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Environmental Tax Reform and Endogenous Growth

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ABSTRACT

This paper explores how an environmental tax reform impacts pollution, economic growth and welfare in an endogenous growth model with pre-existing tax distortions. We find that a shift in the tax mix away from output towards pollution may raise economic growth through two channels. The first channel is an environmental production externality, which determines the positive effect of lower aggregate pollution on the productivity of capital. The second channel is a shift in the tax burden away from the net return on investment towards profits. The paper also shows that, if tax-shifting towards profits is large and environmental amenities are unimportant, the optimal tax on pollution may exceed its Pigovian level.

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1 Introduction

The link between environmental policy and economic performance is a controversial issue. Some people argue that society faces a trade-off between economic growth and a better quality of the environment. Others, in contrast, maintain that a more ambitious environmental policy is a necessary condition for sustainable economic growth. In this connection, environmental taxes seem to be a particularly attractive instrument to enhance environmental quality without seriously damaging growth prospects. In particular, by increasing taxes on dirty activities and using the revenues to cut distortionary taxes on income, governments may be able to reap a 'double-dividend,' namely, not only a cleaner environment but also a less distortionary tax system, thereby stimulating economic growth.

This paper extends the literature on environmental tax reform in three directions. First, the analytical literature has thus far explored the double-dividend issue only in a static framework (see e.g. Bovenberg and De Mooij (1994ab), Bovenberg and Van der Ploeg (1994ab), Oates (1994), Parry (1994) and Schöb (1994)). Numerical analyses have employed an intertemporal framework with exogenous growth (see, e.g., Goulder (1995) and Proost and Van Regemorter (1994)). We, in contrast, use a dynamic model of endogenous growth to analytically explore the link between environmental externalities and distortionary taxes.

A second contribution of the paper is to model the environment as a public capital good. Previous analysis of the double-dividend issue have abstracted from externalities affecting production by modelling the environment as a public consumption good. We show that the incorporation of production externalities makes a double-dividend more likely.

Finally, we explore the impact of alternative instruments of environmental policy that do not charge a price for pollution, such as freely issued pollution permits. In this connection, we show that, in a second-best world with distortionary taxes, instrument selection may have important consequences for welfare and growth. In particular, we demonstrate that, compared to freely issued pollution permits, pollution taxes benefit growth if other inputs are poor substitutes for pollution. In that case, the base of pollution taxes is relatively inelastic so that pollution taxes are relatively efficient instruments for raising revenues. However, if pollution is easily replaced by other inputs, pollution taxes are worse for growth than freely issuing pollution permits. Intuitively, with easy substitution, pollution taxes are a relatively inefficient instrument to raise revenues because they generate a large negative impact on the after-tax return to investment.

Our paper is also closely related to the literature on pollution and long-term growth (see e.g. Bovenberg and Smulders (1995), Den Butter and Hofkes (1993), Gradus and Smulders (1993), Ligthart and Van der Ploeg (1993), and Van Marrewijk, Van der Ploeg and Verbeek (1993)). This literature focuses on optimal environmental policies and explores how the social optimum can be sustained in a decentralized economy. Our analysis departs from this first-best world in two major ways. First, public policy is not necessarily optimal. In particular, we explore the consequences of a reform of the tax system, starting from an initial equilibrium that is not necessarily optimal. Second, in addition to market failures associated with environmental externalities, we allow for tax distortions due to the absence of lump-sum taxation. Hence, the interaction between environmental externalities and distortionary taxes is explored in a second-best world. In this connection, not only do we investigate the consequences of an environmental tax reform but we also show how, in the presence of distortionary taxes, the optimal environmental tax deviates from the Pigovian tax.

We find that an environmental tax reform reduces growth if two conditions are met. First, the positive externality of a better environmental quality on productivity should be small compared to the production elasticity of pollution as a rival input into production. Second, substitution between pollution and other inputs should be rather easy. If these two conditions are met, the government faces a trade-off between environmental care and economic growth. If substitution between pollution and other inputs is difficult, pollution taxes are less powerful in cutting pollution. At the same time, however, they are a more effective device to tax the quasi-rents from pollution, thereby generating revenues to reduce the distortionary tax on output. Accordingly, an

environmental tax reform may raise growth by improving the efficiency of the tax system as a revenue-raising device. A double-dividend may emerge also if the production externality is relatively powerful.

In a second-best world with distortionary taxes, the optimal environmental tax generally deviates from the Pigovian tax. We show that the optimal environmental tax lies below the Pigovian level if substitution between pollution and capital is relatively easy. However, if substitution is more difficult, the optimal pollution tax may exceed the Pigovian level, but only if environmental amenities are relatively unimportant.

