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Economic Growth and the Environment: Welfare Effects of R&D Taxation*

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Abstract

This paper examines the welfare effect of R&D taxation in a model where the innovation of new products drives economic growth, which in turn pollutes the environment. In the presence of the environmental externality, the taxation improves the environment by remedying overconsumption. Taking transitional dynamics into account, we find that there exists a tax rate that maximizes the welfare of a representative consumer.

Keywords: Economic growth, Environment, Innovation, R&D taxation.

JEL Classification Numbers: E1, H2, O4, Q5.

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1 Introduction

The relationship between economic growth and the environment is controversial. Recent economic development especially in the BRICS countries (Brazil, Russia, India, China and South Africa) makes us return to this central issue. Using a general equilibrium model in which the innovation of new products is an engine of economic growth, this paper shows that imposing a tax on R&D activity corrects the distortion caused by the environmental externality and improves welfare.

There are numerous studies that explore the compatibility between economic growth and environmental protection in the context of optimal growth with exogenous technological progress (see for example Keeler *et al.* 1971, Tahvonen and Kuuluvainen 1991, 1993, Chichilnisky *et al.* 1995 and Ayong Le Kama 2001). A typical approach for addressing environmental problems is to introduce a renewable environmental resource as a source of utility and/or an input to production.[1] It causes inefficiency due to externalities, thereby justifying policy interventions. John *et al.* (1995) and Ono (1996) propose income taxes and a consumption tax as instruments for achieving the optimal resource allocation in an overlapping-generations economy.

A lot of literature apply this approach to endogenous growth models in which factor productivity is determined by the innovation of new products, human capital, knowledge spillovers and so on.[2] Among them some studies employ an innovation-driven growth model while they do not focus on the welfare effects of R&D taxation. For example, Papyrakis and Gerlagh (2004) apply the model to demonstrate that an increase in nat-

[1]The model in which renewable environmental resources directly yield utility is extended in various directions. For instance, Li and Löfgren (2000) take account of heterogenous consumers differing with respect to the subjective discount rate. Ayoung Le Kama and Schubert (2007) consider an endogenous discounting depending on the environmental quality and investigate the sustainability of economic growth. Wirl (2004) points out that multiple equilibria and stable limit cycles can arise in the framework of Ayong Le Kama (2001). John and Pecchenino (1994), John *et al.* (1995) and Ono (1996, 2003) adopt an overlapping-generations model to explore intergenerational interactions in environmental preservations.

[2]See Grossman and Helpman (1991) and Aghion and Howitt (1998) for the endogenous growth theory. John and Pecchenino (1994), Smulders and Gradus (1996) and Elíasson and Trunovsky (2004) utilize a model with the externality associated with knowledge spillover in a final output sector. See Smulders (1995) for the case of human capital accumulation and Ligthart and van der Ploeg (1994) for the case of productive public goods. Note that none of them embeds the R&D activity that expands new products.

ural resources impedes income growth by reducing both work effort and a proportion of the labor force allocated to the innovation sector. Elbasha and Roe (1996) analyze the interaction among international trade, economic growth and the environment in a small open economy. Ono (2003) examines the growth effect of environmental taxation using a growth-cycle model where the economy either fluctuates between exogenous and endogenous growth regimes or converges to one of them.

In this paper we develop an innovation-driven growth model with the environmental externality and numerically obtain a tax rate on R&D activity that maximizes the welfare of a representative consumer. While the taxation hampers profit-motivated innovation and reduces factor productivity, it is useful to remedy overconsumption arising from the environmental externality. In the baseline simulation we numerically find that the welfare improves (or deteriorates) at rates below (or above) 3.8% and takes a maximum at the 1.9% tax rate. In this regard the R&D taxation can be interpreted as a type of environmental taxation, which is investigated in e.g., Tahvonen and Kuuluvainen (1991, 1993), Bovenberg and Smulders (1995), Smulders and Gradus (1996) and Ono (2003).[3] They treat a tax on pollution emitted in the process of production in a final output sector, and show beneficial effects of taxation. This paper in contrast focuses on a role of R&D taxation, paying attention also to the threshold at which the R&D sector is inactive and the effectiveness of R&D taxation vanishes.

