Optimal Environmental Policy in Economic Development

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Abstract

In a green-Solow-type model in which the government can allocate the tax revenue between productive capital formation and pollution abatement, we show that it is optimal to appropriate the tax revenue mostly for productive capital accumulation in the transition to the long-term optimum, starting with poor productive capital and pristine environment, and that the tax revenue will be allocated to pollution abatement as well as capital formation at the long-term sustainable state. The Environmental Kuznets Curve, although inverse-V shaped in the present model, may reflect the optimal development and environmental policy.

Keywords: Economic development policy, Environmental Kuznets Curve, Green Solow Model, Pollution abatement, Public investment

JEL Classification: E62, O13, O21, Q28

1. Introduction

Recently, Brock and Taylor (2010, 2005) showed that the Environmental Kuznets Curve may be a by-product of convergence to a sustainable growth path in a "Green" Solow model. Thus, at earlier stages of economic development, pollution emissions increase with income growth but near the steady state these emissions decrease with income. Technological progress especially in pollution abatement is primarily responsible for the inverse U-shape in their model.[1] They tested their view using historical evidence of various countries, and suggested that there is considerable evidence of convergence in pollution emission measures. However, they did not obtain the policy implications, assuming that the abatement expenditure/GDP ratio is kept constant along the converging path to the long-term equilibrium.

In this short note, we are concerned with the second-best optimal policy that a government faces, which can allocate the tax revenue between productive capital formation and pollution abatement, rather than the social planner. Assuming implicitly that, in choosing consumption, individuals take the environmental quality as given, although it varies in the aggregate, we employ a green-Solow-type model with a

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constant private savings rate. Among others, a study somewhat close to ours is that of Economides and Philippopoulos (2008), who investigated the optimal allocation between growth-enhancing public capital formation and pollution abatement, and showed that the more the economy cares about the environment, the more growth-enhancing policies the government should choose, that is, resources are to be saved to improve environment. However, they are concerned only with the stationary states in the Ramsey setting. Our focus is on the transitional properties of the optimal policy along the developing path of an economy, starting with poor stock of productive capital and a pristine natural environment and ending up with the long-term optimum. We show that it is optimal to appropriate the tax revenue exclusively for physical capital formation on the transition to the long-term optimum, and that after reaching the optimum the revenue should be allocated between physical capital accumulation and pollution abatement. Pollution emissions being proportional to capital stock, the optimal developing policy results in an inverse V-shape relationship between pollution and income.

2. Model

We extend the Solow model by incorporating the quality of environment. The aggregate production technology of goods is assumed constant-returns-to-scale, in an intensive form, $y=f(k)$, where y is per capita output and k is the capital labor ratio. For simplicity we assume that there is no technological progress in output production and that the labor population remains constant over time. We normalize the population size to unity. Pollution is emitted as a by-product of output in proportion to the level of output: $P=py$ where $p>0$.[2]

Assuming as in the standard Solow model that the (private) savings rate out of the after-tax income is constant, consumption of a representative agent is given as $c=(1-s)(1-\tau)f(k)$ where s is the savings rate and τ denotes the proportional income tax rate $(0<s, \tau<1)$.

The government collects income tax and allocates the revenue between productive capital accumulation and pollution abatement. Denoting the expenditures on capital formation and pollution abatement by G and A, respectively, the budget constraint of the government is

$$\tau f(k)=G+A \tag{1}$$

[1]For the Environmental Kuznets Curve, see, for example, Grossman and Krueger (1995). As classified by Copeland and Taylor (2003), there have been three types of plausible explanation for the inverse U-shape: first, it may reflect the natural progress of economic development, e. g. López (1994) and Arrow et al. (1995); second, there is a threshold level of economic activity above which clean technologies may be used, e. g. John and Pecchenino (1994) and Stokey (1998); and, finally, it is due to increasing returns in abatement, e. g. Andreoni and Levinson (2001). Recently, Smulders et al. (2005) among others endogenized technological progress, using a two-sector endogenous growth model. For recent literature on growth and environment, see Ricci (2007), Tsurumi and Managi (2010) and references therein.

