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ENVIRONMENTAL TAX ON DIRECTED TECHNOLOGICAL INNOVATION IN A GREEN GROWTH MODEL

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Abstract

To ensure that green growth are achieved and socially optimal, we develops an endogenous growth model featuring a directed technological innovation, environmental taxation and economic activity. Our model investigates the inner dynamic interactions of green growth. Then, a numerical analysis is presented to trace how the green growth will be achieved by the four parameters: the size of tax distortions, the rate of capital tax, the elasticity of pollution conversion and the cost of carbon abatement technological innovation. It is found that a tax distortion for lump-sum transfer payments can explore the double dividend. The benefits arising from the income tax become larger the more stringent capital tax and environmental tax.

Key words: carbon abatement technological innovation, endogenous growth model, environmental externality, tax distortion

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1. Introduction

Green growth is more and more supported by many countries in the world. The Organization for Economic Co-operation and Development (OECD) defined green growth as 'fostering economic growth and development, while ensuring that natural assets continue to provide the resources and environmental services on which our well-being relies'. It believes that environmental policy is an important means to ensure green growth. However, in many circumstances, different environmental policies have various effects, which is typified by the two main kinds of environmental policies, the price form such as environmental tax in EU and the quantities form like carbon trading in USA. Therefore, it is necessary to have further studies on environmental policies related to carbon abatement, so as to provide theoretical basis for policy makers, especially for China, where the first Environmental Protection Tax Law has been implemented on 1st January 2018. Facing the conflict between economic development and environment protection, the government will not reduce the investment in pollution control and environmental protection and attempts to develop carbon abatement research and development (R&D). In fact, the government knows that it is only a matter of time when old polluting technologies will be penalized (e.g., tax or standard), but there is a lot of uncertainty when these environmental policies will actually take place. Under these circumstances, it is instructive to study how rational environmental policies should adjust to an expected carbon abatement technological innovation that will increase the social welfare in the country to achieve green growth some time in future.

1.1. Literature review

(1) Environmental tax

The earliest study on environmental tax is by Weitzman (Germain and Magnus, 2006). As a representative of price-based regulation, environmental tax is a significant form of environmental policy in many countries (Andretta et

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al., 2018; Bovenberg and Ploeg, 1992; Onofrei et al., 2017). Based on the Pigovian tax theory, many studies introduced the environmental externality and tax distortion. The latter is a critical factor to decide if environmental tax can achieve the double dividend (Bovenberg and Goulder, 1996; Bovenberg and Heijdra, 1998; Marino et al., 2017). Bárcena-Ruiz and Garzón (2003), Kato (2006, 2011) and Wang and Wang (2009) analyzed the optimal environmental policy instruments and compared the optimal pollution tax and Pigovian tax. According to classical theories in macroeconomies (Chamley, 1986; Judd, 1985), the extent of tax distortion is higher than that of other taxes. Thus, when exploring the double dividend resulted from environmental tax, the capital tax with high distortion rate is also an important factor. Another key driving force is innovation in long-term growth in consideration of tax distortion (Yan and Hu, 2013). By combining carbon abatement R&D and environmental externality, Li and Yang (2015) explored how to choose the optimal combination of policy instruments. Ebert (1991, 1998) examined the relationship between environmental tax and pollution standard, and investigated the influence of carbon abatement R&D on Pigovian tax. Helfand (1991) evaluated the impact of pollution standard and environmental tax on carbon abatement, and concluded that pollution under pollution standard is larger than that under environmental tax. Hence, when investigating environmental tax, the social value of environmental tax is decided by how it is used (Salanie, 2003).

(2) Endogenous growth model

The development of macroeconomics promoted studies on the dynamic effect of tax, especially studies using the endogenous growth model as their theoretical framework. Therefore, the endogenous growth model is usually used to examine the influence of environmental tax on long-term growth. Ricci (2007) analyzed the impact of different environmental policy on long-term growth, which may be influenced by the stringent environmental regulation mechanisms such as investment, education and R&D. Gradus and Smulders (1993) and Pautrel (2008) discovered that environmental tax can promote long-term growth by influencing learning ability. Using a similar framework, Oueslati (2002) found that leisure activities had an indirect effect on environmental tax in their two-sector endogenous growth model. With the development of the endogenous growth model, it is found that pollution can accelerate the depreciation of capital and productivity. Therefore, some scholars incorporated pollution as a 'negative input' or efficiency loss into the production function. For example, Grossman and Krueger (1995) and Stokey (1998) pointed out that the rise in total factor productivities and the improvement of clean technology will reduce pollution and its impact on economic efficiency losses. In this paper, the opinion that sustainable economic growth can be achieved by the driving force of technological innovation through the mechanisms such as technological progress and product innovation (Fan et al., 2016) is adopted and added in the endogenous growth model.