This paper is closely related to Grimaud (1999) who examines how to implement the optimal path within a Schumpeterian framework with environmental pollution, developed by Aghion and Howitt (1998). The main difference is that Grimaud deals with knowledge spillovers in the research sector, which allows perpetual growth and causes another externality other than the environmental externality. He proposes the R&D subsidy rather than the R&D taxation in the presence of positive knowledge externality in the research sector because he assumes that pollution permits regulated by the government are able to eliminate the environmental externality completely. By contrast, we show that there is a welfare-maximizing positive tax rate on R&D activity in the absence of knowledge spillovers and pollution permits.

[3]Ligthart and van der Ploeg (1994) levy a tax on output in an endogenous growth model with productive government spending.

The remaining of the paper are organized as follows. Section 2 presents a general equilibrium model with R&D activity and the environmental externality. Section 3 analyzes the dynamics, compares the market equilibrium with the social optimum, and numerically derives the welfare effect of R&D taxation. Sensitivity analyses are also conducted. They indicate that the welfare-improving and welfare-maximizing tax rates are somewhat affected by the degree of the environmental externality and the nonseparability in preferences, and that they heavily depend on the estimated value of environmental resources. Finally, we take account of the case where the R&D sector is inactive making the R&D taxation ineffective. Section 5 concludes the paper.

2 The Model

We incorporate the environmental externality into the model developed by Grossman and Helpman (1991, chapter 3). Consumers do not recognize utility generated from the environment. It then leads to overconsumption and under-environment. There is a single final good produced by using differentiated intermediate goods, each of which is monopolistically supplied. Expansions in a variety of intermediate goods as a result of R&D activity improve production efficiency in the final good sector, whereas an increase in production pollutes the environment. In this economy we will show that there is a welfare-maximizing tax rate on R&D activity.

2.1 Production

2.1.1 The final good sector

A representative firm competitively produces a final good, Y_t, according to the technology

$$Y_t = \left[\int_0^{N_t} x_t(j)^\theta \mathrm{d}j \right]^{\frac{1}{\theta}}, \quad 0 < \theta < 1,$$

where $N_t (> 0)$ denotes a variety of intermediate goods and $x_t(j)$ is an input of intermediate good $j (\in [0, N_t])$. The elasticity of substitution between intermediate inputs is represented by $1/(1-\theta) > 1$. Y_t equals consumption, C_t, because there are no capital investment, government purchases and international trade. In a symmetric equilibrium where $x_t(j) =$

x_t, the production function reduces to

$$C_t = N_t^{\frac{1}{\theta}} x_t \tag{1}$$

and hence an increase in N_t raises factor productivity.

Letting the final good be the numeraire and $p_t(j)$ the price of intermediate good j, the optimal condition of profit maximization yields the following demand function:

$$x_t(j) = p_t(j)^{-\frac{1}{1-\theta}} C_t. \tag{2}$$

2.1.2 The intermediate goods sectors

Intermediate good j is produced by a monopolistic firm, which earns positive profits and pays them to the R&D sector as patent fees. We assume that each intermediate firm uses only labor to produce output and has linear-homogeneous technology in which the input-output coefficient is unity. Given the production function and the demand function (2), the firm chooses $p_t(j)$ so as to maximize profit

$$\pi_t(j) = p_t(j)x_t(j) - w_t x_t(j), \tag{3}$$

where w_t is the wage rate and $l_t(j)$ is the labor demand in the sector j. In a symmetric equilibrium, the optimal condition satisfies

$$p_t(j) = p_t \equiv \frac{w_t}{\theta}, \tag{4}$$

$$x_t(j) = x_t \equiv \left(\frac{w_t}{\theta}\right)^{-\frac{1}{1-\theta}} C_t. \tag{5}$$

Substituting (5) into (1) gives

$$w_t = \theta N_t^{\frac{1-\theta}{\theta}}. \tag{6}$$

Using (4), (5) and (6) rewrites (3) as

$$\pi_t(j) = \pi_t \equiv (1-\theta)\frac{C_t}{N_t}. \tag{7}$$

2.1.3 The R&D sector

The R&D sector employs labor L_t to create new intermediate goods, $N_{t+1} - N_t$:

$$N_{t+1} - N_t = L_t \ (\geq 0). \tag{8}$$

With free entry, the marginal benefit from the R&D activity, v_t, equals the present discounted sum of future profits earned by the intermediate goods sector:

$$v_t(j) = v_t \equiv \sum_{s=t}^{\infty} \pi_{s+1} \left(\prod_{t}^{z=s} \frac{1}{1+r_{z+1}} \right),$$

where r_t is the interest rate.[4] It implies

$$1 + r_{t+1} = \frac{v_{t+1} + \pi_{t+1}}{v_t}. \tag{9}$$

The optimal condition of profit maximization is

$$(1-\tau^R)v_t \leq w_t, \quad \text{with equality whenever } N_{t+1} - N_t > 0, \tag{10}$$

where $\tau^R (\in [0,1))$ is the tax rate on the R&D activity.

