國立政治大學經濟學系博士論文

環境政策與內生成長

Environmental Policies and Endogenous Growth

指導教授：賴景昌 教授

研究生：朱 巡 撰

中華民國一百零一年十二月

謝辭

感謝我的指導教授 賴景昌老師。在博士生涯中，老師對我的影響絕對是全面性的。除了知識上的傳授，老師對教學的高標準要求、做研究的態度、看學術的視野、甚至待人處事的方法都為我們樹立了良好的典範。其中最讓我欽佩的是即使老師已有相當傲人的學術成就，對追求學問的熱忱仍是我們這些後輩學者所遠不能及。但老師也告訴我們做學問從不要有壓力，常說的一句口頭禪「快樂的做研究」每每在我寫論文遇到困難時給我重新出發的動力。另外也要感謝老師在求學期間提供了良好的研究環境與充足資源，讓我能更無後顧之憂地完成論文的撰寫。

感謝我的口試委員 周登陽老師、 洪福聲老師、 陳明郎老師、 張俊仁老師與 賴育邦老師，在百忙中願意抽空審閱我的論文，指正疏漏並提供許多寶貴建議，令論文更臻完整，謹此致謝。我也非常感謝 陳鎮洲老師與 賴育邦老師在學校亦師亦友的提攜與照顧。感謝志興學長從不吝嗇分享經驗，給予我諸多指導與幫助。另外感謝映安學姐、祥玉、緁炫、晉祥、惠婷、振維、冠任與平河，互相扶持打氣並為漫長的博士生涯增添色彩。

謝謝老爸、老媽、老哥和家裡的三隻傻貓，家裡因為有你們充滿了歡笑，回到家總是讓我心情愉悅，將煩惱拋諸腦後。最後當然要謝謝竹小君一路走來的陪伴與支持，生命有了你們太美好，我將此論文獻給你們。

朱　巡

2012年12月

摘要

環境保護可以與經濟成長兼顧嗎？本論文試圖回答這個問題。我們發展三個包含環境外部性的內生成長模型，透過不同管道來證明較嚴格的環境政策可能同時改善環境品質與促進經濟成長。更具體言之，在第二章中我們假設中間財廠商向國外以固定價格購買污染要素，此情況下環境政策將存在正的成長率效果；在第三章中我們考慮一個疊代內生成長模型，主張假如環境稅收移轉給年輕世代的部分很大，環境稅有可能提高經濟成長率；在第四章中我們證明當較好的環境品質會提高民眾儲蓄意願，提高環境稅可以促進經濟成長。本論文的主要結果與近二十年來崛起的文獻認為環境保護政策也可能有利經濟成長相一致。

Abstract

Can environmental protection be compatible with economic growth? In this dissertation we attempt to answer this question. We develop three frameworks that incorporate the elements of endogenous growth and environmental externalities. We argue that, via different channels, implementing a tighter environmental policy could simultaneously be beneficial to the environmental quality and the long-term economic growth rate. More specifically, in Chapter II we present the positive growth effect of environmental policies by assuming that the intermediate firms import the polluting inputs from abroad at a fixed price. In Chapter III, we consider an OLG framework and demonstrate that if the portion of tax revenues transferred to young generations is large, it is possible for an environmental tax to boost the growth rate. In Chapter IV, it is shown that when a cleaner environment can induce people more willing to save for future consumption, increasing the environmental tax could stimulate growth. The main findings of this dissertation join the literature advocating a beneficial growth effect of an environment protection policy in the last two decades.

Contents

Chapter I

Introduction

Can environmental protection be compatible with economic growth? Over the last few decades environmentalists and economists have engaged in this fundamental question. However, the answer to this question is hardly conclusive. While earlier theories suggest the answer is no, Bovenberg and Smulders (1995) demonstrate that the environmental taxation may stimulate economic growth by assuming that a better environmental quality is beneficial to input productivity. Since then there has been a rapidly increasing body of researches that advocate a beneficial growth effect of an environment protection policy. In this dissertation we make an attempt to contribute to this debate. We provide three frameworks incorporating the elements of economic growth and environmental externalities. The central goal is to bring up some new channels that are not explored in previous studies, via which a tighter environmental policy may stimulate long-term economic growth.

In Chapter II, we first pay our attention to an important channel in environmental economics, namely the pollution abatement. In standard models on environment and economic growth, pollution is usually treated as an input or a by-product of output. As endogenous growth theory requires output and consumption to grow unlimitedly, it is essential to abate pollution within a survival level in the long run. According to previous studies on the relationship between pollution abatement and economic growth, the research and development (R&D) of the abatement technology/knowledge is conducted only by the public sector. This setting, however, is not very realistic because both real-life observations and empirical evidences show that private and public investment in abatement technology coexist. Indeed, we often observe that abatement technologies are developed in a private upstream sector and then are sold to downstream polluting industries. Motivated by this discrepancy between theories and actuality, in Chapter II we construct a model that is able to consider both possibilities of public and private abatement R&D.

The contribution of the framework is twofold. First, we highlight the positive growth effect of environmental policies by assuming that the intermediate firms import polluting inputs from abroad at a fixed price. We demonstrate that, as the environmental tax raises, the value of abatement knowledge increases so that more abatement knowledge would be invested. In other words, the higher environmental tax reduces the pollution by way of an accumulation of abatement R&D, with the amount of polluting inputs unchanged (because the import price is fixed). Therefore, the environmental quality is better with the same level of polluting inputs. Given that a cleaner environmental quality is beneficial to productivity, the environmental tax has an unambiguously positive effect on economic growth.

Second, within this framework we are able to make a comparison of economic performances under the regimes of private and public abatement investment. In particular, we compare the relative superiority in terms of economic growth and social welfare among various regimes. It is found that a higher growth rate can be achieved if the abatement R&D is conducted privately with the government subsidy. In addition, we show that the economic performance under the private provision of abatement knowledge depends mainly on the monopoly power of the polluting firms. This is because the incentive for the environmental R&D sector to engage in R&D increases with the intermediate firms' profit. As the monopoly power is greater, the benefit arising from the private implementation of abatement is larger, and thus more (private) R&D activities will be conducted, resulting in a higher growth rate. Our results highlight that market imperfections play an important role when integrating abatement investment with private incentives.

In Chapter III, we investigate the linkage between environmental quality and economic growth in an overlapping generations (OLG) model developed by Diamond (1965). The degradation of the environment often requires a period of time. Existing generations who pollute the environment today may not live long enough to bear the consequences of environmental deterioration in the future. An environment protection policy, therefore, should have different effects on the welfare level of different generations. An infinitely-lived agent model, as presented in Chapter II, cannot reflect this effect. Hence we resort to the OLG model.

We show that the growth effect of the environmental tax depends on how the tax revenue is split out among young and elders. When the environmental tax goes up, it reduces the young agents' wage income, and therefore the young generation will tend to reduce both consumption and savings. On the other hand, with part of the tax revenues being transferred to young generations, they will save more with a higher environmental tax since they can receive more transfer income. If the portion of tax revenues transferred to young generations is large, it is possible for an environmental tax to stimulate the growth rate.

The last channel that may result in a positive growth effect of environmental policies is related to an endogenous time preference depending on the environmental quality, which we plan to present in Chapter IV. The notion that as environmental quality changes people will become more patient (or impatient) is first brought up by Pittel (2002). A plausible reason to illustrate the idea might be to think that if the environment is going to be severely damaged and below the physical condition for life, then saving would become meaningless. Therefore, for a rational individual it is very nature to alter the time preference with a different environmental quality. However, in the previous literature on environment and economic growth, this effect is surprisingly overlooked. Hence, in this chapter we will make an effort to examine the implications of such an endogenous time preference on the growth effect of environmental protection policies.

More specifically, we develop an endogenous growth model featuring the capital externality proposed by Romer (1986) and Lucas (1988), in which the agent's time preference is endogenously determined by the environmental quality. We will show that, in the absence of an endogenous time preference, there is a trade-off relationship between environmental quality and economic growth. By contrast, in the presence of an additional external effect arising from environmental quality on time preference, increasing the environmental tax may boost the balanced growth rate, implying that environmental protection can be compatible with economic growth. Moreover, we demonstrate that the famous Pigouvian tax rate may be inefficient in the presence of the environmentally endogenous time preference.

Finally, the main results of each chapter and some implications to the theories are summarized in Chapter V.

References

Bovenberg, A. L. and S. Smulders (1995), Environmental quality and pollution-augmenting technical change in a two-sector endogenous growth model, *Journal of Public Economics* 57, 369-391.

Diamond, P. A. (1965), National debt in the neoclassical growth model, *American Economic Review* 55, 279-293.

Heijdra, B. J., J. P. Kooiman and J. E. Ligthart (2006), Environmental quality, the macroeconomy, and intergenerational distribution, *Resource and Energy Economics* 28, 74-104.

Lucas, R. E., Jr. (1988), On the mechanics of economic development, *Journal of Monetary Economics* 22, 3-24.

Pittel, K. (2002), *Sustainability and Endogenous Growth*. Cheltenham, UK: Edward Elgar.

Romer, P. (1986), Increasing returns and long-run growth, *Journal of Political Economy* 94, 1002-1037.

Chapter II

Abatement R&D, Market Imperfections, and Environmental Policy in an Endogenous Growth Model

2.1. Introduction

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

Recent studies dealing with the relationship between pollution abatement and environmental growth, such as van Ewijk and van Wijnbergen (1995), Bovenberg and Smulders (1995, 1996), Fullerton and Kim (2008), treat abatement as technologies or knowledge that could be accumulated and developed in a separate sector (i.e., the environmental R&D sector).[1] Since knowledge is non-rival and has the characteristic of a public good, the costs associated with the use of abatement knowledge as an input are zero, while knowledge creation and accumulation, in contrast, require rival inputs and are costly.[2] This implies that, as stressed in Bovenberg and Smulders (1995), in a perfectly competitive market, abatement R&D could *not* be rewarded so that no innovation in abatement technologies would be

---

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

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

undertaken without the government's intervention. Therefore, the strand of this literature essentially assumes that abatement R&D activities are publicly conducted by the government.[3]

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

Another key feature of our model is that we introduce imperfect competition in the intermediate good market. As mentioned above, private abatement R&D requires incentives, which are not available in a perfect market because the competitive firms would not be left with any quasi-rent for abatement R&D. Hence, we should resort to a different market structure, such as an imperfectly competitive market. In the 1980s, several studies (e.g., Hart, 1982; Mankiw, 1985; Blanchard and Kiyotaki, 1987) noted that market power in the private sector plays a crucial role in the performance of government policy. More recently, Judd (2002) has also argued that imperfect competition is a key feature of dynamic modern economies.

---

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

The empirical evidence, on the other hand, suggests that polluting industries are often equipped with monopoly power (Beccarello, 1996; Considine, 2001). To reflect the observed facts, a considerable body of studies develop environmental economic models which take market imperfections into account (e.g., Fullerton and Metcalf, 2002; Greaker and Rosendahl, 2008; Chang et al., 2009).

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

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

The analysis of this chapter is also related to recent studies on the effect of environmental taxation on economic growth. The conventional wisdom in the literature (e.g., Huang and Cai, 1994; Ligthart and van der Ploeg, 1994; Grimaud, 1999) is often that there is an unavoidable conflict between economic growth and the conservation of the environment in the economy. However, in recent years a growing body of literature that proposes a positive growth effect of environmental taxation has accumulated. For example, in their frequently cited article, Bovenberg and Smulders (1995) find that environmental taxation has an ambiguous effect on economic growth by assuming that environmental quality is beneficial to input productivity.[4] In departing from this strand of the literature, our analysis assumes that the pollution inputs are purchased from abroad at a non-bargaining price. Accordingly, a higher environmental tax will reduce the pollution by way of an accumulation of abatement R&D, but the polluting inputs will remain unchanged. Since an environmental tax does not decrease the level of polluting inputs (and thereby the marginal productivities of other inputs), it undoubtedly spurs economic growth through the positive environmental productivity effect.

The remainder of this chapter proceeds as follows. Section 2.2 describes the model and solves the firms' and households' optimization problems. Section 2.3

---

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

deals with three distinct regimes associated with different abatement policies. Section 2.4 presents our simulation results and compares the growth rates and the welfare levels among the three regimes. Section 2.5 provides some concluding remarks.

2.2. The Model

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

2.2.1. Production sectors

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

$$Y = \left[\int_0^1 y_i^{1-\theta} di \right]^{\frac{1}{1-\theta}}, \qquad \theta \in [0,1). \tag{2.1}$$

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

Let π_Y denote the profit of the final good firm and q_i be the price of the *i*th intermediate good in terms of final output.[5] The maximization problem of the final good firm can be expressed as:

$$\underset{y_i}{Max}\, \pi_Y = \left[\int_0^1 y_i^{1-\theta} di\right]^{\frac{1}{1-\theta}} - \int_0^1 q_i y_i di\,, \tag{2.2}$$

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

$$y_i = (q_i)^{-\frac{1}{\theta}} Y\,. \tag{2.3}$$

It is quite clear from (2.2) that the demand function of the *i*th intermediate good has a constant price elasticity $1/\theta$. When θ approaches zero, intermediate goods are perfect substitutes in the production of the final good, implying that the intermediate goods sector is perfectly competitive. However, if $0 < \theta < 1$, intermediate good firms face a downward-sloping demand curve so that they can exert monopoly power. Since our main concern lies in the mutual interactions among environmental externality, abatement R&D, and market imperfections, in the following analysis we focus our attention on the case in which $0 < \theta < 1$.

Based on the fact that the final market is perfectly competitive, substituting (2.3) into (2.2) and imposing the zero-profit condition yields:

$$\int_0^1 q_i^{\frac{\theta-1}{\theta}} di = 1\,. \tag{2.4}$$

The technology for producing the *i*th intermediate good is given by:

$$y_i = A(N) k_i^{\alpha} e_i^{1-\alpha} l_{yi}^{\beta}, A'(N) > 0\,,^{6} \tag{2.5}$$

where A is an environment-productivity function, N is environmental quality, and k_i, l_{yi} and e_i are the capital, labor and emission inputs used by the *i*th intermediate

---

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

[6] It is worthy noting that in a monopolistic competition market, although the production function is an increasing-returns-to-scale form, it does not necessary imply negative profits as long as the monopoly power θ is large enough (see, e.g., Benhabib and Farmer, 1994). In fact, as will be seen later in our numerical example, the profit-output ratio of an intermediate firm is around 3.6%.

firm, respectively. To reflect the positive production externality arising from the environmental quality, (2.5) specifies that the output level of the intermediate goods rises with a better natural environment. The profit function of the *i*th intermediate firm π_i can then be expressed as:

$$\pi_i = q_i y_i - rk_i - me_i - \omega l_{yi} - \tau_P p_i , \tag{2.6}$$

where *r* is the capital rental rate, ω is the real wage, *m* is the price of the polluting input, and τ_P denotes a tax (or price of permits) that the government levies on actual pollution p_i. We assume that the intermediate firm purchases polluting input e_i from abroad so that the input price *m* is taken as given (e.g., the polluting input can be treated as if it were petroleum).

2.2.2. Environmental quality

The pollution generated in the production process of the *i*th intermediate firm is of the form:

$$p_i = \left(\frac{e_i}{H}\right)^{\frac{1}{\varepsilon}} , \tag{2.7}$$

where H is the stock of abatement knowledge, and $1/\varepsilon$ ($\varepsilon > 0$) is the elasticity of pollution production with respect to "abated polluting inputs". In (2.7), pollution is specified to be positively related to polluting input e_i and negatively related to abatement knowledge *H*. Accordingly, the total pollution *P* in the economy is the sum of polluting emissions generated by all intermediate firms:

$$P = \int_0^1 p_i di . \tag{2.8}$$

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

$$\dot{N} = bN(1-N) - P\,, \tag{2.9}$$

where a dot denotes the rate of change with respect to time, b is a parameter, and the term $bN(1-N)$ reflects the regeneration capacity of the environment, which might initially increase with a larger N but eventually decline when N exceeds a threshold value. (2.9) indicates that a rise in the level of pollution is associated with a decline in environmental quality in the next period. In the steady state, the environmental quality remains constant over time since pollution equals the regeneration capacity of the environment ($P = bN(1-N)$).

We restrict our analysis to a symmetric equilibrium in which $k_i = k$, $e_i = e$, $l_{yi} = l_y$, $p_i = p$, $\pi_i = \pi$, $y_i = y$, and $q_i = q$ for all *i*. As a result, from (2.1) we have $Y = \left[\int_0^1 y_i^{1-\theta} di\right]^{\frac{1}{1-\theta}} = y$. With $y = y_i$ and $q_i = q$, the profit of the final good firm stated in (2.2) then can be expressed by $\pi_Y = (1-q)y$. Given that the final good sector is perfectly competitive, the profit of the representative final good firm earns zero profit (i.e., $\pi_Y = 0$) in equilibrium. Accordingly, the zero-profit condition in the final good sector $\pi_Y = 0$ requires $q = 1$. Furthermore, let K, E, and L_y denote the aggregate capital stock, aggregate emission, and aggregate labor hired by the intermediate firms. Then, we have: $K = \int_0^1 k_i di = k$, $E = \int_0^1 e_i di = e$, $L_y = \int_0^1 l_{yi} di = l_y$. As a consequence, the intermediate firms' first-order conditions can be arranged as:

$$(1-\theta)\alpha\frac{Y}{K} = r\,, \tag{2.10}$$

$$(1-\theta)(1-\alpha)\varepsilon\frac{Y}{P} = \tau_P + \varepsilon mHP^{\varepsilon-1}\,, \tag{2.11}$$

$$(1-\theta)\beta\frac{Y}{L_y} = \omega\,. \tag{2.12}$$

(2.10)-(2.12) indicate that, given the environmental quality and abatement knowledge, firms equate the marginal product of the capital, labor and pollution to their respective marginal cost.

2.2.3. Households

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

$$W = \int_0^\infty \frac{(CN^\eta)^{1-\sigma} - 1}{1-\sigma} \exp[-\rho t] dt , \tag{2.13}$$

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

Each household is endowed with a fixed amount of labor $\overline{L}$, which is allocated to production between the intermediate goods (L_y) and research (L_H). We assume that labor is homogeneous and perfectly mobile across sectors. A unique wage rate must, as a result, hold. The representative household receives income by supplying labor and capital services to firms. Under the GA regime, it receives profits π in the form of dividends and lump-sum transfers G from the government.[7] Finally, a capital income tax rate τ_K is levied on the capital rentals. Accordingly, the budget constraint faced by the representative household can be expressed as:

---

[7] The budget constraint under PA and PAR regimes will be introduced in Section 2.3.2.

$$\dot{K}=(1-\tau_K)rK+\omega\bar{L}+\pi+G-C.^{8} \tag{2.14}$$

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

$$C^{-\sigma}N^{\eta(1-\sigma)}=\lambda, \tag{2.15}$$

$$\dot{\lambda}/\lambda=\rho-(1-\tau_K)r, \tag{2.16}$$

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

2.2.4. Abatement R&D activity

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

$$\dot{H}=\delta L_H H, \tag{2.17}$$

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

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

$$\frac{\dot{Y}}{Y}=\frac{\dot{C}}{C}=\frac{\dot{K}}{K}=\frac{\dot{H}}{H}=\frac{\dot{E}}{E}=g, \quad \dot{N}=\dot{P}=0, \tag{2.18}$$

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

2.3. Public versus Private Abatement

---

[8] We do not consider a labor income tax because the total labor supply is fixed.