(3) Revenue allocation

Although environmental tax brings the double dividend, the environmental protection fund is inadequate in revenue allocation. What is more, environmental tax does not necessarily reduce carbon dioxide emission, but it impacts social welfare in varying degrees (Jr and Lin, 2016). Thus, the influence of structural change in revenue allocation becomes the focus of many studies. Using the endogenous growth model, Fullerton and Kim (2008) analyzed the influence of environmental tax on economic growth and environmental protection. In particular, they explored the reduction of carbon abatement R&D investment from government revenue. There are some similar studies (Dissou and Siddiqui, 2014; Liu and Lu, 2015). Employing two-sector endogenous growth model, Oueslati (2015) studied how to carry out environmental tax reform while ensuring social welfare, and the so-called environmental tax reform is to require the government adjust revenue allocation. The government is supposed to plan the budget from a more comprehensive point of view. It should get more revenue through environmental tax reform to expand production sector or to increase environmental investment in carbon abatement, so as to reduce pollution. If the government revenue is not enough to meet the need of carbon abatement, the government should encourage private sector to carry out carbon abatement R&D, which can be effectively promoted by appropriate regulation in the incompletely competitive market. To better solve this issue, Chu and Lai (2014) researched whether environmental tax influences carbon abatement technology under the condition of market mechanism failure. Another focus of our model is to explore how to mobilize private investment in carbon abatement technological innovation.

1.2. Objectives

Tian and Chen (2015) argued that China is in the stage of factor-driven economy, and its economic growth is achieved by continuous capital accumulation and extensive consumption of energy resources. Hence, when it comes to China which is in the transition of environmental tax reform, how to make environmental tax conform to that 'the tax burden will finally transform from the levy on productive factors (e.g., labour or capital) to that on environmental factors (e.g., resources and pollution) is a core issue to seek a balanced and coordinated state. Hence, we make efforts for three questions as follows:

- Under what conditions can environmental tax achieve the double dividend?
- What is the greening process of environmental tax to promote green growth?
- If the environmental tax revenues are all managed, will it be beneficial to carbon abatement technological innovation?

For these questions we introduce an analysis framework for the inner dynamic interactions of green growth, which aims to investigate the process of environmental tax's impact on productive factors and environmental factors through directed technological innovation. In Fig. 1, we specify the modules needed.

- Social welfare: As a benchmark against which the performance of the consumption has to be assessed by social planner, social welfare also accounts for environmental quality. This produces corrective environmental policy instruments which, ideally, should take the form of environmental tax able to reproduce the maximization of social welfare associated with green growth.
- Directed technological innovation: Production technological innovation and carbon abatement technological innovation are two forms. Production technological innovation is affected by environmental quality. Meanwhile, pollution is directly related to carbon abatement technological innovation which needs investment from government receipts.
- Environmental taxation: Capital tax from capital gains and environmental tax from pollution are counted as government receipts. The revenues are allocated to investment in carbon abatement technological innovation apart from the lump-sum transfer payments.
- Economic activity: In production, capital accumulation, production technological innovation and non-renewable resource are the input factors, capital gained by production is for consumption, capital reinvestment, taxation and resources fees. Furthermore, pollution caused by both non-renewable resource and carbon abatement technological innovation has a collective effect on environmental quality.

The chapter is organized as follows. In Sect. 2 the optimal control model is developed, motivated by a green growth perspective on the inner dynamic interactions of directed technological innovation, environmental taxation and economic activity. We manage to solve the model analytically for the long-term green growth. The symmetric equilibrium for green growth are presented in Sect. 3 and briefly discussed in Sect. 4. Section 5 summarizes the findings of this study, discusses their relevance and gives an outlook to future research in this area.

2. Methods

2.1. Dynamic interactions of green growth

(1) Social welfare

Green growth should achieve the maximization of social welfare below a stabilization of economic growth and environmental protection. It is assumed that consumption (C) and environmental quality (N) contribute to utility of social welfare, the utility function is described as (Eq. 1):

$$U(C,N)=\begin{cases}\dfrac{(CN^{\phi})^{1-\sigma}-1}{1-\sigma}, & \sigma\neq 1,\ 0\le\phi<1\\ \ln C+\phi\ln N, & \sigma=1,\ 0\le\phi<1\end{cases} \tag{1}$$

where, $\sigma > 0$ is the alternative elasticity of marginal utility; and $\phi > 0$ is the parameter of environmental awareness of the social planner.

Let us note that in the utility theory the logarithmic function describes the relative increment (of consumption in the case) in unit time. Under uncertainty, the logarithmic function defines constant measure of relative risk-aversion. Hence, the utility function is the instantaneous utility expressed by (Eq. 2):

$$W=\int_0^{+\infty}U(C(t),N(t))e^{-\rho t}dt \tag{2}$$

where, $\rho > 0$ is a constant discount coefficient, represents the pure rate of time preference.