2.2 Environmental resources and the consumer behavior

Following Smulders (1995) and Ayong Le Kama (2001), we assume that environment resources recover through natural regeneration processes but are destroyed by the production activity in the final good sector, which equals the level of consumption in the present setting—i.e.,

$$E_{t+1} - E_t = f(E_t) - \delta C_t, \quad \delta > 0,$$

where E_t is the stock of environmental resources at the beginning of period t. As in figure 1, we specify the reproduction function $f(\cdot)$ as

$$f(E_t) = -E_t(E_t - \bar{E}), \quad \bar{E} > 0,$$

and hence, from the above two equations, the environment evolves according to

$$E_{t+1} - E_t = E_t\left(\bar{E} - E_t\right) - \delta C_t. \tag{11}$$

Lifetime utility of a representative consumer, U_0, depends on not only consumption C_t but also the environmental level, E_t:

$$U_0 = \sum_{t=0}^{\infty} \beta^t \frac{\left({C_t}^{\kappa} {E_t}^{1-\kappa}\right)^{1-\gamma} - 1}{1-\gamma}, \qquad 0 < \beta < 1, \quad 0 < \kappa < 1, \quad \gamma > 0,$$

[4] Infinite patent length is assumed in this paper. See e.g., Futagami and Iwaisako (2007) and Iwaisako and Futagami (2003) for the effects of patent length on economic growth.

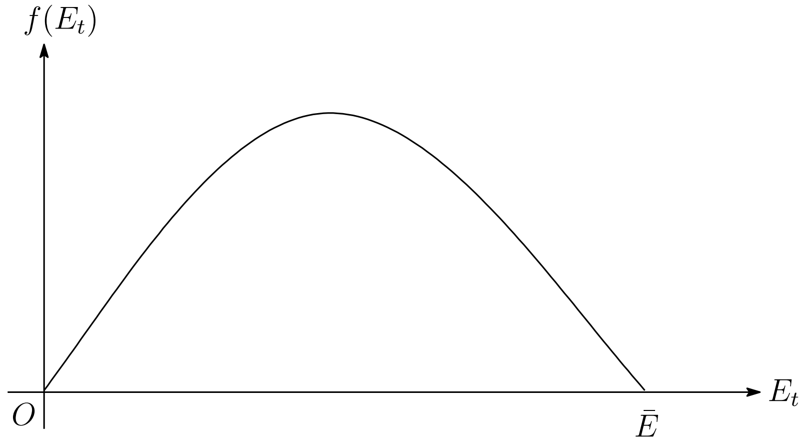

Figure 1. The reproduction function of the environment.

where β is the subjective discount factor. The consumer ignores the evolutionary process of the environmental stock, (11), and maximizes the lifetime utility subject to financial budget constraint,

$$A_{t+1} = (1 + r_t)A_t + w_t\bar{L} - C_t + T_t,$$

where A_t denotes a financial asset, $\bar{L}$ a constant labor endowment, T_t a lump-sum transfer from the government, respectively. It causes a market failure due to the environmental externality leading to overconsumption and under-environment. The optimal condition of utility maximization are the transversality condition and

$$\left(\frac{C_{t+1}}{C_t}\right)^{(1-\kappa)+\kappa\gamma} = (1 + r_{t+1})\beta \left(\frac{E_{t+1}}{E_t}\right)^{-(1-\kappa)(\gamma-1)}. \tag{12}$$

The government transfers the collected funds to the consumer in a lump-sum manner.

$$T_t = \tau^R v_t(N_{t+1} - N_t).$$

The equilibrium condition in the labor markets is given by

$$\bar{L} = \int_0^{N_t} x_t(j)\mathrm{d}j + L_t. \tag{13}$$

3 Dynamics and the R&D Activity

3.1 The case of the active R&D sector

Equation (10) implies that there are two kinds of equilibrium dynamics depending on whether the R&D sector is active or inactive. Let us first analyze the former case where

