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Does Environmental Policy Necessarily Discourage Growth?

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This paper analyzes the long-run impact of an environmental policy on economic growth. A growth model with vertical innovation is modified by including intermediate goods as a source of pollution. Taxation on pollution reduces profits of intermediate firms as well as final outputs. However, it increases their mark-ups and alleviates profit losses. In this setting, profit losses are offset by the general equilibrium effect; thus, the tax enhances R&Ds which drive economic growth while it reduces pollution. If the government provides an R&D subsidy, the growth rate will be accelerated.

Keywords: endogenous growth, environmental policy, monopolistic competition.

JEL classification: D43, O41, Q21.

1 Introduction

This paper investigates the long-run impact of an environmental policy on economic growth and examines whether such a policy can influence economic growth negatively or positively. A model of growth through creative destruction (Aghion and Howitt, 1992) is modified by including intermediate goods as a source of pollution. In this framework, the overall impact of environmental taxation on economic growth will be positive. Furthermore, if the government provides an R&D subsidy, growth will be enhanced.

Traditionally, a conflict between economic growth and environmental conservation has often been postulated. In the neoclassical framework of optimal growth, Forster (1973) states that capital stock is lower with environmental conservation than without it. Thus, the economy consumes less than it would were pollution to be ignored.[1] In empirical analyses, environmental regulations have frequently been regarded as one of the main sources of productivity slowdown (Christainsen and Haveman, 1981; Gollop and Roberts, 1983).

However, there have been considerable debates on this issue from both empirical and theoretical points of view. The "Porter Hypothesis" claims that an environmental policy encourages innovations and that the long-term benefits of innovation could overtake the short-run losses in the economy, a scenario which they call "innovation offsets" (Porter and van der Linde, 1995). Porter and van der Linde use environmental regulations in Japan[2] and Germany as examples. Hamamoto (1998) analyzes how Japanese industries have overcome environmental constraints and improved total factor productivity. He shows that, although environmental policies for pollution reduction decreased the final output in the short run, they encouraged various R&D activities for relevant technologies. These activities ultimately improved the overall productivity of the economy.

From a theoretical point of view, stimulated by the new growth theory (Romer, 1986; Grossman and Helpman, 1991; Aghion and Howitt, 1992), substantial effort has been made to examine how far an environmental policy can affect R&D activities and whether the overall impact of the policy on economic growth is negative or positive. By using an overlapping generations model, Ono (2002) shows that environmental taxation positively affects economic growth below and above certain critical levels. In models of endogenous growth dealing with environmental quality as a factor of production, such as Bovenberg and Smulders (1995), the implementation of a green tax improves the quality of the environment, which directly increases the total factor productivity of the economy. In their models, the positive impact of environmental quality on economic growth may implicitly depend on the existence of Marshallian externalities in a reduced form. Verdier (1995), Elbasha and Roe (1996), and Grimaud (1999) try to explain the microfoundation behind such a framework, applying a growth model with expanding product variety (Romer, 1990; Grossman and Helpman, 1991). Based on the quality-upgrading model of Aghion and Howitt (1992), Ricci (2000) analyzes the

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1 In this framework, due to diminishing returns to scale, the economy converges to a steady state with zero growth even without environmental conservation. See studies such as Gruver (1976), and Asako (1980) in a similar context.

2 Those who are interested in the experience in Japan should see Ueta (1993).

possibility of "green crowding-out" effect, in which environmental taxation crowds out old and dirty intermediates. He provides the positive impact of an environmental policy on economic growth under the condition that the newly invented technologies are cleaner than the old ones.

We propose a simpler model to examine whether environmental policy influences economic growth positively without "green crowding-out". Our model applies the growth model of Aghion and Howitt (1992) because, in their model, the more productive production factor earns the greater profits, which are the payoffs to R&D investment. We have a competitive final sector, and its emissions depend on the level of intermediate inputs which are provided by monopolistic suppliers, whose profits are spent on R&D activities.

Whether the tax affects growth negatively or positively depends on two effects.[3] The first one is called the "profitability effect", i.e., the loss or gain in the profits of the intermediate sector, which are the payoffs from innovative activities. The other one is the "general equilibrium effect" which is associated with a resource constraint on R&D activities. As to the profitability effect, a tax on pollution generally reduces the profits of intermediate firms because it decreases the demand for intermediate goods as well as the level of final outputs. In our model, however, taxation alleviates the losses in intermediate profits because it decreases the price elasticity in the intermediate market and increases its mark-ups. With regard to the general equilibrium effect, taxation and the subsequent reduction in intermediate outputs moderate the resource constraint on R&D activities; hence, it encourages R&Ds. Overall, the tax drives R&Ds, which drive economic growth, as well as reduce the level of pollution, because the profit loss is offset by the general equilibrium effect. Moreover, if the government subsidizes R&D expenditure, the growth rate will be enhanced.

A related paper, Fisher and van Marrewijk (1998), generates a similar result in a different context. They study an overlapping generations model in which rents generated by the scarce environment distort the market of final products. An optimal pollution tax efficiently allocates the scarce environment; hence, the tax increases final outputs and boosts growth. In our model, we apply a model of growth with vertical innovation where taxation encourages growth because the profit loss is

3 We thank an anonymous referee for this comment.

offset by the general equilibrium effect, while the tax reduces final outputs as well as pollution.

In the following sections, we first construct a general model with a continuum of intermediate goods. Second, we reduce the model to a single intermediate good in order to demonstrate the mechanism more clearly. Third, we return to the general case. After examining the impact of taxation on welfare, we will offer a tentative conclusion.

2 The Model

A decentralized economy has a competitive final sector that makes use of a continuum of intermediate goods. Intermediate goods are provided by monopolistic suppliers, employing labor as a single production factor. Each monopolistic firm is assumed to purchase a patent from a research firm and obtain a technology to supply its intermediate good. Consumption is determined by an infinitely lived representative household, maximizing an intertemporal logarithmic utility function derived from consumption, and negative utility derived from pollution. The labor is provided by the consumer and its market is perfectly competitive. Pollution is assumed to have a direct impact on welfare, but not on the level of output.

2.1 The Final Sector

The final producer provides an output by employing labor and a continuum of intermediate inputs, given by the following Cobb-Douglas production function:[4]

$$Y_t = \int_0^1 A_{jt} x_{jt}^{\alpha} \, dj,$$

where A_{jt} is a productivity parameter, x_{jt} denotes an intermediate input and $\alpha \in (0,1)$. We assume that intermediate goods are essential for production, i.e., $x_{jt} > 0$. There is no population growth in this economy.