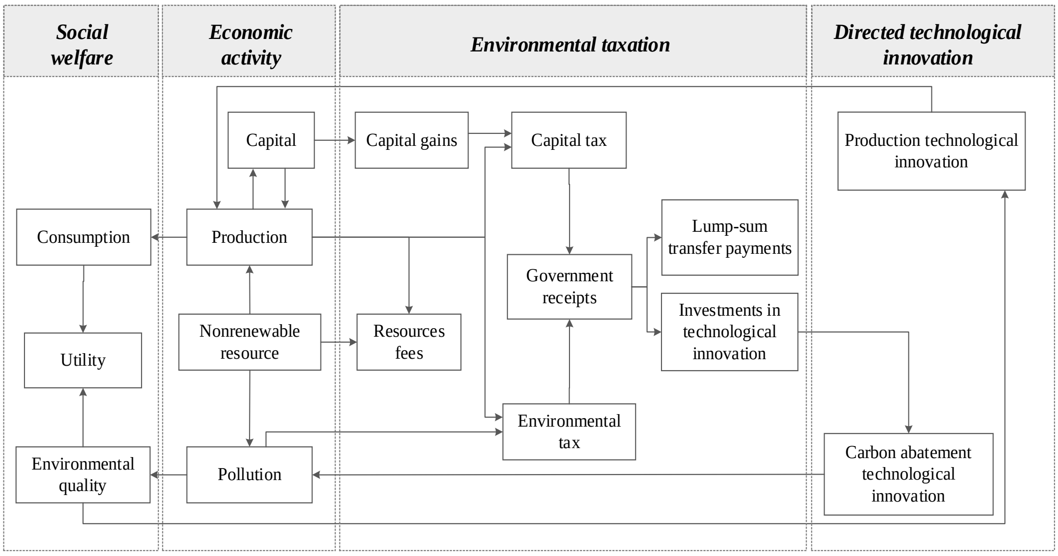

Fig. 1. An analysis framework for the inner dynamic interactions of green growth

(2) Directed technological innovation

Since "clean" environmental quality can promote high productivity, the endogenous function of production technological innovation should be normalized with respect to environmental quality N. Following the model introduced by Greaker and Rosendahl (2008), one obtains (Eq. 3):

$$A(N) = N^{\gamma} \tag{3}$$

where, $\gamma \in [0,1]$ indicates the positive effect of environmental externality.

It is assumed that the dynamics of the current carbon abatement technological innovation (E) grows by technology declines (δ_E), or $E = \dot{E} + \delta_E E$. Then, the required subsidy for carbon abatement technological innovation is given by $q_E E = q_E\left(\dot{E} + \delta_E E\right)$, where q_E is the cost of carbon abatement technological innovation.

Environmental quality (N) should also be considered by the combination of its different elements and environmental regeneration. The differential equation of environmental quality is given by (Eq. 4):

$$\dot{N} = bN(1-N) - P \tag{4}$$

where, b is a parameter that captures the rate of environmental regeneration. Pollution (P) mainly comes from utilization of non-renewable resources (R), so its stock is described by (Eq. 5):

$$P = (R/E)^{1/\varepsilon} \tag{5}$$

where $\varepsilon > 0$ is the elasticity of pollution conversion.

(3) Environmental taxation

The government receipts from capital tax and environmental tax is mainly used for carbon abatement technological innovation (E) and lump-sum transfer payments (G, which corresponds to the inescapable investment for education or public infrastructure, etc.). The revenue allocation equation is expressed as $G + q_E E = \tau_K rK + \tau_P P$, where K is capital, τ_K is the rate of capital tax, r is the rate of capital revenue, and τ_P is the rate of environmental tax.

The government's incentives to invest in carbon abatement technological innovation are based on productivity and subject to its budget constraint which can be stated as (Eq. 6):

$$G + q_E\dot{E} + q_E\delta_E E = \tau_K rK + \tau_P P \tag{6}$$

(4) Economic activity

Consider an economy in which capital (K) and non-renewable resources (R) are the inputs, implying that the role of labour as input is negligible. Production technological innovation (A) is endogenous to the Cobb-Douglas formula, is defined by (Eq. 7):

$$Y = A(N)K^{(1-\alpha)}R^{\alpha} \tag{7}$$

where, α is the elasticity of non-renewable resources.

Production is used for consumption, capital depreciation, non-renewable resources and investment in carbon abatement technological innovation to accumulate capital stock. The differential equation of capital accumulation is $\dot{K} = Y - C - \delta_K K - mR - q_E E$, where, δ_K is the rate of capital depreciation, m is the price of non-renewable resources. Based on the revenue allocation equation, the capital stock is accumulated according to (Eq. 8):

$$\dot{K} = Y - C - \delta_K K - mR - \left(\tau_K rK + \tau_P P - G\right) \tag{8}$$

2.2. Optimal control problem

The problem is to maximize the utility function Eq. (2) by controlling the variable consumption $C(t)$, pollution $P(t)$ and lump-sum transfer payments $G(t)$ in the dynamic process of green growth starting from initial position of state variable capital $K(t)$, environmental quality $N(t)$, carbon abatement technological innovation $E(t)$.

We deal with the following optimal control problem by (Eq. 9):

$$W = \int_0^{\infty} U(C(t), N(t))e^{-\rho t}dt \xrightarrow[(C(\cdot),P(\cdot),G(\cdot))]{} \max \tag{9}$$

under conditions of Eqs. (3-8).