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

2.3.1. Public abatement

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

$$G + q_H \dot{H} = \tau_K rK + \tau_P P, \tag{2.19}$$

where new abatement knowledge $\dot{H}$ is produced according to (2.17), and q_H is the price of abatement knowledge relative to final goods. (2.19) states that the government receives its revenues in the form of capital taxes $\tau_K rK$ and pollution taxes $\tau_P P$ to finance its provision of lump-sum transfer payments to the household G and public abatement investment $q_H \dot{H}$.

The government budget constraint (2.19) is consistent with the Fullerton and Kim (2008) specification, in which abatement knowledge is regarded as a public good and can be used freely by firms. Notice that since labor is perfectly mobile, the marginal revenue product of labor should be the same between two sectors. That is:

$$(1-\theta)\beta \frac{Y}{L_y} = q_H \frac{\partial \dot{H}}{\partial L_H}. \tag{2.20}$$

Using (2.17), (2.19), and (2.20) together with the household budget constraint yields the resource constraint of the economy:

$$\dot{K} = Y - C - mE\,. \tag{2.21}$$

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

$$g^* = \frac{1}{\sigma}\left[(1-\tau_K)(1-\theta)A(N^*)P^{*(1-\alpha)\varepsilon}h^{*1-\alpha}L_y^{*\beta} - \rho\right], \tag{2.22}$$

$$g^* = \delta(\overline{L} - L_y^*)\,, \tag{2.23}$$

$$(1-\theta)(1-\alpha)\varepsilon A(N^*)P^{*(1-\alpha)\varepsilon}h^{*1-\alpha}L_y^{*\beta} = \tau P^* + \varepsilon m h^* P^{*\varepsilon}\,, \tag{2.24}$$

$$(1-\theta)\beta A(N^*)P^{*(1-\alpha)\varepsilon}h^{*1-\alpha}L_y^{*\beta} = w^* L_y^*\,, \tag{2.25}$$

$$c^* = A(N^*)P^{*(1-\alpha)\varepsilon}h^{*1-\alpha}L_y^{*\beta} - g^* - m h^* P^{*\varepsilon}\,, \tag{2.26}$$

$$P^* = bN^*(1-N^*)\,, \tag{2.27}$$

$$\tau_K(1-\theta)\alpha A(N^*)P^{*(1-\alpha)\varepsilon}h^{*1-\alpha}L_y^{*\beta} + \tau P^* = \phi + w^*(\overline{L} - L_y^*)\,, \tag{2.28}$$

where the superscript “$*$” stands for the steady-state value.

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

2.3.2. Private abatement R&D

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

Following the literature of R&D-based endogenous growth models, e.g., Romer, (1990) and Barro and Sala-i-Martin (2004), two important assumptions are made. First, there is free entry into the upstream (R&D) sector so that the R&D firms earn zero profit. Second, an R&D firm charges a price for its ideas at which the intermediate firms are indifferent between buying (to produce) and not buying (to leave the market). More specifically, the *license fee* for new abatement knowledge must be equal to the net profit that a monopolistic firm can extract, that is:[9]

$$q_H = \frac{\pi}{\dot{H}} .^{10} \tag{2.29}$$

The profit function of the R&D firms π_H can be written as:

$$\pi_H = q_H \dot{H} - (1-s)\omega L_H , \tag{2.30}$$

where s is the subsidy rate for the labor employment of the R&D firm. Substituting (2.17) into (2.30) and imposing the zero-profit condition yields:

$$\delta q_H H = (1-s)\,\omega . \tag{2.31}$$

---

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

[10] In the standard R&D-based endogenous models, the intermediate firms make a one-off payment to R&D firms for the right to use the knowledge forever after. However, in our model the intermediate firms need to make flow payments to use the abatement knowledge in every period.

It should be noted that, under the PA regime, the government does not subsidize R&D activities, and hence this regime corresponds to $s = 0$. However, under the PAR regime, the government provides R&D subsidies, and hence this regime is associated with $s \neq 0$. We now deal with these two regimes in turn.

2.3.2.1 Private abatement R&D without tax recycling

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

$$G = \tau_K rK + \tau_P P \,. \tag{2.32}$$

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

$$\dot{K} = (1-\tau_K)rK + \omega\bar{L} + G - C \,. \tag{2.33}$$

Based on the above conditions, it can be shown that the resource constraint reported in (2.21) still holds in the PA regime. At the BGP equilibrium, the economy is described by (2.22)-(2.27) together with the following condition (mathematical derivations are provided in the Appendix):

$$g^* = \frac{\delta[1-(1-\theta)(\alpha+\beta)-(1-\theta)(1-\alpha)\varepsilon]}{(1-\theta)\beta} L_y^* - \frac{\delta(1-\varepsilon)mh^* P^{*\varepsilon}}{w^*} \,. \tag{2.34}$$

2.3.2.2. Private abatement R&D with tax recycling

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

$$G + s\omega L_H = \tau_K rK + \tau_P P \,. \tag{2.35}$$

After some manipulations, (2.34) and (2.35) can be modified as:

$$g^* = \frac{\delta[1-(1-\theta)(\alpha+\beta)-(1-\theta)(1-\alpha)\varepsilon]}{(1-s^*)(1-\theta)\beta} L_y^* - \frac{\delta(1-\varepsilon)mh^* P^{*\varepsilon}}{(1-s^*)w^*}\,, \tag{2.36}$$

$$\tau_K(1-\theta)\alpha A(N^*) P^{*^{(1-\alpha)\varepsilon}} h^{*^{1-\alpha}} L_y^{*\,\beta} + \tau P^* = \phi + s^* w^* (\overline{L} - L_y^*)\,. \tag{2.37}$$

The BGP economy can then be described by (2.22)-(2.27), (2.36), and (2.37), where eight unknowns h^*, c^*, P^*, N^*, L_y^*, w^*, g^*, and s^* are solved in eight equations.

2.4. Quantitative Results

A numerical analysis is presented in this section to trace how the growth rate and welfare level will react following a change in an environmental policy under the three regimes. To construct an illustrative example, we choose benchmark parameter values that are within the plausible ranges used in the literature. Table 2.1 lists the benchmark parameter values, and some interpretations concerning these parameter configurations should be provided here. First, in line with Fullerton and Kim (2008), we specify the environment productivity function as the form $A(N) = N^{\gamma}$ and set the following parameters: $\gamma = 0.77$, $\alpha = 0.24$, $b = 0.04$, $\eta = 0.7$. Second, the values $\sigma = 1.5$, $\beta = 0.67$, and $\rho = 0.05$ are based on the calibration exercises in Lucas (1990) and Stokey and Rebelo (1995). The monopoly power index $\theta = 0.33$ is adopted from Judd (1997), in which he considers the values $\theta \in [0.1, 0.4]$. Accordingly, the resulting profit ratio in our economy is 3.6%, and is conformable to the profit ratio of the typical US industry; see, e.g., Basu and Fernald (1997) and Guo and Lansing (1999).[11]

Third, to reflect the model's plausibility we choose $\tau_K = 0.16$ (based on the estimate reported by Auerbach, 1996) and $\phi = 0.03$ as policy parameters. This in

---

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

turn implies that the government's spending as a proportion of output is 17.4%, and hence this numerical value lies within the reasonable interval in the literature; see e.g., Gali (1994). Fourth, the pollution tax relative to the capital stock $\tau = \tau_P / K$ is set

Table 2.1

Parameter	Value	Parameter	Value
α	0.24	β	0.67
σ	1.5	ρ	0.05
ε	0.6	η	0.7
γ	0.77	θ	0.33
τ_K	0.16	ϕ	0.03
τ	30	δ	0.01
m	2.5	$\overline{L}$	20
b	0.04		

as 30 so that the ratio between the tax revenues and output is about 23.2%.[12] Fifth, as for the pollution conversion parameter, while Bovenberg and Smulders (1995) simply assume that ε is equal to 1, Fullerton and Kim (2008), however, relax this assumption and allow ε to vary from 0.6 to 0.9. A relatively low value of ε means that the elasticity of pollution production with respect to "abated polluting inputs" is high. That is, raising the level of polluting inputs will not only increase pollution, but will also accelerate the generation process. More specifically, the investment in abatement knowledge will be more important if the elasticity is higher. To highlight the role of abatement investment, we set $\varepsilon = 0.6$ as our parameter value. Finally, the values of $(m, \delta, \overline{L})$ are calibrated so that the balanced growth rate is 3.12%, which is close to the average growth rate for the past 30 years in the US.

2.4.1. Comparison of three regimes

---

[12] Supposing $K = 1$, in the steady state we have $P = 0.00133$ and $Y = 0.1721$. Accordingly, the ratio of pollution tax revenues to output is (30)(0.00133)/0.1721 = 23.18%, which is slightly higher than the 17.8% in Fullerton and Kim (2008). As pointed out by Fullerton and Kim, it is inappropriate to compare this pollution share with existing pollution taxes, since actual pollutants are restricted by mandates so that the pollution share should also include scarcity rents resulting from the restrictions.

Table 2.2 presents the key endogenous variables in the benchmark case. Our goal is to compare the steady state growth rate and the welfare level under the three regimes. As shown in Table 2.2, in the GA regime, the steady state growth rate is about 3.12%. In the PA regime, the government switches the abatement spending to a lump-sum transfer, and the intermediate firms are forced to purchase the license fee for abatement knowledge from the R&D firms. Under such an arrangement, the growth rate declines to 1.73% in response. However, if the tax revenues are recycled to subsidize the R&D sector, the growth rate of 4.51% is ranked the highest among the three regimes. In addition, as shown in Table 2.2, the rank of the abatement knowledge among the three regimes is the same as that of the balanced growth rate. The intuition behind this coincident ranking follows from the fact that, as indicated in (2.17), an accumulation of abatement knowledge unambiguously enhances economic growth.

Table 2.2

	Environmental quality	Pollution	Abatement knowledge	Growth rate (%)	Welfare
GA	0.9656	0.00133	0.4506	3.124	-49.1803
PA	0.9720	0.00101	0.3416	1.732	-67.0781
PAR	0.9600	0.00153	0.5786	4.506	-36.3432

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

We now turn to compare the level of welfare under the three regimes. We focus on the welfare along the BGP, denoted by W^*, which is calculated by using (2.13) and (2.26):

$$W^* = \frac{1}{1-\sigma}\left\{\frac{-1}{(1-\sigma)g^* - \rho} C_0^{\,1-\sigma} N^{*\eta(1-\sigma)} - \frac{1}{\rho}\right\}, \tag{2.38}$$

where $C_0 = [A(N^*)P^{*(1-\alpha)\varepsilon} h^{*1-\alpha} L_y^{*\beta} - g^* - mh^* P^{*\varepsilon}]K_0$, C_0 and K_0 are the initial consumption and capital stock, respectively.[13] The numerical values of social welfare under the three regimes are reported in the last column of Table 2.2. It is clear that the ranking of the level of welfare among the three regimes is the PAR regime, the GA regime and the PA regime in that order. The policy implication is that, given the baseline parameter values, the growth rate and welfare are the lowest if abatement activities are conducted privately without government intervention. Nevertheless, they could be both enhanced once the government engages in public abatement or provides incentives for private abatement R&D. If the latter is the case, the growth rate and welfare could achieve the highest levels.

2.4.2. Parameters with policy implications

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

---

[13] Without loss of generality, we set $K_0 = 1$ in our numerical model.

2.4.2.1. Market imperfection

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

Figure 2.1 exhibits the effects of varying the monopoly power parameter (θ). A rise in θ is associated with an increase in both the balanced growth rate and the level of welfare under both the PA and PAR regimes. To explain this result, by substituting (2.29) into (2.30) we obtain $\pi = (1-s)\omega L_H$, where a higher profit implies more employment of research workers. As noted previously, the R&D firms can price their ideas exactly to extract all the profit of the intermediate firms. For this reason, a higher θ (as well as the profit of the intermediate firms) means that more resources are contributed to hire labor in the R&D sector, thereby stimulating the balanced growth rate.

In the GA regime, on the contrary, the effects of θ on long-term growth rate and welfare are negative but almost negligible. The reason for this result stems from the fact that in the GA regime abatement investment is undertaken only by the government, and thus has no direct relationship with the firms' profit. More specifically, the numerical simulations depicted in Figure 2.1 indicate that, under both the PA and PAR regimes, the greater the degree of imperfect competition, the larger the benefit of private abatement will become. When θ is large enough, both the balanced growth rate and social welfare for the PA regime may possibly exceed those for the GA regime. Moreover, if the government can recycle its tax revenues to provide incentives for private abatement R&D, both economic growth and welfare will be further enhanced.

2.4.2.2. The type of government spending

We now discuss the parameter related to the public sector. In their recent study, Fullerton and Kim (2008) show that government spending on transfer payments (ϕ) is a non-environmental parameter with important implications for environmental policy. The effect of changing ϕ is depicted in Figure 2.2. It is quite clear that, in response to an increase in ϕ, the growth rate and social welfare decline in both the PAR and GA regimes but remain intact in the PA regime. The intuition for this result is straightforward. In the PA regime all tax revenues are returned to the households. The abatement investment which stirs up economic growth comes only from the monopolistic rents so that ϕ has no role in economic activities.

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

2.4.2.3. The effect of an environmental tax

We now turn to investigate the effect of environmental tax policy. It is shown in Figure 2.3 that raising an environmental tax can stimulate economic growth as well as reduce the level of pollution. Bovenberg and Smulders (1995) have clearly pointed out the two opposing forces whereby the environmental policy affects the long-term growth rate. First, a lower level of polluting inputs decreases the productivity of reproducible inputs, thereby lowering economic growth. Second, a reduction in pollution improves the environmental quality, which benefits productivity and economic growth. As a result, Bovenberg and Smulders (1995) suggest that there is the environmental tax has an ambiguous effect on economic growth.

In our model, however, by referring to (2.6), the pollution inputs are purchased from abroad at a given price so that a higher environmental tax can simultaneously reduce the pollution $p(=p_i)$ but keep the polluting inputs $e(=e_i)$ unchanged. Under such a situation, a tighter environmental policy no longer decreases the productivity of capital and labor, because a lower level of pollution in production is offset by more abatement knowledge. Hence, our model only presents the second environmental quality effect.

To highlight the importance of this environmental quality effect, we consider the alternative value $\gamma = 0$ to show that production gains no extra benefit from a better environmental quality. The simulation results are depicted in Figure 2.4. It can be seen that, in the absence of an environmental externality, raising an environmental tax has no effect on the long-term growth rate while it reduces pollution. Comparing

Figure 2.3 with Figure 2.4 enables us to realize that whether or not environmental policies affect economic growth crucially depends on the presence of a positive environmental externality.

In our model, as mentioned above, a fixed import price of polluting inputs (m) is the key to screening out the traditional negative policy effect on long-term growth in the literature. Therefore, it is worthwhile discussing why we need to introduce this parameter into our model. Theoretically, although numerous studies model pollution based on the concept of a "dirty input", there are several reasons for treating them differently.[14] First, pollution (i.e., dirty air, messy water or noise) is not directly used in the production process, while the dirty inputs (i.e., petroleum or chemicals) are. Second, abatement knowledge can hardly play any role in the pollution transformation process if we mix the two. Third and most importantly, pollution harms human health but is not internalized by the private agents and thus needs to be priced by the government, while dirty inputs should be priced by the market, because they are production factors just like other clean inputs. Hence, we allow for τ_P and m to denote, respectively, the price of pollution and dirty inputs.

To be more specific, suppose that there is no polluting input price, from (2.5)-(2.7) and $q = 1$ (the zero-profit condition in the final good sector) we have:

$$\pi_i = A(N) k_i^{\alpha} p_i^{\varepsilon(1-\alpha)} H^{1-\alpha} l_{yi}^{\beta} - r k_i - \omega l_{yi} - \tau_P p_i \,. \tag{2.39}$$

One implication stemming from (2.39) is that, in the absence of any policy interference ($\tau_P = 0$), the cost of pollution becomes zero so that the intermediate firms will select an infinitely large level of pollution. As a result, the environmental quality declines to the bottom and the economy cannot survive even temporarily. To

---

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

this end, we introduce such a "non-policy" cost of polluting inputs to restrict the pollution to within a finite level even in the absence of an environmental tax. To be concerned with practicality, since firms usually import petroleum from abroad at a price that they can not bargain for, we believe that the assumption of a given price of polluting inputs is not very far from the real world.

Now we turn to welfare considerations. Figure 2.3 and Figure 2.4 show that the welfare level is increasing with the environmental tax, regardless of whether a positive environmental externality is present or not. As discussed earlier, in the case of $\gamma = 0$ a tighter environmental policy has no effect on long-term growth. However, it can still influence the level of welfare. More specifically, with the growth rate unchanged, a higher environmental tax reduces pollution to improve the environmental quality, and thus unambiguously enhances the welfare level. If the representative household does not care about the environmental quality ($\eta = 0$), it is our conjecture that environmental policy cannot play any role in governing the balanced growth rate and the welfare level.

2.5. Concluding Remarks

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

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

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

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

Appendix

This appendix provides a detailed derivation of (2.34) and (2.36) in the main text. In the PA regime, by substituting the intermediate firm's first-order conditions reported in (2.10)-(2.12) into the profit function, we obtain:

$$\pi = \left[1-(1-\theta)(\alpha+\beta)-(1-\theta)(1-\alpha)\varepsilon\right]Y-(1-\varepsilon)mHP^{\varepsilon}. \qquad \text{(A2.1)}$$

Based on $g=\dot{H}/H$ and (2.29), we have $\dot{H}/H=\pi/q_H H$. Then, putting (2.12), (2.17), and (2.20) and $\dot{H}/H=\pi/q_H H$ together, we can derive:

$$g=\frac{\dot{H}}{H}=\frac{\delta\pi}{\omega}. \qquad \text{(A2.2)}$$

Substituting (A2.1) into (A2.2) yields:

$$g=\frac{\delta\left[1-(1-\theta)(\alpha+\beta)-(1-\theta)(1-\alpha)\varepsilon\right]}{(1-\theta)\beta}L_y-\frac{\delta(1-\varepsilon)mHP^{\varepsilon}}{\omega}. \qquad \text{(A2.3)}$$

By substituting the relevant variables along the balanced growth equilibrium into (A2.3) and reminding $h=H/K$ and $w=\omega/K$, we can obtain (2.34) in the main text.

In the PAR regime, from (2.17), (2.30) and (2.31) we have $g=\delta\pi/(1-s)\omega$. Similar to the derivation of (2.34) in the PA regime, we can obtain (2.36) in the main text.

