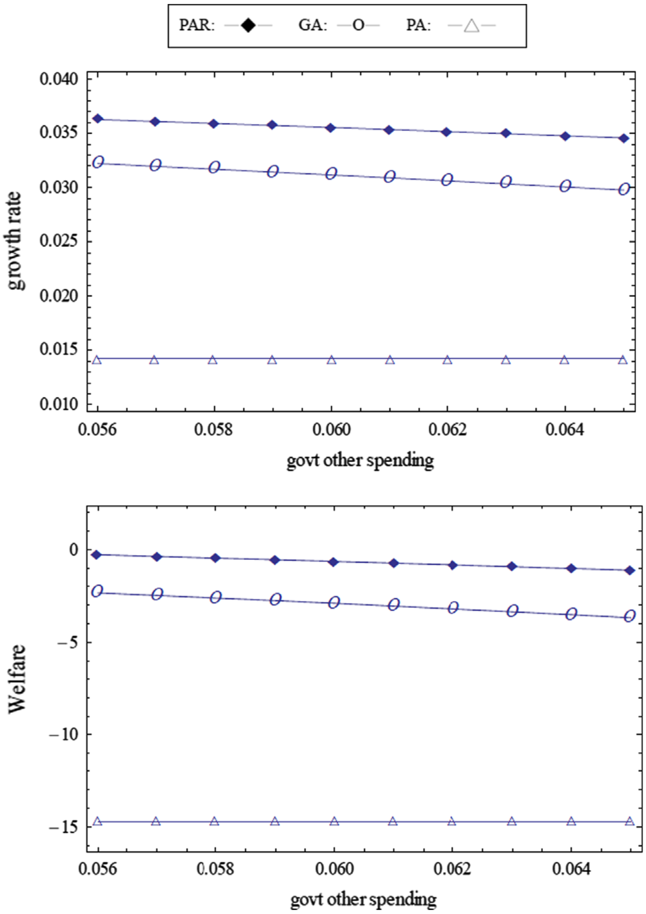

Fig. 2. The effect of increasing other government spending.

growth rate while it reduces pollution. Comparing Fig. 3 with Fig. 4 enables us to realize that whether or not environmental policies affect economic growth crucially depends on the presence of a positive environmental externality.

Now we deal with the welfare analysis. Figs. 3 and 4 show that the welfare level is increasing with the environmental tax, regardless of whether a positive environmental externality is present or not. As discussed earlier, in the case of $\gamma=0$ a tighter environmental policy has no effect on long-term growth. However, it can still influence the level of welfare because, with the growth rate unchanged, a higher environmental tax improves the environmental quality and thus unambiguously enhances the welfare level. If the representative household does not care about the environmental quality ($\eta=0$), it is an obvious conjecture that environmental tax cannot play any role either in governing the balanced growth rate or the welfare level.

5. Discussions and extensions

In this section we provide two detailed discussions of previous settings which may need further debate. The first one concerns the properties of the abatement technology, and the second one has to do with why our model makes a distinction between pollution emissions and dirty inputs. In addition, we also conduct two interesting extensions. In the first extension we examine the effects of the environmental tax under an alternative setting of pollution. In the second extension we investigate the impact of an increase in tariffs that raises the price of pollution inputs.

5.1. The properties of the abatement technology/knowledge

5.1.1. What is the abatement technology/knowledge?

In our model, the concept of the abatement knowledge is not much different from that in the previous literature, such as Bovenberg and Smulders (1995, 1996) and Fullerton and Kim (2008). It generally represents the amount of resources that the economy has devoted to developing or applying the new technical knowledge which enables production to occur in a less polluting way. As for practical concerns, the abatement technology might, as an example, refer to the CO_2 capture and