The rest of this paper is organized as follows. Section 2 discusses the model. Section 3 explores the effects of pollution taxes on growth, environmental quality and welfare for the case of a Cobb-Douglas production function. The case with small substitution possibilities between capital and pollution is investigated in section 4. Section 5 discusses the effects of environmental policy instruments that do not charge a price for pollution. Finally, section 6 concludes.

2 The model

This section presents the dynamic model for a closed economy. The model equations are contained in table I. Notation is explained at the end of the table.

Production function

By using production technology (I.1), firms combine four factors of production to produce output (Y) (see figure 1). On the one hand, physical capital (K) and productive government spending (S), which can be thought of as infrastructure, are combined to produce an intermediate input, M. The function $m(K,S)$ exhibits constant returns to scale with respect to the two inputs. On the other hand, by combining pollution (P) and private abatement (A), firms produce intermediate input, N.¹ The function $n(A,P)$ features constant returns with respect to abatement, which, in contrast to pollution, is growing on a balanced-growth path (see below). Combining the two intermediate inputs, N and M, by using a CRS production function, firms produce intermediate output. Together with the services from the environment (E), this intermediate output yields actual output (Y).²

For balanced-growth to be feasible, the production function must meet a number of restrictions. First, the production function should exhibit constant returns with respect to the growing inputs:³

$$\delta + \beta + \gamma = 1 \tag{2.1}$$

where δ , β and γ are the production elasticities of the growing inputs S, K and A, respectively.

The second condition for balanced-growth is that the production elasticities of the various inputs at the left-hand side (LHS) of (2.1), as well as the production elasticity of pollution ($\alpha\gamma$), remain constant over time. This imposes restrictions on the substitution possibilities between the

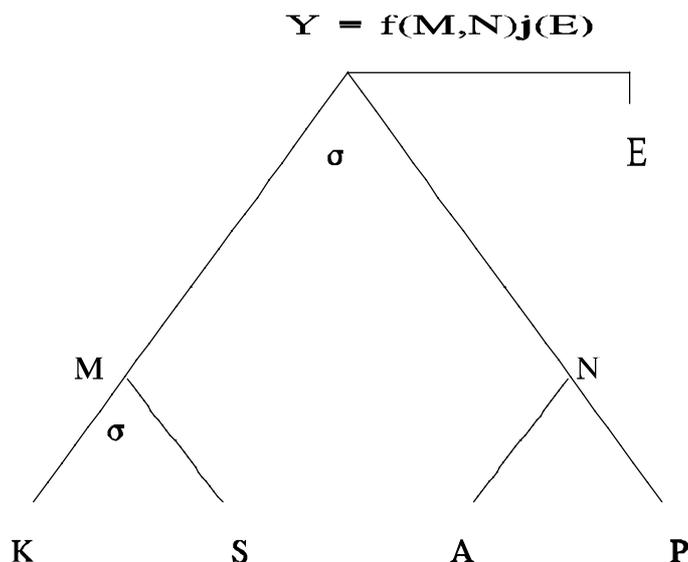
¹ Pollution can be interpreted as a polluting input with unlimited supply and zero extraction costs. Emissions are proportional to the use of this input. Abatement is assumed to be a private input, which enables firms to increase the level of output without causing more pollution. Other studies take abatement as a public, rather than a private, input (see e.g. Sørensen, Pedersen and Nielsen, 1994). In that case, abatement can be viewed as the knowledge about 'clean' production methods. Abatement plays a major role in the model, see footnote 4.

² Pollution, P, can be viewed as the extractive, rival use of the environment. At the same time, the environment, E, yields non-extractive, non-rival services as an input into production.

³ The endogenous growth literature refers to this restriction as the 'core' property (see Rebelo (1991)).

various inputs. In particular, on a sustainable growth path the flow of pollution (P) is constant, while abatement grows at the same rate as output. In the face of these diverging growth rates, the production elasticities of pollution and abatement (i.e. $\alpha\gamma$ and γ) remain constant only if the elasticity of substitution between the non-growing input, P, and the growing input, A, equals unity. In particular, if substitution would be too easy (i.e. the substitution elasticity > 1), the production elasticity of pollution would approach zero as the growing input (abatement) would crowd out the non-growing input (pollution). If substitution would be too difficult (i.e. the substitution elasticity < 1), in contrast, the production elasticity of abatement would go to zero because the marginal product of abatement would fall substantially as the abatement-pollution ratio rises. For the same reasons, the elasticity of substitution between intermediate output, which grows on the balanced-growth path, and the quality of the environment, which remains constant, should equal unity. Finally, the substitution elasticity between K and S, denoted by σ_m , as well as the substitution elasticity between M and N, denoted by σ_y , should be constant. However, these elasticities are allowed to differ from unity as the arguments in m and f (i.e. K, S and M, N, respectively) grow at the same constant rate. Consequently, the ratios K/S and M/N, which determine the production elasticities, are fixed on the balanced-growth path.⁴