(10) has equality. Substituting (7) and (10) into (9) and using (6) gives

$$1 + r_{t+1} = \left(\frac{N_{t+1}}{N_t}\right)^{\frac{1-\theta}{\theta}} + \frac{(1-\tau^R)(1-\theta)C_{t+1}}{\theta N_t^{\frac{1-\theta}{\theta}} N_{t+1}},$$

which reduces the dynamic equation of consumption, (12), to

$$\left(\frac{C_{t+1}}{C_t}\right)^{(1-\kappa)+\kappa\gamma} = \left[1 + \frac{(1-\tau^R)(1-\theta)}{\theta} C_{t+1} N_{t+1}^{-\frac{1}{\theta}}\right] \left(\frac{N_{t+1}}{N_t}\right)^{\frac{1-\theta}{\theta}} \beta \left(\frac{E_{t+1}}{E_t}\right)^{-(1-\kappa)(\gamma-1)}. \tag{14}$$

Next, we substitute (5) into (13) and apply (6) to the result to obtain

$$L_t = \bar{L} - C_t N_t^{-\frac{1-\theta}{\theta}}.$$

Using this equation to eliminate L_t from (8) generates the dynamic equation of product varieties,

$$N_{t+1} - N_t = \bar{L} - C_t N_t^{-\frac{1-\theta}{\theta}}. \tag{15}$$

Equations (11), (14) and (15) constitutes an autonomous dynamic system, which has the steady-state values (C^*, N^*, E^*):

$$C^* = \left[\frac{(1-\tau^R)(1-\theta)\beta}{\theta(1-\beta)}\right]^{\frac{1-\theta}{\theta}} \bar{L}^{\frac{1}{\theta}}, \qquad N^* = \frac{(1-\tau^R)(1-\theta)\beta\bar{L}}{\theta(1-\beta)}. \tag{16}$$

We assume the existence of E^* that is dynamically stable:[5]

$$E^* = \frac{\bar{E} + \sqrt{\bar{E}^2 - 4\delta\left[\frac{(1-\tau^R)(1-\theta)\beta}{\theta(1-\beta)}\right]^{\frac{1-\theta}{\theta}} \bar{L}^{\frac{1}{\theta}}}}{2}, \qquad f'(E^*) < 0. \tag{17}$$

From (16) and (17), it is straightforward that an increase in τ^R reduces C^* and N^* and increases E^*, implying a trade-off between economic growth and environmental protection:

$$\frac{\mathrm{d}C^*}{\mathrm{d}\tau^R} = -\frac{(1-\theta)C^*}{(1-\tau^R)\theta} < 0, \qquad \frac{\mathrm{d}N^*}{\mathrm{d}\tau^R} = -\frac{N^*}{1-\tau^R} < 0,$$
$$\frac{\mathrm{d}E^*}{\mathrm{d}\tau^R} = \frac{\delta(1-\theta)C^*}{(1-\tau^R)\theta\sqrt{\bar{E}^2 - 4\delta C^*}} > 0.$$

This result is summarized in the following proposition:

[5] Ogawa and Nakamura (2016) theoretically analyze how government interventions on R&D activity affect the existence of E^* and the dynamic stability of the economy.

Table 1. Parameters in the baseline simulation.

θ^{-1}	β	δ	$\bar{E}$	$\bar{L}$	κ	γ
1.2	$(0.995)^4$	0.01	1	5.761	0.5	1

Proposition 1. *Imposing a tax on R&D activity reduces steady-state consumption and increases the steady-state level of the environment in the market equilibrium.*

The social optimum is to maximize the lifetime utility subject to (11) and (15); i.e., the optimal allocation $\{C_t^o, N_t^o, E_t^o\}_{t=0}^{\infty}$ satisfies the transversality condition and

$$\delta\mu_t + (N_t^o)^{-\frac{1-\theta}{\theta}}\xi_t = \kappa(C_t^o)^{-[(1-\kappa)+\kappa\gamma]}(E_t^o)^{-(1-\kappa)(\gamma-1)},$$

$$\mu_t = \beta\left[(1-\kappa)(C_{t+1}^o)^{-\kappa(\gamma-1)}(E_{t+1}^o)^{-[\kappa+(1-\kappa)\gamma]} + (1+\bar{E}-2E_{t+1}^o)\mu_{t+1}\right],$$

$$\xi_t = \left[1 + \frac{1-\theta}{\theta}C_{t+1}^o(N_{t+1}^o)^{-\frac{1}{\theta}}\right]\beta\xi_{t+1},$$

where μ_t and ξ_t are respectively the Lagrange multiplier of (11) and that of (15). Note that in the present setting the optimal path converges to the same steady state as (16) and (17) in which $\tau^R = 0$. In the presence of environmental externality, however, the transitional path of the market equilibrium deviates from the optimal path. It will be formally shown in the following.