[2]We do not assume a choice of production technologies of producers à la Stokey (1998).

Since our purpose in the present analysis is to investigate the optimal allocation of the revenue, we denote the allocation ratios β and $1-\beta$, respectively; i.e. $G=\beta\tau f(k)$ and $A=(1-\beta)\tau f(k)$.

The evolution of the quality of the environment can be written as

$$\dot{Q}=\eta Q-P+\theta A \tag{2}$$

where Q is the quality of environment (stock), η is the regeneration rate of the nature and θ denotes the efficiency of the abatement expenditure. The dot on a variable means the time derivative of the variable. Assuming for simplicity that public productive capital and private productive capital are perfect substitutes, the evolution of productive capital stock in the economy is then given as

$$\dot{k}=s(1-\tau)f(k)-\delta k+G \tag{3}$$

where δ is the depreciation rate.

The social objective is assumed as the discounted instantaneous utility of a representative individual $U(c, Q)$: $\int_0^T U(c, Q)e^{-\rho t}dt$ where ρ is the discount rate and T is the planning time horizon. We assume that T is sufficiently great. For expositional simplicity, we also assume the instantaneous utility, $U(c, Q)$, is additively separable, i.e. $U(c, Q)=u(c)+v(Q)$ where $u'=du/dc>0$, $u''=d^2u/dc^2<0$, $v'dv/dQ>0$ and $v''=d^2v/dQ^2<0$.[3] Given the initial condition $(k(0), Q(0))=(k_0, Q_0)$ and the end-point conditions $(k(T), Q(T))=(k^*, Q^*)$, the problem for the government is to choose the time path of tax rate τ and allocation ratio β so as to maximize the social objective subject to the constraints, (2) and (3), and the initial and end point conditions.

In the present study we start with a sufficiently small stock of productive capital and a pristine environment, while the end-point conditions of the economic policy are specified such that the capital labor ratio and the quality of environment, (k^*, Q^*), satisfy the following two conditions:

$$\rho=\left(1-\frac{p}{\theta}\right)f'(k^*)-\delta \tag{4a}$$

$$\frac{u'(c^*)}{v'(Q^*)}=\frac{\theta}{\rho-\eta} \tag{4b}$$

where $f'(k)=df/dk$, $c^*=(1-s)(1-\tau^*)f(k^*)$, and τ^* is the long-term-optimal tax rate. Batabyal (1998) among others mentioned that the nature of the underlying equilibrium depends on the government's ability to commit to its announced policy, while Batabyal and Beladi (2006) asserted that the renewable resources should be managed so as to stay away from irreversible or crisis states. From $\dot{Q}=\dot{k}=0$, we have $\beta^*=1-[p-\eta Q^*/f(k^*)]/(\theta\tau^*)$.[4] We must have $1-(p/\theta)>0$ and $\rho-\eta>0$ for conditions (4) to be

[3]The additively separable specification can often be seen in the literature, e. g. Tahvonen and Salo (2001). If they are not separable, the complementarity, i.e. $U_{Qc}>0$ (or substitutability, i.e. $U_{Qc}<0$) tends to make the long-term quality of the environment greater (or smaller, respectively) than that which would be obtained when $U_{Qc}=0$.

[4]Although the possibility that $\beta^*=1$ cannot be ruled out a priori, we will have $\beta^*<1$ since the problem is trivial when $\eta Q-pf(k)>0$, i.e. when natural regeneration is greater than pollution emissions.

economically meaningful. The left-hand side of (4a) is the marginal cost of productive investment and the right-hand side is the marginal net-of-depreciation benefit of investment, taking into account pollution abatement costs. Condition (4b) implies that the marginal benefit of the quality of environment owing to an additional pollution abatement, $v'/(\rho-\eta)$, is equal to the marginal cost in terms of the marginal utility of consumption, u'/θ. These conditions are obtained at the social (first-best) optimum (see Appendix).