3. Results

3.1. The symmetric equilibrium

We restrict our analysis to a symmetric equilibrium which ensure a steady state of green growth. In this situation, the features of the marginal productivity of capital are equivalent to pollution concern. As a consequence, we estimate the optimal conditions for productivity as Eqs. (10-11):

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

$$\frac{\partial(Y - mEP^{\varepsilon})}{\partial P} = \tau_P \Rightarrow \alpha\varepsilon\frac{Y}{P} - m\varepsilon EP^{\varepsilon-1} = \tau_P\,. \tag{11}$$

Eqs. (10-11) indicate that, given the environmental quality and carbon abatement technological innovation, the economy equate the marginal revenue of capital and pollution to their respective marginal cost.

In Appendix A, we derive the following general relationship for capital, environmental quality, carbon abatement technological innovation. According to Eq. (2), the optimal conditions for the steady state of green growth with Eqs. (12-14):

$$\frac{\dot{K}}{K}=(1-\tau_K)r+\frac{1-\varepsilon}{\varepsilon}\frac{\tau_P}{K}P-\frac{C}{K}+\frac{G}{K} \tag{12}$$

$$\frac{\dot{N}}{N}=b(1-N)-\frac{P}{N} \tag{13}$$

$$\frac{\dot{E}}{E}=\frac{1}{q_E}\left[\tau_K r\frac{K}{E}+\frac{\tau_P}{K}\frac{K}{E}P-\frac{G}{K}\frac{K}{E}\right]-\delta_E \tag{14}$$

In our model, the green growth equilibrium values are characterized as a path where environmental quality remains constant and all other economic variables grow at a common endogenous growth rate g. These features of the steady state are characterized by Eqs. (15-16):

$$\frac{\dot{N}}{N}=0 \tag{15}$$

$$\frac{\dot{Y}}{Y}=\frac{\dot{C}}{C}=\frac{\dot{K}}{K}=\frac{\dot{E}}{E}=\frac{\dot{\tau}_P}{\tau_P}=g \tag{16}$$

3.2. The optimal steady state values

The long-term green growth rate of all variables can be determined using Eqs. (1-16). To reformulate the whole dynamic system of green growth into a more simplified framework, define four new "fundamental" variables that are constant on the green growth path: $c\equiv\frac{C}{K}$, $e\equiv\frac{E}{K}$, $\tau\equiv\frac{\tau_P}{K}$ and $\varphi\equiv\frac{G}{rK}$, governed by the government budget constraint in Eq. (6), and the capital accumulation conditions in Eq. (8). Appendix B derives the optimal steady state values for the optimal green growth equilibrium values $(g^*,\ c^*,\ e^*,\ \tau^*,\ P^*,\ N^*)$ in Eqs. (17-22):

$$g^*=\frac{\dot{C}}{C}=\frac{1}{\sigma}\left[(1-\tau_K)r+\frac{\tau_K r}{q_E}-\rho\right] \tag{17}$$

$$c^*\equiv\frac{C}{K}=(1-\tau_K)r+(1-\varepsilon)(\rho+\delta_E+\sigma g)e^*+\frac{G}{K}-g^* \tag{18}$$

$$e^*\equiv\frac{E}{K}=\frac{(\tau_K/\varphi-1)G/K}{q_E\delta_E+g^*(q_E-\varepsilon\sigma)-\varepsilon(\rho+\delta_E)} \tag{19}$$

$$\tau^*\equiv\frac{\tau_P}{K}=\frac{\varepsilon e^*(\rho+\delta_E+\sigma g^*)}{P^*} \tag{20}$$

$$P^*=\left[\frac{\alpha(r+\delta_K)}{m(1-\alpha)e^*}-\frac{\rho+\delta_E+\sigma g^*}{m}\right]^{1/\varepsilon} \tag{21}$$

$$N^*=\begin{cases}\dfrac{b+\sqrt{b^2-4bP^*}}{2b}\\[2ex] \dfrac{b-\sqrt{b^2-4bP^*}}{2b} \quad \rightarrow \quad (P^*\uparrow, N^*\uparrow)\end{cases} \tag{22}$$

where, the superscript "*" denotes the steady state value.

Note that Eqs. (17-22) represent six equations in six unknowns $(g^*,\ c^*,\ e^*,\ \tau^*,\ P^*,\ N^*)$. Then, we offer interpretations and discussion of how these equations can be used to characterize optimal environmental policy instruments.

Eq. (17) describes the long-term green growth rate g as one of the endogenous variables of the dynamic system. Eq. (18) determines the optimal equilibrium consumption ($c = C/K$) relative to capital. Eq. (19) shows the socially optimal choice for carbon abatement technological innovation ($e = E/K$), where $\varphi = G/rK$ is the size of tax distortions. In particular, φ has critical effects on the optimal configurations of the corrective policy instruments. Then Eq. (20) shows the equilibrium rate of environmental tax ($\tau\equiv\frac{\tau_P}{K}$) to capital, determined by pollution (P^*) along the green growth path. Then Eqs. (21-22) determines the optimal pollution P^* and environmental quality N^*. Also note that the steady state value of environmental quality N^* should adopt Eq. (22-1), as it is incredible that P^* and N^* will evolve in the same direction for Eq. (22-2). Moreover, Social optimality requires that government set the corrective levels of pollution P^*, which might increase with a smaller pollution P^*, but will eventually decline when pollution P^* exceeds a threshold value b/4, according to Eqs. (21-22).

