A Note on Environment-dependent Time Preferences

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Abstract

In this paper we investigate the growth effect of environmental taxes when the time preference is endogenously determined by the environmental quality. We find that if people become more patient due to a cleaner environment, raising the environmental tax may reduce pollution and stimulate growth. Moreover, the Pigouvian principle may be inefficient in the presence of an endogenous time preference.

Keywords: endogenous time preference; endogenous growth; the Pigouvian tax
JEL classification: O11, Q56, Q58

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1. Introduction

In the literature on environmental economics, environmental externalities mainly affect the economy via two channels. First, they affect the households' welfare. A better environment undoubtedly brings us more happiness (see, e.g., Bovenberg and de Mooij, 1994; Chen et al., 2003; Pommeret and Schubert, 2009; Prieur and Bréchet, 2013). Second, they may be related to the firm's productivity. For example, better water quality improves workers' health, and better air quality slows the depreciation of equipment, both of which make the production process more productive (see, e.g., Bovenberg and Smulders, 1995; Smulders and Gradus, 1996; Fullerton and Kim, 2008; Chang et al., 2009).

Compared with the impact of the environment on welfare and production, what is not so widely noticed is that the people's *degree of time preferences* can also be influenced by environmental quality. For example, supposing that the environmentalists declare that the problem of global warming will become very severe in the near future, one would expect that consumption will increase and that saving will fall, because saving (for future consumption) now becomes more uncertain. This means that fears of an environmental disaster may alter people's time preferences so that they will prefer current consumption. By the same token, we can also imagine that a better air quality may cause agents to be more willing to save for the future.

In addition to the common logic, we could also rationalize the assumption of environment-dependent time preferences based on theoretical arguments.[1] In their

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[1] There are few (if not no) empirical studies that directly examine the linkage between time preferences and environmental quality. Nonetheless, the experiments in Viscusi et al. (2008), which

seminal paper, Becker and Mulligan (1997) indicate that mortality and wealth are important factors that affect time preferences. Although environmental quality has not been explicitly included, it can and does play an influential role in affecting these factors. As an immediate example, a cleaner environment makes us healthier and reduces mortality, which increases the incentives to save (Agénor, 2010). This positive link between life expectancy and patience supports the theory that a better environment decreases time preferences.

As for the alternative case where a better environment increases time preferences, the reasoning could be theoretically justified through the following two channels. The first channel highlights the relationship between environmental quality and utility. On the one hand, a better environmental quality increases the household utility based on the fact that environmental quality can improve a household's amenities and health; while on the other hand many studies have recognized that time preferences increase with utility (see, e.g., Uzawa, 1968; Nairay, 1984; Epstein, 1987; Chang et al., 1998). The second channel emphasizes the linkage between environmental quality and wealth. On the one hand, environmental quality has been treated as a "natural asset" by environmental economists (Hartwick, 1991; Bovenberg and Smulders, 1995, 1996). The notion of a "natural asset" or "environmental capital" can be extensively regarded as a kind of wealth. On the other hand, allowing impatience to depend positively on wealth has both theoretical and empirical identifications (Lucas and Stocky, 1984; Mohsin, 2004; Kam, 2005).[2] Equipped with these two possible channels, we have

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show that people who have access to water quality have a lower rate of time preference than those who do not, provide some indirect evidence of such a linkage.

[2] These studies argue that this time preference specification generates a Tobin effect, and moreover is consistent with the life-cycle hypothesis that regards consumption as an increasing function of wealth.

good grounds for considering the case where time preferences increase with the environmental quality.

Despite the logical rationale, existing theoretical studies on how environmental quality affects agents' time preferences are scarce and inconclusive. Pittel (2002) is the first attempt to develop a model in which the environment can, negatively or positively, influence the society's discount rate. Ayong Le Kama and Schubert (2007) consider a discount rate that is positively associated with the environmental quality. The basic idea is that the society chooses to discount at a lower rate when the environmental quality is low, because in this case the environmental problem becomes more pressing and doing so can help to prevent further deteriorations in the environment. On the contrary, Yanase (2011) and Vella et al. (2014) use the assumption that a better environment leads to increased patience. The justification is that, intuitively, lower pollution implies better health and thus a lower mortality rate, which makes households more patient and willing to trade current consumption for future consumption.