4 The production function does not include labor as an input. However, the original version of this paper with labor as an input produces the same result as this analysis, which is available upon request.

As for the pollution function, the aggregated level of pollution P_t depends on the level of intermediate inputs x_{it} and an environmental technology index $z_j \in [0, 1]$.[5] The index describes the ratio of emission to intermediate input $j \in [0, 1]$, where higher values for z_j produce more pollution per unit of intermediate input. Although the index should depend on the time period, we assume it to be exogenously given following Stokey (1998), and Aghion and Howitt (1998). Although there is a possibility that the relationship between pollution and factor input could become nonlinear, the pollution function is represented by

$$P_t = \int_0^1 z_j x_{jt} \, dj, \tag{1}$$

for the simplicity of the analysis.

Let us consider an economy in which the government is to levy an environmental tax on polluters in order to offer an incentive to reduce such pollution. In turn, the government employs its revenues to give a lump-sum transfer to the consumer or to provide a subsidy to the R&D sector. We assume that the environmental tax is levied proportionally to the level of pollution from the final production sector, which depends on the pollution intensity, and on its intermediate input.

The profit function of the final production sector in the presence of environmental taxation is given by

$$\Pi_t = \int_0^1 A_{jt} x_{jt}^{\alpha} \, dj - \int_0^1 p_{jt} x_{jt} \, dj - h_t \int_0^1 z_j x_{jt} \, dj,$$

where the final good is chosen as the numeraire, p_t denotes the price of an intermediate input, and $h_t \in (0, 1)$ is the tax rate, assuming $p_t > h_t$. Because the final market is competitive, the zero-profit condition provides the factor demand function of the final sector:

$$p_{jt} = \alpha A_{jt} x_{jt}^{\alpha - 1} - h_t z_j. \tag{2}$$

5 We do not analyze consumption externalities in this model. Those who are interested in consumption externalities should consult papers such as Ono (1998).

2.2 The Intermediate Sector

The intermediate sector is monopolistically competitive. Several firms, faced with their demands (2), provide intermediates to the final production sector and compete with each other, whereby the number of firms is assumed to be constant. However, each firm has its own monopolistic market. The only input to intermediate production is labor. For each monopolistic firm j to produce one unit of output x_{jt}, one unit of labor is required. Thus, the problem of the intermediate firm is given by the following equation:

$$\pi_{jt} = \alpha A_{jt} x_{jt}^{\alpha} - h_t z_j x_{jt} - w_t x_{jt}. \tag{3}$$

Equation (3) can be slightly modified as

$$\pi_{jt} = \alpha A_{jt} x_{jt}^{\alpha} - \left(1 + \frac{h_t z_j}{w_t}\right) w_t x_{jt}. \tag{4}$$

Here, we assume that the government controls the environmental tax by using the indicator ψ, which denotes the emission tax in labor units, i.e., $\psi = \frac{h_t z_j}{w_t}$. The wage rate is proportional to the level of output; thus, the government changes its tax rate in proportion to GDP. We follow the method in Verdier (1995) mainly for the simplicity of the analysis because a general taxation method would complicate the analysis.[6] Those who are interested in such a general method should consult Ricci's (2000) careful and elaborate analysis. Equation (4) can be rewritten as

$$\pi_{jt} = \alpha A_{jt} x_{jt}^{\alpha} - (1 + \psi) w_t x_{jt}. \tag{5}$$

The first-order condition of the profit-maximizing monopolistic firm j gives the labor demand function below:

$$x_{jt} = \left[\frac{\alpha^2}{(1 + \psi) w_t / A_{jt}}\right]^{\frac{1}{1-\alpha}} = \tilde{x}(w_t / A_{jt}), \tag{6}$$

where $\tilde{x}(w_t / A_{jt})$ denotes the productivity adjusted labor demand of firm j with taxation. Substituting (6) into (5) provides the profit of each monopolistic firm:

6 The application of an ad valorem tax would circumvent the necessity of this redefinition. From the viewpoint of environmental economics, however, a tax on pollution is levied per unit of emission in general.

$$\pi_{jt} = \frac{1-\alpha}{\alpha} w_t (1+\psi) \tilde{x}(w_t/A_{jt}). \tag{7}$$

2.3 Research and Technology Spillover

We assume that research firms freely carry out R&D activities. Although a single research firm can obtain a patent for a particular technology, all technological findings in the R&D sector flow into the same pool of knowledge. Applying the method of Aghion and Howitt (1998), this state of knowledge at time t is represented as the leading-edge technology A_t^{max}. Though the innovation follows a Poisson process, this index is assumed to grow gradually at a rate proportional to the aggregate flow of innovations:

$$\dot{A}_t^{max}/A_t^{max} = \lambda n_{At} \ln \gamma, \quad \gamma > 1, \tag{8}$$

where λ is the productivity in the R&D sector, γ is the size of new innovation and $n_{At}(= 1 - n_{xt})$ is the number of researchers in an R&D sector. The payoffs of all the innovators with the leading-edge technology can be rewritten as

$$\pi_t = A_t^{max} \frac{1-\alpha}{\alpha} \omega_t (1+\psi) \tilde{x}(\omega_t) = A_t^{max} \tilde{\pi}(\omega_t), \tag{9}$$

where $\omega_t \equiv w_t/A_t^{max}$ is the productivity adjusted wage rate, $\tilde{x}(\omega_t)$ is the productivity adjusted total intermediate supply and $\tilde{\pi}(\omega_t)$ is the productivity adjusted level of profit.

In Aghion and Howitt's model with monopolistic competition, the equilibrium is asymmetric since not every monopolistic firm has the leading-edge technology; hence, productivity parameters vary across the sectors. Following Aghion and Howitt (1998), we assume that the long-run sectoral distribution of the relative productivity parameters $a_{jt} = \frac{A_{jt}}{A_t^{max}}$ is given by the cumulative distribution function $H(a) = a^{\frac{1}{\ln \gamma}}$, where $a \in [0, 1]$. Then, the labor demand function of the intermediate sector can be rearranged by the relative productivity, a:

$$\begin{aligned} x_{jt} &= \left[\frac{\alpha^2 A_{jt}/A_t^{max}}{(1+\psi) w_t/A_t^{max}}\right]^{\frac{1}{1-\alpha}} = \left[\frac{\alpha^2}{(1+\psi)\omega_t/a}\right]^{\frac{1}{1-\alpha}} \\ &= \tilde{x}(\omega_t/a). \end{aligned} \tag{10}$$

As we can see in Appendix 1, the labor demand in the intermediate sector is $n_{xt} = \tilde{x}(\omega_t)\frac{1}{\Gamma}$ where $\Gamma = 1 + \frac{\ln \gamma}{1-\alpha} > 1$. Thus, the labor market clearing condition is given as the following equation:

$$\tilde{x}(\omega_t) = \Gamma(1 - n_{At}). \tag{11}$$

This equation indicates that the level of intermediate input is a function of the level of research activities, where the increase in research activities reduces the level of intermediate input.