The optimal equilibrium growth rate g^* is not just from Eq. (17), because the other endogenous variables in that equation depend on all parameters in the entire dynamic system. Since the dynamic system is in a nonlinear form and is too complicated to enable a closed-form solution to be obtained, we present our results via numerical analysis.

4. Discussions

4.1. A numerical simulation

To see directly how economic-related parameters and environment-related parameters affect the optimal steady state values, we alter each key parameter to conduct a numerical sensitivity analysis. Hence, we choose benchmark parameter values that are within the plausible ranges used in the literature. Table 1 lists the benchmark parameter values.

4.2. Sensitivity analysis

In choosing "central case" parameter values, we rely primarily on values that are frequently used in the relevant literature. The central parameters chosen from Fullerton and Kim (2008), Li and Yang (2015) and Chu and Lai (2014) are: $\varphi = 0.25$, $\tau_K = 0.355$, $\varepsilon = 0.75$ and $q_E = 100$, but each is also varied to test the sensitivity of results.

In Table 2, Row A uses those "central case" parameter values and shows the outcome for optimal environmental policy rates in a normalized economy. On the green growth path, the optimal equilibrium growth rate $g^* = 0.1576$ and the rate of environmental tax is $\tau_P = 0.215$. The optimal results are $P = 160$, $E = 0.18$, $Y = 273$, $K = 150$ and $W = 180$. Although the above optimal steady state values are hard to compare to existing indexes for this normalized economy (calibrated to China), we might compare them to investigate the effects of environmental policy instruments.

We now turn to sensitivity analysis. In panel B of Table 2 we consider the usual economic-related parameters to confirm the extent to which revenue allocation for government receipts requires distortionary taxation. Required lump-sum transfer payments, $\varphi = G/rK$ is a non-environmental parameter with important implications for environmental tax. Considering a distorting tax on labor or on consumption, Metcalf (2000) and Gaube (2005) asked if increases in other public goods crowd out provision of the environmental public good. Because more public spending leads to higher labor tax or consumption tax that discourages production, they find that it can improve the environment. Our results are consistent with these studies of environmental taxation in second-best, but we extend the model to a dynamic setting.

Table 1. The benchmark parameter values

Parameter	***Value***	***Definition***	***References***
ρ	0.05	The pure rate of time preference	Yang and Hu (2013)
σ	0.67	The alternative elasticity of marginal utility;	Yang and Hu (2013)
ϕ	0.7	The parameter of environmental awareness of the social planner	Chu and Lai (2014)
α	0.24	The elasticity of non-renewable resources	Fullerton and Kim (2008)
r	0.171	The rate of capital revenue	Li and Yang (2015)
γ	0.77	The positive effect of environmental externality	Li and Yang (2015)
b	0.0018	The rate of environmental regeneration	Li and Yang (2015)
δ_K	0.08	The rate of capital depreciation	Fullerton and Kim (2008)
δ_E	0.05	The rate of carbon abatement technological innovation depreciation	Fullerton and Kim (2008)
m	1.8	The price of non-renewable resources	Fullerton and Kim (2008)
φ	0.1~0.35	The size of tax distortions	Li and Yang (2015)
τ_K	0.352~0.362	The rate of capital tax	Chu and Lai (2014)
ε	0.6~0.9	The elasticity of pollution conversion	Li and Yang (2015)
q_E	50~400	The cost of carbon abatement technological innovation	Fullerton and Kim (2008)

Table 2. Sensitivity analysis of optimal steady state values to key parameters

	Optimal steady state values						
	P	***E***	***Y***	***K***	τ_P	***W***	***g***
A. Central case (φ=0.25, τ_K=0.355, ε=0.75 and q_E=100)	160	0.18	273	150	0.215	180	0.1576
B. Economic-related parameters							
1. The size of tax distortions φ							
a. Lower (0.1)	100	0.275	170	104	5.7	0	0.5
b. Central case (0.25)	160	0.18	273	150	0.215	180	0.1576
c. Higher (0.35)	$+\infty$	0.018	900	158	0.1	210	0.09
2. The rate of capital tax τ_K							
a. Lower (0.1)	0	-0.12	400	100	1.6	0	0.18
b. Central case (0.355)	160	0.18	273	150	0.215	180	0.1576
c. Higher (0.55)	0	0.61	200	156	2.22	370	0.06
C. Environment-related parameters							
3. The elasticity of pollution conversion ε							
a. Lower (0.6)	580	0.122	218	100	0.2	1	0.1576
b. Central case (0.75)	160	0.18	273	150	0.215	180	0.1576
c. Higher (0.9)	70	0.27	368	220	7.2	360	0.1576
4. The cost of carbon abatement technological innovation q_E							
a. Lower (50)	90	0.24	160	100	5.7	1	0.1430
b. Central case (100)	160	0.18	273	150	0.215	140	0.1576
c. Higher (400)	1200	0.06	520	220	0.1	335	0.1767

Rows B3a-B3c indicate that an increase in φ (from 0.1 to 0.35) raises optimal values of production (Y) and capital (K). It lowers the optimal long-term green growth rate (g), the rate of environmental tax (τ_P) and accelerates pollution (P), but it still improves the social welfare (W).