On the other hand, and perhaps due to analytical simplicity, most theoretical studies on the interaction between growth and the environment assume a constant time preference.[3] However, as emphasized by Weitzman (1994), the assumption of a constant time preference may be inappropriate especially in a world with increasing environmental concerns. Accordingly, once we take into consideration the effect of environmental quality on people's patience, the following questions naturally arise:

It is worth noting that there are also some studies (e.g., Lawrence, 1991; Ogaki and Atkenson, 1997; Samwick, 1998) which on the contrary support the theory that time preferences decrease with wealth.

[3] See, e.g., Ligthart and van der Ploeg (1994), Bovenberg and Smulders (1995), Chen et al. (2003), Itaya (2008), and Fullerton and Kim (2008).

What are the consequences of environmental policies for economic growth? What is the optimal rate of the environmental tax? Owing to the fact that none of the aforementioned articles with environmentally endogenous time preferences deals with these issues, we aim to explore them in this paper.

To this end, we develop a simple endogenous growth model featuring the capital externality suggested by Romer (1986) and Lucas (1988), in which the time preference is endogenized in the sense that it will be influenced by the environmental quality. As in Pittel (2002), we do not restrict the direction of such an effect. We allow three possibilities to occur, that is: the environmental quality may positively or negatively affect or not at all affect the agents' time preferences. Our results show that, in the absence of an endogenous time preference, there will always exist a trade-off relationship between the environmental protection and economic growth. However, in the presence of an additional external effect arising from the impact of environmental quality on the time preference, a higher environmental tax may boost the balanced growth rate. Although there are already numerous studies that advocate a positive growth effect of the environmental tax,[4] our analysis contributes to the literature by focusing on the positive effect resulting from an endogenous time preference depending on the environment.

Another interesting finding concerns the optimal rate of the environmental tax. The well-known Pigouvian tax requires that the optimal environmental tax rate be equal to the marginal social damage from pollution. Our result shows that, when

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[4] For the positive growth effect of the environmental tax, see, for instance, van Ewijk and van Wijnbergen (1995), Bovenberg and Smulders (1995, 1996), Bovenberg and de Mooij (1997), Smulders and Gradus (1996), Hettich (1998), Chen et al. (2003), Ono (2003a, 2003b), van Zon and Yetkiner (2003), Nakada (2004, 2010), Ricci (2007), Itaya (2008), and Pautrel (2012).

agents' time preferences can be influenced by the environment, the Pigouvian tax rate may be inefficient because it fails to internalize the impact of the additional environmental externality on time preferences. Furthermore, the optimal environmental tax rate could be higher than, lower than, or equal to the marginal damage from pollution, depending on the distinctive features of the time preference.

The remainder of this paper is organized in the following way. Section 2 presents the basic growth model with endogenous time preferences. Section 3 discusses the policy implications of an endogenous time preference on economic growth. Section 4 examines the efficiency of the Pigouvian environmental tax. The final section concludes.

2. The Model

We consider an infinite-horizon economy comprised of a continuum of identical households, a large number of polluting firms, and a government. All firms are assumed to be identical and we normalize the number to unity. A representative firm produces a single final good y using the technology $y = \Lambda k^{\alpha} z^{1-\alpha}$ ($1 > \alpha > 0$)[5], where k is the capital employed and z denotes a "dirty input". To ensure sustainable growth, we assume that the term Λ represents the Romer-type externality on capital, i.e., $\Lambda = AK^{1-\alpha}$, where K is the aggregate capital stock, and $A > 0$ is a constant technology parameter.[6] Because the number of firms is unity,

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[5] The time arguments are omitted for notational simplicity.

[6] The role of Λ is to ensure constant returns to scale to (a broad sense of) capital, and is thus able to sustain ongoing growth. This technology, which has been known as the AK-type endogenous growth model, exhibits a merit of obtaining tractable results and has been extensively used to analyze the effects of policies on growth performance. Moreover, it should be noted that because each firm is

we will have $K = k$ in equilibrium. Let τ_k and T_P denote the capital tax rate and the pollution tax rate, and r the capital rental rate. The firm's profit can then be expressed as follows:

$$\pi = y - (1+\tau_k)rk - T_p z \,. \tag{1}$$

To prevent pollution from continuously growing, we must assume that T_p evolves with the aggregate capital stock, i.e., $T_p = \tau_p K$ where $\tau_p > 0$ is a policy parameter.[7] It is quite easy to derive first-order conditions for k and z:

$$\alpha \Lambda k^{\alpha-1} z^{1-\alpha} = (1+\tau_k) r \,, \tag{2}$$

$$\beta \Lambda k^{\alpha} z^{-\alpha} = T_p \,. \tag{3}$$

The use of the dirty input generates pollution emissions, which affect both the household's felicity and time preference. A representative household's instantaneous felicity function is given by:

$$u = \frac{(cz^{-\eta})^{1-\sigma}}{1-\sigma} \,, \tag{4}$$

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small relative to the aggregate level, it takes the aggregate stock K as given when choosing k. That is, there are diminishing returns to capital at the microeconomic (firm) level, but the existence of externalities results in constant returns to capital at the macroeconomic level. For a comprehensive rationale of the AK technology, see Turnovsky (2000) and Heijdra (2009).