2.4 The Consumer and the Government

The representative consumer maximizes the present value stream of following utilities, i.e.,

$$\max \int_0^\infty e^{-\rho t}(\ln Y_t - \ln P_t)dt,$$

where $\rho > 0$, subject to her budget constraint. As usual, the optimal condition is given by

$$g \equiv \dot{Y}_t / Y_t = r_t - \rho, \tag{12}$$

and the transversality condition.

The government regulates the quality of the environment and subsidizes the $s \in [0, 1)$ rate of marginal cost of R&D activities for accelerating the technological change. Thus, the government should have corresponding tax revenue for that purpose. The productivity-adjusted budget constraint is assumed to be balanced within the time period:

$$\begin{aligned}\int_0^\infty s\omega_\tau n_{A\tau} e^{-\int_0^\tau r_u du} d\tau &= \int_0^\infty \psi \omega_\tau \tilde{x}_\tau(\omega_\tau)\frac{1}{\Gamma} e^{-\int_0^\tau r_u du} d\tau \\ &= \int_0^\infty h_\tau z \tilde{x}_\tau(\omega_\tau)\frac{1}{\Gamma} e^{-\int_0^\tau r_u du} d\tau, \end{aligned} \tag{13}$$

with the respective transversality condition.

3 A Simple Case: A Single Intermediate Good

We now present a simple model with a single intermediate good to demonstrate the mechanism more clearly.[7]

The problem of the representative consumer is exactly the same as in the general model. However, for the simplicity of the analysis, the government spends its revenues not in order to provide an R&D subsidy but to give a lump-sum transfer to the consumer. The final producer provides an output by employing a single intermediate input, given by the Cobb-Douglas production function, $y_t = A_t F(x_t) = A_t x_t^\alpha$. The pollution function is represented by the equation, $P_t = zx_t$. The consumer's problem in this case is to maximize, $\int_0^\infty e^{-\rho t}(\ln y_t - \ln P_t)dt$, which provides the same condition as (12), $g \equiv \dot{y}_t/y_t = r_t - \rho$. The profit function of the final production sector is given by the equation, $\Pi_t = A_t x_t^\alpha - p_t x_t - h_t z x_t$. The zero-profit condition provides the factor demand function of the final sector:

$$p_t = \alpha A_t x_t^{\alpha-1} - h_t z. \tag{14}$$

The intermediate monopolist, faced with the factor demand (14), provides an intermediate good to the final production sector. As in the general model, the problem of the monopolist is given by the following equation:

$$\pi_t = \alpha A_t x_t^\alpha - h_t z x_t - w_t x_t. \tag{15}$$

Let η denote the price elasticity of demand under taxation, that is, $\eta = \left(\frac{\partial x_t}{\partial p_t}\right)\frac{p_t}{x_t}$. Compared to the elasticity with no taxation, i.e., $h_t = 0$, the following proposition is obtained.

Proposition 1: The intermediate demand is less elastic with respect to its price if there is environmental taxation than otherwise.

Proof:

$$\eta = \left|\frac{F_x - h_t z}{(\alpha - 1)F_x}\right| < \left|\frac{1}{\alpha - 1}\right|,$$

where $F_x (> h_t z)$ is the marginal productivity of an intermediate good. Thus, the rate of mark-up is larger with taxation than without it. The proposition indicates that, if α is smaller, then the elasticity with an

7 The author is deeply indebted to a referee for the argument in this section.

environmental tax is much less elastic than the one with no tax. In other words, the more monopolistic the intermediate market is, the greater the difference between mark-ups. On the contrary, the less monopolistic the intermediate market is, the less significant will be the impact of the tax on the price elasticity. Equation (15) is modified as

$$\pi_t = \alpha A_t x_t^{\alpha} - (1+\psi) w_t x_t, \tag{16}$$

where $\psi = \frac{h_t z}{w_t}$. The first-order condition provides the intermediate labor demand

$$x_t = \left[\frac{\alpha^2}{(1+\psi)w_t/A_t}\right]^{\frac{1}{1-\alpha}} = \tilde{x}(w_t/A_t). \tag{17}$$

For the labor market to be cleared, the condition

$$\tilde{x}(\omega) = 1 - n_{A_t}, \tag{18}$$

should be satisfied.

Assume that the intermediate monopolist has leading-edge technology A_t^{max}. Substituting (17) into (16) gives the profits of the monopolist as follows:

$$\pi_t = A_t^{max} \frac{1-\alpha}{\alpha} \omega_t (1+\psi) \tilde{x}(\omega_t) = A_t^{max} \tilde{\pi}(\omega_t). \tag{19}$$

The research sector is assumed to generate the same growth rate in the leading-edge technology as (8). The flow of monopoly profits is discounted by the rate of return and the arrival rate of innovation, considering the replacement effect of incumbent monopolistic rent (Tirole, 1988; Aghion and Howitt, 1992). The discounted expected value of an innovation is given as: $V_t = \int_t^{\infty} e^{-\int_t^{\tau} r_u du} e^{-\int_t^{\tau} \lambda n_u du} \pi_\tau d\tau$.