Note, carbon abatement technological innovation (E), capital (K) and the rate of environmental tax (τ_P) are not monotonically changing with φ. It is shown in Fig. 2 that initial increases in φ (from 0 to 0.14) raise E and τ_P proportionately, while φ further increases (to 0.35) falls E and τ_P. Similarly, K is rising to peak at $\varphi = 0.25$ and then it starts to decrease. Hence, we clearly see that the government increases the capital tax with high distortion rate by its lump-sum transfer payments, which also explores the double dividend.

Next, as seen in rows B2a-B2c, a society with a higher rate of capital tax (τ_K) optimally invests more in capital (K), but it obtains a lower level of production (Y) and the optimal endogenous growth rate (g). To invest more in carbon abatement technological innovation (E), the government needs to raise its rate of environmental tax (τ_P). In the case of extremely high ($\tau_K = 0.55$), the income tax could help finance other spending, since it is flexible enough to put off pollution (P) to a later date, eventually leading to a higher social welfare (W).

Figs. 3 and 4 exhibit the effects of τ_P, K, Y and P by varying the rate of capital tax (τ_K). It is depicted in Fig. 3 that the higher τ_K directly makes the accumulation of more capital (K) associated with an increase in the rate of environmental tax (τ_P), but if the government further increases τ_K (from 0.45), both K and τ_P will fall. As noted previously, it is not true that the bigger the rate of capital tax the better for continuous capital accumulation. The Y and P have to be specified in Fig. 4. When the rate of capital tax (τ_K) equals to 0.25, there are great changes (increases or decreases rapidly) for production (Y) and pollution (P). When $\tau_K < \varphi = 0.25$, the income tax is not enough for government to pay for lump-sum transfer payments, the additional Y needed raises but P remains unchanged. In response to an increase in $\tau_K > \varphi = 0.25$, production decline and pollution will return to initial state.