[7] If we assume a constant tax rate, the dirty inputs (pollution) will grow to infinity in the endless future. In this case, the economy will be forced to break down when the level of pollution exceeds the amount that human beings can bear. Thus, in the environmental endogenous growth literature, it is common and necessary for the (private or public) price of pollution to evolve with another growing factor (see, e.g., Bovenberg and Smulders, 1995; Ono, 2007; Fullerton and Kim, 2008). See also Smulders (1995) for a comprehensive discussion on this point.

where c is the consumption and σ the intertemporal substitution elasticity. We follow Ayong Le Kama and Schubert (2007) to assume that $\sigma > 1$ to ensure that the felicity function is concave, i.e., $u_{11}u_{22} - (u_{12})^2 \geq 0$ where $u_1 = \partial u / \partial c$ and $u_2 = \partial u / \partial z$. The parameter $\eta > 0$ measures the negative impact of pollution on felicity.

The representative household's lifetime utility can be written as:

$$U = \int_0^{\infty} u(\cdot) \exp[-\Theta] dt \,, \tag{5}$$

where

$$\Theta_t \equiv \int_0^t \theta(z_s) ds \,, \quad \dot{\Theta} = \theta(z) \,, \text{ and } \quad \theta'(z) \gtreqless 0 \,.$$

Here Θ is the endogenous discount factor determined by the past and current levels of the environmental quality. It can also be referred to as an indicator of accumulated impatience (Obstfeld, 1990). As revealed in (5), pollution not only has a negative impact on the level of utility, but also influences the household's time preference, described by the term $\theta(z)$.[8]

The sign of $\theta'(z)$ is crucial throughout the analysis. To reflect different specifications in the existing literature, we assume that the sign of $\theta'(z)$ can be greater than, less than, or equal to zero. The specification $\theta'(z) < 0$ reflects the

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[8] In our model, the dirty inputs z could specifically refer to petroleum, fuel oil or natural gas. These inputs, when used in the production process, generate pollution that harms environmental quality. For the sake of simplicity, we assume that the amount of dirty inputs directly represents the index of environmental quality and, accordingly, serves as a factor that affects the household's utility and time preferences. A similar setup may be found in, e.g., Chang et al. (2009) and Yanase (2011). Abandoning this assumption and using a more complicated environmental system will not affect our results as long as dirty inputs are monotonically related to environmental quality.

type of time preference in Ayong Le Kama and Schubert (2007); in this case a higher z (i.e., a worse environment) causes patience. By contrast, the specification $\theta'(z) > 0$ reflects the type of time preference in Yanase (2011) and Vella et al. (2014); in this case a higher z (i.e., a worse environment) induces impatience. Finally, $\theta'(z) = 0$ represents the traditional approach of an exogenous time preference.

Let $\hat{\varphi}$ be the co-state variable associated with the capital stock. The representative household maximizes the lifetime utility reported in equation (5), subject to the budget constraint $\dot{k} = rk + R - c$ by choosing $\{c, k, \hat{\varphi}\}_{t=0}^{\infty}$ where R is the lump-sum transfer from the government. We can then define the Hamiltonian for the household's optimization as:

$$H^h = \frac{(cz^{-\eta})^{1-\sigma}}{1-\sigma}\exp[-\Theta] + \hat{\varphi}(rk + R - c), \tag{6}$$

The optimum conditions for the representative household with respect to the indicated variables are:

$$c: \quad c^{-\sigma} z^{-\eta(1-\sigma)} = \varphi, \tag{7a}$$

$$k: \quad \dot{\varphi} = \theta(z)\varphi - r\varphi, \tag{7b}$$

$$\hat{\varphi}: \quad \dot{k} = rk + R - c, \tag{7c}$$

where $\varphi = \hat{\varphi}\exp[\Theta]$ and the transversality condition is $\lim_{t\to\infty} \hat{\varphi}k = 0$. Equations (7a) and (7b) are the first-order conditions with respect to c and k, respectively. Equation (7c) is the household budget constraint. Of particular note, the household cannot affect the level of pollution so that it takes as given pollution z and the rate of time preference Θ.