3.1 The Balanced Growth Path Analysis in the Simple Case

We now focus on balanced growth, where the rate of interest and the level of research are constant, $r_t \equiv r$ and $n_{At} \equiv n_A$.[8] Since no population

8 This paper does not analyze the impact of taxation on the transitional dynamics. On this topic, see Futagami, Morita and Shibata (1993).

growth is assumed in this analysis, the growth rate of aggregate output is equal to the rate of growth in the leading-edge parameter, $g = g_A$. Thus, the productivity adjusted wage rate is also constant, $\omega_t \equiv \omega$. The free-entry condition of the R&D sector is given as $w = \lambda V$, where $V = \frac{\pi}{r+\lambda n_A}$. From the free-entry condition, we can obtain the following R&D arbitrage condition:

$$1 = \frac{\lambda \frac{1-\alpha}{\alpha}(1+\psi)\tilde{x}}{r + \lambda n_A}. \tag{20}$$

Thus, substituting (17) into (20), we rewrite the arbitrage condition as

$$\omega = \left[\frac{\lambda(1-\alpha)}{r+\lambda n_A}\right]^{1-\alpha} \frac{\alpha^{1+\alpha}}{(1+\psi)^{\alpha}}, \tag{21}$$

which should be satisfied along the balanced growth path. Substituting (17) into (18) provides the labor market clearing condition:

$$\omega = \frac{\alpha^2}{(1+\psi)(1-n_A)^{1-\alpha}}. \tag{22}$$

Now we characterize the balanced growth path. As it is derived in Appendix 2, we obtain the following equilibrium in the simple case:

$$r_h = \frac{\lambda\Psi \ln\gamma + (\Psi+\alpha)\rho}{\alpha(1+\ln\gamma)+\Psi}, \tag{23}$$

$$n_{A_h} = \frac{\lambda\Psi - \alpha\rho}{\lambda[\alpha(1+\ln\gamma)+\Psi]}, \tag{24}$$

$$\tilde{x}_h = \frac{\alpha[\lambda(1+\ln\gamma)+\rho]}{\lambda[\alpha(1+\ln\gamma)+\Psi]}, \tag{25}$$

where $\Psi = (1-\alpha)(1+\psi)$. Because we focus on the balanced growth path, every variable grows constantly, which implies $\lambda\psi - \alpha\rho > 0$. This condition ensures that a unique stationary equilibrium exists. As we can see in Appendix 2, the impacts of taxation on growth and the intermediate input are $\frac{dn_{A_h}}{d\psi} > 0$, $\frac{d\tilde{x}_h}{d\psi} < 0$, respectively. The equilibrium and the impact of taxation on growth are illustrated in Fig. 1.

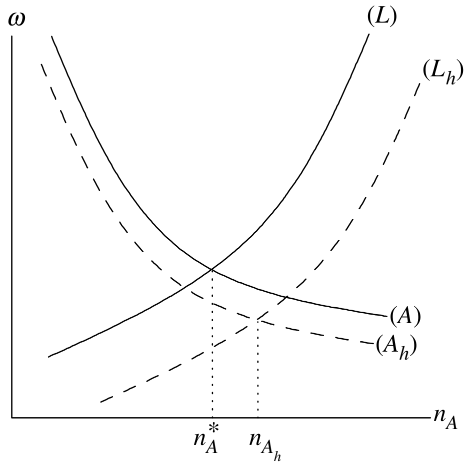

Fig. 1. The equilibrium and taxation in the simple case

Figure 1 shows the mechanism of how environmental taxation affects growth. The R&D arbitrage condition (21) is downward sloping, and denoted as (A), and the labor market clearing condition (22) is upward sloping, designated as (L). A tax on pollution reduces the intermediate profits in general, because it decreases not only final outputs but also intermediate demand. Thus, environmental taxation shifts the (A) curve downwards, which is called the "profitability" effect. However, in our model, taxation moderates the loss in intermediate profits due to an increase in its price elasticity of demand. As it is explained in Proposition 1, the more monopolistic the intermediate market is, the larger this positive effect. On the other hand, taxation shifts (L) downwards because it reduces final outputs; subsequently, it decreases intermediate supplies which alleviate the resource constraint on R&D activities. Overall, the profit losses are offset by the general equilibrium effect; consequently, the tax encourages R&Ds which drive economic growth. The next figure shows the relationship between the level of pollution and growth.

In Fig. 2, the R&D arbitrage condition (20) is designated as (A') which is upward sloping and the labor market clearing condition (18) is (L'), which is downward sloping. While (L') does not change with taxation, a tax on pollution turns (A') counterclockwise, since the general equilibrium effect exceeds the profitability effect. Hence, environmental taxation drives growth and reduces the level of intermediate use. Because the level

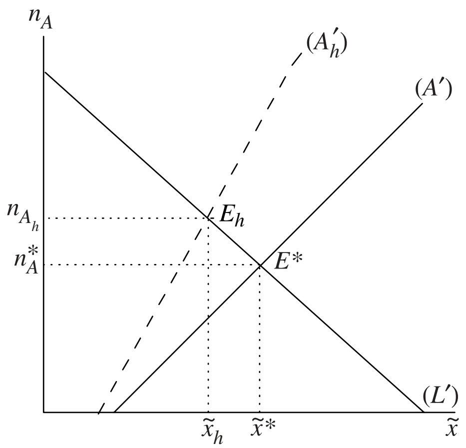

Fig. 2. Pollution and growth in the simple case

of pollution is proportional to intermediate inputs, the tax also decreases the level of pollution.

4 A General Case: A Continuum of Intermediate Goods

We have discussed the impact of taxation on growth in the simplified model with a single intermediate good. Now we return to the general model and examine whether the result obtained in the simple case holds even if the model is generalized to include a continuum of intermediate goods. In addition, we investigate the impact of an R&D subsidy on growth.

4.1 The Balanced Growth Path Analysis in the General Case

Following Aghion and Howitt (1998), consider a research firm which innovates at date t. The productivity parameter A_t^{max} will not change until it is substituted for the next innovation. If the firm is not replaced at some future period $t+\tau$, its flow of profit (9) can be rewritten as $A_t^{max}\tilde{\pi}(\omega e^{g\tau})$. The probability that the firm will not yet be replaced is $e^{-\lambda n_A \tau}$. The expected present value of all the profits from time t until infinity is given as

$$V_t = A_t^{max} \int_0^{\infty} e^{-(r+\lambda n_A)\tau} \tilde{\pi}(\omega e^{g\tau}) d\tau.$$

Because the marginal cost of R&D becomes $(1-s)w_t$ for $s \in [0, 1)$, the free-entry condition is given by $(1-s)w_t = \lambda V_t$. As it is derived in Appendix 3, we obtain the R&D arbitrage condition with and without the R&D subsidy under environmental taxation:

$$1 = \frac{\lambda \frac{1-\alpha}{\alpha}(1+\psi)\tilde{x}(\omega)}{(1-s)(r+\lambda n_A \Lambda)}, \quad \text{for } s \in [0, 1), \tag{26}$$

where $\Lambda = 1 + \frac{\alpha}{1-\alpha} \ln \gamma > 1$. Substitute (17) into (26) and we rewrite the arbitrage condition as follows:

$$\omega = \left[\frac{\lambda(1-\alpha)}{(1-s)(r+\lambda n_A \Lambda)}\right]^{1-\alpha} \frac{\alpha^{1+\alpha}}{(1+\psi)^{\alpha}}. \tag{27}$$

Substituting (10) into (11) provides the following labor market clearing condition:

$$\omega = \frac{\alpha^2}{(1+\psi)[\Gamma(1-n_A)]^{1-\alpha}}. \tag{28}$$

The government's budget should be balanced along this path. From (13), we obtain

$$sn_A = \psi \tilde{x}(\omega) \frac{1}{\Gamma}, \tag{29}$$

which provides the following lemma.