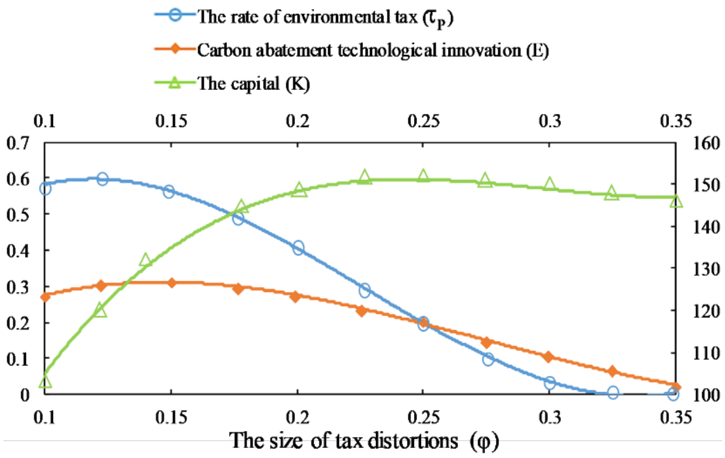

Fig. 2. The effect of τ_P, E and K relative to the size of tax distortions

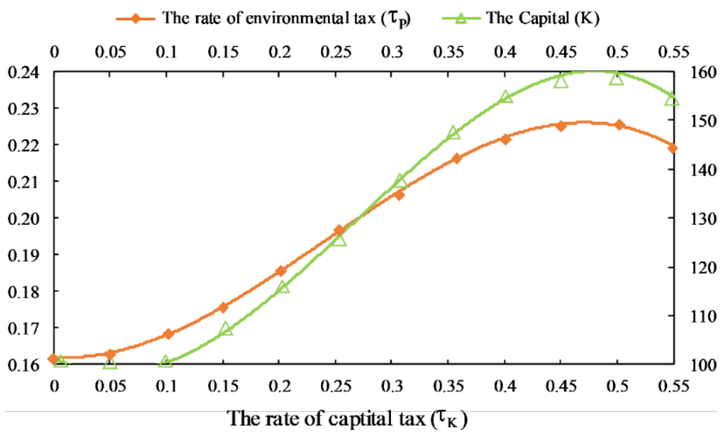

Fig. 3. The effect of τ_P and K relative to the rate of capital tax

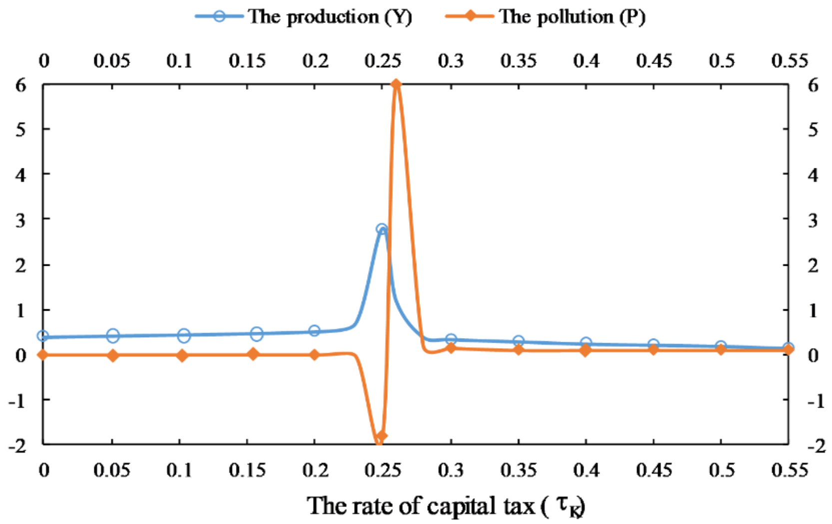

Fig. 4. The effect of *Y* and *P* relative to the rate of capital tax

We now vary parameters that specifically relate to the environment. Consider our added the elasticity of pollution conversion, ε. As shown in rows C3a–C3c, Higher ε prevents pollution (*P*) more effective, but keeps the green growth rate (*g*) in the optimum steady state unchanged. It benefits from that the government responds optimally with a higher rate of environmental tax (τ_P), more carbon abatement technological innovation (*E*), and better productive assets like production (*Y*) and capital (*K*), all dedicated to enhance the higher social welfare (*W*). Since the environmental tax becomes a more efficient instrument to raise government receipts, the rate of environmental tax τ_P is higher. Thus, ε plays a critical role when integrating environmental taxes with distortionary income taxes.

If the cost of carbon abatement technological innovation, q_E increases from 50 to 400 in rows C4a-C4c, then the optimal carbon abatement technological innovation (*E*) decreases. The results indicate that a decreased q_E makes it easier for the economy to prevent pollute (*P* decreases from 1200 to 90) with more stringent environmental tax (τ_P), and thus to achieve a less productivity with lower the green growth rate (*g*). Hence, the lower q_E for carbon abatement technological innovation (*E*) calls for more ambitious environmental policy and slower economic growth in the optimum steady state.

5. Conclusions

This paper develops an endogenous growth model featuring a directed technological innovation, environmental taxation and economic activity. The salient trait of the model is that it is able to deal with the corrective environmental policy instruments which enable a country to achieve green growth some time. We incorporate production technological innovation concerning environmental externality, capital and non-renewable resource as a productive asset.

These three assets evolve by the endogenous flows of production technological innovation or carbon abatement technological innovation, government receipts from capital tax and environmental tax, pollution and environmental quality. In particular, we focus on parameters representing public spending that requires distorting taxes (φ), government receipts that associate with the rate of capital tax (τ_K), and the cost (q_E) and productivity (ε) of carbon abatement technological innovation relative to pollution. In this paper, we look only at long-term green growth paths which are feasible and sustainable, whereas results might differ during transitions from one path to another.

Some main findings are obtained from our sensitivity analysis. First, we add a tax distortion for lump-sum transfer payments which can also explore the double dividend, but the results might differ for other distorting taxes on other aspects. Second, the beneficial effects arising from the income tax become larger the greater the strict degree of capital tax. This potentially implies that environmental policy might in some way enhance growth and welfare. Third, a higher the elasticity of pollution conversion and a lower cost of carbon abatement technological innovation might mean higher growth, but we find that more stringent environmental policy should be carried out.

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Appendix A

This appendix provides a detailed derivation of Eqs. (12-14) in the main text. For the optimal control problem by (Eq. 9), the Hamiltonian in the Pontryagin's maximum principle is given by (Eq. A.1):

$$\tilde{H}=\frac{\left(CN^{\phi}\right)^{1-\sigma}-1}{1-\sigma}+\lambda_K\left(Y-C-\delta_K K-\tau_K rK-mR-\tau_P P+G\right)+\lambda_N\left(bN(1-N)-P\right)+\frac{\lambda_E}{q_E}\left(\tau_K rK+\tau_P P-G-q_E\delta_E E\right) \tag{A.1}$$

where adjoint variables λ_K, λ_N and λ_E are representing shadow prices for capital, environmental quality, carbon abatement technological innovation respectively. To exclude time dependent exponential term from Eq. (A.1), consider necessary condition of maximum of the Hamiltonian by Eqs. (A.2-A.4):

$$\frac{\partial H}{\partial C}=0\Rightarrow C^{-\sigma}\left(N^{\phi}\right)^{1-\sigma}-\lambda_K=0\,, \tag{A.2}$$

$$\frac{\partial H}{\partial G}=0\Rightarrow \lambda_K-\lambda_E=0\,, \tag{A.3}$$

$$\frac{\partial H}{\partial P}=0\Rightarrow \lambda_K\left(\frac{\partial Y}{\partial P}-m\varepsilon EP^{\varepsilon-1}-\tau_P\right)+\lambda_E\frac{\tau_P}{q_E}-\lambda_N=0\quad . \tag{A.4}$$