The government rebates its tax revenues to the household in the form of a lump-sum transfer R. As a result, the government's flow budget constraint can be written as:

$$R = \tau_k rk + \tau_p kz \tag{8}$$

2.1. The decentralized equilibrium

The decentralized equilibrium is described by six equations, (2), (3), (7a), (7b), (7c), and the government budget constraint (8), in which the six unknowns, c, k, r, z, φ, and R, can be solved (see Appendix A for the full solution). Moreover, by defining the transformed variable $x \equiv c/k$, we can demonstrate that $\mathrm{d}\dot{x}/\mathrm{d}x > 0$, which means that the steady state is unstable and the competitive equilibrium path has no transitional dynamics.

Proposition 1. *The macro equilibrium under the decentralized economy is unique and locally determinate.*

Proof: See Appendix A.

3. The Growth Effect of an Environmental Tax

We now deal with the growth effect of the environmental tax in the presence of an endogenous time preference. Following the literature on the environment and endogenous growth, we assume that in the steady state of balanced growth the total pollution emissions are limited in a physical sense, and all other economic variables grow at a common constant endogenous growth rate *g*. By letting a tilde denote the value along the balanced growth path (BGP), we introduce the following definition:

Definition 1. *The steady state of balanced growth is characterized by an equilibrium where* $\dot{z} = 0$ *and* $\dot{k}/k = \dot{c}/c = \dot{y}/y = \tilde{g}$.[9]

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[9] From (3) and $T_p = \tau_p k$ we can derive $z = \left[(1-\alpha)A/\tau_p\right]^{1/\alpha}$, which depends only on the exogenous parameters. This means that the condition $\dot{z} = 0$ is always met under the decentralized economy.

Based on Definition 1, we can obtain the balanced growth rate in the decentralized economy (see Appendix B), denoted by $\tilde{g}^d$, as:

$$\tilde{g}^d = \frac{1}{\sigma}\left[\frac{1}{1+\tau_k} A\alpha \tilde{z}^{1-\alpha} - \theta(\tilde{z})\right], \tag{9}$$

where $\tilde{z} = \left[(1-\alpha)A/\tau_p\right]^{1/\alpha}$ denotes the (constant) value of the dirty input in the steady state of balanced growth.

The relationship between the environmental tax and the long-term growth rate can be derived by differentiating $\tilde{g}^d$ with respect to τ_p, which yields:

$$\frac{\mathrm{d}\tilde{g}^d}{\mathrm{d}\tau_p} = \frac{(1-\alpha)A}{\sigma\alpha\tau_p^{\;2}} \tilde{z}^{1-\alpha}\left[-\frac{\alpha\tau_p}{1+\tau_k} + \theta'(\tilde{z})\right]. \tag{10}$$

The result reported in (10) leads to the following proposition:

Proposition 2. *In the cases of time preferences featuring* $\theta'(z) < 0$ *and* $\theta'(z) = 0$, *raising the environmental tax reduces the growth rate. However, in the cases of time preferences featuring* $\theta'(z) > 0$, *the growth effect of the environmental tax is uncertain, implying that a rise in the environmental tax may boost economic growth.*

Proposition 2 indicates that if people become impatient due to their experience of a worse environmental quality, any policies that protect the environment can also positively contribute to economic growth. A similar result (i.e., an environmental tax that induces a positive growth effect) is obtained in different setups considering, for example, the impact of a positive environmental externality on production (Bovenberg and Smulders, 1995; Fullerton and Kim, 2008), a positive externality in relation to abatement activities (Smulders and Gradus, 1996), an elastic labor supply (Hettich, 1998; Chen et al., 2003), the international accumulation of environmental assets (Ono, 2003a), and the existence of an indeterminate equilibrium path (Itaya, 2008). Despite the fact that a growth-stimulating environmental tax is not novel in the literature, none of these previous contributions is related to endogenous time preferences. Thus, the major contribution of this present paper is to highlight the role of environment-dependent time preferences in the context of the impact of environmental policies on economic growth. In particular, Proposition 2 draws our attention to the point that different types of time preferences can generate diverse consequences of an environmental tax. Overlooking this time preference effect may lead policy-makers to devise inadequate environmental policies.