The current-value Hamiltonian can be given as

$$H=[u(c)+v(Q)]+\lambda[s(1-\tau)f(k)-\delta k+\beta\tau f(k)]+\sigma[\eta Q-pf(k)+\theta(1-\beta)\tau f(k)]$$

where λ and σ are the shadow prices of productive capital and quality of environment, respectively. The optimal conditions are as follows:

$$H_\tau=[-u'(1-s)-\lambda(s-\beta)+\sigma\theta(1-\beta)]f=0 \tag{5a}$$

$$H_\beta=\tau f(\lambda-\sigma\theta) \tag{5b}$$

$$\dot{\lambda}=\lambda\rho-u'(1-s)(1-\tau)f'-\lambda\{[s(1-\tau)+\beta\tau]f'-\delta\}+\sigma[p-\theta(1-\beta)\tau]f' \tag{5c}$$

$$\dot{\sigma}=\sigma(\rho-\eta)-v' \tag{5d}$$

Assuming the existence of the optimal plan at the end-point of which $\lambda=\sigma\theta$, we investigate the properties of the optimal plan. From (4a) to (4d), we can show that the conditions (5a) and (5b) hold when $\lambda=\sigma\theta$.

The dynamic system of the model is that of non-linear four-dimensional differential equations of state variables, k and Q, and co-state variables, λ and σ, i.e. (2), (3), (5c) and (5d). Since it is difficult to solve, we investigate the optimal path to the end point in terms of the shadow prices of productive capital and environmental quality in this and the next sections, while the relation between the shadow prices and the state variables will be examined in Section 4. In the following two sections, therefore, we implicitly consider the state variables in examining the phases of the shadow prices. Since, as is well known, the Solow model does not necessarily lead to the long-term optimum (4) even in infinite time, we may assume that there is an optimal path of the tax rate, $\tau>0$, satisfying (5a) without loss of generality. Because of the constraint $0\leq\beta\leq1$, form (5b), we have the following three cases: (i) $\beta=1$ as $\lambda>\sigma\theta$; (ii) $\beta=0$ as $\lambda<\sigma\theta$; and (iii) $\beta\in(0,1)$ as $\lambda=\sigma\theta$, where the long-term optimum is case (iii).

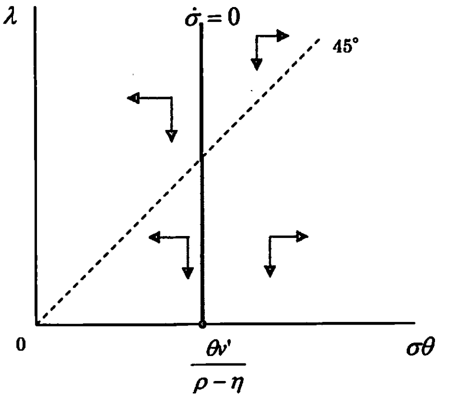
Case (i) $\lambda>\sigma\theta$

From (5b) we have $\beta=1$, i.e. all taxes go to the expenditure on productive capital formation, and, from (5a), $u'=\lambda$. Condition (5c) can be rewritten as

$$\dot{\lambda}=\lambda[(\rho+\delta)-f']+\sigma\theta(p/\theta)f' \tag{6}$$

At this stage, we assume that the (initial) productive capital is sufficiently small, i.e. $f'-(\rho+\delta)>0$. If the initial capital stock is great enough to make $\sigma\theta(p/\theta)/[f'-(\rho+\delta)]>1$, the slope of line $\dot{\lambda}=0$ is greater than one in the $(\lambda,\sigma\theta)$ plane. In this case we can readily show that the social optimum $\lambda=\sigma\theta$, which is represented as a point on the 45 degree line in Figure 1, can be attained only at the origin, i.e. a trivial solution, since $\dot{\lambda}>0$ under line $\dot{\lambda}=0$. Thus, the slope of line $\dot{\lambda}=0$ is positive but less than one in the

Figure 1 *Phase Diagram*



$(\lambda, \sigma\theta)$ plane, and $\dot{\lambda}<0$ for $\lambda>\sigma\theta$ as illustrated in Figure 1.[5] On the other hand, the line $\dot{\sigma}=0$ is represented by a vertical line through $\sigma\theta=\theta v'/(\rho-\eta)$ for a given Q at that time.[6] Therefore, given productive capital and environmental quality, k and Q, we have a phase diagram for case $\lambda>\sigma\theta$ as in Figure 1.