3.2 Simulation

Now we numerically analyze transitional dynamics using Dynare++4.3.3. The parameter values are reported in table 1. We follow Sugo and Ueda (2008) in setting $\theta^{-1} = 1.2$ and $\beta = (0.995)^4$.[6] $\bar{E}$ is normalized to unity. δ and $\bar{L}$ are calculated from the trial estimates for Japan's integrated environmental and economic accounting, presented by the Economic Planning Agency, government of Japan, in July 1998 (see appendix A for details). We assume $\kappa = 0.5$ and $\gamma = 1$ in the baseline simulation and then consider the alternative values later. In simulating the model, the terminal point is assumed to be the 1,000 period (1,000 year).

[6]Sugo and Ueda (2008) estimate a dynamic stochastic general equilibrium model with new-Keynesian features using quarterly Japanese data. See Christiano *et al.* (2005) and Levin *et al.* (2006) for the U.S. economy.

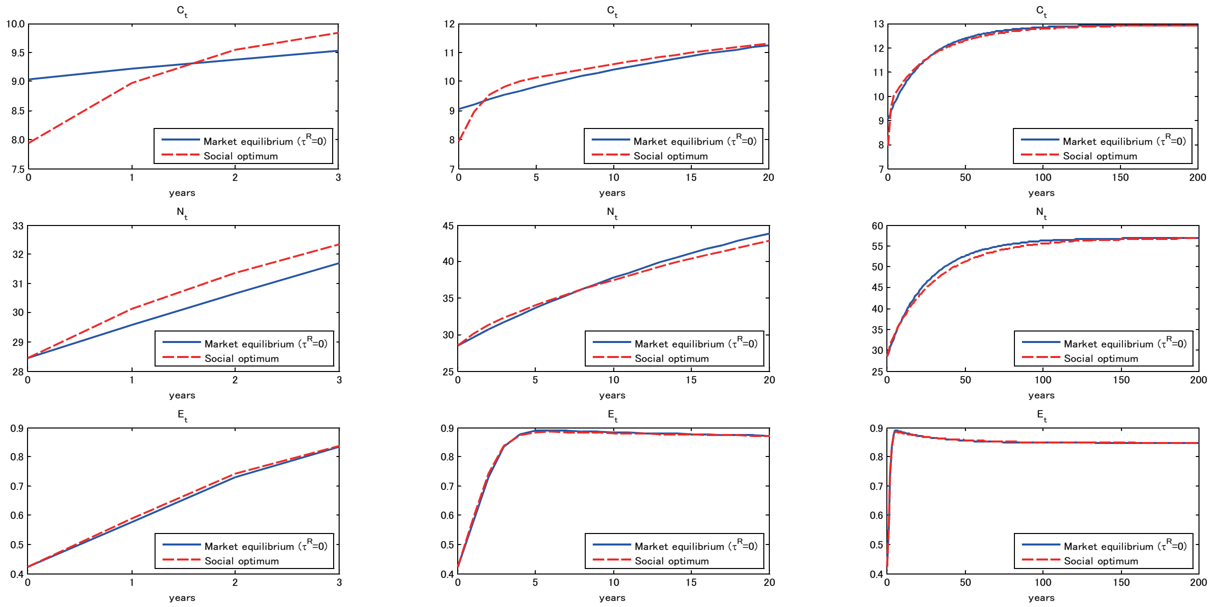

Figure 2. The market-equilibrium path and the optimal path.