References

Auerbach, A.J. (1996), Tax reform, capital accumulation, efficiency, and growth. In: Aaron, H.J., Gale, W.G. (Eds.), *Economic Effects of Fundamental Tax Reform*, Brookings Institution Press, Washington, DC, 29-81.

Barro, R. J. and X. Sala-i-Martin (2004), *Economic Growth*, 2nd edition, MIT Press, Cambridge, MA.

Basu, S. and J. G. Fernald (1997), Returns to scale in U.S. production: estimates and implications, *Journal of Political Economy* 105, 249-283.

Beccarello, M. (1996), Time series analysis of market power: Evidence from G-7 manufacturing, *International Journal of Industrial Organization* 15, 123-136.

Benhabib, J. and R. E. A. Farmer (1994), Indeterminacy and increasing returns, *Journal of Economic Theory* 63, 19-41.

Berman, E. and L. T. M. Bui (2001), Environmental regulation and productivity: evidence from oil refineries, *Review of Economics and Statistics* 83, 498-510.

Blanchard, O. J. and N. Kiyotaki (1987), Monopolistic competition and the effects of aggregate demand, *American Economic Review* 77, 647-666.

Bovenberg, A. L. and R. A. de Mooij (1997), Environmental tax reform and endogenous growth, *Journal of Public Economics* 63, 207-237.

Bovenberg, A. L. and S. Smulders (1995), Environmental quality and pollution-augmenting technical change in a two-sector endogenous growth model, *Journal of Public Economics* 57, 369-391.

Bovenberg, A. L. and S. Smulders (1996), Transitional impacts of environmental policy in an endogenous growth model, *International Economic Review* 37, 861-893.

Bréchet, T. and P. Michel (2007), Environmental performance and equilibrium, *Canadian Journal of Economics* 40, 1078-1099.

Chang, J. J., J. H. Chen, J. Y. Shieh and C. C. Lai (2009), Optimal tax policy, market imperfections, and environmental externalities in a dynamic optimizing macro model, *Journal of Public Economic Theory* 11, 623-651.

Chen, J. H., C. C. Lai and J. Y. Shieh (2003), Anticipated environmental policy and transitional dynamics in an endogenous growth model, *Environmental and Resource Economics* 25, 233-254.

Considine, T. J. (2001), Mark-up pricing in petroleum refining: A multiproduct framework, *International Journal of Industrial Organization* 19, 1499-1526.

Dixit, A. K. and J. E. Stiglitz (1977), Monopolistic competition and optimum product diversity, *American Economic Review* 67, 297-308.

Farmer, R. E. A. and J. T. Guo (1994), Real business cycles and the animal spirits hypothesis, *Journal of Economic Theory* 63, 42-71.

Fullerton, D. and S. R. Kim (2008), Environmental investment and policy with distortionary taxes, and endogenous growth, *Journal of Environmental Economics and Management* 56, 141-154.

Fullerton, D. and G. E. Metcalf (2002), Cap and trade policies in the presence of monopoly and distortionary taxation, *Resource and Energy Economics* 24, 327-347.

Gali, J. (1994), Government size and macroeconomic stability, *European Economic Review* 38, 117-132.

Gradus, R. and S. Smulders (1993), The trade-off between environmental care and long-term growth: Pollution in three prototype growth models, *Journal of Economics* 58, 25-51.

Greaker, M. and K. M. Rosendahl (2008), Environmental policy with upstream pollution abatement technology firms, Journal of Environmental Economics and Management 56, 246-259.

Grimaud, A. (1999), Pollution permits and sustainable growth in a Schumpeterian model, *Journal of Environmental Economics and Management* 38, 249-266.

Guo, J. T. and K. J. Lansing (1999), Optimal taxation of capital income with imperfectly competitive product markets, *Journal of Economic Dynamics and Control* 23, 967-995.

Hart, O. (1982), A simple model of imperfect competition with Keynesian features, *Quarterly Journal of Economics* 97, 109-138.

Hettich, F. (1998), Growth effect of a revenue-neutral environmental tax reform, *Journal of Economics* 67, 287-316.

Huang, C. H. and D. Cai (1994), Constant returns endogenous growth with pollution control, *Environmental and Resource Economics* 4, 383-400.

Itaya, J. (2008), Can environmental taxation stimulate growth? The role of indeterminacy in endogenous models with environmental externalities, *Journal of Economic Dynamics and Control* 32, 1156-1180.

Jones, C. I. (1995), R&D-based models of economic growth, *Journal of Political Economy* 103, 759-784.

Judd, K. L. (1997), The optimal tax on capital income is negative. National Bureau of Economic Research, Working 6004.

Judd, K. L. (2002), Capital-income taxation with imperfect competition, *American Economic Review* 92, 417-421.

Kamien, M. I. and Y. Tauman (1986), Fees versus royalties and the private value of a patent, *Quarterly Journal of Economics* 101, 471-491.

Ligthart, J. E. and F. van der Ploeg (1994), Pollution, the cost of public funds and endogenous growth, *Economic Letters* 46, 351-361.

Lucas, R. E. (1990), Supply-side economics: an analytical review, *Oxford Economic s* 42, 293-316.

Mankiw, N. G. (1985), Small menu costs and large business cycle: A macroeconomic model of monopoly, *Quarterly Journal of Economics* 100, 529-537.

Nakada, M. (2004), Does environmental policy necessarily discourage growth?, *Journal of Economics* 81, 249-275.

OECD (2000), Workshop on Innovation and the Environment: Rapporteur's Report in Innovation and the Environment, OECD, Paris.

OECD (2007), Pollution abatement and control expenditure in OECD countries, OECD, Paris.

Ono, T. (2003), Environmental tax policy in a model of growth cycles, *Economic Theory* 22, 141-168.

Romer, P. M. (1990), Endogenous technological change, *Journal of Political Economy* 98, s71-s102.

Schumpeter, J. (1942), *Capitalism, Socialism, and Democracy*, Harper and Row, New York.

Smulders, S. (1995), Entropy, environment and endogenous economic growth, *International Tax and Public Finance* 2, 319-340.

Smulders, S. and R. Gradus (1996), Pollution abatement and long-term growth, *European Journal of Political Economy* 12, 505-532.

Stokey, N. L. and S. Rebelo (1995), Growth effects of flat-rate taxes, *Journal of Political Economy* 103, 519-550.

van Ewijk, C. and S. van Wijnbergen (1995), Can abatement overcome the conflicts between the environment and economic growth?, *De Economist* 143, 197-216

van Zon, A. and I. H. Yetkiner (2003), An endogenous growth model with embodied energy-saving technical change, *Resource and Energy Economics* 25, 81-103.

Figure 2.1. The effect of monopoly power

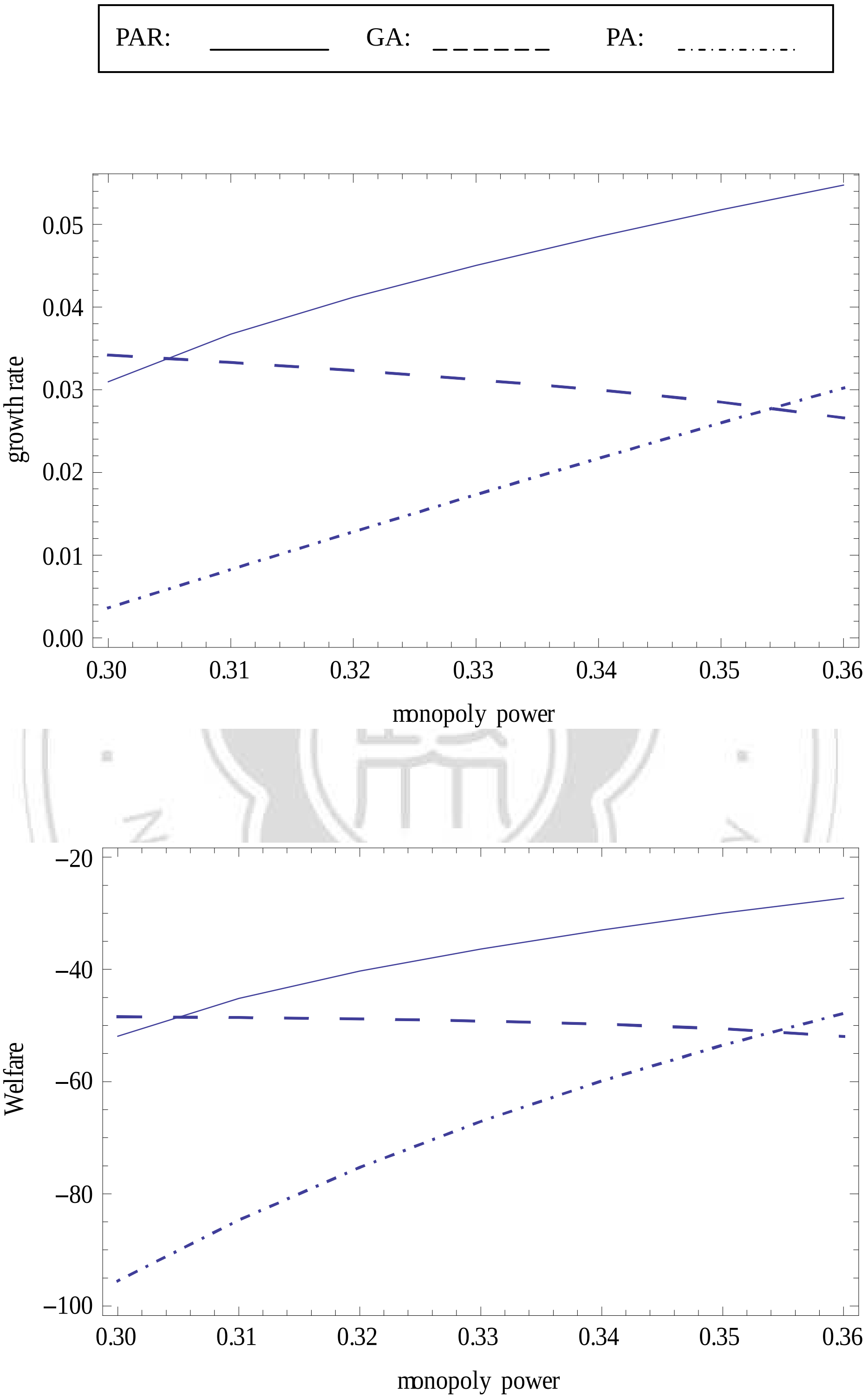


Figure 2.2. The effect of increasing other government spending

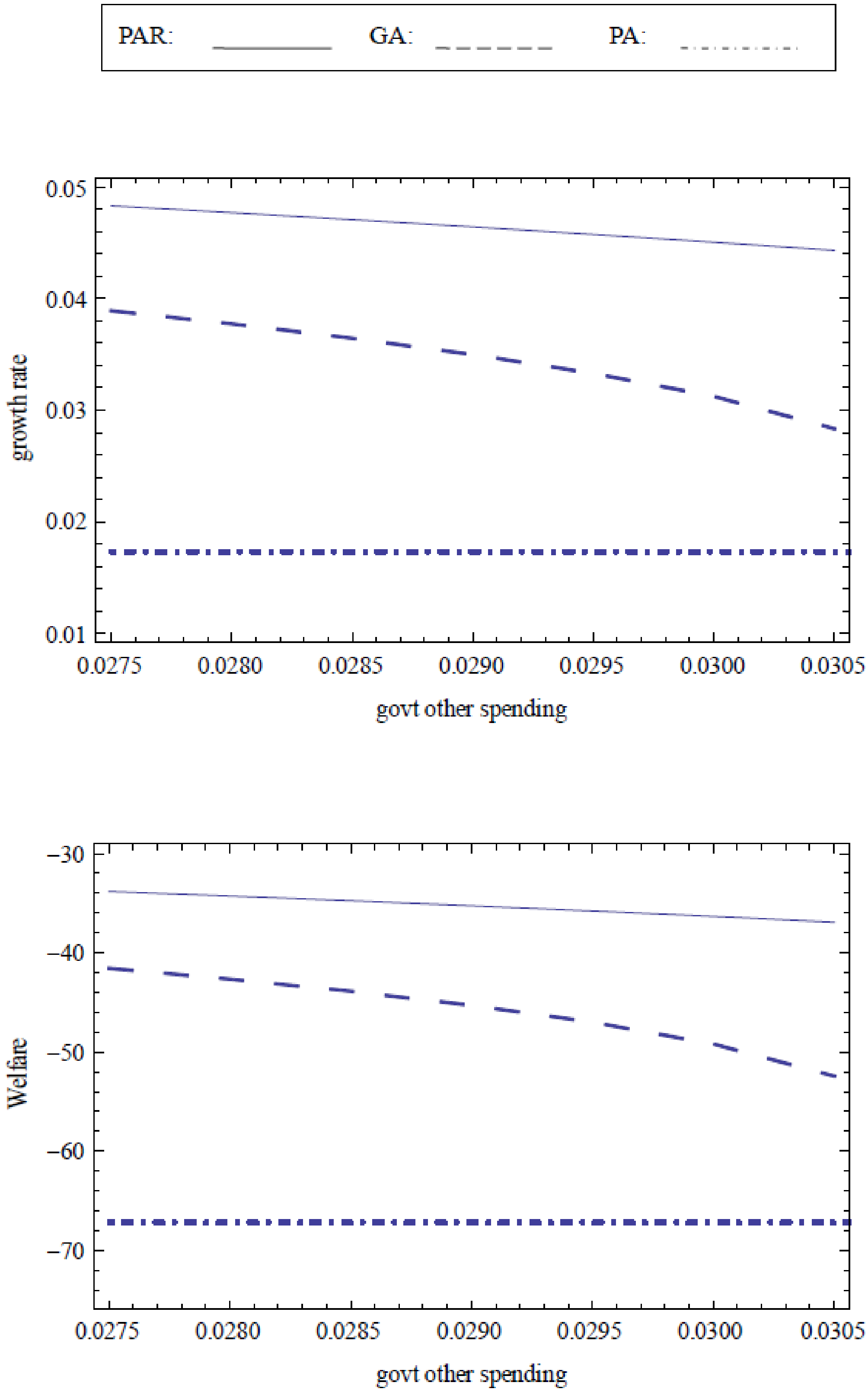


Figure 2.3. The effect of an environmental tax ($\gamma = 0.77$)

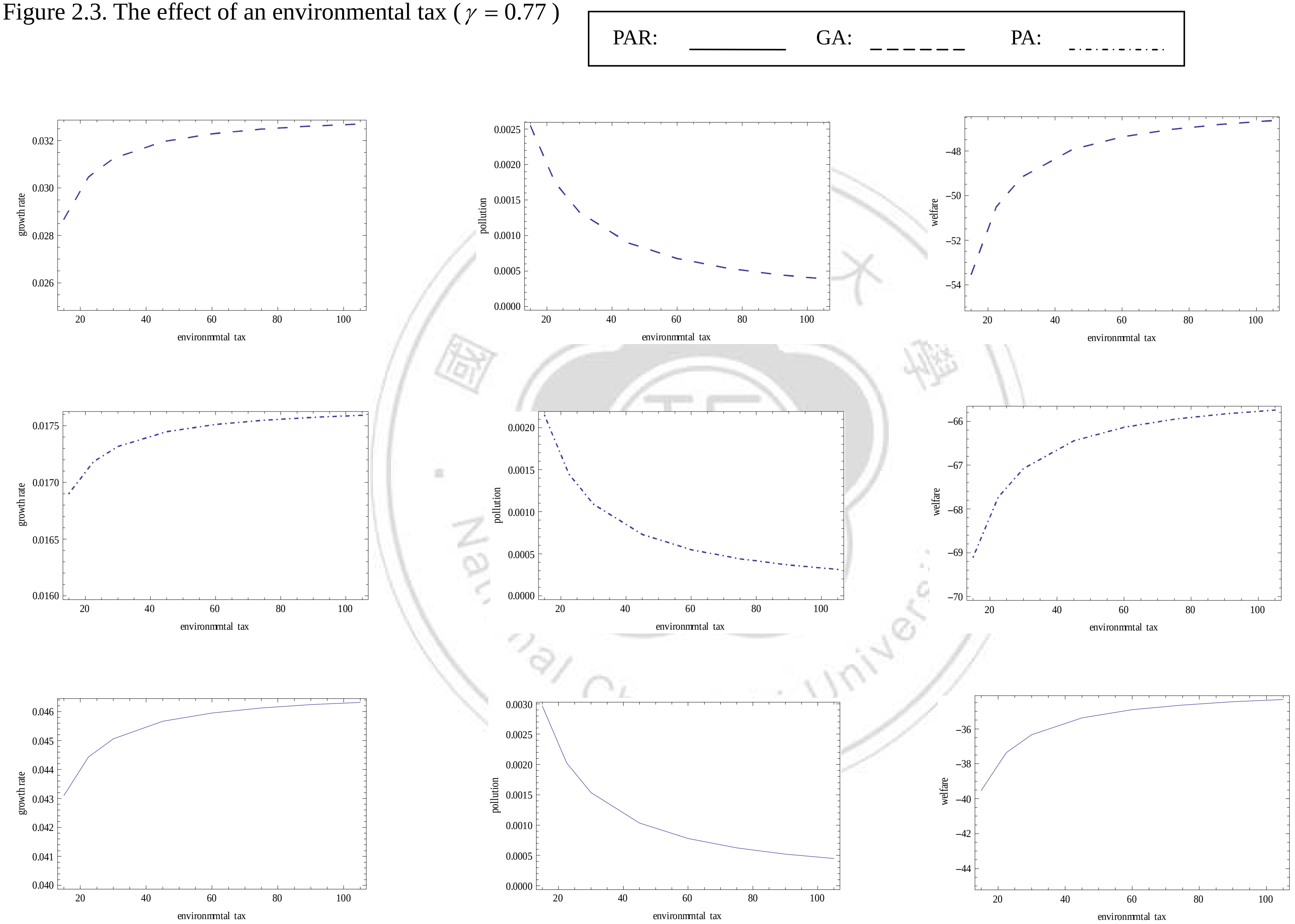
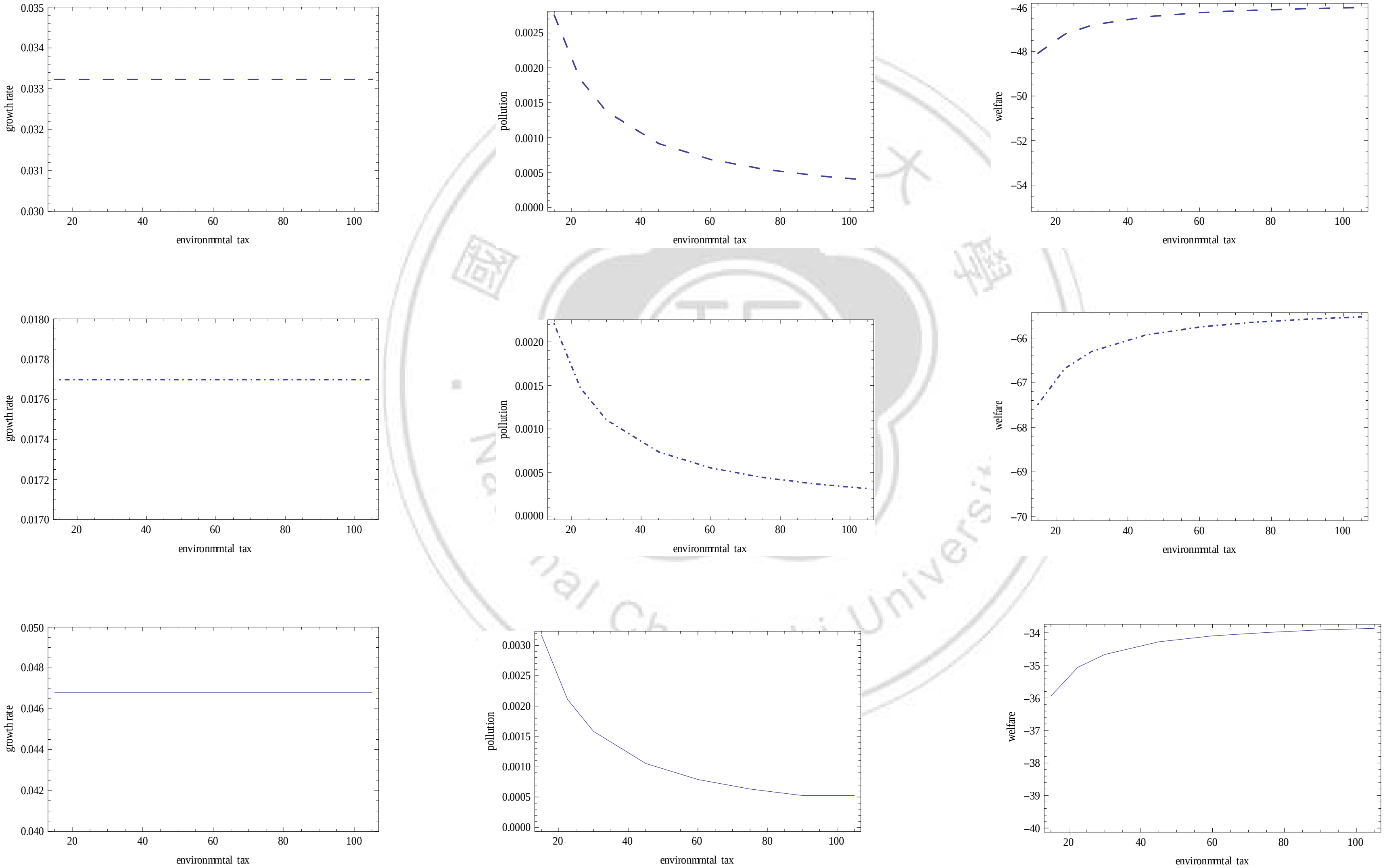