Figure 1: The production structure



Firm behavior

The model describes a decentralized economy with perfect competition. A representative firm maximizes its value (I.2) with respect to abatement, pollution and investment. It ignores the environmental production externality. The value of the firm amounts to the present value of all future dividends, represented by (I.3). T_y stands for a

⁴ If abatement would not enter the model, the substitution elasticity between (constant) pollution and the (growing) intermediate input, M, would be restricted to unity (see the analysis in section 3). Incorporating abatement thus enables us to examine alternative substitution possibilities. Section 4 indicates that this is potentially important.

tax on output, T_a represents an abatement subsidy and T_p denotes a pollution tax. The interest rate, denoted by r , is constant on a balanced-growth path. We abstract from depreciation of capital. Hence, the accumulation of capital (\dot{K}) equals gross investment (I) (see (I.4)). Profits in (I.5) are defined as dividends plus investment minus capital costs. Solving the maximization problem of the firm, we find the implicit demand equations for private inputs (I.6), (I.7) and (I.8). These expressions reveal that firms equalize the marginal productivity of private inputs to their respective producer prices.⁵

Household Behavior

A representative household maximizes an intertemporal utility function (I.9) subject to a dynamic budget constraint (I.10). Two arguments enter instantaneous utility: private consumption (C) and the quality of the environment (E). The substitution elasticity between the growing variable, C, and the quality of the environment, E, must be unity to ensure that sustainable growth is optimal (see Gradus and Smulders (1993) and Bovenberg and Smulders (1995)). Maximizing household utility subject to the household budget constraint, one finds the Keynes-Ramsey rule (I.11).⁶

Government

The government budget is balanced according to (I.12). The government does not issue public debt and raises revenues by adopting a tax on output (T_y) and a tax on pollution (T_p). The revenues are used to finance two types of government spending: public investment (S) and abatement subsidies (T_a). The government balances its budget at each point in time by adjusting the tax rate on output.

Environmental Quality

Relation (I.13) formalizes the inverse relationship between the quality of the environment and the flow of pollution.⁷ Environmental quality in the initial equilibrium is assumed to be above a certain ecological threshold level. Furthermore, we assume that $\lim_{p \rightarrow \infty} j[e(P)] = 0$ in the production function (I.1). Pollution thus should remain bounded for production to remain feasible. Hence, on a balanced-growth path, pollution cannot

⁵ We assume that firm profits are non-negative, i.e. $s_w = (1 - T_y)(\delta - \alpha\gamma) \geq 0$. This requires that the production elasticity of pollution at the firm level ($\alpha\gamma$) should not exceed the production elasticity of public investment (δ). Since production features constant returns with respect to the growing inputs, S, A and K (see (2.1)), the non-negativity condition for profits guarantees that the production function does not exhibit increasing returns with respect to the 'private' inputs P, A and K. Merger across firms is thus not beneficial and a competitive equilibrium can be sustained. In equilibrium, positive profits can exist due to the presence of a fixed factor in production (e.g. land, know how, managerial talent). Hence, perfect competition is possible only if public infrastructure enters the production function.

⁶ For the steady state to be meaningful, the consumption share of output should be non-negative. This condition ensures also that utility is bounded. From (I.5) and (I.10), we know that $s_c = s_d$. On a balanced-growth path, D is growing at a constant rate, π . Solving the integral (I.2), we derive: $s_c = s_d = (r - \pi)s_v$. Hence, the growth rate, π , should not exceed the interest rate. This condition restricts the rate of time preference (θ) and the intertemporal elasticity of substitution (σ). In particular, by using (I.11), we find that a non-negative consumption share requires that: $\theta\sigma + (1 - \sigma)r \geq 0$. Hence, the intertemporal substitution possibilities cannot be too large, especially if the rate of time preference is small.

⁷ Alternatively, the quality of the environment could be modelled as a stock rather than as a flow (see e.g. Bovenberg and Smulders (1995)). However, this would complicate the model substantially as it would imply a second state variable, thereby introducing transitional dynamics. More importantly, the qualitative steady-state results do not change if a stock, rather than a flow, determines the external effects (see Gradus and Smulders (1993)). Hence, if one is interested in long-term effects, the assumption of a flow of pollution involves no loss of generality.

grow at a positive rate.