4. Social Planner and the Optimal Environmental Tax

Now we turn to study the optimal environmental tax. In line with the Bovenberg and Goulder (1996) definition, the Pigouvian principle requires that the environmental tax be equal to the marginal environmental damage (MED) from pollution. With this definition, in this section, we focus on whether the Pigouvian principle is optimal when time preferences can be influenced by environmental quality.

To derive the optimal tax policies, we first solve the social planner's optimization problem. The social planner maximizes (5) subject to the resource constraint, $\dot{k} = y - c$, which can be derived by combining the household's budget constraint, the government's budget constraint, and the firm's profit function. The Hamiltonian for the social planner's optimization H^{sp} is given by:

$$H^{sp} = \frac{(cz^{-\eta})^{1-\sigma}}{1-\sigma}\exp[-\Theta] + \hat{\lambda}(y-c) - \hat{\mu}\theta(z), \tag{11}$$

where $\hat{\lambda}$ and $\hat{\mu}$ are the co-state variables associated with, respectively, the capital stock and the "stock of accumulated impatience" (Obstfeld, 1990). The first-order conditions for this problem are:

$$c^{-\sigma} z^{-\eta(1-\sigma)} = \lambda, \tag{12}$$

$$Az^{1-\alpha}\lambda = -\dot{\lambda} + \theta(z)\lambda, \tag{13}$$

$$-\eta c^{1-\sigma} z^{-\eta(1-\sigma)-1} + \lambda(1-\alpha)Akz^{-\alpha} - \mu\theta'(z) = 0, \tag{14}$$

$$-\frac{(cz^{-\eta})^{1-\sigma}}{1-\sigma} = \dot{\mu} - \mu\theta(z), \tag{15}$$

where $\lambda = \hat{\lambda}\exp[\Theta]$, $\mu = \hat{\mu}\exp[\Theta]$, and we need to impose the transversality condition $\lim_{t\to\infty} H^{sp} = 0$ to ensure utility maximization.

Some comments with regard to the optimal conditions of the social planner are worth mentioning here. First, in contrast to the representative household, the social planner takes into account the capital externality and social marginal cost of pollution when choosing k and z. Second, in contrast to the representative household, the social planner reckons in the effect of pollution on time preferences when selecting z. Third, let us first consider the case of exogenous time preferences $\theta'(z) = 0$. It can be seen from (14) that increasing one unit of z is accompanied by two consequences: a decrease in the household's felicity (captured by the first term), and a higher output (captured by the second term). To put it more plainly, the social planner faces a trade-off between the environmental concerns and economic development. However, when the time preference depending on environmental quality is present, the social planner must additionally consider the effect of pollution on time preferences. This obviously complicates the decision-making process regarding pollution. Moreover, we will show in the following that this linkage may have important implications for the optimal environmental tax.

4.1. Stability of the socially optimal BGP

In this subsection, we discuss the stability property of the socially balanced growth path. First, we define $\varepsilon(z) \equiv z\theta'(z)/\theta(z)$ as the elasticity of the utility discount rate $\theta(z)$. Accordingly, the dynamic system of the centralized economy in z can be described by (see Appendix C)

$$\frac{\dot{z}}{z}=\frac{x}{\Delta}\left\{\left[\eta+\frac{\sigma}{1-\sigma}\varepsilon(z)\right]\theta(z)-[\sigma(1-\alpha)+\eta(1-\sigma)]Az^{1-\alpha}\right\}, \tag{16}$$

where

$$x=\frac{[1-\alpha-\varepsilon(z)]Az^{1-\alpha}}{\eta+\sigma\varepsilon(z)/(1-\sigma)}, \tag{16a}$$

$$\Delta\equiv\frac{\varepsilon'(z)}{\varepsilon(z)}z\sigma[(1-\alpha)Az^{1-\alpha}-\eta x]+[\varepsilon(z)-1+\alpha][\sigma(1-\alpha)+\eta(1-\sigma)]Az^{1-\alpha}. \tag{16b}$$

We assume that the condition $\varepsilon(z)<\min[\eta(\sigma-1)/\sigma,1-\alpha]$ is met throughout, which is sufficient to ensure that x is strictly positive. Finally, by linearizing (16) around the steady-state equilibrium and performing a few steps of mathematical manipulation, we obtain

$$\dot{z}=\tilde{x}\cdot(z-\tilde{z}), \tag{17}$$

where $\tilde{x}=x(\tilde{z})$ can be derived from (16a). Let ξ be the characteristic root of the dynamic system. Then, from (17) we have $\xi=\tilde{x}>0$. Given that ξ is an unstable characteristic root and z is a control variable, we can thus conclude that the socially balanced growth equilibrium is locally determinate. In other words, the social planner's economy jumps to a unique balanced growth path.