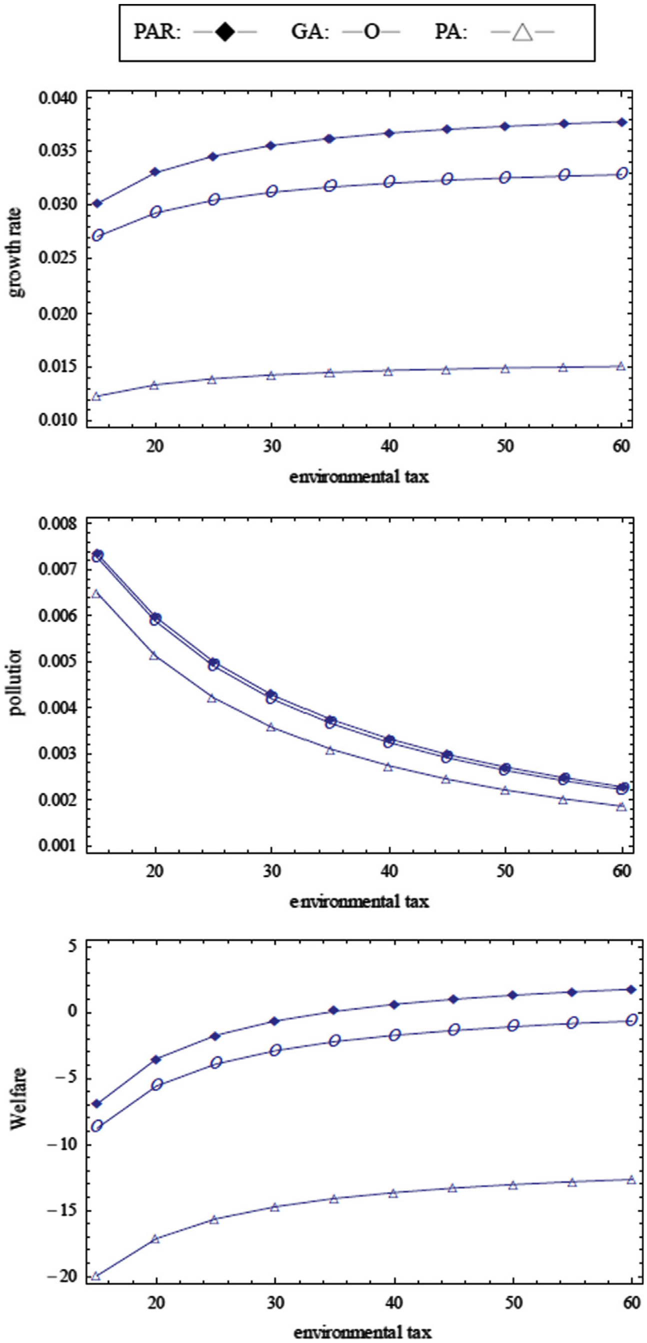

Fig. 3. The effect of an environmental tax ($\gamma = 0.77$).

storage (CCS) system, and therefore the value of H represents the available resources for the adoption of the CCS technology. Within the model, a plausible way of thinking how the abatement technology works might be to consider that the intermediate firms are endowed with a common abatement machine, and that H is concerned with the technology to operate it. As such, a higher level of H is associated with a superior technology, and hence leads the intermediate-goods firm to implement the abatement machine better so as to further reduce pollution.

5.1.2. Non-rivalry

Gerlagh et al. (2008) establish an endogenous growth model incorporating the R&D, environmental policy and innovation policy. In their model, there are many (intermediate) producers of abatement equipment. The upstream R&D firm creates new ideas that expand the varieties of the intermediate producers, and then sells the new technology embodied