Lemma 1: For the subsidy rate to be constant, the environmental tax should increase following the condition:

$$g_h = g.$$

Proof: The government determines the tax rate to maintain a constant subsidy rate. For s to be constant along the balanced growth path, $\psi = \frac{h_t z}{w_t}$ should be constant; therefore, $g_w = g = g_h$ should be satisfied.

Lemma 1 describes the policy rule for the government in order to determine the rate of increase in environmental taxation over time. Next, we characterize the balanced growth path.

4.2 The Equilibrium with Taxation but no Subsidy

As derived in Appendix 4, we determine the equilibrium under taxation as

$$r_H = \frac{\lambda\Psi\Gamma \ln\gamma + (\Psi\Gamma + \alpha\Lambda)\rho}{\alpha(\Lambda + \ln\gamma) + \Psi\Gamma}, \tag{30}$$

$$n_{A_H} = \frac{\lambda\Psi\Gamma - \alpha\rho}{\lambda[\alpha(\Lambda + \ln\gamma) + \Psi\Gamma]}, \tag{31}$$

$$\tilde{x}_H = \frac{\alpha[\lambda(\Lambda + \ln\gamma) + \rho]}{\lambda[\alpha(\Lambda + \ln\gamma) + \Psi\Gamma]}, \tag{32}$$

where $\Psi = (1 - \alpha)(1 + \psi) > 0$. By using the results above, we can derive the following proposition.

Proposition 2: In the case where the revenue from an environmental tax is not used for an R&D subsidy but instead for a lump-sum transfer to the consumer, the increase in its rate raises the equilibrium level of growth, as well as reduces the level of pollution.

Proof: As described in Appendix 5, $dn_{A_H}/d\psi > 0$, $d\tilde{x}_H/d\psi < 0$, $\forall\psi > 0$. From (1), pollution is proportional to the level of intermediate inputs. Then, we obtain $g^{**} < g_H$ and $P_H < P^{**}$ because $\tilde{x}_H < \tilde{x}^{**}$.[9]

Proposition 2 shows that environmental taxation enhances growth and improves the quality of the environment along the balanced growth path. Thus, the result of the simple case can be generalized to the case with a continuum of intermediate goods.

4.3 The Equilibrium with Both Taxation and Subsidy

Similarly, we obtain the equilibrium with a subsidy, i.e., $s \in (0, 1)$, also derived in Appendix 4:

9 ** indicates the equilibrium without taxation in the general case.

$$r_S = \frac{\lambda\Psi\Gamma \ln\gamma + [\Psi\Gamma + \alpha\Lambda(1-s)]\rho}{\alpha(\Lambda + \ln\gamma)(1-s) + \Psi\Gamma}, \tag{33}$$

$$n_{A_S} = \frac{\lambda\Psi\Gamma - \alpha(1-s)\rho}{\lambda[\alpha(\Lambda + \ln\gamma)(1-s) + \Psi\Gamma]}, \tag{34}$$

$$\tilde{x}_S = \frac{\alpha[\lambda(\Lambda + \ln\gamma) + \rho](1-s)}{\lambda[\alpha(\Lambda + \ln\gamma)(1-s) + \Psi\Gamma]}. \tag{35}$$

The equilibrium provides the proposition below.

Proposition 3 Suppose that both the initial rate of an environmental tax and the rate of an R&D subsidy are equal to zero. The marginal increase in the tax rate accompanied by the corresponding increase in the subsidy rate increases the growth rate and reduces the level of pollution to a greater extent than in the case of the lump-sum transfer.

Proof: Appendix 5 shows us $dn_{A_S}/ds > 0$ and $d\tilde{x}_S/ds < 0$. Therefore, we obtain $g^{**} < g_H < g_S$ and $P_S < P_H < P^{**}$.

Proposition 3 shows that, provided that the initial tax rate is zero, a small increase in taxation with an R&D subsidy has a greater positive impact on both growth and the environment than without it.

Figure 3 demonstrates that the results in the simple case can be generalized in a multisector context and how the R&D subsidy affects

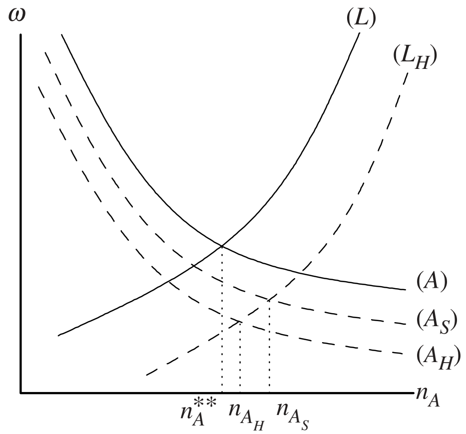

Fig. 3. The equilibrium and taxation in the general case

growth. As it was mentioned in the simple case, a tax shifts the (A) curve, which represents the arbitrage condition (27), downwards due to the "profitability" effect. Taxation shifts (L), the labor market clearing condition (28), downwards because of the general equilibrium effect. Because the profit loss is offset by the general equilibrium effect, environmental taxation, on the whole, boosts R&Ds and growth. Next, what happens if the government provides an R&D subsidy associated with taxation? As we can see from (28), the subsidy does not change (L). However, it shifts (A_H) upwards because the subsidy reduces the marginal cost of R&D activities, raising the net expected value of innovation.

Figure 4 demonstrates the impact of the R&D subsidy as well as taxation both on the level of pollution and on growth. As in the simple case, the tax does not change the labor market clearing condition (11) denoted as (L'), but only shifts the R&D arbitrage condition (26), designated as (A'), upwards, since the general equilibrium effect surpasses the profitability effect. Hence, at equilibrium $(\tilde{x}_H, n_{A_H})$, the level of pollution as well as intermediate inputs declines, however, the overall impact of environmental taxation on growth is positive. Moreover, the R&D subsidy shifts (A') upwards. Hence, in equilibrium $(\tilde{x}_S, n_{A_S})$, although it reduces both intermediate inputs and pollution, the subsidy increases the growth rate even further.