Proposition 3. *The socially optimal BGP is unique and locally determinate.*

4.2. Optimal environmental tax

Now we deal with the optimal environmental tax policy. Of particular note, we focus on the optimal tax rule in the sense that it achieves the socially optimal steady state of balanced growth. By comparing (12) with the household's first-order conditions, we can derive the necessary condition $\lambda=\varphi$ to reach the optimal outcome. In Appendix D we derive the optimal tax rates on capital and the pollution input, which are:

$$\tau_k^* = \alpha - 1, \tag{18}$$

$$\tau_p^* = \eta \frac{\tilde{x}}{\tilde{z}} + \frac{\theta'(\tilde{z})}{1-\sigma}. \tag{19}$$

To examine the efficiency of the Pigouvian principle, we follow Bovenberg and Goulder (1996) to define the MED of pollution (in terms of the marginal utility of capital), denoted by D, as

$$D \equiv -\frac{\partial u / \partial z}{\lambda}. \tag{20}$$

We define $\tilde{D} \equiv D/k$ to evaluate the MED in the steady state, and by using (12) and (20) we can obtain

$$\tilde{D} = \eta \frac{\tilde{x}}{\tilde{z}}. \tag{21}$$

By inserting (21) into (19) and given $\sigma > 1$, we can see that τ_p^* is higher than, lower than, or equal to MED if $\theta'(z)$ is lower than, higher than, or equal to zero. Thus we have the following proposition:

Proposition 4. *In the case of an exogenous time preference, the Pigouvian principle is optimal. In the case of an endogenous time preference, by contrast, the optimal environmental tax rate should be higher (lower) than MED if* $\theta'(z) < 0$ ($\theta'(z) > 0$).

In the decentralized economy, there exist three kinds of externalities (distortions): (i) the capital externality, (ii) the pollution externality in terms of felicity, and (iii) the pollution externality in terms of time preferences. In view of (16), it should be noted that the optimal capital tax rate $\tau_k^* = \alpha - 1$ is strictly negative, which indicates that the government should subsidize the use of capital to remove distortion (i). This is because the atomistic firms do not recognize the positive externality of capital, so that the level of aggregate capital in the decentralized equilibrium will be inefficiently low. Therefore, to achieve the social optimum, it is necessary to motivate the firm to employ more capital by subsidizing it (see, for example, Barro and Sala-i-Martin, 1992).

More importantly, in (19) we see that the optimal environmental tax should be utilized to correct distortions (ii) and (iii). Nevertheless, the well-known Pigouvian principle suggests that a tax rate on the pollution emissions is equal to MED. As a consequence, it can remedy distortion (ii) but fails to correct distortion (iii). This means that the Pigouvian principle is efficient only when distortion (iii) is absent, that is, only when the time preferences do not depend on the environmental quality ($\theta'(z)=0$). In the presence of distortion (iii) ($\theta'(z)\neq 0$), however, the Pigouvian principle cannot remedy such an inefficiency arising from the environment-dependent time preferences.[10]

Proposition 4 shows us that whether the optimal environmental tax rate should be higher or lower than MED depends crucially on the types of time preferences. The intuition can be explained by inspecting equation (14), which is the social planner's optimal choice of z. We first consider the case of $\theta'(z)>0$. In this case, the third term on the left-hand-side of (14) is positive (note that $\mu<0$; see Appendix D). This represents a beneficial effect of raising z, and thus implies that the social

[10] A considerable number of studies (e.g., Bovenberg and de Mooij, 1994; Bovenberg and Goulder, 1996; Williams, 2002, 2003; Bento and Jacobsen, 2007; Liu, 2013) have examined whether the Pigouvian principle is efficient and many of them have reached the conclusion that the answer is no. A main reason for the inefficiency of a Pigouvian tax in previous studies is the preexistence of other distortionary taxes. In departing from these studies, our paper instead stresses that the inefficiency of a Pigouvian tax comes from the existence of the environment-dependent time preferences.

planner tends to choose a higher level of z. To interpret this result, we must notice that by implementing the optimal capital tax rate $\tau_k^* = \alpha - 1$, the social planner can reconcile the decentralized growth rate with the socially optimal growth rate. With the consumption path being the same, a higher time preference implies that the households can enjoy a higher level of welfare. By taking this effect into account, the social planner will tend to choose a higher z (i.e., a higher $\theta(z)$). As a consequence, the optimal environmental tax should be lower than that in the case of an exogenous time preference (i.e., in the case where the optimal environmental tax is equal to MED). Following a similar inference, we can conclude that under the case where $\theta'(z) < 0$, the optimal environmental tax rate should be higher than MED.