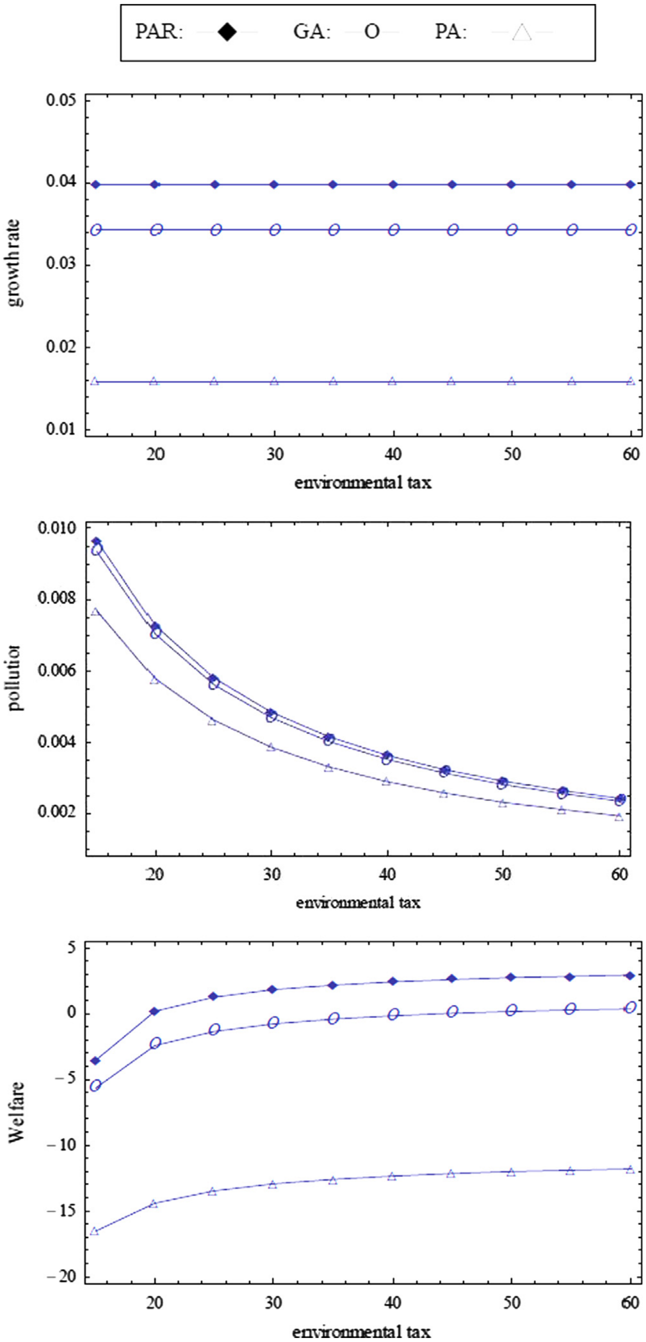

Fig. 4. The effect of an environmental tax ($\gamma = 0$).

in these rival goods. It should be emphasized that our setting is different from theirs because in our model the variety of the intermediate goods is constant. The role of market imperfection in this economy is to allow intermediate firms to have a positive profit such that they can pay for abatement R&D. New ideas, the products of R&D, are about the technology/knowledge used to abate pollution, which are featured with *non-rivalry* due to the property of knowledge. It is not specific for each intermediate good and thus could be used by all intermediate firms once produced. Due to non-rivalry, when the R&D firm produces the state-of-the-art technology $\dot{H}$, it sells the same blueprint to *each and all* of the intermediate firms. After paying for $\dot{H}$, an intermediate firm has the right to use that technology forever, but for the next period it has to pay another fee for the right to use newly generated technology. In other words, in each period the firms pay for new technology $\dot{H}$, but use the whole of the existing stock of technology H to abate pollution.

5.1.3. Incentives and indivisible technology

It is worth discussing the incentives (or necessity) to use the abatement technology. First of all, we need to explain why intermediate firms must pay *all* of their profits to buy the abatement technology. In line with the literature on R&D-based endogenous growth including Romer (1990) and Jones (1995), the upstream R&D firms have the pricing power to determine the price of their blueprints. Specifically, the R&D firms unilaterally determine the price of their innovations, and the intermediate firms then determine whether or not to buy blueprints. Therefore, the R&D sector will charge a price that fully extracts the profits of the midstream firms.

We then turn to explain why the intermediate firms could not choose to use divisible technology. This specification can be justified by the following two economic rationales. The first rationale is that the government enforces the utilization of the latest abatement technology by, for example, imposing stricter pollution standards. This regulation forces the firms to leave the market if they stop using the latest abatement technology.[19] The second rationale is that we can assume that the technology generated in each instance has a property of indivisibility. This assumption rules out the possibility that the intermediate firm chooses to use a partition of $\dot{H}$. More specifically, for the intermediate firm, there are only two choices: to accept the price of the blueprint and use the indivisible technology, or to reject the price of the blueprint and stop using the abatement technology (and thus leave the market).[20] The indivisibility of the abatement technology stems from the fact that new technology and old existing technology are often highly correlated. If a firm does not buy all of the new technology in this period, it will be very costly for it to utilize (upgrade to) the newest technology in the next period. To simplify the analysis, we assume that this cost is too high to be considered. Hence, the firms actually confront an all-or-nothing decision regarding the use of the technology.