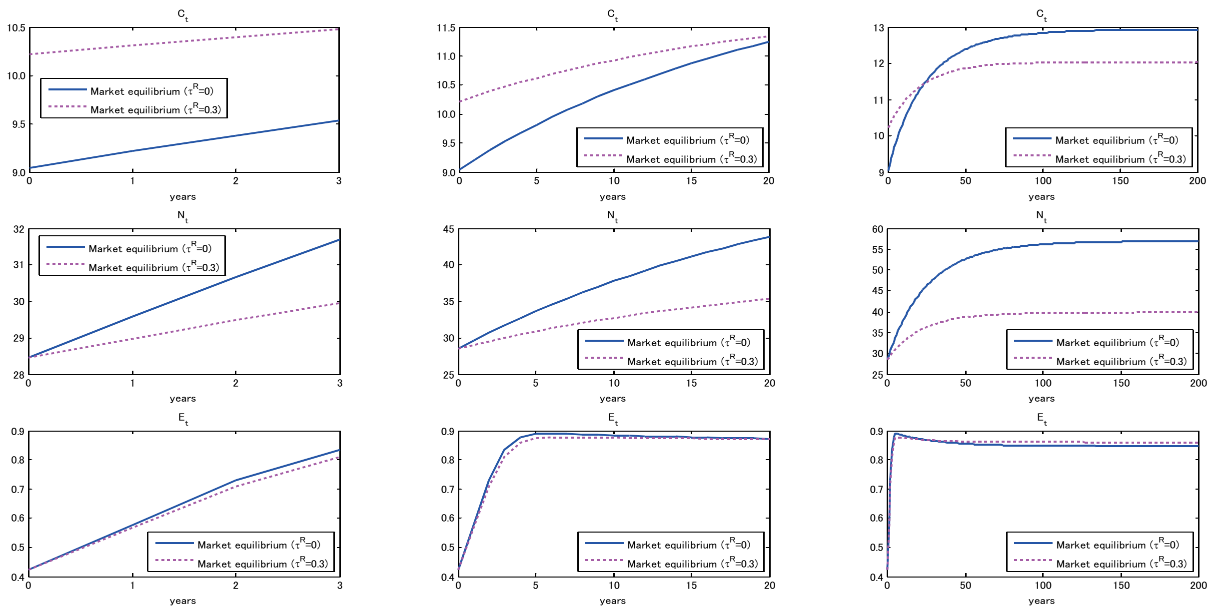

Figure 3. The market-equilibrium paths if $\tau^R = 0$ and $\tau^R = 0.3$.

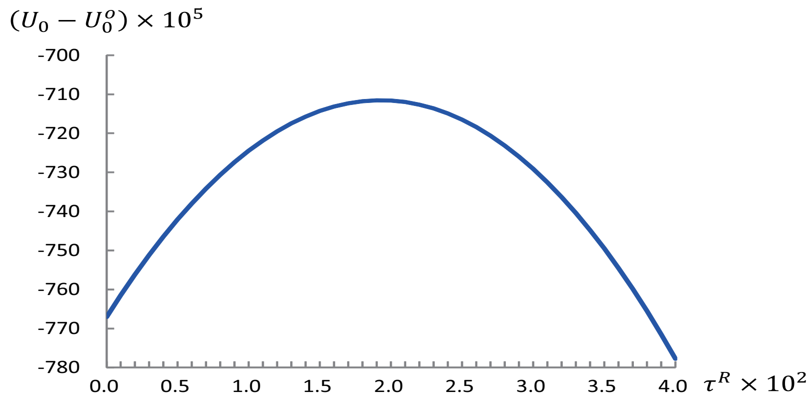

Figure 4. The welfare effect of τ^R.

Figure 2 depicts the dynamic path in the case where the initial stock variables (N_0, E_0) are given by $N_0 = 0.5N^{o*}$ and $E_0 = 0.5E^{o*}$. The solid line shows the market equilibrium in which $\tau^R = 0$, whereas the broken line is the social optimum. The market-equilibrium path is inefficient. In early periods, consumption is excessive and both the R&D activity and the environmental level are too small relative to the optimum due to the environmental externality (see figures on the left-hand side). The underinvestment in the R&D sector leads to a subsequent decrease in consumption, which in turn raises labor supply allocated to the R&D sector. Eventually both market-equilibrium and optimal paths converge to the same steady state if $\tau^R = 0$ (see figures on the right-hand side).

Imposing a tax on R&D activity affects not only the transitional path but also the steady state in the market equilibrium. The dotted line in figure 3 represents the market-equilibrium path of $\tau^R = 0.3$, whereas the solid line is that of $\tau^R = 0$. In the short-run, the R&D taxation discourages the R&D activity, increases labor supply allocated to the final good sector, and deteriorates the environment. In the steady state, an increase in τ^R reduces N^* and C^* but raises E^* (see proposition 1). The long-run effects dominates the short-run effects, so that the taxation can be useful to solve the inefficiency arising from the environmental externality. However, too high tax rates harms the welfare leading to too low factor productivity and consumption. Figure 4 finds that the lifetime utility rises within $0 < \tau^R \leq 0.038$ and takes a maximum at $\tau^R = 0.019$. We can summarize the results as follows:

Result 1. *In the presence of the environmental externality, the R&D taxation can improve*

Table 2. Pareto-improving taxation on the R&D activity.