5. Concluding Remarks

This paper sets up a simple endogenous growth model in which time preferences are endogenously determined by the environmental quality. Our model comprehends different types of time preferences in the previous literature. We show within this framework that both the growth effect of environmental taxes and the efficiency of the Pigouvian tax rate are crucially related to the distinctive feature of the time preferences. In particular, we demonstrate that a Pigouvian tax may be inefficient in the presence of an endogenous time preference.

Regarding future research, it would be relevant to investigate empirically what types of time preferences the public owns. Another interesting line would be to examine whether countries differ in the types of time preferences and, if they do, what factors cause the differences. Based on our theoretical analysis, we believe that these empirical studies would be valuable in designing environmental policies.

Appendix A: The Decentralized Equilibrium

In this Appendix, we first derive the full solution in the decentralized economy, and then examine the stability property of the dynamic system. The decentralized equilibrium is described by six equations: (2), (3), (7a), (7b), (7c), and the government budget constraint (8) together with $\Lambda = AK^{1-\alpha}$ and $K = k$, which are restated as follows:

$$(1+\tau_k)r = \alpha A z^{1-\alpha}, \tag{A1}$$

$$(1-\alpha)Akz^{-\alpha} = \tau_p k, \tag{A2}$$

$$c^{-\sigma} z^{-\eta(1-\sigma)} = \varphi, \tag{A3}$$

$$\dot{\varphi} = \theta(z)\varphi - r\varphi, \tag{A4}$$

$$\dot{k} = rk + R - c, \tag{A5}$$

$$R = \tau_k rk + \tau_p kz. \tag{A6}$$

The above six equations determine six unknowns: r, z, c, k, φ, and R.

To derive the optimal choice of the firms, we first make use of (A2) to obtain the steady-state dirty input $\tilde{z} = \left[(1-\alpha)A/\tau_p\right]^{1/\alpha}$. By substituting $\tilde{z}$ into (A1), the steady state capital rental rate is $\tilde{r} = \left[\alpha A/(1+\tau_k)\right]\left[(1-\alpha)A/\tau_p\right]^{(1-\alpha)/\alpha}$.

Given that other endogenous variables { c, k, φ, R } evolve continuously, we then need to define the transformed variables $x \equiv c/k$, $f \equiv \varphi k^{\sigma}$, and $q \equiv R/k$ to obtain the stationary values of these transformed variables. Differentiating (A3) with respect time and using the household's budget constraint (A5), we can derive $\tilde{x} = A\tilde{z}^{1-\alpha} - \left[\tilde{r} - \theta(\tilde{z})\right]/\sigma$ in which we have used the steady state condition $\dot{x} = \dot{z} = 0$ (recall that in footnote 9 we have shown that $\dot{z} = 0$ is always met). Based on (A3), we obtain $\tilde{f} = \tilde{x}^{-\sigma}\tilde{z}^{-\eta(1-\sigma)}$. Finally, from (A6) we can derive $\tilde{q} = \tau_k\tilde{r} + \tau_p\tilde{z}$.

We now turn to examine the stability property of the dynamic system. From (7a), (7b), and (7c) we can derive

$$\frac{\dot{k}}{k} = r + \tau_k r + \tau_p z - x\,, \tag{A7}$$

$$\frac{\dot{c}}{c} = \frac{[r - \theta(z)]}{\sigma}\,. \tag{A8}$$

Thus, the dynamics of the consumption-capital ratio can be derived as

$$\frac{\dot{x}}{x} = \frac{\dot{c}}{c} - \frac{\dot{k}}{k} = \frac{(1-\sigma)r - \theta(z)}{\sigma} - \tau_k r - \tau_p z + x\,, \tag{A9}$$

It is clear from equations (A1) and (A2) that r and z are solely determined by the exogenous parameters. As a result, the right-hand side of (A9) is increasing in x, implying that the decentralized equilibrium is characterized by local instability and determinacy.