5.2. The distinction between pollution emissions and dirty inputs

In our model, as mentioned above, a fixed import price of polluting inputs (m) is the key to screening out the traditional negative policy effect on long-term growth in the literature. Hence, it is worthwhile discussing why we need to make a distinction between pollution emissions and dirty inputs, and to introduce m into our model. Theoretically, although numerous studies model pollution based on the concept of a "dirty input", there are several reasons for treating them differently.[21] First, pollution (i.e., dirty air, messy water or noise) is not directly used in the production process, while the dirty inputs (i.e., petroleum or chemicals) are. Second, abatement knowledge can hardly play any role in the pollution transformation process if we mix the two. Third, and most importantly, pollution harms human health but is not internalized by the private agents and thus needs to be priced by the government, while dirty inputs should be priced by the market, because they are production factors just like other clean inputs. Hence, we allow for τ_P and m to denote, respectively, the price of pollution and dirty inputs.

To be more specific, supposing that there is no polluting input price, from Eqs. (5)–(7) and $q=1$ (the zero-profit condition in the final good sector) we have

$$\pi_i = A(N)k_i^{\alpha} p_i^{\varepsilon(1-\alpha)} H^{1-\alpha} l_{yi}^{\beta} - rk_i - \omega\, l_{yi} - \tau_P p_i. \tag{38}$$

One implication stemming from Eq. (38) is that, in the absence of any policy interference ($\tau_P=0$), the cost of pollution becomes zero so that the intermediate firms will use an infinitely large level of pollution. As a result, the environmental quality declines to the bottom and the economy cannot survive even temporarily. To this end, we introduce such a "non-policy" cost of polluting inputs to restrict the pollution to within a finite level even in the absence of an environmental tax. To be concerned with practicality, since firms usually import petroleum from abroad at a price that they cannot bargain for, we believe that the assumption of a given price of polluting inputs is not very far from the real world.

5.3. An alternative pollution setting

There are some studies introducing a private cost of pollution in order to prevent pollution from growing to infinity in the absence of policy intervention; see, e.g., Jouvet et al. (2005) and Ono (2007). The main departure between these studies and our paper is that they do not make a distinction between pollution emissions and dirty inputs. Therefore, raising the environmental tax leads to a negative impact on growth. In this subsection, we examine the effects of the environmental tax under such an alternative setting of pollution.

To simplify the analysis and highlight the negative growth effect, we temporarily remove the role of abatement technology. By denoting z as the private cost of pollution, the profit function of an intermediate firm can now be

[19] It would be interesting to further examine the effect of this kind of regulation on macroeconomic performance. However, due to the space constraint, we would like to leave this to a future study. For an analysis on the implementation of the optimal path in a growing economy with pollution permits, see, for example, Grimaud (1999).

[20] Once a firm stops using abatement technology, as time goes on, the burden of the environmental tax will become infinitely large, thereby leading the intermediate firms to have a negative profit and forcing them to leave the market.

[21] Some studies (e.g., Ligthart and van der Ploeg, 1994; Smulders and Gradus, 1996; and Bréchet and Michel, 2007), on the other hand, treat pollution as a by-product of capital or final output. However, under such a situation, since an environmental tax levied on pollution is equivalent to that levied on physical capital or output, it might be difficult to tell whether economic growth is affected by an environmental tax or by a similar capital (output) tax.

Table 3a
An alternative pollution setting ($b=0.04$, $\gamma=0.77$).

Environmental tax	Pollution	Growth rate (%)	Welfare
$\tau=15$	0.000341	3.547	−2.7910
$\tau=20$	0.000319	3.527	−2.9048
$\tau=25$	0.000299	3.508	−3.0135
$\tau=30$	0.000282	3.490	−3.1175
$\tau=35$	0.000267	3.472	−3.2173
$\tau=40$	0.000253	3.456	−3.3131
$\tau=45$	0.000240	3.440	−3.4052
$\tau=50$	0.000229	3.425	−3.4939
$\tau=55$	0.000218	3.411	−3.5794
$\tau=60$	0.000209	3.397	−3.6619

Table 3b
An alternative pollution setting ($b=0.004$, $\gamma=0.99$).