Figure 2.4. The effect of an environmental tax ($\gamma = 0$)

PAR: ———— GA: – – – – – – PA: -·-·-·-·-·-



Chapter III

Intergenerational Welfare and Pareto-improving Environmental Policies

3.1. Introduction

One important feature of environmental issues is that the degradation of the environment requires a period of time. The existing generations who create pollution today may not live long enough to bear the consequences of environmental deterioration in the future. Environmental policies, therefore, should be responsible for internalizing both *intratemporal* and *intertemporal* environmental externalities (Heijdra et al., 2006). As heterogeneous generations are considered, the following questions naturally arise: What is the environmental policy impact on the welfare of different generations? Does an intergenerational welfare conflict emerge from raising an environmental tax? Is it possible for an environmental tax to be Pareto-improving (i.e., to improve the welfare of all generations)? This makes an attempt to deal with these questions.

To this end, we set up an overlapping generations (OLG) growth model building on the work proposed by Samuelson (1958) and Diamond (1965), and use it to examine the welfare effects of an environmental tax on different generations. Based on this OLG growth model, several main results emerge from our analysis. First, the pattern whereby tax revenues are distributed to either the young generation or the elderly generation plays an important role in determining intergenerational welfare and economic growth. Second, the growth effect of environmental policies is governed by evaluating the welfare changes of the generations born in the endless future. Third, the diverse environmental policy effects may emerge from the *environmental utility of the existing generations*. Finally, we show that a Pareto-improving environmental policy is achievable in the presence of positive environmental production externalities.

Two studies closely related to the present chapter are Bovenberg and Heijdra (1998) and Heijdra et al. (2006), who build on the OLG model proposed by Yaari (1965) and Blanchard (1985) and study the intergenerational welfare effect of an environmental tax. It is therefore worthwhile discussing the major differences between our analysis and theirs. First, they show that, in response to a rise in the environmental tax rate, the returns of productive factors decline so that the existing *older* generations who have accumulated a huge amount of physical capital must accordingly suffer from an immense non-environmental loss. The newborn generations, on the contrary, have not yet accumulated wealth and thus enjoy a welfare gain from the distributed tax revenues. This result is the basic spirit of the Yaari-Blanchard OLG model in that the older generations are inevitably the richer generations (by accumulating more wealth). Based on this feature, in their analysis the environmental tax is essentially more harmful to the *richer generations* than to the *older* generations. To escape from such a rigid and somewhat unrealistic intergenerational linkage, in the present we instead use the Samuelson-Diamond OLG model to deal with the intergenerational welfare distribution effect of the environmental tax.

Second, the Yaari-Blanchard OLG model assumes that all existing generations face the same mortality and thus expect the same remaining life time (the so-called "perpetually youth" assumption). Based on this distinctive trait, as the environmental tax rises, the changes in the environmental utility of all existing generations－no matter how old or young, are entirely equivalent. In reality, however, the existing old generation who may have no further remaining life time can hardly wait for the reaping of environmental fruits. From this perspective, raising the environmental tax should affect only the (environmental) welfare of the existing young generation rather than of all existing generations. While the Yaari-Blanchard OLG model can not reflect such an intergenerational welfare contradiction, our analysis can escape from this drawback and provide an insight for this issue.

Moreover, in Bovenberg and Heijdra (1998) and Heijdra et al. (2006) featured with Yaari-Blanchard OLG, the asset stock of the older generations is greater than that of the younger generations. Then, in response to a rise in the environmental tax rate, the older generations must bear a higher part of the environmental tax burden and their welfare level is certainly lowered. Their result essentially stands in line with John and Pecchenino (1994), who argue that with no private maintenance investment, an environmental policy can hardly be Pareto-improving.[15] Our analysis instead possesses an advantage in that it assigns a specific proportion of government transfers to each generation. In particular, we introduce the positive environmental externality in production, and hence are able to show that, even in a quite reasonable way to distribute the tax revenues, an environmental tax could be Pareto-improving.

This chapter is also related to the strand of the literature on the linkage between environmental policies and endogenous economic growth. Most of these studies confine their analysis to the model with the infinitely-lived household (e.g., Bovenberg and Smulders (1995), Mohtadi (1996), Smulders and Gradus (1996), Byrne (1997), Bovenberg and de Mooij (1997), Stokey (1998), Grimaud (1999), Nakada (2004), Itaya (2008), Fullerton and Kim (2008)).[16] Others deal with an OLG model either based on the Yaari-Blanchard framework (Pautrel, 2008; 2009) or on the

---

[15] However, Bovenberg and Heijdra (1998) demonstrate that if the government can implement an intergenerational redistribution policy (public debt) to allow the future generations who enjoy most of the environmental gain to compensate the existing generations, then it is possible for all generations to benefit from the environmental tax.

[16] See Xepapadeas (2005) for a survey of this literature.

Samuelson-Diamond framework (John and Pecchenino (1994), John et al. (1995), Ono (2003a; 2003b), Jouvet et al. (2010), Mariani et al. (2010)). Within these existing studies, the model this develops is more close to Ono (2003a; 2003b). However, compared with Ono (2003a; 2003b), this has the following major distinctions. First, we introduce the positive environmental externality in the production function. Second, we do not consider private investment in environmental maintenance.[17] Lastly, Ono (2003a; 2003b) do not discuss the possibility of Pareto-improving environmental policy, which is our main focus in this .

When heterogeneous agents are taken into consideration, how the environmental tax revenues are distributed between generations plays an important role in determining the tax effect on growth.[18] More specifically, the transfer of income to the young generation is divided into consumption and saving, while the transfer of income to the old generation is totally expended on consumption. Given the fact that saving is the main driving force for economic growth, the transfer of income received by the young is more beneficial to growth than that received by the old. Our model captures this feature by assuming that the government can assign a different portion of transfers distributed to the different generations. It is found that, as we expected, the larger the proportion of government transfers distributed to the young generation, the more likely it is that the environmental tax will have a positive effect on economic growth.

---

[17] In their models, the environmental externalities are mitigated since young agents can invest in environmental maintenance in order to enjoy a better environmental quality when they are old. The intergenerational welfare conflict is also mitigated since investment in environmental capital (maintenance) serves as a bequest to future generations. However, given the fact that each individual is insignificantly small in the world, our assumes that no individual takes into consideration the influence that his/her decision has on the environment, and hence will not invest in any environmental maintenance activities.

[18] For example, Belan et al. (1998) and Gyárfás and Marquardt (2001) find that the types of social security system financed by a wage income tax can affect the long-term growth rate. These studies, however, do not deal with the issue of the environment. Another related paper is Gutierrez (2008), who considers environmental tax design to achieve the optimal allocation in a non-growing overlapping generations model in which pollution arises from production.

The remainder of this chapter is organized as follows. Section 3.2 describes the economy. Section 3.3 characterizes the equilibrium and the balanced-growth path. Section 3.4 analytically investigates the growth and welfare effects of an environmental tax in the absence of a positive environmental production externality. Section 3.5 examines the possibilities of a Pareto-improving environmental policy with or without the positive production externality via numerical simulation. Section 3.6 concludes.

3.2. The Model

The general structure of our model incorporates environmental elements into a standard Samuelson-Diamond OLG growth model. We consider an infinite-horizon economy comprised of finitely-lived individuals, perfectly competitive firms, and the government. Production creates pollution that damages environmental quality, which is treated as a renewable resource and can possibly be beneficial to both individuals' utility and productive activities. In what follows, we in turn describe the structure of the economy.

3.2.1. Individuals

Time is discrete. A new generation (called generation t) is born in each period $t=1$, 2,…, and lives for two periods. There is also an initial old generation (called generation 0) that lives only in period 1. For simplicity we assume no population growth and the size of each generation is normalized to unity. All individual agents are identical except for their ages. Accordingly, the representative generation t has the following utility function:

$$U_t = \begin{cases} \ln c_t^y + \eta \ln E_t + \rho(\ln c_{t+1}^o + \eta \ln E_{t+1}) & \text{for } t \geq 1 \\ \ln c_{t+1}^o + \eta \ln E_{t+1} & \text{for } t = 0 \end{cases}, \tag{3.1}$$

where c_t^y is consumption in youth age in period t and c_{t+1}^o is consumption in old age in period $t+1$; E_t is environmental quality in period t; $\rho \in (0,1)$ is the subjective discount factor; and $\eta > 0$ denotes the weight in terms of the utility attached to environmental quality.

All individual agents live for two periods. In the first period (in youth age) each of the agents is endowed with one unit of labor inelastically, and it allocates its total income (the sum of wage income and government transfer payments) between savings and young-age consumption. In the second period (in old age), each of the agents is retired from the labor market and receives the return from savings and governments' transfer payments as its old-age consumption. Therefore, the budget constraints of generation t in youth and old age are respectively given by:

$$c_t^y + s_t = w_t + (1-\theta)g_t, \tag{3.2}$$

$$c_{t+1}^o = R_{t+1}s_t + \theta g_{t+1}, \tag{3.3}$$

where s_t is savings, w_t is labor income, R_{t+1} is the gross return on savings, and g_t denotes the government transfer payments. Equations (3.2) and (3.3) state that, in each period, the government returns environmental tax revenues to the young and the elderly as lump-sum transfer payments according to the proportions $1-\theta$ and θ, respectively.[19]

Notice that, for generation 0, there is no savings and consumption decision for each of the agents since the agent only lives in period 1. Each of the agents possesses s_0 as its initial asset and passively receives both transfer payments and the return from savings as its consumption in old age. Without loss of generality, we assume $s_0 = 1$ in the following analysis. For generation $t \geq 1$, each of the agents maximizes U_t in (3.1) subject to (3.2) and (3.3), and yields the following

---

[19] A more detailed discussion of θ will be presented in section 3.2.4.

consumption and saving functions:

$$c_t^y = \frac{1}{1+\rho}\left[w_t + (1-\theta)g_t + \frac{\theta}{R_{t+1}} g_{t+1} \right], \tag{3.4}$$

$$c_{t+1}^o = \frac{\rho R_{t+1}}{1+\rho}\left[w_t + (1-\theta)g_t + \frac{\theta}{R_{t+1}} g_{t+1} \right], \tag{3.5}$$

$$s_t = \frac{1}{1+\rho}\left[\rho w_t + \rho(1-\theta)g_t - \frac{\theta}{R_{t+1}} g_{t+1} \right]. \tag{3.6}$$

3.2.2. Production

There is a continuum of identical and perfectly competitive firms. The number of firms is normalized to unity. The representative firm produces a single final good Y_t using the following production function:

$$Y_t = \Lambda_t K_t^{\alpha} P_t^{\beta} L_t^{\nu};\ 1 > \alpha, \beta, \nu > 0,\ \alpha + \beta + \nu = 1 \tag{3.7}$$

where Λ_t is the technology level that stands for the production externalities, K_t is the aggregate physical capital, L_t is the aggregate labor, and P_t is aggregate pollution that can be regarded as a "dirty input". Firms hire labor, capital, and dirty inputs to maximize profits taking all factor prices and the technology level as given. The representative firm's problem can be written as:

$$\underset{K_t, L_t, P_t}{Max}\ \Pi_t = Y_t - r_t K_t - w_t L_t - (1+\tau) b_t P_t,^{20} \tag{3.8}$$

$$\text{s.t.}\quad Y_t = \Lambda_t K_t^{\alpha} P_t^{\beta} L_t^{\nu},$$

where Π_t is the gross profits, r_t is the capital rental rate, and $\tau \geq 0$ denotes the environmental tax that the government levies on dirty inputs. The private price of dirty inputs b_t is assumed to evolve with the aggregate capital, i.e., $b_t = bK_t$ where

---

[20] It should be noted that the final good serves as the *numeraire* in this .

b is a constant parameter.[21] The first-order conditions for the firm's optimizing problem, in per-worker terms, are thus given by:

$$\alpha \Lambda_t k_t^{\alpha-1} p_t^{\beta} = r_t , \tag{3.9}$$

$$\beta \Lambda_t k_t^{\alpha} p_t^{\beta-1} = (1+\tau) b_t , \tag{3.10}$$

$$\nu \Lambda_t k_t^{\alpha} p_t^{\beta} = w_t , \tag{3.11}$$

where $k_t = K_t / L_t$ and $p_t = P_t / L_t$. (3.9)-(3.11) indicate that the firm equates the marginal product of the capital, labor and pollution to their respective marginal cost.

We assume that there exist two kinds of positive externalities in the production sector. The first one is the *capital externality* suggested by the standard literature of endogenous growth theory such as Romer (1986) and Lucas (1988). The second one is the *environmental production externality*, which indicates that the output level can rise with a better environmental quality (see, e.g., Bovenberg and Smulders (1995), Mohtadi (1996), Fullerton and Kim (2008)).[22] Given these two positive externalities, the technology level can be specified in the following form:

$$\Lambda_t = A K_t^{1-\alpha} E_t^{\lambda} , \tag{3.12}$$

where A is a constant, and $\lambda (\geq 0)$ is a parameter that reflects the extent of the environmental externality.

3.2.3. Environmental quality

Following Tahvonen and Kuuluvainen (1991), Bovenberg and Smulders (1995) and Fullerton and Kim (2008), the natural environment is treated as a renewable

---

[21] If b_t is constant over time (i.e., b_t=b), as time goes on, the aggregate pollution will become infinite and nothing will survive. Hence, in the environmental and endogenous growth literature (e.g., Bovenberg and Smulders, 1995; Nielsen et al. 1995, Oueslati, 2002; Fullerton and Kim, 2008; Pautrel, 2008) it is necessary for the price of pollution (the price could be the private price or environmental tax, or both) to evolve with another growing factor. See Smulders (1995) for an excellent discussion.

[22] See also, for example, Pearce and Warford (1993) for empirical evidences suggesting that pollution can reduce productivities.

resource. We specify that environmental quality grows and declines in the following manner:

$$E_{t+1} = E_t + \delta(\overline{E} - E_t) - P_t,^{23} \tag{3.13}$$

where δ is a regeneration parameter, and $\overline{E}$ denotes the maximum level of environmental quality (i.e., environmental quality with zero pollution). We impose a condition on $(\delta, \overline{E})$ to assume that they are large enough to avoid negative environmental quality ($E_t > 0 \forall t$). (3.13) indicates that environmental quality in the next period is specified to be positively related to the regeneration capacity of the environment $\delta(\overline{E} - E_t)$ and negatively related to the level of pollution created in this period.[24]

3.2.4. Government

The government is subject to a balanced-budget requirement, which levies an environmental tax on pollution and transfers the revenue to individuals. Let g_t be total transfer payments. In each period t, the young (generation t) receive $(1-\theta)g_t$ while the elderly (generation $t-1$) receive θg_t. Hence, the government budget constraint in period t is given by:

$$\tau b_t P_t = (1-\theta)g_t + \theta g_t . \tag{3.14}$$

The weight parameter θ plays an important role throughout the analysis. It stands for the revenue weight that the government assigns to the young and the elderly. As we will see later, θ is also a parameter that reflects the welfare conflict between different generations. It can be seen from the individual's budget constraint reported

---

[23] Let $J(E,P)=E_{t+1} - E_t$ denote the evolving function of the environment. The function satisfies the properties that $J_P < 0$, $J_E < 0$ and $J(\tilde{E}, \tilde{P})=0$.

[24] As in John et al. (1995) and Ono (1996, 2003a; 2003b), we consider a linear evolving function of environmental quality for the purpose of deriving analytical solutions. On the other hand, Tahvonen and Kuuluvainen (1991) and Bovenberg and Smulders (1995) consider a more complicated nonlinear form of evolving function.

in (3.2) and (3.3) that, when $\theta = 0$, the whole of the tax revenues are returned to the young. However, when $\theta = 1$, the elderly receive all of the tax revenues and we can treat this case as a kind of pay-as-you-go public pension system financed by environmental taxes. In particular, we refer to the case of $\theta = 0.5$ as an *equal transfer policy* that indicates that tax revenues are equally distributed to each generation.

3.3. Competitive Equilibrium

This section deals with the competitive equilibrium and characterizes the balanced-growth path. We first deal with the market clearing condition for physical capital. In line with the literature on the Samuelson-Diamond OLG model (see, e.g., John et al., 1995; Agnani et al., 2005; Heijdra, 2009), we assume that capital fully depreciates in the process of production. Hence, given that labor is stationary and normalized to unity, the market clearing condition for physical capital is written as:

$$s_t = k_{t+1}. \tag{3.15}$$

This condition indicates that savings from young agents determine the stock of physical capital in the next period. In addition, the gross return on the individual's savings is equal to one plus the capital rental rate, i.e., $R_t = 1 + r_t$.