Appendix B: Derivation of the Balanced Growth Rate

First, by utilizing the conditions of the BGP, $\dot{z}/z = 0$, and (7a) and (7b) it is easy to obtain that

$$\tilde{g}^d = \frac{\dot{c}}{c} = \frac{1}{\sigma}\left[\tilde{r} - \theta(\tilde{z})\right]. \tag{A10}$$

Then, by substituting $\Lambda = AK^{1-\alpha}$ into (2) and (3) as well as using the equilibrium condition $K = k$, we can obtain $\alpha A\tilde{z}^{1-\alpha} = (1+\tau_k)\tilde{r}$ and $(1-\alpha)A\tilde{z}^{-\alpha} = T_p / k = \tau_p$. Lastly, inserting these two conditions into (A10) gives the balanced growth rate (9) in the main text.

Appendix C: Derivation of Equation (16)

First, we define $\varepsilon(z) \equiv z\theta'(z)/\theta(z)$ as the elasticity of the utility discount rate $\theta(z)$ and make use of the transversality condition $H^{sp}(t) = 0\ \forall t$ to derive

$$-\eta x+\beta A z^{1-\alpha}=\varepsilon(z)\left(\frac{\sigma}{1-\sigma}x+Az^{1-\alpha}\right). \tag{A11}$$

Differentiating (A11) with respect to time t, we obtain

$$\left[\frac{\varepsilon'(z)}{\varepsilon(z)}z+\frac{(\varepsilon(z)-1+\alpha)(1-\alpha)Az^{1-\alpha}}{(1-\alpha)Az^{1-\alpha}-\eta x}\right]\frac{\dot{z}}{z}=-\frac{x}{(1-\alpha)Az^{1-\alpha}-\eta x}\left[\eta+\frac{\sigma}{1-\sigma}\varepsilon(z)\right]\frac{\dot{x}}{x}. \tag{A12}$$

Moreover, equation (12) can be rearranged as $x^{-\sigma}z^{-\eta(1-\sigma)}=\lambda k^{\sigma}$. Differentiating this equation with respect to time t yields

$$\frac{\dot{x}}{x}=-\frac{1}{\sigma}\left[\theta(z)-(1-\sigma)Az^{1-\alpha}-\sigma x+\eta(1-\sigma)\frac{\dot{z}}{z}\right], \tag{A13}$$

where we have used (13) and the resource constraint $\dot{k}=Az^{1-\alpha}-c$. Combining (A12) and (A13) and using (A11), we can derive equation (16) in the main text.

Appendix D: Derivation of Equations (18) and (19)

In line with the proof in Palivos et al. (1997) and Ayong Le Kama and Schubert (2007), by the transversality condition $H^{sp}(t)=0\ \forall t$ we have

$$\mu=\frac{1}{\theta(z)}\left[\frac{(cz^{-\eta})^{1-\sigma}}{1-\sigma}+\lambda(Akz^{1-\alpha}-c)\right]. \tag{A14}$$

In line with Ayong Le Kama and Schubert (2007), we can demonstrate that $\mu<0$ given that $\sigma>1$. By inserting (12) and (A14) into (14) we can obtain

$$-\eta\frac{c}{z}+(1-\alpha)Akz^{-\alpha}=\frac{\theta'(z)}{\theta(z)}\left(\frac{\sigma}{1-\sigma}c+Akz^{1-\alpha}\right), \tag{A15}$$

and by evaluating the steady state, we have

$$-\eta\frac{\tilde{x}}{\tilde{z}}+(1-\alpha)A\tilde{z}^{-\alpha}=\frac{\theta'(\tilde{z})}{\theta(\tilde{z})}\left(\frac{\sigma}{1-\sigma}\tilde{x}+A\tilde{z}^{1-\alpha}\right). \tag{A16}$$

Then, utilizing (12) and (13) yields

$$\tilde{g}^{sp}=\frac{1}{\sigma}\left(A\tilde{z}^{1-\alpha}-\theta(\tilde{z})\right). \tag{A17}$$

The first-best tax rates are derived by comparing (A16) and (A17) with the decentralized decisions (3) and (9).

Lastly, from (A8) and the resource constraint $\dot{k} = y - c$ we can derive

$$\frac{\dot{x}}{x} = \frac{\dot{c}}{c} - \frac{\dot{k}}{k} = \frac{r - \theta(z)}{\sigma} - Az^{1-\alpha} + x, \tag{A18}$$

At the steady state, $\dot{x} = 0$ such that $\tilde{x} = -(r - \theta(z))/\sigma + Az^{1-\alpha}$. Next, by inserting $\tilde{x}$ into (A16) as well as by utilizing $\tau_k = \alpha - 1$ and $\alpha A\tilde{z}^{1-\alpha} = (1 + \tau_k)\tilde{r}$, we can obtain (19) in the main text.

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