Environmental tax	Pollution	Growth rate (%)	Welfare
$\tau=15$	0.000313	2.978	−7.8225
$\tau=20$	0.000294	2.997	−7.5862
$\tau=25$	0.000278	3.012	−7.3901
$\tau=30$	0.000263	3.024	−7.2265
$\tau=35$	0.000249	3.034	−7.0893
$\tau=40$	0.000237	3.041	−6.9739
$\tau=45$	0.000226	3.048	−6.8765
$\tau=50$	0.000216	3.052	−6.7943
$\tau=55$	0.000207	3.056	−6.7248
$\tau=60$	0.000198	3.058	−6.6662

Table 4
The impact of a tariff.

Tariff	GA			PA			PAR		
	P	$g(\%)$	W	P	$g(\%)$	W	P	$g(\%)$	W
$\tau_f=0$	0.00420	3.116	−2.900	0.00358	1.427	−14.717	0.00429	3.554	−0.639
$\tau_f=0.01$	0.00417	3.108	−2.985	0.00355	1.413	−14.882	0.00425	3.536	−0.766
$\tau_f=0.02$	0.00414	3.099	−3.070	0.00353	1.400	−15.048	0.00422	3.518	−0.892
$\tau_f=0.03$	0.00411	3.091	−3.155	0.00351	1.386	−15.213	0.00419	3.500	−1.020
$\tau_f=0.04$	0.00408	3.082	−3.241	0.00349	1.372	−15.379	0.00415	3.482	−1.148
$\tau_f=0.05$	0.00405	3.074	−3.328	0.00346	1.359	−15.546	0.00412	3.463	−1.277

expressed as

$$\pi_i = q_i A(N,K) k_i^{\alpha} p_i^{\nu}\, l_{yi}^{\beta} - r k_i - \omega l_{yi} - (z+\tau_P) p_i. \tag{39}$$

Notice that in $A(N,K)$, it is assumed that, in line with the approach adopted in Ono (2007), the main force that drives economic growth is the capital externality.

With this specification, we then reexamine the growth and welfare effects of an environmental tax. The detailed process is provided in Appendix B. Table 3a depicts the numerical results in association with a sufficiently greater ecological regeneration and a sufficiently smaller environmental externality on production (i.e., $b=0.04$ and $\gamma=0.77$). As indicated in Table 3a, when τ is increased from 15 to 60, pollution directly declines in response (from 0.000341 to 0.000209), which generates two opposing growth effects. First, a better environmental quality is beneficial to input productivity, and thus tends to stimulate the growth rate. Second, fewer pollution inputs in the production function lower the marginal productivity of capital, which is harmful to the growth rate. Under our calibrated economy the latter effect outweighs the former, so that the growth rate declines from 3.55% to 3.40%. As for the welfare effect, the household's utility gains from a cleaner environment but suffers from a lower growth rate. Again, the latter effect exceeds the former, leading to a negative overall welfare effect of the environmental tax (from −2.7910 to −3.6619).

Nevertheless, if the environmental externality in production is very important, it is also possible that the beneficial effect of a better environment outweighs the harmful effect resulting from the decrease in the marginal productivity of capital. As exhibited in Table 3b, with a sufficiently small ecological regeneration and a sufficiently large environmental externality on production (i.e., $b=0.004$ and $\gamma=0.99$), the first effect may dominate the second effect and hence the environmental tax tends to boost the growth rate. This result reveals the fact that the environmental tax can still stimulate the growth rate under this alternative pollution setting.