Definition 3.1. *A competitive equilibrium is an infinite sequence of allocations* $\{c_t^y, c_t^o, s_t, p_t, k_{t+1}, g_t\}_{t=1}^{\infty}$, *prices* $\{w_t, r_t, b_t, R_t\}_{t=1}^{\infty}$, *and environmental tax policies* $\{\tau, \theta\}$, *such that, given the initial condition* $s_0 > 0$, *in each period:*

(i). for generation $t \geq 1$, *agents choose* $\{c_t^y, c_{t+1}^o, s_t\}$ *to maximize utility taking* $\{w_t, R_{t+1}, g_t, g_{t+1}, \theta\}$ *as given;*

(ii). firms choose $\{k_t, p_t\}$ *to maximize profit taking* $\{w_t, r_t, b_t, \tau\}$ *and the technology*

level Λ_t *as given;*

(iii). markets clear;

(iv). the government budget constraint is balanced, i.e., $\tau b_t p_t = g_t$.

3.3.1. The balanced-growth path

The balanced-growth path is characterized by a set of constant growth rates of all economic variables. Let γ_z denote the ratio z_{t+1}/z_t for all variables along the balanced-growth path. In line with the environmental growth literature (see, e.g., Bovenberg and Smulders, 1995; Fullerton and Kim, 2008), we provide the following definition that describes the balanced-growth path in our economy.

Definition 3.2. *A balanced-growth path is a competitive equilibrium where (i) pollution and environmental quality remain constant, i.e.,* $\gamma_p = \gamma_E = 1$, *and (ii) all other variables grow at a common endogenous growth rate, which implies that* $\tilde{\gamma} = \gamma_Y = \gamma_{c^y} = \gamma_{c^o} = \gamma_k = \gamma_g$.[25]

We focus our analysis on steady-state solutions along the balanced-growth path. Hence, it would be useful for us to define the following transformed variables. Let a tilde denote the steady-state values. We define $\tilde{x}^{gro} \equiv x_t^{gro}/k_t$ for growing variables ($x^{gro} = c^y, c^o, w, g$), and $\tilde{x}^{non} \equiv x_t^{non}$ for non-growing variables ($x^{non} = r, p, E$).

3.4. Policy Effects without Environmental Production Externality

In this section, we examine the growth and welfare effects under the situation where environmental quality is not beneficial to the production process (i.e., $\lambda = 0$).

---

[25] It should be noted that $\tilde{\gamma}$ is the gross growth rate and $\tilde{\gamma}-1$ is what we all understand as the (net) growth rate.

We temporarily ignore this productivity benefit of a cleaner environment due to the following two advantages. First, doing so would be helpful for us to obtain an analytical closed-form solution. Second, and more importantly, it would enable us to clarify the channels through which an environmental tax influences the welfare of different generations.

By imposing $\lambda = 0$ and substituting the transformed variables and the underlying technology $\Lambda_t = Ak_t^{1-\alpha}$ into (3.9)-(3.11), it is easy to obtain the following steady-state values of pollution and factor prices:

$$\tilde{p} = \left(\frac{\beta A}{b(1+\tau)} \right)^{\frac{1}{1-\beta}}, \tag{3.16}$$

$$\tilde{r} = \alpha A \left(\frac{\beta A}{b(1+\tau)} \right)^{\frac{\beta}{1-\beta}}, \tag{3.17}$$

$$\tilde{w} = \nu A \left(\frac{\beta A}{b(1+\tau)} \right)^{\frac{\beta}{1-\beta}}. \tag{3.18}$$

Based on the above expressions, we have the following proposition:

Proposition 3.1. *If* $\lambda = 0$*, an increase in an environmental tax reduces pollution and the returns of both physical capital and labor inputs.*

Proof. See the Appendix. ■

This result is quite intuitive. A rise in the environmental tax increases the cost of the dirty input, and thereby reduces the pollution. Given less pollution in production, the marginal product of the other two factors, capital and labor, must decrease as well.

3.4.1. Growth effect

To examine how the environmental tax affects the growth rate, we first derive the endogenous growth rate in the steady state.

Lemma 3.1. *In the case of* $\lambda = 0$, *all growing factors along the balanced-growth path grow at a common endogenous rate, given by:*

$$\tilde{\gamma} = \frac{\rho\tilde{w} + \rho(1-\theta)\tilde{g}}{1+\rho+\theta\tilde{g}/(1+\tilde{r})}, \tag{3.19}$$

where $\tilde{g} = \tau b \tilde{p}$.

Proof. See the Appendix. ■

This lemma indicates that two important policy instruments, namely, the environmental tax rate (τ) and the distribution of tax revenues (θ), affect the endogenous growth rate in our economy.

Before analyzing the growth effect, we first impose an upper bound on τ.

Condition L. (the upward-sloping portion of the Laffer curve): $\tau < (1-\beta)/\beta$.[26]

To be more precise, Condition L ensures that the environmental tax rate is not too high to decrease the environmental tax revenues. In other words, it guarantees a tax rate that lies within the interval where the Laffer curve is upward sloping.

Equipped with Lemma 3.1 and Condition L, we can derive the relationship between environmental policies and the growth rate, which is characterized by the following proposition:

Proposition 3.2. *Supposing that* $\lambda = 0$, *and that the growth effect of an environmental tax crucially depends on the value of the distribution parameter*

---

[26] The derivation of condition L is provided in the Appendix. This is quite a relaxed condition. Given that β is about 5%~20% in the literature, Condition L simply implies that the environmental tax rate does not exceed 400%. Similar results regarding this condition are reported by recent works. For example, Agnani et al. (2005) shows that β has to be high enough to satisfy the characteristics of their growing economy.

between different generations θ. *Under such a scenario, two special situations may occur. First, when tax revenues are returned to the young generation (i.e.,* $\theta = 0$*), an environmental tax enhances (reduces) the balanced growth rate if and only if the initial tax rate is smaller (greater) than* $\alpha/(1+\alpha)$. *Second, when tax revenues are returned to the elderly generation (i.e.,* $\theta = 1$*), an environmental tax unambiguously reduces the balanced growth rate.*

Proof. See the Appendix. ■

Proposition 3.2 shows how the growth rate depends on how the tax revenue is split out among young and elders. The intuition behind Proposition 3.2 can be explained as follows. In this OLG economy, the growth rate depends crucially upon the consumption-saving decision of young agents. As indicated in (3.6), there are two forces that affect the young agents' saving decision when the environmental tax rate goes up. The first one is the negative *wage effect*, which states that a higher environmental tax rate reduces the young agents' wage income (Proposition 3.1), and therefore the young generation will tend to reduce both consumption and savings in response. The second one is the positive *transfer effect*, which means that young agents will save more with a higher environmental tax since they can receive more transfer income. Based on these two conflicting effects, we can then deal with the following two distinct scenarios to explain how θ influences the growth effect of environmental taxes.

The first scenario is that the young generation receives all tax revenues (i.e., $\theta = 0$). Under such a situation, when the young receive all tax revenues, they also realize that they will not receive any transfer in the old-age period; this gives them a stronger incentive to save for old-age consumption. That is to say, the transfer effect is greater with a lower value of θ. Supposing that the environmental tax rate is initially small, as it goes up, tax revenues will rise significantly and will therefore lead to a greater transfer effect. Accordingly, when θ is small and the environmental tax rate is initially small enough, the positive transfer effect will dominate the negative wage effect and so the growth rate will be enhanced.

The second scenario, on the contrary, is that all tax revenues are distributed to the elderly generation (i.e., $\theta = 1$). Under such a situation, the transfer effect simply vanishes since the individuals receive nothing in the young-age period. Furthermore, the young are willing to consume more (save less) in their young-age period because they know they will obtain a large transfer of income when they are old. Hence, in this case only the first negative wage effect works, and a higher environmental tax always leads to a deterioration in the growth rate.

Figure 3.1 provides a numerical example regarding how the growth rate varies with different combinations of policy instruments. The parameter values we utilize are: $\alpha = 0.3$, $\beta = 0.17$, $\nu = 0.53$, $\rho = 0.22$, $A = 9.65$, and $b = 1$. Some of the parameters we use are close to those from Zeng and Zhang (2007), Fullerton and Kim (2008), and Heijdra et al. (2010), while the parameters A and b are calibrated so that the balanced growth rate is around 2% in the absence of an environmental tax. It can be seen in Figure 3.1 that, consistent with Proposition 3.2, if θ is small enough, the relationship between growth and the environmental tax can be described by an inverted U-shaped curve. On the other hand, in association with a higher value of θ, a negative relationship is exhibited between the balanced growth rate and the environmental tax rate. Moreover, in association with the given environmental tax rate, the balanced growth rate decreases with θ.

3.4.2. Welfare effect

Now we turn to investigate the effect of the environmental tax on the welfare of different generations. We first examine the welfare of the initial old generation. Note that in our model all variables are jump variables except for the capital stock and the renewable environmental quality. Supposing that the government raises the environmental tax rate in period t, the consumption, savings, and pollution will change instantaneously, while the capital stock and environmental quality will adjust over time. Therefore, we have the following lemma:

Lemma 3.2. *For the initial old generation, an environmental tax increases (decreases) their welfare level if and only if the tax increases (decreases) their present consumption. That is,*

$$sign[\frac{dU_0}{d\tau}] = sign[\frac{dc_1^o}{d\tau}] \tag{3.20}$$

Proof. See the Appendix. ■

Although the welfare of each individual is composed of two parts (i.e., environmental utility and non-environmental utility), for the initial old generation, the change in the welfare level stemming from an environmental tax is entirely measured by the change in non-environmental utility. Lemma 3.2 is quite straightforward yet successfully captures the idea that the accumulation or degradation of environmental quality needs to take time, while the initial old individuals have no time to wait for it. More specifically, since there is “no next period” for the initial old generation to enjoy a better environment, all their welfare concerns come from the consumption in their present period.

Turning now to the environmental tax effect on generation $t \geq 1$, we have the following lemma:

Lemma 3.3. *Supposing that* $\lambda = 0$, *the welfare effect of raising an environmental tax rate for generation* $t \geq 1$ *can be described by:*

$$\frac{dU_t}{d\tau} = \frac{(t-1)+\rho t}{\tilde{\gamma}} \frac{d\tilde{\gamma}}{d\tau} + \frac{1}{\tilde{c}^y} \frac{d\tilde{c}^y}{d\tau} + \frac{\rho}{\tilde{c}^o} \frac{d\tilde{c}^o}{d\tau} + \frac{\eta(1+\rho)}{\tilde{E}} \frac{d\tilde{E}}{d\tau} \quad for \quad t > 1, \tag{3.21}$$

$$\frac{dU_t}{d\tau} = \frac{\rho}{\tilde{\gamma}} \frac{d\tilde{\gamma}}{d\tau} + \frac{1}{\tilde{c}^y} \frac{d\tilde{c}^y}{d\tau} + \frac{\rho}{\tilde{c}^o} \frac{d\tilde{c}^o}{d\tau} + \frac{\eta\rho}{\tilde{E}} \frac{d\tilde{E}}{d\tau} \quad for \quad t = 1, \tag{3.22}$$

where $\tilde{E} = \overline{E} - \tilde{p} / \delta$.

Proof. See the Appendix. ■

In contrast to the initial old generation, the tax effect on the welfare of other generations is much more complicated. As shown in Lemma 3.3, an environmental tax influences the existing young and all future generations via the channels of affecting the growth rate, young-age consumption, old-age consumption, and environmental quality. For simplicity we would not like to analyze the welfare effect of each generation one by one. Instead, to provide some useful hints concerning how to compare the relative extent between different channels, we turn our attention toward the change in the welfare level in association with the generation born in the endless future (i.e., $t = \infty$). To this end, based on Lemma 3.2 and Lemma 3.3, the conditions regarding how an environmental tax affects the initial old generation and the generations born in the endless future can be summarized by the following proposition:

Proposition 3.3. *Supposing that* $\lambda = 0$, *the intergenerational welfare effects of raising the environmental tax rate have the following properties: (i) The initial old generation has a welfare gain (loss) if* τ *is smaller (greater) than* $(\theta - \theta\beta - \alpha)/(\alpha + \theta\beta)$; *(ii) the generation born in the endless future has a welfare gain (loss) if environmental taxes enhance (reduce) the balanced growth rate.*

Proof. See the Appendix. ■

The first part of Proposition 3.3 expresses the condition that an environmental tax can improve the welfare level of the initial old generation. It reveals that a smaller initial τ or a larger θ increases the possibility for the elderly to enjoy a welfare gain. The reasoning behind this result is very clear. Starting from a smaller initial τ, raising the environmental tax rate results in more tax revenues, and a larger θ means more revenues are transferred to the elderly. In particular, in the extreme case where the elderly receive nothing ($\theta = 0$), $\tau > (\theta - \theta\beta - \alpha)/(\alpha + \theta\beta) = -1$ is always true, indicating that an environmental tax always lowers the welfare (consumption) level of the initial old generation by reducing their savings income.

The result reported in the second part of Proposition 3.3 can be interpreted as follows. Provided that an environmental tax boosts the balanced growth rate, all generations (except the initial old) are definitely better off by enjoying both a better environmental quality and more consumption. However, if an environmental tax depresses the balanced growth rate, the generations born in the future will suffer from a loss in non-environmental utility (since they consume less with a lower growth rate) and thus the overall welfare effect is uncertain. The further away the future they are born in, the larger the loss in non-environmental utility. In the endless future, the loss must eventually exceed the environmental gains. As a consequence, such a welfare changes of the generations in the endless future are governed solely by the growth effect (i.e., $sign[dU_\infty] = sign[d\tilde{\gamma}]$).

3.5. Environmental Production Externality and Pareto-improving Policies

In this section, we deal with the growth and welfare effects in the presence of the positive environmental externality in production (i.e., $\lambda > 0$). Substituting

$\Lambda_t = Ak_t^{1-\alpha}E_t^{\lambda}$ into (3.9)-(3.11) and implementing some calculations, the economy along the balanced-growth path can then be described by the following set of non-linear equations:

$$\tilde{c}^y = \frac{1}{1+\rho}\left[\tilde{w} + (1-\theta)\tilde{g} + \frac{\theta}{1+\tilde{r}}\tilde{g}\,\tilde{\gamma}\right], \tag{3.23}$$

$$\tilde{c}^o = \frac{\rho(1+\tilde{r})}{1+\rho}\left[\tilde{w} + (1-\theta)\tilde{g} + \frac{\theta}{1+\tilde{r}}\tilde{g}\,\tilde{\gamma}\right], \tag{3.24}$$

$$\tilde{\gamma} = \frac{1}{1+\rho}\left[\rho\tilde{w} + \rho(1-\theta)\tilde{g} - \frac{\theta}{1+\tilde{r}}\tilde{g}\,\tilde{\gamma}\right], \tag{3.25}$$

$$\alpha A\tilde{p}^{\beta}(\bar{E} - \tilde{p}/\delta)^{\lambda} = \tilde{r}\,, \tag{3.26}$$

$$\beta A\tilde{p}^{\beta-1}(\bar{E} - \tilde{p}/\delta)^{\lambda} = (1+\tau)b\,, \tag{3.27}$$

$$\nu A\tilde{p}^{\beta}(\bar{E} - \tilde{p}/\delta)^{\lambda} = \tilde{w}\,, \tag{3.28}$$

$$\tilde{g} = \tau b\tilde{p}\,. \tag{3.29}$$

The non-linear system expressed in (3.23)-(3.29) determines seven unknowns, i.e., $\tilde{c}^y, \tilde{c}^o, \tilde{\gamma}, \tilde{w}, \tilde{r}, \tilde{p}$, and $\tilde{g}$.

Running in sharp contrast to our analysis in the previous section, introducing a positive value of λ complicates the model enormously such that no closed form solution is attainable. We thus present our results via numerical simulations. In a relatively quantitative study by Fullerton and Kim (2008), the extent of the environmental externality λ is chosen to be 0.77, but is allowed to vary to test the sensitivity within the range of [0.3, 1.2]. In our model, we choose the lowest value of $\lambda = 0.3$ exercising caution not to overstate the positive externality of environmental quality. We also follow Fullerton and Kim (2008) to set the parameter of environmental preference $\eta = 0.7$. Moreover, the parameters associated with the regeneration function in (3.13) are set to be $\bar{E} = 2.82$ and $\delta = 1$, which are jointly calibrated so that the balanced growth rate is around 2% in the absence of environmental taxes. Other parameters are the same as in Section 3.4.1

for consistency.

3.5.1. Growth effect

Figure 3.2 depicts the growth effect of an environmental tax with or without the environmental externality in production. It is clear from Figure 3.2 that the positive externality in production, as we expected, benefits the growth effect of raising an environmental tax. The intuition behind this result is quite straightforward. With $\lambda > 0$, a higher environmental tax improves environmental quality and in turn leads to a higher technology level, thereby causing an increase in the marginal product of capital and labor.

3.5.2. Welfare effect and Pareto-improving policies

This subsection makes an effort to examine the possibilities of Pareto-improving policies. By definition, an environmental tax is Pareto-improving if it improves the welfare of at least one generation without worsening the others. One implication exhibited in Figure 3.2 is that, in association with a larger environmental production externality, an environmental policy with a higher probability is Pareto-improving. To see this, let us consider the case of an *equal transfer policy* (i.e., $\theta = 0.5$). In Figure 3.2(a) we can observe that the growth rate declines with environmental taxes in the absence of the environmental production externality ($\lambda = 0$), while in Figure 3.2(b) the growth rate may increase as long as environmental taxes are not too high in the presence of the environmental production externality ($\lambda = 0.3$). That is to say, in association with $\lambda = 0$, if the government implements an equal transfer policy, then any rate of environmental tax can never be Pareto-improving since it will certainly worsen the generations in the endless future via reducing growth. Nevertheless, an equal transfer policy is not necessary for a deterioration in growth in the presence of the environmental production externality ($\lambda > 0$) so that a Pareto-improving policy can possibly be achieved under such circumstances.

Figure 3.3 illustrates the overall welfare of generations 0-5 before and after raising the environmental tax rate from 0 to 0.5. Some main findings that are consistent with our expectations can be summarized as follows. First, as θ goes up, the generation 0 is better off while all other generations are worse off. Second, as θ goes up, generations born in the more distant future lose more than generations born earlier. Third, a positive λ increases the welfare effect of environmental taxes on all generations. Fourth, in the presence of environmental production externalities, it is possible with an environmental policy combination of θ and τ to achieve a Pareto-improvement, as illustrated in Figure 3.3(d) and 3.3(e).[27]

3.6. Concluding Remarks

This chapter sets up the Samuelson-Diamond OLG model featuring two kinds of externalities. The first is capital externalities proposed by Romer (1986) and Lucas (1988), and the second is environmental externalities proposed by Bovenberg and Smulders (1995). Based on the model, we examine how a higher environmental tax influences the balanced growth rate and intergenerational welfare. In particular, we focus on how the government's transfer policy between current and subsequent generations affects the efficacy of the environmental tax policy.