Case (ii) $\lambda<\sigma\theta$

From (5b) we have $\beta=0$, i.e. all taxes are spent on pollution abatement, and from (5a) we obtain $-u'(1-s)=\lambda s-\sigma\theta$. Using it we rewrite (5c) as

$$\dot{\lambda}=\lambda(\rho+\delta)+\sigma\theta[(p/\theta)-1]f' \tag{7}$$

From (7) we have the $\dot{\lambda}=0$ line, i.e. $\lambda=\{[1-(p/\theta)]f'(\rho/\delta)\}\sigma\theta$ whose slope is greater than 1 when $k<k^*$. Therefore, we have $\dot{\lambda}<0$ when $\lambda<\sigma\theta$.[7] The line $\dot{\sigma}=0$ is obtained for a given environmental quality at that time, from (5d), as in the previous case. Therefore, given productive capital and environmental quality, k and Q, we obtain the phase diagram as depicted in Figure 1 for $\lambda<\sigma\theta$.

3. Optimal Policy

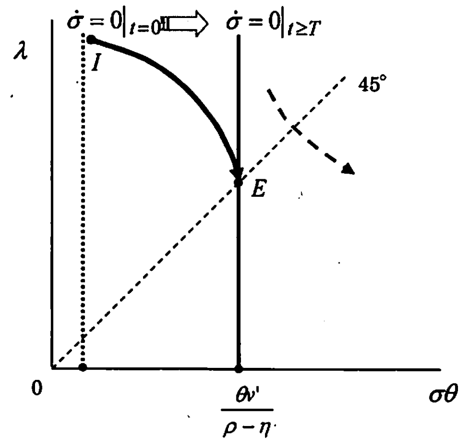
Now we consider the optimal policy in the transition to the long-term optimum. Poor physical capital stock and a pristine environment will be reflected in a higher shadow price of physical capital and a lower shadow price of the quality of the environment, say, point I in Figure 2. At the initial point in time, the relatively high quality of the environment will make the marginal utility from the environmental quality

[5] We can show that when the slope of line $\dot{\lambda}=0$ is greater than one, there is no optimal path converging to the end-point. The $\dot{\lambda}=0$ line does not appear in the part of $\lambda>\sigma\theta$ in Figure 1.

[6] We can show that if $U_{Qc}>0$ (*or* $U_{Qc}<0$), the $\dot{\sigma}=0$ line is downward sloping (or upward sloping, respectively).

[7] As in the previous case, if the slope of $\dot{\lambda}$ is greater than one, we can show that the social optimum besides the trivial one cannot be attained.

Figure 2 *Optimal Path*



very low, that is, v' is very small. The $\dot{\sigma}=0$ line is close to the origin. The line is depicted by a dotted line. An optimal transition path of the economy starting from I can be depicted as in Figure 2. It seems plausible that the shadow price of the environment is very small at the initial point in time, and that it increases along the development path. Thus, from (5d), we will have $\sigma\theta > \theta v'/(\rho-\eta)$ at the initial point, that is, $\sigma\theta$ lies on the right-hand side of the $\dot{\sigma}=0$ line.[8] On the other hand, when the capital labor ratio is very small, its shadow price will be very high. Thus, we assume $\lambda > \sigma\theta$ in the initial state.