5.4. The impact of a tariff

Our previous analysis focuses on the effects of the environmental tax that is levied on pollution emissions. Given our different treatments of pollution emissions and dirty inputs, it would be interesting to investigate the impact of a tariff which influences the prices of the polluting inputs. To this end, in this subsection we assume that the government implements a tariff rate τ_f on dirty inputs. Therefore, the profit function of the ith intermediate firm π_i stated in Eq. (6) is modified as

$$\pi_i = q_i y_i - rk_i - (1+\tau_f)me_i - \omega\, l_{yi} - \tau_P p_i, \tag{40}$$

Accordingly, the term $\tau_f me$ needs to be added to the government budget constraints under different regimes, i.e., Eqs., (19), (31) and (34), on the right-hand-side.

Table 4 reports the summary results of the changes in relevant variables in response to distinctive tariff rates on dirty inputs. It is found that, under all the three regimes, raising the tariff on dirty inputs tends to reduce the growth rate, the level of pollution, and the level of social welfare. Intuitively speaking, raising the tariff has several mixed effects. First, since the tariff rate is levied on e instead of p, it directly lowers the use of dirty inputs. On the one hand, this improves the environmental quality, while on the other hand it reduces the marginal productivity of capital and thus harms the growth rate. Second, an increase in the tariff boosts the tax revenues, which means that more resources are devoted to environmental R&D under GA and PAR, generating an additional beneficial effect on growth and welfare. Third, under PA and PAR, a higher tariff reduces the profits of intermediate firms, causing fewer resources to be directed towards environmental R&D. It is obvious that the net effect depends upon the extent of these three effects. However, with our parameter values, the negative growth-impeding effect always dominates under all three regimes. As a result, we find that a decline in the growth rate and welfare is coupled with a rise in environmental quality.

6. Concluding remarks

This paper develops an endogenous growth model featuring an environmental externality, abatement R&D, and market imperfections. The salient trait of the model is that it is able to deal with three distinct regimes including public abatement, private abatement without tax recycling, and private abatement with tax recycling. Some main findings are obtained from our numerical analysis. First, there exists a trade-off between economic growth and environmental quality in a "regime selection" sense. Second, the benefit arising from the private conduct of abatement becomes larger the greater the degree of the firms' monopoly power. This potentially implies that antitrust policies might in some way reduce growth and welfare in a private abatement R&D model. Third, if the government recycles the environmental tax revenues to subsidize private abatement R&D, the growth rate and welfare will be higher than in almost all other regimes. Fourth, the beneficial effects of public abatement policies will be eroded when government spending on transfer payments increases.

The effects of environmental tax policies are also investigated in this paper. We show that a rise in the environmental tax could possibly simultaneously reduce pollution and stimulate growth if the intermediate firms import polluting inputs from abroad at a fixed price. However, care should be taken regarding the implications because such a desirable result is in part due to the rigidity of the polluting input price. If the import price can be adjusted endogenously, the above result should be modified as well.

Although our model indicates that an environmental tax policy is beneficial to economic growth, we would like to mention that this result should be accepted with some caution. In fact, our main intention is not to emphasize the beneficial effect of an environmental tax on economic growth, but to highlight the importance of distinct pricing between pollution emissions and polluting inputs. Doing so will be helpful for us to clarify the two channels through which an environmental tax influences the long-term growth rate, i.e., the (negative) traditional productivity effect and the (positive) Bovenberg–Smulders environmental quality effect.

Some remaining extensions could be considered in future research. First, in this paper R&D firms can extract all of their buyers' profit via their unilateral determination of the license fee. It would be interesting to consider the case where the license fee for abatement knowledge is decided by a Nash-bargaining process between R&D firms and intermediate firms instead of by R&D firms only. Second, the price of polluting inputs is not internalized in this paper. It would be natural to extend our model by proposing a channel to endogenize the polluting input price. For instance, we could introduce an additional domestic energy sector, or assume a nonlinear adjustment cost of polluting inputs. These extensions inevitably complicate the model, but they deserve future study.