Several major findings are summarized as follows. First, the growth effect of environmental policies is dominant when evaluating the welfare changes of our children born in the endless future. This growth effect is ignored in previous studies.

---

[27] We cannot conclude whether a Pareto-improving environmental tax is attainable in the case of $\lambda=0$ due to the lack of a mathematical proof. However, by running a number of simulations and varying the parameters within a reasonable range, we find it is extremely hard, if not impossible, to implement a Pareto-improving environmental tax in the absence of environmental production externalities.

Second, how environmental tax revenues are transferred to different generations may be irrelevant in an infinitely-lived agent model; however, in an OLG model the transfer policy plays an important role in determining not only the intergenerational welfare level, but also the balanced growth rate. We show that an environmental tax is not necessarily harmful to economic growth even in the absence of positive environmental externalities in production. Third, our model is capable of capturing the fact that an environmental policy has diverse environmental utility effects on the different existing generations. Fourth, we numerically illustrate that a Pareto-improving environmental policy might be achievable in the presence of a positive environmental externality in production.

Two extensions may be worth-mentioning. First, our model assumes that tax revenues are transferred to the households. An interesting extension would be to consider that the revenues of environmental taxation are used to finance public abatement or environmental maintenance. Second, as a normative analysis, one could think of setting up and solving the maximization problem of a forward-looking social planner who takes into consideration the utility of all generations.[28] Fruitful results might be obtained if future studies were extended to include these issues.

---

[28] See, for example, Ono (1996).

Appendix

Proof of Proposition 3.1. It is straightforward to take the differential of $\tilde{p}$, $\tilde{r}$, and $\tilde{w}$ in (3.16)-(3.18) with respect to τ to derive the results.

Proof of Lemma 3.1. Combining (3.6) and (3.15) and dividing both sides by k_t, we have:

$$\frac{k_{t+1}}{k_t} = \frac{1}{1+\rho}\left[\rho\frac{w_t}{k_t} + \rho(1-\theta)\frac{g_t}{k_t} - \frac{\theta}{R_{t+1}}\frac{g_{t+1}}{k_{t+1}}\frac{k_{t+1}}{k_t}\right]. \tag{A3.1}$$

Using Definition 3.2, $R_{t+1} = 1 + r_{t+1}$, and substituting the transformed variables into (A3.1), on the balanced growth path we then have:

$$\tilde{\gamma} = \gamma_k = \frac{k_{t+1}}{k_t} = \frac{1}{1+\rho}\left[\rho\tilde{w} + \rho(1-\theta)\tilde{g} - \frac{\theta}{1+\tilde{r}}\tilde{g}\tilde{\gamma}\right]. \tag{A3.2}$$

Rearranging (A3.2) yields (3.19) in the text.

Derivation of Condition L. The upward-sloping Laffer curve means there exists a positive relationship between the tax rate and tax revenues, i.e., $\partial\tilde{g}/\partial\tau > 0$. Rearranging (3.16) and differentiating $\tilde{g} = \tau b\tilde{p}$ with respect to τ yields:

$$\frac{\partial\tilde{g}}{\partial\tau} = b\left\{\left(\frac{\beta A}{b(1+\tau)}\right)^{\frac{1}{1-\beta}} + \tau\frac{1}{1-\beta}\left(\frac{\beta A}{b(1+\tau)}\right)^{\frac{1}{1-\beta}-1}(-1)\frac{\beta A}{b}\frac{1}{(1+\tau)^2}\right\}$$

$$= b\tilde{p}\left\{1 - \frac{1}{1-\beta}\frac{\tau}{1+\tau}\right\}. \tag{A3.3}$$

It is easy from (A3.3) to obtain the following expression:

$$\tau \,\substack{<\\>}\, \frac{1-\beta}{\beta} \Leftrightarrow \frac{\partial\tilde{g}}{\partial\tau} \,\substack{>\\<}\, 0. \tag{A3.4}$$

Condition L also implies that the tax revenue is maximized at $\tau = (1-\beta)/\beta$.

Proof of Proposition 3.2. We first prove Proposition 3.2(i). Substituting $\theta = 0$ into (3.19) yields $\tilde{\gamma}(\tau, 0) = \rho(\tilde{w} + \tau b\tilde{p})/(1+\rho)$. Using (3.16)-(3.18) and differentiating

$\tilde{\gamma}(\tau,0)$ with respect to τ, we obtain:

$$\frac{\partial\tilde{\gamma}(\tau,0)}{\partial\tau}=\frac{\rho}{1+\rho}\left\{\frac{\beta}{1-\beta}\nu A\Omega^{\frac{2\beta-1}{1-\beta}}\frac{\beta A}{b}\frac{(-1)}{(1+\tau)^2}+b\Omega^{\frac{1}{1-\beta}}+\frac{1}{1-\beta}\tau b\Omega^{\frac{\beta}{1-\beta}}\frac{\beta A}{b}\frac{(-1)}{(1+\tau)^2}\right\}$$

$$=\frac{\rho}{1+\rho}\Omega^{\frac{1}{1-\beta}}\left\{\frac{\beta}{1-\beta}\nu A\Omega^{-2}\frac{\beta A}{b}\frac{(-1)}{(1+\tau)^2}+b+\frac{1}{1-\beta}\tau b\Omega^{-1}\frac{\beta A}{b}\frac{(-1)}{(1+\tau)^2}\right\}$$

$$=\frac{\rho}{1+\rho}\Omega^{\frac{1}{1-\beta}}\left\{-\frac{\nu b}{1-\beta}+b-\frac{\tau b}{(1-\beta)(1+\tau)}\right\}$$

$$=\frac{b\rho}{1+\rho}\Omega^{\frac{1}{1-\beta}}\left\{\frac{-(1+\tau)\nu+(1-\beta)(1+\tau)-\tau}{(1-\beta)(1+\tau)}\right\}, \qquad \text{(A3.5)}$$

where $\Omega\equiv\beta A/b(1+\tau)>0$. Imposing the condition $\alpha+\beta+\nu=1$ and rearranging (A3.5), we can infer the following result:

$$\tau\lessgtr\frac{\alpha}{1-\alpha}\Leftrightarrow\frac{\partial\tilde{\gamma}(\tau,0)}{\partial\tau}\gtrless 0. \qquad \text{(A3.6)}$$

The proof of Proposition 3.2(ii) is much more complicated mathematically. We first substitute $\theta=1$ into (3.19) to obtain

$$\tilde{\gamma}(\tau,1)=\rho\nu A\Omega^{\beta/(1-\beta)}\Delta^{-1}, \qquad \text{(A3.7)}$$

where $\Delta\equiv 1+\rho+\tau b\Omega^{1/(1-\beta)}[1+\alpha A\Omega^{\beta/(1-\beta)}]^{-1}>0$. Then, differentiating $\tilde{\gamma}(\tau,1)$ with respect to τ yields:

$$\frac{\partial\tilde{\gamma}(\tau,1)}{\partial\tau}=\frac{1}{\Delta^2}\left\{-\Theta\Delta-\rho b\tilde{w}\left[\frac{1}{1+\tilde{r}}\Omega^{\frac{1}{1-\beta}}+\frac{\tau}{(1+\tilde{r})^2}\right.\right.$$
$$\left.\left.\times\left(-\frac{1}{1-\beta}\Omega^{\frac{\beta}{1-\beta}}\frac{\beta A}{b}\frac{1+\tilde{r}}{(1+\tau)^2}+\frac{\beta}{1-\beta}\alpha A\Omega^{\frac{2\beta}{1-\beta}}\frac{\beta A}{b}\frac{1}{(1+\tau)^2}\right)\right]\right\}$$

$$=\frac{1}{\Delta^2}\left\{-\Theta\Delta-\rho b\tilde{w}\left[\frac{1}{1+\tilde{r}}\Omega^{\frac{1}{1-\beta}}+\frac{-\tau}{(1+\tilde{r})^2(1+\tau)^2}\right.\right.$$
$$\left.\left.\times\left(\frac{\beta A}{(1-\beta)b}\left[\Omega^{\frac{\beta}{1-\beta}}+\alpha A\Omega^{\frac{2\beta}{1-\beta}}\right]-\frac{\beta^2A^2\alpha}{(1-\beta)b}\Omega^{\frac{2\beta}{1-\beta}}\right)\right]\right\}$$

$$= \frac{1}{\Delta^2}\left\{ -\Theta\Delta - \rho b\tilde{w}\left[\frac{1}{1+\tilde{r}}\Omega^{\frac{1}{1-\beta}} + \frac{-\tau}{(1+\tilde{r})^2(1+\tau)^2} \right.\right.$$

$$\left.\left. \times\left(\frac{\beta A}{(1-\beta)b}\Omega^{\frac{\beta}{1-\beta}} + \frac{\alpha\beta A^2\alpha}{b}\Omega^{\frac{2\beta}{1-\beta}} \right) \right] \right\}$$

$$= \frac{1}{\Delta^2}\left\{ -\Theta\Delta - \frac{\rho b\tilde{w}}{(1+\tilde{r})^2}\left[\Omega^{\frac{1}{1-\beta}} + \alpha A\Omega^{\frac{1+\beta}{1-\beta}} - \frac{\tau\beta A\Omega^{\frac{\beta}{1-\beta}}}{(1-\beta)(1+\tau)^2 b} - \frac{\tau\alpha\beta A^2\Omega^{\frac{2\beta}{1-\beta}}}{(1+\tau)^2 b} \right] \right\}$$

$$= \frac{1}{\Delta^2}\left\{ -\Theta\Delta - \frac{\rho b\tilde{w}}{(1+\tilde{r})^2}\left[\frac{\beta A[(1-\beta)(1+\tau)-\tau]}{b(1+\tau)^2(1-\beta)}\Omega^{\frac{\beta}{1-\beta}} + \frac{\alpha\beta A^2}{(1+\tau)^2 b}\Omega^{\frac{2\beta}{1-\beta}} \right] \right\} \quad \text{(A3.8)}$$

where $\Theta \equiv \dfrac{\rho\nu\beta^2 A^2\Omega^{(2\beta-1)/(1-\beta)}}{b(1+\tau)^2(1-\beta)} > 0$. Since Condition L implies $[(1-\beta)(1+\tau)-\tau] > 0$, from (A3.8) we can obtain the result $\partial\tilde{\gamma}(\tau,1)/\partial\tau < 0$.

Proof of Lemma 3.2. The utility of the initial old generation is $U_0 = \ln c_1^o + \eta \ln E_1$. Given that the environmental quality is a pre-determined variable (E_1 is given in period 1), by differentiating U_0 with respect to τ, we can easily obtain the relationship reported in (3.20).

Proof of Lemma 3.3. Using the transformed variables and evaluating the balanced growth path, we can rewrite the utility function of generation $t > 1$ as follows:

$$U_t = \ln(k_1\tilde{\gamma}^{t-1}\tilde{c}^y) + \rho\ln(k_1\tilde{\gamma}^t\tilde{c}^o) + \eta(1+\rho)\ln\tilde{E}\,. \quad \text{(A3.9)}$$

Differentiating U_t with respect to τ yields:

$$\frac{dU_t}{d\tau} = \frac{1}{k_1\tilde{\gamma}^{t-1}\tilde{c}^y}\left[k_1(t-1)\tilde{\gamma}^{t-2}\frac{d\tilde{\gamma}}{d\tau}\tilde{c}^y + k_1\tilde{\gamma}^{t-1}\frac{d\tilde{c}^y}{d\tau} \right]$$

$$+\frac{\rho}{k_1\tilde{\gamma}^t\tilde{c}^o}\left[k_1 t\,\tilde{\gamma}^{t-1}\frac{d\tilde{\gamma}}{d\tau}\tilde{c}^o + k_1\tilde{\gamma}^t\frac{d\tilde{c}^o}{d\tau} \right] + \eta(1+\rho)\frac{1}{\tilde{E}}\frac{d\tilde{E}}{d\tau}, \quad \text{(A3.10)}$$

which reduces to (3.21) in the text. As for generation 1, the utility function can be rewritten as:

$$U_1 = \ln(k_1\tilde{c}^y) + \eta E_1 + \rho \ln(k_1\tilde{\gamma}\tilde{c}^o) + \eta\rho \ln \tilde{E} \ . \qquad \text{(A3.11)}$$

Then, by differentiating U_1 with respect to τ, we can derive (3.22) in Lemma 3.3.

Proof of Proposition 3.3. The initial old generation only live in period 1 and receive transfer payments and the return from savings as their consumption in old age. This can be expressed by:

$$c_1^o = (1+\tilde{r})s_0 + \theta\tilde{g} \ . \qquad \text{(A3.12)}$$

Note that since we assume $s_0 = 1$, the tax effect on the consumption of the initial old is thus:

$$\frac{dc_1^o}{d\tau} = \frac{-\beta}{1-\beta}\alpha A \Omega^{\frac{2\beta}{1-\beta}} \frac{\beta A}{b(1+\tau)^2} + \theta b\left(\Omega^{\frac{1}{1-\beta}} - \frac{\tau}{1-\beta}\Omega^{\frac{\beta}{1-\beta}} \frac{\beta A}{b(1+\tau)^2}\right) \qquad \text{(A3.13)}$$

$$= b\Omega^{\frac{1}{1-\beta}}\left[\frac{(\theta - \beta\theta - \alpha) - (\alpha + \theta\beta)\tau}{(1-\beta)(1+\tau)}\right]$$

Equipped with Lemma 3.2, Proposition 3.3(i) is proved.

The proof of Proposition 3.3(ii) is straightforward from (3.21) when evaluated at $t \to \infty$. Since $d\tilde{\gamma}$, $d\tilde{c}^y$, $d\tilde{c}^o$ and $d\tilde{E}$ are finite, as $t \to \infty$ the first term on the right-hand side of (3.21) must exceed other terms. In other words, we have the result $sign[dU_\infty] = sign[d\tilde{\gamma}]$ provided that $d\tilde{\gamma}$ is not equal to zero.

References

Agnani, B. M. J. Gutiérrez and A. Iza (2005), Growth in overlapping generation economies with non-renewable resources, *Journal of Environmental Economics and Management* 50, 387-407.

Belan, P., P. Michel and P. Pestieau (1998), Pareto-improving social security reform, *The Geneva s on Risk and Insurance* 23, 119-125.

Blanchard, O. J. (1985), Debt deficits, and finite horizons, *Journal of Political Economy* 93, 223-247.

Bovenberg, A. L. and B. J. Heijdra (1998), Environmental tax policy and intergenerational distribution, *Journal of Public Economics* 67, 1-24.

Bovenberg, A. L. and R. A. de Mooij (1997), Environmental tax reform and endogenous growth, *Journal of Public Economics* 63, 207-237.

Bovenberg, A. L. and S. Smulders (1995), Environmental quality and pollution-augmenting technical change in a two-sector endogenous growth model, *Journal of Public Economics* 57, 369-391.

Byrne, M. M. (1997), Is growth a dirty word? Pollution, abatement and endogenous growth, *Journal of Development Economics* 54, 261-284.

Diamond, P. A. (1965), National debt in the neoclassical growth model, *American Economic Review* 55, 279-293.

Fullerton, D. and S. R. Kim (2008), Environmental investment and policy with distortionary taxes, and endogenous growth, *Journal of Environmental Economics and Management* 56, 141-154.

Grimaud, A. (1999), Pollution permits and sustainable growth in a Schumpeterian model, *Journal of Environmental Economics and Management* 38, 249-266.

Gutierrez, M. (2008), Dynamic inefficiency in an overlapping generation economy with pollution and health costs, *Journal of Public Economic Theory* 10, 563-594.

Gyárfás, G. and M. Marquardt (2001), Pareto-improving transition from a pay-as-you-go to a fully funded pension system in a model of endogenous growth, *Journal of Population Economics* 14, 445-453.

Heijdra, B. J. (2009), *Foundations of Modern Macroeconomics*, 2nd edition, Oxford University Press, New York.

Heijdra, B. J., J. P. Kooiman and J. E. Ligthart (2006), Environmental quality, the macroeconomy, and intergenerational distribution, *Resource and Energy Economics* 28, 74-104.

Heijdra, B. J., J. O. Mierau and L. S. M. Reijnders (2010), The tragedy of annuitization, *CESifo Working No. 3141*.

Itaya, J. (2008), Can environmental taxation stimulate growth? The role of indeterminacy in endogenous models with environmental externalities, *Journal of Economic Dynamics and Control* 32, 1156-1180.

John, A. and R. Pecchenino (1994), An overlapping generations model of growth and the environment, *Economic Journal* 104, 1393-1410.

John, A., R. Pecchenino, D. Schimmelpfennig and S. Schreft (1995), Short-lived agents and the long-lived environment, *Journal of Public Economics* 58, 127-141.

Jouvet, P. A., P. Pestieau and G. Ponthiere (2010), Longevity and environmental quality in an OLG model, *Journal of Economics* 100, 191-216.

Lucas, R. E., Jr. (1988), On the mechanics of economic development, *Journal of Monetary Economics* 22, 3-24.

Mariani, F., A. Perez-Barahona and N. Raffin (2010), Life expectancy and the environment, *Journal of Economic Dynamic and Control* 34, 798-815.

Mohtadi, H. (1996), Environment, growth and optimal policy design, *Journal of Public Economics* 63, 119–140.

Nakada, M. (2004), Does environmental policy necessarily discourage growth? *Journal of Economics* 81, 249-275.

Nielsen, S. B., L. H. Pedersen and P. B. Sørensen (1995), Environmental policy, pollution, unemployment, and endogenous growth, *International Tax and Public Finance* 2, 185-205.

Ono, T. (1996), Optimal tax schemes and the environmental externality, *Economics Letters* 53, 283-289.

Ono, T. (2003a), Environmental tax policy and long-run economic growth, *Japanese Economic Review* 54, 203-217.

Ono, T. (2003b), Environmental tax policy in a model of growth cycles, *Economic Theory* 22, 141-168.

Oueslati W. (2002), Environmental policy in an endogenous growth model with human capital and endogenous labor supply, *Economic Modelling* 19, 487-507.

Pautrel, X. (2008), Reconsidering the impact of the environment on long-run growth when pollution influences health and agents have a finite-lifetime, *Environmental and Resource Economics* 40, 37-52.

Pautrel, X. (2009), Pollution and life expectancy: how environmental policy can promote growth, *Ecological Economics* 68, 1040-1051.

Pearce, D. W. and J. J. Warford (1993), *A World Without End: Economics, Environment, and Sustainable Development*, Oxford University Press, Oxford.

Romer, P. (1986), Increasing returns and long-run growth, *Journal of Political Economy* 94, 1002-1037.

Samuelson, P. A. (1958), An exact consumption-loan model of interest with or without the social contrivance of money, *Journal of Political Economy* 66, 467-482.

Smulders, S. (1995), Entropy, environment and endogenous economic growth, *International Tax and Public Finance* 2, 319-340.