Near the initial point, the productive capital accumulation is accelerated by the tax revenue allocation policy since $\lambda > \sigma\theta$. The accumulation of productive capital decreases its shadow price. Given that the initial point I is on the right-hand side of the $\dot{\sigma}=0$ line, the shadow price of the environmental stock rises as the environmental quality deteriorates. However, the accumulated capital makes the allocation policy less pro-capital-accumulation, and thereby brings about greater consumption relative to output. The deceleration of productive capital accumulation tends to set back the deterioration of the environmental quality. In other words, while the $\dot{\sigma}=0$ line shifts rightward as the quality of environment deteriorates owing to pollution emissions caused by high productive capital accumulation, the rightward shift becomes sufficiently rapid, and the path of the shadow prices $(\sigma\theta, \lambda)$ will be on the intersection of the 45 degree line and the $\dot{\sigma}=0$ line, i.e. the long-term optimum (E in Figure 2), by the end of the planning period, T.[9]

In the transition, therefore, the shadow price of productive capital declines and the shadow price of environment quality increases monotonically.[10] The optimal transitional path is above the 45 degree line,

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[8]We cannot rule out the possibility that the shadow price of the environmental quality satisfies $\sigma\theta = \theta v'/(\rho-\eta)$, i.e. on the $\dot{\sigma}=0$ line. Even in this case, our result is not altered essentially.

[9]If the path continues to be on the right-hand side of the $\dot{\sigma}=0$ line, it soon crosses the 45 degree line and will then diverge to the southeast, as depicted by the dotted arrow in Figure 2.

[10]Changes in productive capital and environmental quality associated with the changes in the shadow prices will be analyzed in the next section.

that is, in the range of $\lambda > \sigma\theta$. Finally, at the long-term optimum where $\lambda = \sigma\theta$, the tax revenue will be allocated to pollution abatement as well. Therefore, the policy specified in pollution abatement ($\beta = 0$) cannot be optimal on the transition to the long term optimum.

Therefore, we have the following results:

Result 1: On the transition to the long-term optimum, the resources should be allocated mostly to productive capital formation rather than pollution abatement, while, once the long-term optimum is attained, the environmental quality should be supported optimally by the environmentally sustainable investment policy.

The abatement investment policy will be undertaken only after the optimal level of capital stock is attained, that is, the optimal allocation to pollution abatement moves from a corner solution to an interior solution. On the long-term optimum, the positive environment investment prevents the environment from deteriorating with output production.[11]

4. Productive Capital and Environmental Quality

The optimal paths of state variables, k and Q, are depicted in Figure 3. As mentioned in the text, when $k > k^*$, we have

$$\dot{\lambda} = \lambda\,[(\rho+\delta) - f'] + \sigma\theta\,(p/\theta)f' < \lambda\{(\rho+\delta) - [1-(p/\theta)]f'\} < 0 \tag{8}$$

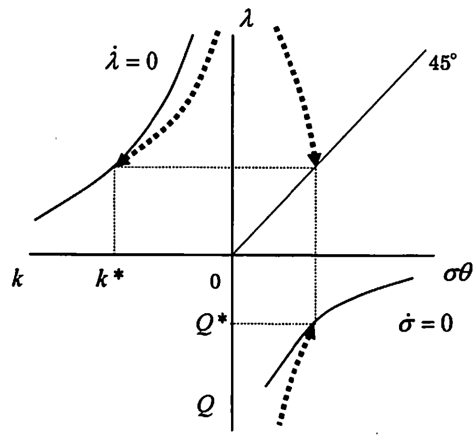
i.e. the shadow price of capital stock per capita monotonically decreases along the optimal path. The path is illustrated in the (k, λ) plane of the second quadrant of Figure 3. It should be noted that the $\dot{\lambda} = 0$ line in the (k, λ) plane shifts as the shadow price of the environmental quality changes.

On the other hand, the $\dot{\sigma} = 0$ line in the $(Q, \sigma\theta)$ plane of the fourth quadrant of Figure 3, is given as the combinations Q and $\sigma\theta$ satisfying $\sigma\theta = \theta v'(c, Q)/(\rho - \eta)$. When the environmental quality is at the pristine level and the consumption level is low due to poor capital stock, v' is very low. At earlier stages in which productive capital accumulation is politically accelerated, the quality of environment declines due to pollution emissions, while the shadow price, σ, increases. Then, since capital accumulation brings about greater output and thereby consumption, the marginal utility of the environmental quality rises together with degradation of the environment. At the long-term optimum point, we have $\dot{\sigma} = 0$, or equivalently, $\sigma\theta = \theta v'(c, Q)/(\rho - \eta)$.