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Appendix A

This appendix provides a detailed derivation of Eqs. (33) and (35) in the main text. In the PA regime, by substituting the intermediate firm's first-order conditions reported in Eqs. (10)–(12) into the profit function, we obtain

$$\pi = [1-(1-\theta)(\alpha+\beta)-(1-\theta)(1-\alpha)\varepsilon]Y-(1-\varepsilon)mHP^{\varepsilon}. \tag{A.1}$$

Based on $g=\dot{H}/H$ and Eq. (30), we have $\dot{H}/H=\pi/q_H H$. Then, putting Eqs. (12), (17), and (20) and $\dot{H}/H=\pi/q_H H$ together, we can derive

$$g=\frac{\dot{H}}{H}=\frac{\delta\pi}{\omega}. \tag{A.2}$$

Substituting Eqs. (A.1) into (A.2) yields

$$g=\frac{\delta[1-(1-\theta)(\alpha+\beta)-(1-\theta)(1-\alpha)\varepsilon]}{(1-\theta)\beta}L_y-\frac{\delta(1-\varepsilon)mHP^{\varepsilon}}{\omega}. \tag{A.3}$$

By substituting the relevant variables along the balanced growth equilibrium into Eq. (A3) and being reminded that $h=H/K$ and $w=\omega/K$, we can obtain Eq. (33) from the main text.

In the PAR regime, from Eqs. (17) and (30) and the zero-profit condition we have $g=\delta\pi/(1-s)\omega$. Similar to the derivation of Eq. (33) in the PA regime, we can obtain Eq. (35) in the main text.

Appendix B

This appendix deals with the growth and welfare effects of an environmental tax under the alternative pollution setting proposed by Jouvet et al. (2005) and Ono (2007). Given the profit function reported in Eq. (39), the intermediate firm's first-order conditions with $q_i=1$ and the symmetric conditions are given by the following equation:

$$(1-\theta)\alpha A(N,K)K^{\alpha-1}P^{\nu}L_y^{\beta}=r, \tag{B.1}$$

$$(1-\theta)\nu A(N,K)K^{\alpha}P^{\nu-1}L_y^{\beta}=z+\tau_P, \tag{B.2}$$

$$(1-\theta)\beta A(N,K)K^{\alpha}P^{\nu}L_y^{\beta-1}=\omega. \tag{B.3}$$

To ensure sustainable growth, we must assume that, in addition to the environmental externality, the productivity function $A(\cdot)$ also contains the capital externality (as in Ono, 2007). Specifically, $A(\cdot)$ is specified to be of the form

$$A(N,K)=XN^{\gamma}K^{1-\alpha}, \tag{B.4}$$

where X is a productivity parameter. Moreover, it is required that the private cost of pollution z evolve with capital, i.e., $z=\bar{z}K$ where $\bar{z}$ is a constant. The tax revenues are all returned to the households and thus the resource constraint can be easily derived as $\dot{K}=Y-C$.

Under such a situation, Eqs. (22) and (26) should be modified as

$$g^*=\frac{1}{\sigma}\left[(1-\tau_K)(1-\theta)\alpha XN^{\gamma}P^{*\nu}L_y^{*\beta}-\rho\right], \tag{B.5}$$

$$c^*=XN^{\gamma}P^{*\nu}L_y^{*\beta}-g^*. \tag{B.6}$$

It should be noted that, given the fact that we remove the abatement technology sector, all the endowed labor supply $\bar{L}$ is devoted to the intermediate good, implying that $\bar{L}=L_y$ is true. The macroeconomy along the BGP can then be described by $\bar{L}=L_y$, Eqs. (B.1)–(B.3), (B.5), (B.6) and (27), which determine seven unknowns: c^*, P^*, N^*, L_y^*, w^*, r^* and g^*. As for the parameter values, we set $z_0=60$, $\bar{L}=1$, $X=0.772$, $\nu=0.05$ (see Agnani et al., 2005) such that the balanced growth rate is 3.5%. Furthermore, the monopoly power index is adjusted to $\theta=0.005$ to match the profit ratio 4%. In Table 3a, the parameters regarding the environment are set the same as in Section 4 as $(b,\gamma)=(0.04,0.77)$. In Table 3b, however, to highlight the importance of ecological regeneration and the environmental externality in production, we adjust the two parameters as $(b,\gamma)=(0.004,0.99)$. All other parameter values not mentioned above are the same as those used in Section 4. With these parameter values, Tables 3a and 3b show how the calibrated values of macroeconomic variables will react in association with the environmental tax τ under different extents of ecological regeneration and the environmental externality.

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