$\bar{L}$	κ	γ	Improving within	Maximum at
5.761	0.5	1	$0 < \tau^R \leq 0.038$	$\tau^R = 0.019$
5.761	0.8	1	$0 < \tau^R \leq 0.008$	$\tau^R = 0.004$
5.761	0.5	1.249	$0 < \tau^R \leq 0.031$	$\tau^R = 0.016$
0.179	0.5	1	$0 < \tau^R \leq 0.00026$	$\tau^R = 0.00013$

the welfare of the representative consumer, and there is a welfare-maximizing R&D tax rate.

Table 2 reports the results of sensitivity analyses. First, the larger κ indicates that the utility from the environment is less important and thus mitigates the inefficiency. In the case of $\kappa = 0.8$, the lifetime utility improves at tax rates below 0.008, which is lower than 0.038 in the case of $\kappa = 0.5$. With the higher κ, the welfare-maximizing tax rate is also smaller.

We shall next consider the role of nonseparable preferences by setting γ equal to 1.249, which value is estimated by Sugo and Ueda (2008). Under the felicity function given in section 2.2, the marginal utility of consumption becomes

$$\lambda_t = \kappa C_t^{-[(1-\kappa)+\kappa\gamma]} E_t^{-(1-\kappa)(\gamma-1)},$$

and is decreasing with respect to the environment level if $\gamma > 1$. For this reason, along the growing path of the environment, consumption is more in early periods and becomes less toward the steady state if $\gamma > 1$. Since the long-run effect dominates the short-run effect, the inefficiency of the market equilibrium is totally small. Therefore, the range within which the taxation is beneficial narrows ($0 < \tau^R \leq 0.031$) and the welfare-maximizing tax rate is lower ($\tau^R = 0.016$) relative to the case of $\gamma = 1$.

Finally, we shall confirm that the results are sensitive to the magnitude of $\bar{L}$ in the present simple framework. In the baseline simulation we interpret E^* as the "Environmental Protection Assets," of which amount is consistent with $\bar{L} = 5.761$. If the "Non-Produced Assets" is used as a proxy for E^*, we have $\bar{L} = 0.179$ and C^* becomes smaller. As a result, there is almost no need for taxation. To calculate accurate tax rates that improve or maximize the welfare, we should estimate the rigorous value of environmental resources although it is a difficult task. (See appendix A for the calculation of $\bar{L}$.)

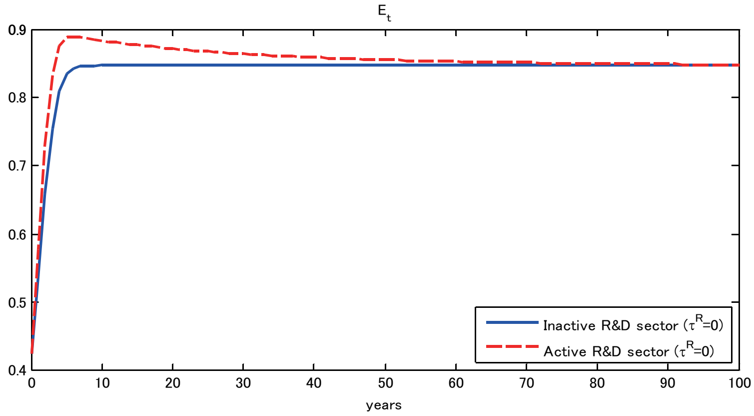

Figure 5. The market-equilibrium path of E_t if the R&D sector is inactive ($N_0 = N^{o*}$) or if the R&D sector is active ($N_0 = 0.5N^{o*}$).

3.3 The Case of the inactive R&D sector

Move on to the case where the R&D sector is inactive, that is, $L_t = 0$. Since the initial stock satisfies $N_0 \geq N^*$, (10) has inequality and N_t keeps constant at N_0. We have $x_t = \bar{L}/N_0$ from (13) and $L_t = 0$, so that consumption also stays constant at

$$C_t = N_0^{\frac{1-\theta}{\theta}} \bar{L},$$

which comes from (1). The environment evolves according to (11):

$$E_{t+1} - E_t = E_t(\bar{E} - E_t) - \delta N_0^{\frac{1-\theta}{\theta}} \bar{L}.$$

It is obvious that the R&D taxation has no effect on equilibrium dynamics.