Smulders, S. and R. Gradus (1996), Pollution abatement and long-term growth, *European Journal of Political Economy* 12, 505-532.

Stokey, N. L. (1998), Are there limits to growth? *International Economic Review* 39, 1-31.

Tahvonen, O. and J. Kuuluvainen (1991), Optimal growth with exhaustible resources and pollution, *European Economic Review* 35, 650-661.

Xepapadeas, A, (2005), Economic growth and the environment, in K.-G. Mäler and J.R. Vincent (eds.), *Handbook of Environmental Economics*, Vol. 3, 1219–1271, North-Holland, Amsterdam.

Yaari, M. E. (1965), Uncertain lifetime, life insurance and the theory of the consumer, *Review of Economic Studies* 32, 137-150.

Zeng, J. and J. Zhang (2007), Subsidies in an R&D growth model with elastic labor, *Journal of Economic Dynamics and Control* 31, 861-886.

Figure 3.1. Growth effects of environmental policies

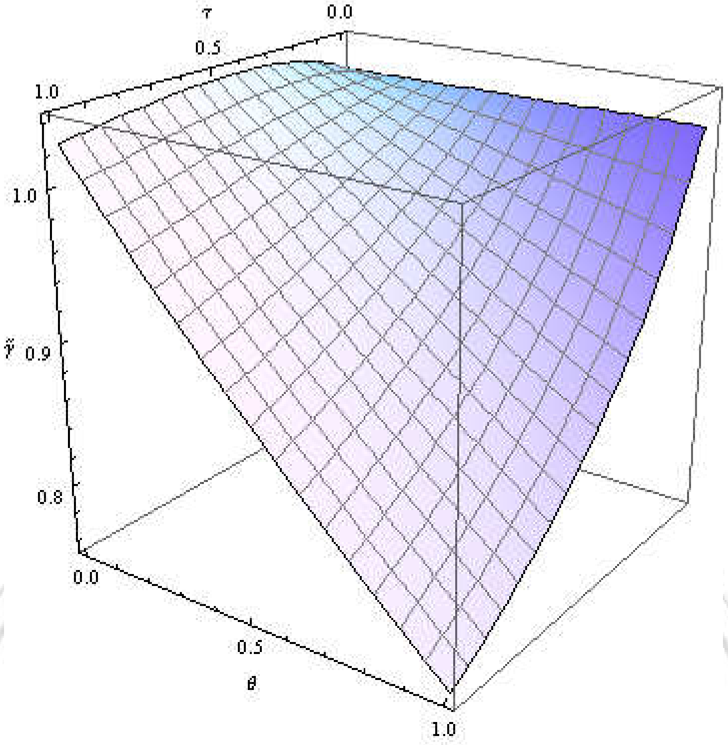
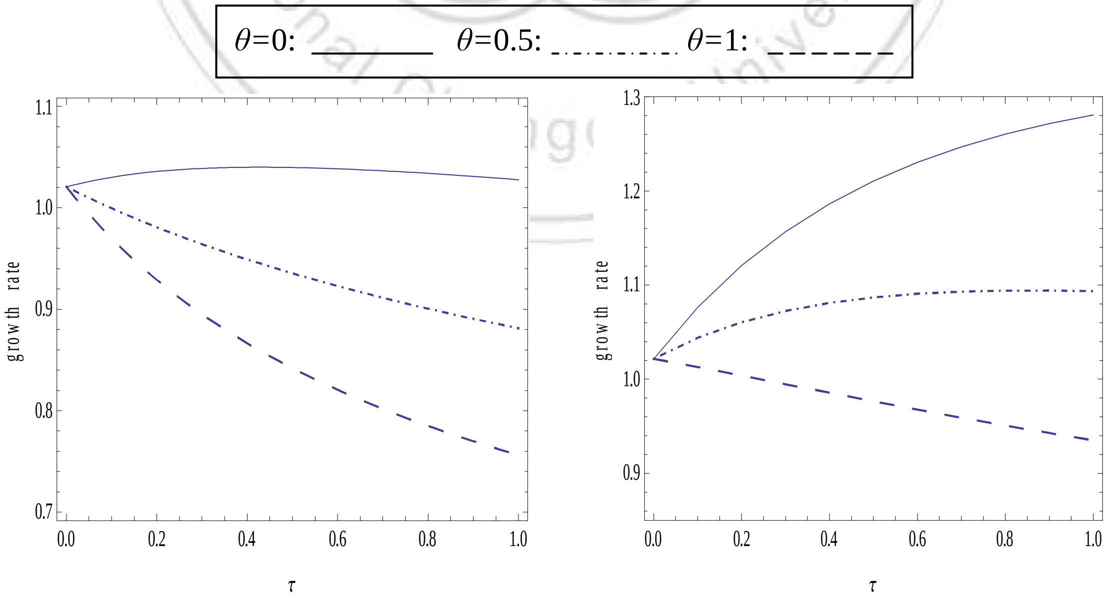


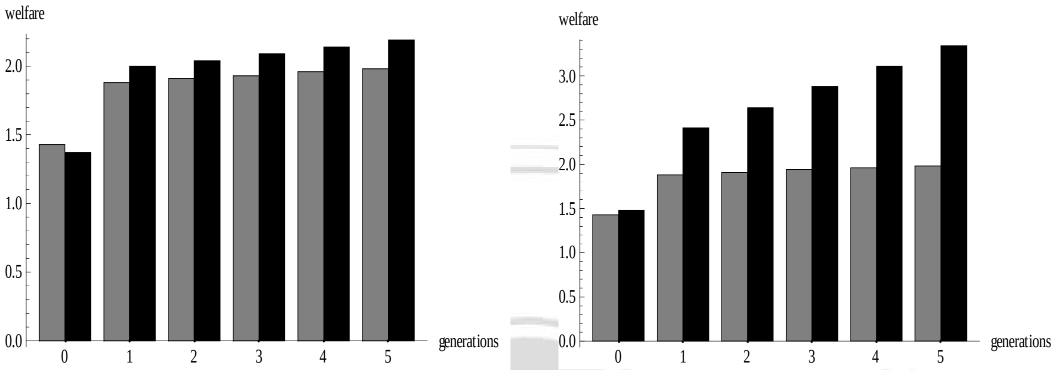
Figure 3.2. Productivity externality and the growth effects



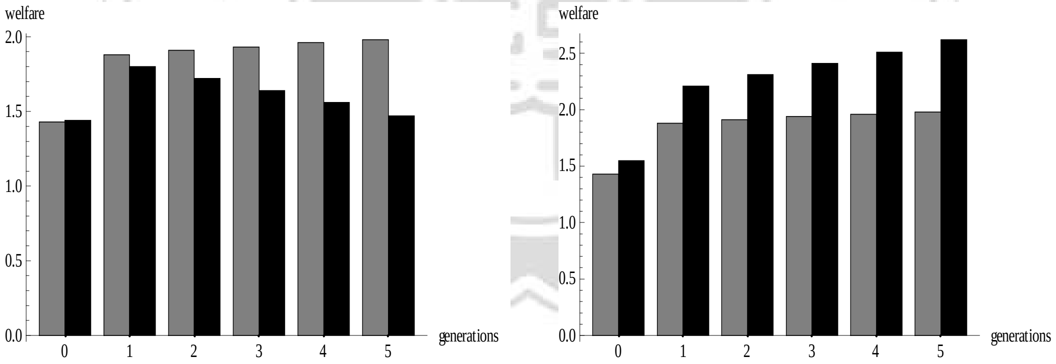
(a) $\lambda = 0$ (b) $\lambda = 0.3$

Figure 3.3. The intergenerational welfare effects of an environmental tax

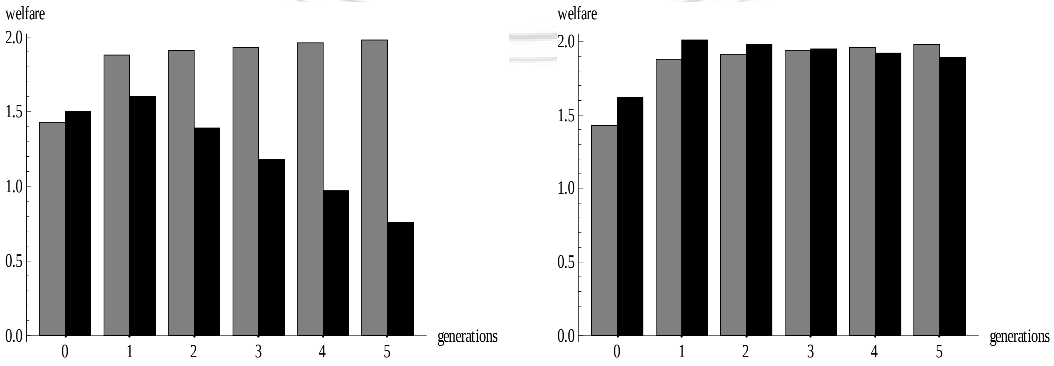
▨ : $\tau = 0$, ■ : $\tau = 0.5$



(a) $\lambda = 0, \theta = 0$ (d) $\lambda = 0.3, \theta = 0$



(b) $\lambda = 0, \theta = 0.5$ (e) $\lambda = 0.3, \theta = 0.5$



(c) $\lambda = 0, \theta = 1$ (f) $\lambda = 0.3, \theta = 1$

Chapter IV

Endogenous Time Preference Depending on the Environmental Quality: Economic Growth and Policy Implications

4.1. Introduction

In the literature on environmental economics, environmental externalities mainly affects the economy via two channels. First, it affects the households' welfare. A better environment undoubtedly brings us more happiness (see, e.g., Bovenberg and de Mooij, 1994; Ligthart and van der Ploeg, 1994; Chen et al., 2003, Itaya, 2008). Second, it may be related to the firm’s productivity. For example, a cleaner water quality improves workers' health; a better air quality slows the depreciation of equipments, both of which makes 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 environment on welfare and production, what is not so widely noticed is that the *time preferences* of agents can also be influenced by environmental quality. For example, suppose the environmentalists declare that the problem of global warming will become very severer in the near future, one would expect that consumption will increase and saving will fall, because now that saving (for future consumption) become more uncertain. This means that fears of climate change may alter people's time preference to 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.

Despite the sensible logic, existing studies on how environmental quality affects agents’ time preferences are very scarce and inconclusive. Pittel (2002) would be 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 of the environment. On the contrary, Yanase (2011) uses the assumption that a better environment can cause patience. His 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, perhaps due to analytical simplicity, most theoretical studies on the interaction of growth and the environment assume a constant time preference.[29] However, as emphasized by Weitzman (1994), the assumption of a constant time preference may be inappropriate especially in a world with increasing environmental concern. Accordingly, once we take into consideration the effect of environmental quality on people's patience, the following natural questions arise: What are the consequences of environmental policies on economic growth? What are the policy implications? What is the optimal rate of the environmental tax? Owing to the fact that all the abovementioned articles with environmentally endogenous time preference do not deal with these issues, we aim to explore them in this chapter.

To this end, we develop a simple endogenous growth model featuring the capital externality suggested by Romer (1986) and Lucas (1988), in which time preference is endogenized in the sense that it will be influenced by the environmental quality. As in Pittel (2002), we will not restrict the direction of such an effect. We allow three

---

[29] See, e.g., Ligthart and van der Ploeg (1994), Bovenberg and Smulders (1995), Chen et al. (2003), Hopkins and Kornienko (2006), Itaya (2008), and Fullerton and Kim (2008).

possibilities to occur, that is: the environmental quality may positively, negatively, or not affect the agents' time preferences. Our result shows 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 environmental quality on time preference, a higher environmental tax may boost the balanced growth rate. Although there are already numerous studies that advocates a positive growth effect of the environmental tax,[30] our analysis can contribute by focusing on the positive effect resulting from an endogenous time preference depending on the environment.

Another interesting finding concerns the optimal rate of environmental tax. The well-known Pigouvian tax requires the optimal environmental tax rate being equal to the marginal social damage of pollution. Our result shows that, when agents' time preferences can be influenced by the environment, the Pigouvian tax rate may be inefficient because it fails to internalize 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 of pollution, depending on the distinctive feature of time preference.

The rest of this chapter is organized in the following way. Section 4.2 presents the basic growth model with endogenous time preference. Section 4.3 shows our main results. We focus on the policy implications of an endogenous time preference on growth and the optimal environmental tax. Section 4.4 discusses some extensions of the baseline model. Section 4.5 concludes.

---

[30] 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 Aloi and Tournemarin (2011).

4.2. The Model

We consider an infinite-horizon economy comprised of a continuum of identical households, a polluting firm, and a government. The firm produces a single final good y using the technology $y = \Lambda k^{\alpha} z^{\beta}$ ($\alpha, \beta > 0$)[31] where k is the capital stock and z denotes a "dirty input".[32] The term Λ represents the positive capital externalities. To ensure sustainable growth, we assume $\Lambda = Ak^{1-\alpha}$ where $A > 0$ is a constant technology parameter. For the basic model we will assume that there is no environmental externality in the production process. The positive externality of a better environment on production will be introduced in Section 4. 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:

$$\pi = y - (1+\tau_k) rk - T_p z \, . \qquad (4.1)$$[33]

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.[34] It is quite easy to derive first-order conditions for k and z:

$$\alpha \Lambda k^{\alpha-1} z^{\beta} = (1+\tau_k) r \, , \qquad (4.2)$$

$$\beta \Lambda k^{\alpha} z^{\beta-1} = T_p \, . \qquad (4.3)$$

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:

---

[31] To ensure zero profit, we assume β=1-α.

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

[33] We assume the capital tax is levied on firms and thus is not into the households budget constraint. Changing the tax burden from the firms to the households will not alter our results.

[34] In the environmental endogenous growth literature, for sustainable growth it is necessary that the (private or public) price of pollution evolves with another growing factor (see, e.g., Fullerton and Kim, 2008). See Smulders (1995) for a discussion on this point.

$$u=\frac{(cz^{-\eta})^{1-\sigma}}{1-\sigma},\sigma>0\,, \tag{4.4}$$

where c is the consumption and σ the intertemporal substitution elasticity. The parameter $\eta>0$ measures the negative impact of pollution on felicity.

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

$$U=\int_0^\infty u(\cdot)\exp[-\int_0^t\theta(z_s)ds]dt\,,\quad \theta'(z)\overset{>}{\underset{<}{=}}0\,, \tag{4.5}$$

As revealed in (4.5), pollution not only has a negative impact on the level of utility, but also influences the household's time preference, described by the term $\theta(\cdot)$.

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 Ayong Le Kama and Schubert (2007)-type time preference rate. Given that $\theta'(z)<0$ implies that the environmental quality and current consumption are complementary, in the following analysis $\theta'(z)<0$ is referred to as the *eco-complementary* time preference. By contrast, the specification $\theta'(z)>0$ reflects the Yanase (2011)-type time preference rate. Following a similar interpretation, we can refer to $\theta'(z)>0$ as the *eco-substitutionary* time preference. Finally, $\theta'(z)=0$ represents the traditional approach of an exogenous time preference.

Tax revenues are rebated to the household as a form of lump-sum transfer $R\,(=\tau_k rk+T_p z\,)$. The household thus faces a budget constraint $\dot{k}=rk+R-c$.[35] We can then define the Hamiltonian for the household's optimization as:

$$H^h=\frac{(cz^{-\eta})^{1-\sigma}}{1-\sigma}\exp[-\int_0^t\theta(z_s)ds]+\hat{\phi}(rk+R-c)-\hat{\psi}\theta(z)\,, \tag{4.6}$$

where $\hat{\varphi}$ and $\hat{\psi}$ are the co-state variable associated with, respectively, the capital

---

[35] A dot denotes the time derivative.

stock and the "stock of accumulated impatience" (Obstfeld, 1990). Note that the atomistic households choose c and k to maximize (4.4) while treating pollution as given. The first-order conditions are

$$c^{-\sigma} z^{-\eta(1-\sigma)} = \varphi , \tag{4.7}$$

$$r\varphi = -\dot{\varphi} + \theta(z)\varphi , \tag{4.8}$$

where $\varphi = \hat{\varphi} \exp[\int_0^t \theta(z_s) ds]$.

4.3. Policy Implications

4.3.1. The growth effect of the environmental tax

Now we are in a position to examine the growth effect of the environmental tax in the presence of an endogenous time preference. Following the literature on the environment and growth, we assume that in the steady state the total pollution emissions are limited in a physical sense, and all other economic variables grow at a common constant endogenous growth rate *g*. That is, the balanced growth path (BGP) in the steady state is characterized by $\dot{z} / z = 0$ and $\dot{k} / k = \dot{c} / c = \dot{y} / y = \tilde{g}$ (a tilde denotes the value along the BGP, hereafter). Based on this feature and the first-order conditions, we can obtain the balanced growth rate in the decentralized economy, denoted by $\tilde{g}^d$, as:

$$\tilde{g}^d = \frac{1}{\sigma} \left[\frac{1}{1+\tau_k} A\alpha \tilde{z}^{\beta} - \theta(\tilde{z}) \right], \tag{4.9}$$

where $\tilde{z} = (\beta A / \tau_p)^{1/(1-\beta)}$.

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 is:

$$\frac{\mathrm{d}\tilde{g}^d}{\mathrm{d}\tau_p} = \frac{\beta A}{\sigma \tau_p{}^2 (1-\beta)} \tilde{z}^{\beta} \left[-\frac{\alpha \tau_p}{1+\tau_k} + \theta'(\tilde{z}) \right]. \tag{4.10}$$

The result reported in (4.10) leads to the following proposition:

Proposition 4.1. *In the case of exogenous and eco-complementary time preference, raising the environmental tax reduces the growth rate. However, if the households have an eco-substitutionary time preference, the growth effect of environmental tax is uncertain, implying that a rise in the environmental tax may boost economic growth.*

Proposition 4.1 indicates that if people become impatient due to their experience of a worse environmental quality, any policies that protect the environment can also contribute positively to economic growth. In other words, it suggests that a broadly-defined "double dividend hypothesis" may occur if the agents have an eco-substitutionary time preference. The existing studies on the double dividend hypothesis focus on a reduction in other distortion taxation (Pearce, 1991; Oates, 1993), or on the assumption that a cleaner environment can benefit the production (Bovenberg and Smulders, 1995, 1996). We instead provide another possibility of a dividend that arises through the endogenous preference of the agents.

This finding can also be correlated to the famous "environmental Kuznets curve", which indicates that per capita income and environmental degradation have an inverted-U relationship (see, e.g., Selden and Song, 1994; Grossman and Krueger, 1995). In our analysis, with the traditional exogenous time preferences, pollution and growth must be monotone, meaning that the inverted-U relationship cannot occur. However, Proposition 4.1 delivers an important message that, with endogenous time preferences depending on the environmental quality, pollution and growth need not be positively related. On this ground, it is possible to explain the phenomenon that pollution decreases with income at the later stage of economic development.