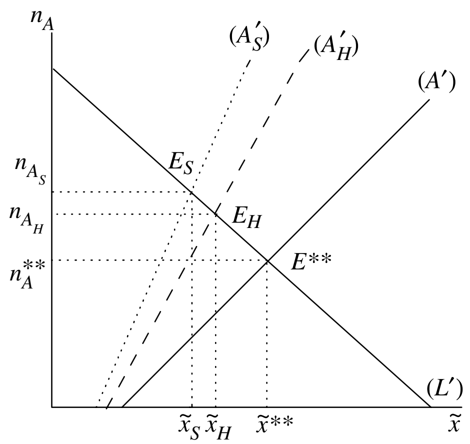

Fig. 4. Pollution and growth in the general case

4.4 On Welfare

In this subsection, we examine whether an impact of environmental taxation on welfare is positive or negative. We pay attention to the equilibrium along the balanced growth path and do not deal with its transition. The welfare along the balanced growth path in the general case is given by the following equation:

$$
\begin{aligned}
W^{**} &= \int_0^\infty (\ln Y_t - \ln P^{**}) e^{-\rho t} dt, \\
&= \ln Y_0 \int_0^\infty e^{-(\rho - g)t} dt - \frac{\ln P^{**}}{\rho}, \\
&= \frac{\ln Y_0}{\rho - g} - \frac{\ln P^{**}}{\rho}.
\end{aligned}
$$

Then, we have the impact of taxation on the welfare as follows:

$$
\frac{dW^{**}}{d\psi} = \frac{1}{\rho - g} \frac{1}{Y_0} \frac{dY_0}{d\psi} + \frac{\ln Y_0}{(\rho - g)^2} \frac{dg}{d\psi} - \frac{1}{\rho P^{**}} \frac{dP^{**}}{d\psi}.
$$

Because $Y_0 = A_0^{max} \tilde{x}_0^{\alpha} \frac{1}{\Gamma}$, we obtain $\frac{1}{Y_0} \frac{dY_0}{d\psi} = \frac{\alpha}{\tilde{x}_0} \frac{d\tilde{x}_0}{d\psi}$. Proposition 2 indicates that $\frac{d\tilde{x}_0}{d\psi} < 0, \frac{dg}{d\psi} > 0, \frac{dP^{**}}{d\psi} < 0$. Then, the sign of the first term on the right-hand side is likely to be negative, since initially the level of consumption as well as final output decrease. The sign of the second term is positive, because taxation has a positive impact on growth. The sign of the last term is positive, because the tax negatively affects pollution. Thus, the impact of environmental taxation on the welfare depends on the three effects listed above. As a consequence, the impact is ambiguous. It is very important to find out whether this impact is positive or negative. However, due to space limitations we would like to leave this as a task for the future.

4.5 Discussion

Our analysis shows that, although environmental taxation decreases the level of final production and the intermediate inputs, it raises the mark-up rate of the intermediate sector. Overall, we find that the profitability effect is offset by the general equilibrium effect; thus, the tax enhances R&D activities which drive economic growth as well as reduce the level of pollution. In the empirical analysis of Japanese industries (Hamamoto, 1998), although environmental policies for pollution reduction decreased the final output in the short run, they encouraged various R&D activities for relevant technologies and ultimately improved overall productivity of the economy. In our model, moreover, if the government spents its tax revenue for research activities, the subsidy reduces the marginal cost of R&D activities and increases the expected net value of innovation. Hence, the R&D subsidy increases the growth rate even further. The Japanese government provided an R&D subsidy for the purpose of promoting technological development. As Watanabe (1999) analyzes, such a subsidy is estimated to have a positive impact on private R&D activities, especially in the energy sector.

Obviously, the above empirical studies have applied different assumptions; thus, our model does not necessarily explain the details of each observation. Nevertheless, overall findings in our model appear to be consistent with those observations. It may be essential to re-examine the relationship between an environmental policy and economic growth, focusing on market structures and microeconomic behavior of each economic agent.

The impact of taxation on welfare is not clear. This is because, although the tax has a positive impact on growth as well as the environment, it decreases the initial level of consumption. However, according to our conjecture, the more monopolistic the intermediate sector is, the more environmental taxation will have an impact on growth. As a result, the positive impact of taxation on growth will dominate the negative impact on the initial consumption; hence, taxation may have a positive impact on welfare as well. If the optimal level of pollution is uniquely determined, then the equilibrium level of pollution may be more than the optimum, when the tax is too small. In this case, the rise in the tax rate will increase the welfare as well as decrease pollution. When the tax is too high, this will not be the case. These points should be examined in future research.

5 Conclusion

In this paper, we have discussed the long-run impact of an environmental policy on economic growth and examined whether the policy can positively influence economic growth. Although pollution abatement is often considered to be an additional financial burden for production, as indicated by the idea of "innovation offsets", it is more likely to encourage R&D activities which contribute to overall productivity from the longer-term perspective. We modify Aghion and Howitt's (1992) growth model because we can describe the situation where the more productive production factor earns greater payoffs from R&D investment. The market structure of the intermediate sector is assumed to be imperfect competition. The profits of intermediate suppliers are spent on R&D activities.

The analysis shows that environmental taxation decreases the level of final production and the demand for intermediate goods; thus, it decreases the intermediate profits. However, in our setting, taxation alleviates this impact because it decreases the price elasticity of intermediate demand and raises its rate of mark-up. In addition, the general equilibrium effect has a positive impact on growth. Overall, we find that the environmental tax enhances R&D activities which drive economic growth as well as reduce the level of pollution. Furthermore, if the government spends their tax revenue to research activities, the subsidy reduces the marginal cost of R&D activities and increases the net expected value of innovation. Hence, such an R&D subsidy increases the growth rate even further.

There are obvious limits to the above argument. For instance, we have not internalized the technology index of emission intensity per unit of intermediate input. To explain Porter's hypothesis of "innovation offsets" in more detail, the change in this intensity should also be internalized and analyzed from a microeconomic viewpoint. In addition, the Schumpetarian notion of creative destruction highlights the substitution of new technology for the old one. However, in practice, new technology is often complementary to its predecessor, possibly due to the effect of a "network externality" (Tirole 1988). These points should be further investigated.