So far we are not concerned with the path of the tax rate since our purpose in the present paper is to

[11] In the present model, environmental quality will not improve even with pollution abatements, but should be kept at the "threshold" level in contrast to John and Pecchenino (1994), who suggested that environmental quality will begin improving with economic growth after the "threshold" point.

Figure 3 *Time Paths of Stocks*



analyze how the tax revenue should be allocated between growth-encouraging and environment-enhancing policies. Although we cannot solve explicitly the path of the tax rate, we can conjecture it from the above analysis. In the earlier stages, the tax rate is likely to be high in order to accelerate and finance (public) capital formation. However, as it draws near to the long-term optimum, the government will seek to improve the welfare by increasing consumption through lower tax rates.

Finally, we examine the time path of the tax rate: As shown in Figure 2, the optimal path $(\lambda, \sigma\theta)$ lies in the range $\lambda > \sigma\theta$. In this case, from (5a) and $\beta=1$, we have $u'[(1-s)(1-\tau)f(k)]=\lambda$. Differentiating with respect to time, we obtain

$$\dot{\tau}=\frac{(1-\tau)f'\dot{k}-\dot{\lambda}}{(1-s)u''f} \tag{9}$$

From Figure 3, we have $\dot{\lambda}<0$ and $\dot{k}>0$ along the optimal path. Therefore, we can show that $\dot{\tau}<0$. That is, the optimal tax rate monotonically decrease along the optimal path, and reaches $\tau^*>0$ at the steady state optimum.

5. Concluding Remarks

We have showed that it may be optimal to spend on productive capital formation rather than on pollution abatement along the transition path toward the long-term optimum, and that, starting with poor stock of productive capital and a pristine natural environment, the tax revenue is also optimally allocated to pollution abatement after the long-term optimum is attained. Since the setup of the model is simplified for expositional purpose, resources would be spent on pollution abatement even during the transition in the real world.[12] Even so, the relationship between income and pollution along the development path in the present model therefore has an inverted-V shape, where pollution is measured in net-of-abatement terms. The Environmental Kuznets Curve may reflect the optimal development and environmental policy.

Appendix

End point condition: In order to set the end point condition, we consider the optimization problem of the social planner in the long term:

$$\underset{c,A,k,Q}{Max}\int_0^\infty [u(c)+v(Q)]e^{-\rho t}dt$$
$$\text{subject to } \dot{k}=f(k)-c-A-\delta k$$
$$\dot{Q}=\eta Q-pf(k)+\theta A$$
$$\text{and } k(0)=k_0; Q(0)=Q_0$$

where A denotes output allocated to pollution abatement. The current-value Hamiltonian is $H=[u(c)+v(Q)]+\lambda[f(k)-c-A-\delta k]+\sigma[\eta Q-pf(k)+\theta A]$. The optimal conditions are as follows:

$$H_c=u'-\lambda=0 \tag{A1}$$
$$H_A=-\lambda+\sigma\theta=0 \tag{A2}$$
$$\dot{\lambda}=\lambda\rho-\lambda(f'-\delta)+\sigma pf' \tag{A3}$$
$$\dot{\sigma}=\sigma\rho-v'-\sigma\eta \tag{A4}$$

and the transversality conditions. We consider here that case $A>0$ at the optimum is plausible. Letting $\dot{\lambda}=\dot{\sigma}=0$ in (A3) and (A4) and making use of (A1) and (A2), we obtain (4a) and (4b) in the text.

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[12] In the real world, the governments, central and local, may not directly undertake environmental abatement activities, but they instead induce producers (i.e., polluters) to allocate their resources into environmental abatement activities, for example, by regulating the emission levels. For experience in Yokkaichi where emissions of SO_x from the petrochemical complex caused Yokkaichi asthma, see Asahi and Yakita (2010).

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