For shadow prices one can compose the dynamics of adjoint Eqs. (A.5-A.6):

$$\dot{\lambda}_K=-\frac{\partial H}{\partial K}+\rho\lambda_K \tag{A.5}$$

$$\dot{\lambda}_N=-\frac{\partial H}{\partial N}+\rho\lambda_N\,, \tag{A.6}$$

$$\dot{\lambda}_E=-\frac{\partial H}{\partial E}+\rho\lambda_E \tag{A.7}$$

which balance the increment in capital, environmental quality, carbon abatement technological innovation.
The transversality conditions of the Pontryagin maximum principle are expressed in the Hamiltonian system of Eqs. (A.8-A.10):

$$\lim_{t\to\infty}e^{-\rho t}\lambda_K K=0 \tag{A.8}$$

$$\lim_{t\to\infty}e^{-\rho t}\lambda_N N=0 \tag{A.9}$$

$$\lim_{t\to\infty}e^{-\rho t}\lambda_E E=0 \tag{A.10}$$

Combine Eqs. (A.5-A.7), the control variables are completely described by the following differential Eqs. (A.11-A.13):

$$\frac{\dot{\lambda}_K}{\lambda_K}=\rho-\left(1-\tau_K\right)r-\frac{\tau_K r}{q_E} \tag{A.11}$$

$$\frac{\dot{\lambda}_E}{\lambda_E}=\rho-\alpha\frac{Y}{E}+mP^{\varepsilon}+\delta_E \tag{A.12}$$

$$\frac{\dot{\lambda}_N}{\lambda_N}=\rho-b+2bN-\phi\frac{C}{N}-\gamma\frac{Y}{N}\,. \tag{A.13}$$

Take the partial derivatives Eqs. (A.2-A.4) into Eqs. (A.11-A.13), we have Eqs. (A.14-A.16):

$$\frac{\dot{\lambda}_K}{\lambda_K}=-\sigma\frac{\dot{C}}{C}+\phi(1-\sigma)\frac{\dot{N}}{N} \tag{A.14}$$

$$\frac{\dot{\lambda}_E}{\lambda_E}=\frac{\dot{\lambda}_K}{\lambda_K}=-\sigma\frac{\dot{C}}{C}+\phi(1-\sigma)\frac{\dot{N}}{N} \tag{A.15}$$

$$\frac{\dot{\lambda}_N}{\lambda_N}=\frac{\dot{\tau}_P}{\tau_P}-\sigma\frac{\dot{C}}{C}+\phi(1-\sigma)\frac{\dot{N}}{N} \tag{A.16}$$

These Eqs. (A.11-A.16), can be resolved according to (Eq. A.17):

$$\begin{cases}-\sigma\dfrac{\dot{C}}{C}+\phi(1-\sigma)\dfrac{\dot{N}}{N}=\rho-\left(1-\tau_K\right)r-\dfrac{\tau_K r}{q_E}\\ -\sigma\dfrac{\dot{C}}{C}+\phi(1-\sigma)\dfrac{\dot{N}}{N}=\rho-\alpha\dfrac{Y}{K}\dfrac{K}{E}+mP^{\varepsilon}+\delta_E\\ \dfrac{\dot{\tau}_P}{\tau_P}-\sigma\dfrac{\dot{C}}{C}+\phi(1-\sigma)\dfrac{\dot{N}}{N}=\rho-b+2bN-\phi\dfrac{C}{K}\dfrac{K}{N}-\gamma\dfrac{Y}{K}\dfrac{K}{N}\end{cases} \tag{A.17}$$

After an elementary transformation to Eq. (A.17), we finally get the differentiating Eqs. (12-14) in the main text.

Appendix B

This appendix deals with optimal green growth equilibrium values in Eqs. (17-22). We can obtain Eq. (17) from the main text by combining Eq. (A.17) and Eq. (13). Then, substitute Eqs. (10-11) into Eq. (A.17-2), we can get (Eq. B.1):

$$\begin{cases}g=\dfrac{1}{q_E}\left[\tau_K r\dfrac{K}{E}+\dfrac{\tau_P}{K}\dfrac{K}{E}P-\dfrac{G}{K}\dfrac{K}{E}\right]-\delta_E\\ -\sigma g=\rho-\dfrac{1}{\varepsilon}\dfrac{\tau_P}{K}\dfrac{K}{E}P+\delta_E\end{cases} \tag{B.1}$$

We solve the Eq. (B.1) to get Eqs. (19-20) in the main text. Compute Eq. (12) to obtain (Eq. B.2):

$$\frac{C}{K}=\left(1-\tau_K\right)r+\frac{1-\varepsilon}{\varepsilon}\frac{\tau_P}{K}P+\frac{G}{K}-g \tag{B.2}$$

From Eqs. (10-11), we also can get (Eq. B.3):

$$\alpha\varepsilon \frac{Y}{K}\frac{1}{P} - m\varepsilon \frac{E}{K} P^{\varepsilon-1} = \frac{\tau_P}{K} \quad \text{(B.3)}$$

Inserting Eq. (20) into Eqs. (B.2-B.3), we can obtain Eq. (18) and Eq. (21) in the main text. We arrive at the Eq. (22) in the text from Eq. (13) and Eq. (15). Finally, Eqs. (17-22) determine six unknowns $\left(g^*,\ c^*,\ e^*,\ \tau^*,\ P^*,\ N^*\right)$.

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