Suppose two types of countries, both of which face either natural or human-caused disasters that damage the environment causing $E_0 = 0.5E^{o*}$. The one has the variety of available intermediate goods sufficient to make the R&D sector inactive, whereas the other has the active R&D sector satisfying $N_0 = 0.5N^{o*}$. One may refer to the former as a developed country and the latter as a developing country. Figure 5 compares the E_t dynamics in the two countries. After the disasters, the environment stock recovers more slowly in the developed country than in the developing country, which has smaller consumption. Furthermore, the government of the developed country cannot intervene the market in a Pareto-improving way because the R&D taxation has no role. This result is summarized in the following:

Result 2. *In the economy that has the variety of available intermediate goods sufficient to make the R&D sector inactive, the environment recovers slowly after disasters while the R&D taxation affects neither equilibrium dynamics nor welfare.*

4 Conclusion

In this paper we show that imposing a tax on R&D activity can be beneficial in an innovation-driven growth model with the utility-enhancing environment stock. The R&D taxation mitigates overconsumption, thereby partly solving the distortion generated by the environmental externality. We find a positive tax rate that maximizes the welfare if the R&D sector is active. It is also shown that the taxation has no effect if the R&D sector is inactive.

There are several directions for future research. First, the introduction of e.g., capital accumulation, endogenous labor supply and price rigidities needs to obtain more accurate welfare-improving tax rates. Second, it is crucial to estimate the value of environmental resources and the imputed environmental costs. The third direction is to take account of the R&D activity that promotes pollution abatement technology (see for example Bovenberg and Smulders 1995, 1996 and Hart 2004). Finally, the presence of knowledge externalities in the R&D sector tends to make research effort less than the social optimum, thereby changing quantitative and qualitative implications of the R&D taxation (such as Grossman and Helpman 1991 and Grimaud 1999).

Appendix A. Data and Parameters

This appendix explains how to derive the parameter values, δ and $\bar{L}$. The data used in the simulation is available from the website of the Cabinet Office, government of Japan.[7] They are the results of trial estimates of the "Satellite System for Integrated Environmental and Economic Accounting" in 1990 at constant prices—i.e.,

We employ two alternatives as a proxy of E^*. The one is the "Environmental Protection Assets," a part of which is used by industries in the production processes. The other is the "Non-Produced Assets" that is composed mainly of Land and Subsoil Resources.

[7] http://www.esri.cao.go.jp/en/sna/satellite/1998/19980714g-eco-e.html

Table 3. Data.

Description	Value (billion yen)	Variable
Net Domestic Product	429,860.4	$Y^* = C^*$
Imputed Environmental Costs	4,186.4	δY^*
Environmental Protection Assets	33,253.7	E^*
Non-Produced Assets	2,148,317.9	

Since it is more difficult to estimate the latter value accurately, we follow the former value in the baseline simulation. Actually the data set does not give the stock value of Air, Water and Soil that should be categorized into the "Non-Produced Assets."

δ is calculated by dividing "Imputed Environmental Costs" by "Net Domestic Product."

$$\delta = \frac{\text{Imputed Environmental Costs}}{\text{Net Domestic Product}} \simeq 0.01.$$

Let us next derive the value of $\bar{L}$. Evaluating (11) in the steady state and using the data in table 3 yields

$$\bar{E} = E^* + \frac{\delta Y^*}{E^*} \simeq \begin{cases} 33,253.8 & \text{if} \quad E^* = \text{Environmental Protection Assets}, \\ 2,148,317.9 & \text{if} \quad E^* = \text{Non-Produced Assets}. \end{cases}$$

We normalize this value to unity in both cases, and then obtain the value of $\bar{L}$ from the first equation in (16) in which $\tau^R = 0$:[8]

$$\begin{aligned} \bar{L} &= (\text{Net Domestic Product})^{\theta} \left[\frac{(1-\theta)\beta}{\theta(1-\beta)}\right]^{\theta-1} \\ &\simeq \begin{cases} 5.761 & \text{if} \quad E^* = \text{Environmental Protection Assets}, \\ 0.179 & \text{if} \quad E^* = \text{Non-Produced Assets}, \end{cases} \end{aligned}$$

where the values of θ and β are given in table 1 and the "Net Domestic Product" is the normalized value—i.e.,

$$\text{Net Domestic Product} = \begin{cases} \frac{429{,}860.4}{33{,}253.8} & \text{if} \quad E^* = \text{Environmental Protection Assets}, \\ \frac{429{,}860.4}{2{,}148{,}317.9} & \text{if} \quad E^* = \text{Non-Produced Assets}. \end{cases}$$

[8]In simulating the model, we normalize the variables by $\bar{E}$ rather than $\bar{L}$ because the reproduction function does not vary across countries relative to the labor force. However, this manipulation is not essential.

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