Appendix 1

Labor Demand in the Intermediate Sector

One unit of intermediate good needs one unit of labor: thus, total labor required in this sector is given by the equation

$$n_{xt} = \int_0^1 x_{jt} dj.$$

Substitute (10) into the above and rearrange it by a and we have

$$n_{xt} = \int_0^1 \tilde{x}(\omega_t/a)h(a)da,$$

where the density function is given as $h(a) \equiv H'(a) = \frac{1}{\ln\gamma} a^{\left(\frac{1}{\ln\gamma}-1\right)}$. Substituting this density function into the above equation provides the intermediate labor demand

$$\begin{aligned} n_{xt} &= \tilde{x}(\omega_t)\frac{1}{\ln\gamma}\int_0^1 a^{\left(\frac{1}{\ln\gamma}+\frac{1}{1-\alpha}-1\right)}da, \\ &= \tilde{x}(\omega_t)\frac{1}{\Gamma}, \end{aligned}$$

where $\Gamma = 1 + \frac{\ln\gamma}{1-\alpha} > 0$.

Appendix 2

The Equilibrium and the Impact of Taxation on Growth in the Simple Case

Substituting (18) into (20) gives the following condition:

$$1 = \frac{\lambda\frac{1-\alpha}{\alpha}(1+\psi)(1-n_A)}{r+\lambda n_A}.$$

$g = g_A$ with (8) and (12) implies:

$$\lambda n_A \ln\gamma = r - \rho.$$

The above two equations determine the following equilibrium:

$$\begin{aligned} r_h &= \frac{\lambda\Psi\ln\gamma + (\Psi+\alpha)\rho}{\alpha(1+\ln\gamma)+\Psi}, \\ n_{A_h} &= \frac{\lambda\Psi - \alpha\rho}{\lambda[\alpha(1+\ln\gamma)+\Psi]}, \\ \tilde{x}_h &= \frac{\alpha[\lambda(1+\ln\gamma)+\rho]}{\lambda[\alpha(1+\ln\gamma)+\Psi]}, \end{aligned}$$

where $\Psi = (1-\alpha)(1+\psi) > 0$. Therefore, the impacts of taxation on growth and pollution is examined, respectively:

$$\frac{dn_{A_h}}{d\Psi} = \frac{\lambda\alpha[\lambda(1+\ln\gamma)+\rho]}{\{\lambda[\alpha(1+\ln\gamma)+\Psi]\}^2} > 0,$$
$$\frac{d\tilde{x}_h}{d\Psi} = -\frac{\lambda\alpha[\lambda(1+\ln\gamma)+\rho]}{\{\lambda[\alpha(1+\ln\gamma)+\Psi]\}^2} < 0.$$

Thus, we obtain $\frac{dn_{A_h}}{d\psi} = \frac{dn_{A_h}}{d\Psi}\frac{d\Psi}{d\psi} > 0, \frac{d\tilde{x}_h}{d\psi} = \frac{d\tilde{x}_h}{d\Psi}\frac{d\Psi}{d\psi} < 0$. Since the level of pollution depends on the level of intermediate input, we have $\frac{dP}{d\psi} < 0$.

Appendix 3

The R&D Arbitrage Condition

Divide both sides of the free-entry condition by A_t^{max}, and we have the following equation:

$$(1-s)\omega = \lambda\int_0^\infty e^{-(r+\lambda n_A)\tau}\tilde{\pi}(\omega e^{g\tau})d\tau, \text{ for } s\in[0,1).$$

Because $\tilde{\pi}(\omega e^{g\tau}) = \frac{1-\alpha}{\alpha}\omega(1+\psi)\tilde{x}(\omega)e^{-\frac{\alpha}{1-\alpha}g\tau}$, and $g \equiv g_A$, the arbitrage equation can be rewritten as

$$1-s = \lambda\int_0^\infty e^{-(r+\lambda n_A)\tau}\frac{1-\alpha}{\alpha}(1+\psi)\tilde{x}(\omega)e^{-\frac{\alpha}{1-\alpha}\lambda n_A\ln\gamma\tau}d\tau.$$

Therefore, we have the following R&D arbitrage condition without and with an R&D subsidy:

$$1 = \frac{\lambda\frac{1-\alpha}{\alpha}(1+\psi)\tilde{x}(\omega)}{(1-s)(r+\lambda n_A\Lambda)}, \quad \text{for } s\in[0,1),$$

where $\Lambda = 1+\frac{\alpha}{1-\alpha}\ln\gamma > 1$.

Appendix 4

The Derivation of Each Equilibrium in the General Case

The equilibrium under taxation without R&D subsidy. Assume that the government imposes a tax without an R&D subsidy but instead reimburses the consumer, i.e., $s = 0$. Substitute (11) into (26) and we have the following condition:

$$1 = \frac{\lambda \frac{1-\alpha}{\alpha}(1+\psi)\Gamma(1-n_A)}{r + \lambda n_A \Lambda}.$$

Since $g = g_A$, substituting (8) and (12) into this provides the following equation:

$$\lambda n_A \ln \gamma = r - \rho.$$

The two conditions above determine the equilibrium with taxation, but without an R&D subsidy, as follows:

$$r_H = \frac{\lambda \Psi \Gamma \ln \gamma + (\Psi\Gamma + \alpha\Lambda)\rho}{\alpha(\Lambda + \ln \gamma) + \Psi\Gamma},$$
$$n_{A_H} = \frac{\lambda \Psi \Gamma - \alpha\rho}{\lambda[\alpha(\Lambda + \ln \gamma) + \Psi\Gamma]},$$
$$\tilde{x}_H = \frac{\alpha[\lambda(\Lambda + \ln \gamma) + \rho]}{\lambda[\alpha(\Lambda + \ln \gamma) + \Psi\Gamma]}.$$

The equilibrium under taxation with an R&D subsidy. When the government provides an R&D subsidy under taxation, i.e., $s \in (0, 1)$, we obtain the equilibrium below:

$$r_S = \frac{\lambda \Psi \Gamma \ln \gamma + [\Psi\Gamma + \alpha\Lambda(1-s)]\rho}{\alpha(\Lambda + \ln \gamma)(1-s) + \Psi\Gamma},$$
$$n_{A_S} = \frac{\lambda \Psi \Gamma - \alpha(1-s)\rho}{\lambda[\alpha(\Lambda + \ln \gamma)(1-s) + \Psi\Gamma]},$$
$$\tilde{x}_S = \frac{\alpha[\lambda(\Lambda + \ln \gamma) + \rho](1-s)}{\lambda[\alpha(\Lambda + \ln \gamma)(1-s) + \Psi\Gamma]}.$$