To see this, one can imagine that at the early stage of economic development, it is more likely that people do not alter their time preferences duo to the change in environmental quality because the environmental consciousness is usually quite low at this period. Thus based on our theory, pollution increases with economic growth because agents have a constant time preference. At the later stage of development, pollution problem becomes more severe, which may lead to two consequences. First, policymakers may tighten the environmental policies (via an increase in τ_P). Second, people begin to increase the environmental concern, and accordingly changes the time preferences. Suppose people follow an eco-substitutionary time preference (i.e., a worse environment causes impatience), tighter environmental policies can simultaneously reduce pollution and boost growth. The underlying changes may therefore result in an inverted-U relationship between environmental degradation and economic growth. Noticeably, it is the endogenous time preference that lead to such a non-monotone relationship.

4.3.2. The optimal environmental tax

Now we turn to study the optimal environmental tax. In particular, we focus on whether the Pigouvian tax rate is first-best when time preferences can be influenced by environmental quality.

Under the first-best tax policy, the social planner maximizes (4.5) 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. Thus we first solve the social planner's optimization problem. The Hamiltonian for the social planner's optimization H^{sp} is given by:

$$H^{sp} = \frac{(cz^{-\eta})^{1-\sigma}}{1-\sigma}\exp[-\int_0^t \theta(z_s)ds] + \hat{\lambda}(y-c) - \hat{\mu}\theta(z)\,, \tag{4.11}$$

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

$$c^{-\sigma} z^{-\eta(1-\sigma)} = \lambda\,, \tag{4.12}$$

$$Az^{\beta}\lambda = -\dot{\lambda} + \theta(z)\lambda\,, \tag{4.13}$$

$$-\eta c^{1-\sigma} z^{-\eta(1-\sigma)-1} + \lambda\beta Akz^{\beta-1} + \mu\theta'(z) = 0\,, \tag{4.14}$$

$$-\frac{(cz^{-\eta})^{1-\sigma}}{1-\sigma} = -\dot{\mu} + \mu\theta(z)\,, \tag{4.15}$$

where $\lambda = \hat{\lambda}\exp[\int_0^t \theta(z_s)ds]$, $\mu = \hat{\mu}\exp[\int_0^t \theta(z_s)ds]$, and the transversality condition $\lim_{t\to\infty} H^{sp} = 0$ must be satisfied. In contrast to the representative household, the social planner takes into account the capital externality and social marginal cost of pollution when choosing z. By comparing (4.12) with the household's first-order conditions, we can derive the necessary condition $\lambda = \varphi$ to reach the first-best outcome. In the Appendix we derive the first-best tax rates on capital and the pollution input, which are:

$$\tau_k^{\ *} = \alpha - 1\,, \tag{4.16}$$

$$\tau_p^{\ *} = \eta\frac{\tilde{x}}{\tilde{z}} + \frac{\theta'(\tilde{z})}{\theta(\tilde{z})}\left(A\tilde{z}^{\beta} + \frac{\sigma}{1-\sigma}\tilde{x}\right). \tag{4.17}$$

where $x \equiv c/k$ is a transformed variable.

To examine the efficiency of a Pigouvian tax rate, we first need to define the marginal social damage of pollution (in terms of the marginal utility of private consumption), denoted by D, as

$$D \equiv -\frac{\partial u/\partial z}{\partial u/\partial c} = \eta\frac{c}{z}\,. \tag{4.18}$$

or, evaluating at the steady state

$$\tilde{D} = \eta \frac{\tilde{x}}{\tilde{z}}. \tag{4.19}$$

By inserting (4.19) into (4.17), we can clearly see that $\tau_p{}^*$ is higher than, lower than, or equal to the marginal social damage if $\theta'(z)$ is higher than, lower than, or equal to zero. Hence we have the following proposition.

Proposition 4.2. *In the case of an exogenous time preference, the optimal environmental tax rate is equal to the Pigouvian tax rate. However, the optimal environmental tax rate should be higher (lower) than the Pigouvian tax rate if the households have an eco-substitutionary (eco-complementary) time preference.*

In the decentralized economy, there exist three kinds of externalities (distortions): (i) the capital externality, (ii) the pollution externality in felicity, and (iii) the pollution externality in time preferences. It follows from (4.16) and (4.17) that the government should subsidize the use of capital to remove the distortion (i) and the optimal environmental tax should be utilized to correct distortions (ii) and (iii). However, the well-known Pigouvian tax suggests that a tax rate on the pollution emissions is equal to MSD. As a result, it can remedy distortion (ii) but fails to correct distortion (iii). More precisely, our result shows that a Pigouvian tax rate cannot remedy the inefficiency arising from the time preference. Under the situation where the eco-substitutionary time preference is present, the eco-substitutionary time preference rate can be thought of as a negative externality of pollution due to its harmful impact on economic growth. This implies that the level of emission exceeds its optimal level even when a Pigouvian tax is implemented. Therefore, to correct this negative externality arising from the eco-substitutionary time preference, the optimal environmental tax rate should exceed the Pigouvian tax rate. With a similar inference we can conclude that, under the situation where the eco-complementary time preference is present, the optimal environmental tax rate should fall short of the Pigouvian tax rate.

4.4. Extensions

In this section, we consider two extensions of the baseline model. In the first extension, we consider pollution as a stock variable instead of a flow variable. In the second extension, we consider the case in which the production can be influenced by the environmental quality. To be summarized, the main result of our baseline model remains robust to each of these extensions.

4.4.1. Pollution as a stock

In the previous analysis we essentially treat pollution as a flow variable, which means that it affects the environment only at the current period. However, pollutants such as CO_2 emissions, nuclear waste, or non-biodegradable plastics can accumulate and harm the environment over time. Some studies (e.g., Byrne, 1997; Chen et al., 2003; Goeschl and Perino, 2007) thus set up an analytical framework embodying the stock of pollution. It is then worthwhile to consider the setting of a stock pollution and reexamine the growth effect and the optimal rate of an environmental tax.

In line with Michel and Rotillon (1995) and Goeschl and Perino (2007), we assume that the pollution stock, denoted by S, accumulates by the rule $\dot{S} = az - \delta S$, where a denotes the rate of accumulation on the basis of emission input, and δ denotes the natural rate of decay in the stock of pollution. Also, the endogenous time preference now depends on the pollution stock S rather than the flow z, i.e.,

$\theta = \theta(S)$, and the felicity function is related to S, i.e., $u = (cS^{-\eta})^{1-\sigma}(1-\sigma)^{-1}$. Note that our analysis focuses on the steady-state solutions, in which the total pollution stock must be limited in a physical sense, i.e., $\dot{S} = 0$. Hence we have $\tilde{S} = a\tilde{z} / \delta$ in the steady state equilibrium, or equivalently:

$$\tilde{S} = \frac{a}{\delta}[\frac{\beta A}{\tau_p}]^{1/(1-\beta)}. \tag{4.20}$$

It can be easily seen that the pollution stock has a one-to-one relationship with the pollution flow. Therefore, replacing $\tilde{z}$ by $\tilde{S}$ in our previous analysis will not change any of the results qualitatively. That is to say, our results are still valid in the case of a stock pollution.

4.4.2. Externalities on the production side

In our basic model setting, the environmental quality does not affect production. A natural extension is to consider that the production process can benefit from a better environment. To introduce such an externality into the model, we follow Chang et al. (2009) to assume the production technology $y = \Lambda X k^{\alpha} z^{\beta}$ where $X = z^{-\phi}$ refers to the negative externality of pollution on production.

We first reexamine the growth effect of the environmental tax. Now that (4.10) can be rewritten as:

$$\frac{\mathrm{d}\tilde{g}^d}{\mathrm{d}\tau_p} = \frac{\beta A}{\sigma \tau_p{}^2 (1-\beta+\phi)} \tilde{z}^{\beta-\phi} \left[-\frac{\alpha(\beta-\phi)\tau_p}{(1+\tau_k)\beta} + \theta'(\tilde{z}) \right]. \tag{4.21}$$

Hence we have the following proposition:

Proposition 4.3. *If* $\phi < \beta$*, then Proposition 4.1 applies. If* $\phi > \beta$ *,an environmental tax will boost growth in the case of exogenous and eco-substitutionary time preference, but may deteriorate growth if the agents have an eco-complementary time preference.*

If the negative externality of pollution on production exceeds the return from utilizing the polluting input ($\phi > \beta$), Chang et al. (2009) show that an increase in the environmental tax will increase consumption and output. The intuition is quite clear because in this case more pollution in fact contributes to less output. Hence, raising the environmental tax can both reduce pollution and stimulate the economy. In our model, however, this result holds for certain only when the agents have an exogenous or eco-substitutionary time preference. In the case of an eco-complementary time preference, raising the environmental tax has two opposite forces on growth. On one hand, it reduce pollution and thus, given that $\phi > \beta$, is beneficial to production. On the other hand, as pollution decreases, agents with an eco-complementary time preference will tend to increase consumption and reduce saving. As a consequence, less capital is being used for production, which is harmful to growth. The overall growth effect thus is uncertain and depends on the magnitudes of the two effects.

As for the optimal rate of environmental tax, after introducing the externality in production we can rewrite (4.17) as (detailed calculation is provided in Appendix)

$$\tau_p{}^* = \tilde{D} + \phi A \tilde{z}^{\beta-\phi-1} + \frac{\theta'(\tilde{z})}{\theta(\tilde{z})}\left(A\tilde{z}^{\beta-\phi} + \frac{\sigma}{1-\sigma}\tilde{x} \right). \tag{4.22}$$

Obviously, the second term on the right-hand side captures the externality of pollution on production. It shall not be surprising that the optimal environmental tax is higher with the presence of the production externality because it has to correct this additional externality.

4.5. Concluding Remarks

This chapter sets up a simple endogenous growth model in which time preference is 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 time preference. In particular, we demonstrate that a Pigouvian tax may be inefficient in the presence of an endogenous time preference.

Regarding the future research, since our analysis focuses mainly on the first-best policies, it would be interesting to derive the second-best policies and then compare both outcomes. Additionally, it is also important to examine empirically whether the public have an eco-substitutionary or eco-complementary time preference. Another interesting line is to examine whether countries differ in the types of time preference and, if they do, what causes the differences. Based on our theoretical analysis, we believe that these empirical studies would be valuable in designing environmental policies.

Appendix A: Derivation of Equations (4.16) and (4.17)

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

$$\mu = \frac{-1}{\theta(z)}\left[\frac{(cz^{-\eta})^{1-\sigma}}{1-\sigma} + \lambda(Akz^{\beta} - c)\right]. \tag{A4.1}$$

By inserting (4.12) and (A4.1) into (4.14) we can get

$$-\eta\frac{c}{z} + \beta A z^{\beta-1} = \frac{\theta'(z)}{\theta(z)}\left(\frac{\sigma}{1-\sigma}c + Az^{\beta}\right), \tag{A4.2}$$

and evaluating at the steady state, we have

$$-\eta\frac{\tilde{x}}{\tilde{z}} + \beta A \tilde{z}^{\beta-1} = \frac{\theta'(\tilde{z})}{\theta(\tilde{z})}\left(\frac{\sigma}{1-\sigma}\tilde{x} + A\tilde{z}^{\beta}\right). \tag{A4.3}$$

Then, utilizing (4.12) and (4.13) yields

$$\tilde{g}^{sp} = \frac{1}{\sigma}\left(A\tilde{z}^{\beta} - \theta(\tilde{z})\right). \tag{A4.4}$$

The first-best tax rates are derived by comparing (A4.3) and (A4.4) with the decentralized decisions (4.3) and (4.9).

Appendix B: Derivation of Equation (4.22)

The social planner takes into account all the externalities (Λ and X) when choosing z. The first-order conditions becomes:

$$c^{-\sigma} z^{-\eta(1-\sigma)} = \lambda, \tag{A4.5}$$

$$Az^{\beta-\phi}\lambda = -\dot{\lambda} + \theta(z)\lambda, \tag{A4.6}$$

$$-\eta c^{1-\sigma} z^{-\eta(1-\sigma)-1} + \lambda(\beta-\phi)Akz^{\beta-\phi-1} + \mu\theta'(z) = 0, \tag{A4.7}$$

$$-\frac{(cz^{-\eta})^{1-\sigma}}{1-\sigma} = -\dot{\mu} + \mu\theta(z). \tag{A4.8}$$

Following a similar calculation process as in Appendix A we can obtain:

$$-\eta\frac{\tilde{x}}{\tilde{z}} + (\beta-\phi)A\tilde{z}^{\beta-\phi-1} = \frac{\theta'(z)}{\theta(z)}\left[\frac{1}{1-\sigma}\tilde{x} + A\tilde{z}^{\beta-\phi} - \tilde{x}\right]. \tag{A4.9}$$

Comparing (A4.9) with the steady-state level of pollution $\tilde{z} = (\beta A/\tau_p)^{1/(1-\beta+\phi)}$ gives the optimal environmental tax rate in the text.

References

Aloi M. and F. Tournemaine (2011), Growth effects of environmental policy when pollution affects health, *Economic Modelling* 28, 1683-1695.

Ayong Le Kama, A. and K. Schubert (2007), A note on the consequence of an endogenous discounting depending on the environmental quality, *Macroeconomic Dynamics* 11, 272-289.

Bovenberg, A. L. and R. A. de Mooij (1994), Environmental levies and distortionary taxation, *American Economic Review* 84, 1085-1089.

Bovenberg, A. L. and R. A. de Mooij, (1997), Environmental tax reform and endogenous growth, *Journal of Public Economics* 63, 207-237.

Bovenberg, A. L. and S. Smulders (1995), Environmental quality and pollution-augmenting technical change in a two-sector endogenous growth model, *Journal of Public Economics* 57, 369-391.

Bovenberg, A. L. and S. Smulders (1996), Transitional impacts of environmental policy in an endogenous growth model, *International Economic Review* 37, 861-893.

Byrne, M. M. (1997), Is growing a dirty word? Pollution, abatement, and endogenous growth, *Journal of Development Economics* 54, 261-285.

Chang, J. J., J. H. Chen, J. Y. Shieh and C. C. Lai (2009), Optimal tax policy, market imperfections, and environmental externalities in a dynamic optimizing macro model, *Journal of Public Economic Theory* 11, 623-651.

Chen, J. H., C. C. Lai and J. Y. Shieh (2003), Anticipated environmental policy and transitional dynamics in an endogenous growth model, *Environmental and Resource Economics* 25, 233-254.

Fullerton, D. and S. R. Kim (2008), Environmental investment and policy with distortionary taxes, and endogenous growth, *Journal of Environmental Economics and Management* 56, 141-154.

Goeschl, T. and G. Perino (2007), Innovation without magic bullets: Stock pollution and R&D sequences, *Journal of Environmental Economics and Management* 54, 146-161.

Grossman, G. M. and A. B. Krueger (1995), Economic growth and the environment, *Quarterly Journal of Economics* 110, 353-377.

Hettich, F. (1998), Growth effect of a revenue-neutral environmental tax reform, *Journal of Economics* 67, 287-316.

Hopkins, E. and T. Kornienko (2006), Inequality and growth in the presence of competition for status, *Economics Letters* 93, 291-296.

Itaya, J. (2008), Can environmental taxation stimulate growth? The role of indeterminacy in endogenous models with environmental externalities, *Journal of Economic Dynamics and Control* 32, 1156-1180.

Ligthart, J. E. and F. van der Ploeg (1994), Pollution, the cost of public funds and endogenous growth, *Economics Letters* 46, 351-361.

Lucas, R. E., Jr. (1988), On the mechanics of economic development, *Journal of Monetary Economics* 22, 3-24.

Michel, P. and G. Rotillon (1995), Disutility of pollution and endogenous growth, *Environmental and Resource Economics* 6, 279-300.

Nakada, M. (2004), Does environmental policy necessarily discourage growth?, *Journal of Economics* 81, 249-275.

Nakada, M. (2010), Environmental tax reform and growth: Income tax cuts or profits tax reduction, *Environmental and Resource Economics* 47, 549-565.

Oates, W. E. (1993), Pollution charges as a source of public revenues, in *Economic Progress and Environmental Concerns* (H. Giersch, Ed.), Berlin: Springer-Verlag.

Obstfeld, M. (1990), Intertemporal dependence, impatience, and dynamics, *Journal of Monetary Economics* 26, 45-75.

Ono, T. (2003a), Environmental tax policy in a model of growth cycles, *Economic Theory* 22, 141-168.

Ono, T. (2003b), Environmental tax policy and long-run economic growth, *Japanese Economic Review* 54, 203-217.

Palivos, T., P. Wang and J. Zhang (1997), On the existence of balanced growth equilibrium, *International Economic Review* 38, 205-223.

Pearce, D. W. (1991), The role of carbon taxes in adjusting to global warming, *Economic Journal* 101, 938-948.

Pittel, K. (2002), *Sustainability and Endogenous Growth*. Cheltenham, UK: Edward Elgar.

Ricci, F. (2007), Environmental policy and growth when inputs are differentiated in pollution intensity, *Environmental and Resource Economics* 38, 285-310.

Romer, P. (1986), Increasing returns and long-run growth, *Journal of Political Economy* 94, 1002-1037.

Selden, T. M. and D. Song (1994), Environmental quality and development: Is there a Kuznets curve for air pollution emissions?, *Journal of Environmental Economics and Management* 27, 147-162.

Smulders, S. (1995), Entropy, environment and endogenous economic growth, *International Tax and Public Finance* 2, 319-340.

Smulders, S. and R. Gradus (1996), Pollution abatement and long-term growth, *European Journal of Political Economy* 12, 505–532.

van Ewijk, C. and S. van Wijnbergen (1995), Can abatement overcome the conflicts between the environment and economic growth?, *De Economist* 143, 197-216

van Zon, A. and I. H. Yetkiner (2003), An endogenous growth model with embodied energy-saving technical change, *Resource and Energy Economics* 25, 81-103.

Weitzman, M. L. (1994), On the “environmental” discount rate, *Journal of Environmental Economics and Management* 26, 200-209.

Yanase, A. (2011), Impatience, pollution, and indeterminacy, *Journal of Economic Dynamics and Control* 35, 1789-1799.

Chapter V

Conclusions

With rising concern over environmental quality, the importance of reconciling economic growth with limited pollution could never be too emphasized. This dissertation studies the interaction between environmental policies and economic growth. We provide some reasons for which we believe that an environmental protection policy may also contribute to a higher growth rate. In Chapter II, we present the positive growth effect of environmental policies by assuming that the intermediate firms import polluting inputs from abroad at a fixed price. In Chapter III, we consider an OLG framework and show that if the portion of tax revenues transferred to young generations is large, it is possible for an environmental tax to boost the growth rate. In Chapter IV, it is shown that when a cleaner environment could induce people more willing to save for future consumption, increasing the environmental tax may stimulate growth.

Nevertheless, it is worth noting that our results should not be pushed too far. Any environmental protection policies will come at some costs. For example, it may increase the factor prices, lower the incentive for investment, or distort the firm's behavior. As implementing the environmental tax we may be mistaken if we do not fully consider both the beneficial side and the cost side of an environmental tax. It is important to keep this in mind when reading many papers on a positive effect of environmental taxation.