Appendix 5

The Impact of Taxation and an R&D Subsidy

(i) We evaluate the impact of an environmental tax as follows. Its impact on the rate of interest is positive since:

$$\frac{dr_H}{d\Psi} = \frac{\alpha\Gamma \ln\gamma[\lambda(\Lambda + \ln\gamma) + \rho]}{[\alpha(\Lambda + \ln\gamma) + \Psi\Gamma]^2} > 0.$$

Hence, we have $\frac{dr_H}{d\psi} = \frac{dr_H}{d\Psi}\frac{d\Psi}{d\psi} > 0$. The impact on the level of research is positive because

$$\frac{dn_{A_H}}{d\Psi} = \frac{\lambda\alpha\Gamma[\lambda(\Lambda + \ln\gamma) + \rho]}{\{\lambda[\alpha(\Lambda + \ln\gamma) + \Psi\Gamma]\}^2} > 0.$$

Therefore, we obtain $\frac{dn_{A_H}}{d\psi} = \frac{dn_{A_H}}{d\Psi}\frac{d\Psi}{d\psi} > 0$.
The impact on the level of intermediate inputs is negative because of

$$\frac{d\tilde{x}_H}{d\Psi} = -\frac{\lambda\alpha\Gamma[\lambda(\Lambda + \ln\gamma) + \rho]}{\{\lambda[\alpha(\Lambda + \ln\gamma) + \Psi\Gamma]\}^2} < 0.$$

Thus, we have $\frac{d\tilde{x}_H}{d\psi} = \frac{d\tilde{x}_H}{d\Psi}\frac{d\Psi}{d\psi} < 0$.

(ii) We examine the impact of an R&D subsidy. For that purpose, the partial derivatives with respect to an environmental tax and an R&D subsidy can be determined, respectively:

$$\frac{\partial r_S}{\partial\Psi} = \frac{\alpha\Gamma \ln\gamma(1-s)[\lambda(\Lambda + \ln\gamma) + \rho]}{[\alpha(\Lambda + \ln\gamma)(1-s) + \Psi\Gamma]^2} > 0,$$
$$\frac{\partial r_S}{\partial s} = \frac{\alpha\Psi\Gamma \ln\gamma[\lambda(\Lambda + \ln\gamma) + \rho]}{[\alpha(\Lambda + \ln\gamma)(1-s) + \Psi\Gamma]^2} > 0,$$
$$\frac{\partial n_{A_S}}{\partial\Psi} = \frac{\lambda\alpha\Gamma(1-s)[\lambda(\Lambda + \ln\gamma) + \rho]}{\{\lambda[\alpha(\Lambda + \ln\gamma)(1-s) + \Psi\Gamma]\}^2} > 0,$$
$$\frac{\partial n_{A_S}}{\partial s} = \frac{\lambda\alpha\Gamma\Psi[\lambda(\Lambda + \ln\gamma) + \rho]}{\{\lambda[\alpha(\Lambda + \ln\gamma)(1-s) + \Psi\Gamma]\}^2} > 0,$$
$$\frac{\partial \tilde{x}_S}{\partial\Psi} = -\frac{\lambda\alpha\Gamma(1-s)[\lambda(\Lambda + \ln\gamma) + \rho]}{\{\lambda[\alpha(\Lambda + \ln\gamma)(1-s) + \Psi\Gamma]\}^2} < 0,$$
$$\frac{\partial \tilde{x}_S}{\partial s} = -\frac{\lambda\alpha\Gamma\Psi[\lambda(\Lambda + \ln\gamma) + \rho]}{\{\lambda[\alpha(\Lambda + \ln\gamma)(1-s) + \Psi\Gamma]\}^2} < 0.$$

Therefore, we obtain: $\frac{\partial r_S}{\partial\psi} = \frac{\partial r_S}{\partial\Psi}\frac{d\Psi}{d\psi} > 0, \frac{\partial r_S}{\partial s} > 0, \frac{\partial n_{A_S}}{\partial\psi} = \frac{\partial n_{A_S}}{\partial\Psi}\frac{d\Psi}{d\psi} > 0, \frac{\partial n_{A_S}}{\partial s} > 0, \frac{\partial \tilde{x}_S}{\partial\psi} = \frac{\partial \tilde{x}_S}{\partial\Psi}\frac{d\Psi}{d\psi} < 0, \frac{\partial \tilde{x}_S}{\partial s} < 0$. Because it is difficult to obtain a clear result under a general setting, in the following analysis, we set the initial tax rate equal to zero.

(a) The impact of an R&D subsidy on the level of research is positive. Take the total derivative with respect to the subsidy to obtain:

$$\frac{dn_{A_S}}{ds} = \frac{\partial n_{A_S}}{\partial s} + \frac{\partial n_{A_S}}{\partial \psi}\frac{d\psi}{ds}.$$

Totally differentiate (29) and evaluate it around the initial tax rate, i.e., $\psi = 0, s = 0$, and we have: $\frac{d\psi}{ds} = \frac{n_{A_S}}{\tilde{x}_S}\Gamma$. Substituting into the above derivative yields:

$$\frac{dn_{A_S}}{ds} = \frac{\partial n_{A_S}}{\partial s} + \frac{\partial n_{A_S}}{\partial \psi}\frac{n_{A_S}}{\tilde{x}_S}\Gamma > 0.$$

(b) The impact of an R&D subsidy on the level of intermediate inputs is negative because

$$\frac{d\tilde{x}_S}{ds} = \frac{\partial \tilde{x}_S}{\partial s} + \frac{\partial \tilde{x}_S}{\partial \psi}\frac{d\psi}{ds} = \frac{\partial \tilde{x}_S}{\partial s} + \frac{\partial \tilde{x}_S}{\partial \psi}\frac{n_{A_S}}{\tilde{x}_S}\Gamma < 0.$$

(c) The impact of an R&D subsidy on the interest rate is positive, which is shown as follows:

$$\frac{dr_S}{ds} = \frac{\partial r_S}{\partial s} + \frac{\partial r_S}{\partial \psi}\frac{d\psi}{ds} = \frac{\partial r_S}{\partial s} + \frac{\partial r_S}{\partial \psi}\frac{n_{A_S}}{\tilde{x}_S}\Gamma > 0.$$

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