Walras Law: equilibrium conditions and budget constraints

The model describes a closed economy. The equilibrium condition on the goods-market (I.14) can be found by combining (I.3), (I.4), (I.5), (I.10) and (I.12) for dividends, investment, profits, the household budget constraint and the government budget constraint, respectively.

Sustainable Balanced-Growth

Most variables in the economy grow endogenously at the same constant rate. This situation is known as balanced economic growth. Growth is also sustainable because pollution and, therefore, environmental quality remain constant on the balanced-growth path. In order to keep pollution from growing, the pollution tax grows at the same rate as output (Y) and the other inputs (K,A and S). Transitional dynamics in the model are absent. Hence, after a policy shock the economy moves immediately towards a new steady state in which ratios between the growing variables remain constant.

Table I: The model in levels

Firms

Production function

$$Y = f[m(K, S), n(A, P)]j(E) \quad (I.1)$$

$$\text{where } n(A, P) = AP^\alpha$$

Firm Value

$$V = \int_0^{\infty} D e^{-rt} dt \quad (I.2)$$

Dividends

$$D = (1 - T_y)Y - (1 - T_a)A - T_p P - I \quad (I.3)$$

Investment

$$I \equiv \dot{K} \quad (I.4)$$

Profits

$$W = D + I - rK \quad (I.5)$$

First-Order Conditions

$$(1 - T_y) \frac{\partial Y}{\partial A} = (1 - T_a) \quad (I.6)$$

$$(1 - T_y) \frac{\partial Y}{\partial P} = T_p \quad (I.7)$$

$$(1 - T_y) \frac{\partial Y}{\partial K} = r \quad (\text{I.8})$$

Households
Utility

$$U = \int_0^{\infty} \frac{[C E^\phi]^{1 - \frac{1}{\sigma}}}{1 - \frac{1}{\sigma}} e^{-\theta t} dt \quad (\text{I.9})$$

Household Budget Constraint

$$\dot{K} = rK + W - C \quad (\text{I.10})$$

First-Order Condition

$$\frac{\dot{C}}{C} = \sigma(r - \theta) \quad (\text{I.11})$$

Government

Government Budget Constraint

$$T_y Y + T_p P = T_a A + S \quad (\text{I.12})$$

Environmental Quality

$$E = e(P) \quad (\text{I.13})$$

Walras Law

Goods-market equilibrium

$$I = Y - S - A - C \quad (\text{I.14})$$

Exogenous: T_a, T_p, S, K_0

Endogenous: $Y, P, A, V, D, I, W, C, T_y, E, r, \pi$

Growth rate

$$\pi = \frac{\dot{Y}}{Y} = \frac{\dot{K}}{K} = \frac{\dot{S}}{S} = \frac{\dot{A}}{A} = \frac{\dot{C}}{C} = \frac{\dot{I}}{I} = \frac{\dot{T}_p}{T_p} = \frac{\dot{V}}{V} = \frac{\dot{D}}{D} = \frac{\dot{W}}{W}$$

Notation

Y = output

K = capital stock

S = public investment

A = abatement spending

P = pollution

I = investment in private capital

V = value of the firm

D = Dividends

C = private consumption

W = profits

E = quality of the environment

T_y = tax on output

T_a = abatement subsidy

T_p = pollution tax

r = interest rate

π = growth rate

Parameters

ϕ = environmental externality parameter in utility

σ = intertemporal substitution elasticity

θ = pure rate of time preference

σ_m = substitution elasticity between private capital and public investment

σ_y = substitution elasticity between intermediates $N = n(A,P)$ and $M = m(K,S)$

Linearized model

To solve the model, we log-linearize it around a steady state. Appendix A derives the log-linearized factor-demand equations. Table II contains the log-linearized model. Notation is explained at the end of the table. A tilde ($\tilde{\cdot}$) denotes a relative change, unless indicated otherwise. Relative changes in the growing variables are presented relative to the relative change in the capital stock and are presented as lower case variables. Hence, these variables represent relative changes of variables as a ratio of the capital stock (which is initially predetermined). For example, the change in the pollution tax, which is a growing variable, is given by $\tilde{t}_p = \tilde{T}_p - \tilde{K}$.

Expression (II.2) reveals that a higher relative price of pollution induces substitution from pollution towards other inputs. The strength of the substitution effect towards either abatement or capital depends on the magnitude of σ_y . In particular, if $\sigma_y < 1$, substitution between the intermediate factors M and N is difficult relative to substitution between A and P. In that case, pollution and abatement are substitutes: a higher price for abatement increases pollution. However, if $\sigma_y > 1$, pollution is a poor substitute for abatement compared to other inputs. Therefore, a higher relative price for abatement lowers pollution. Pollution can be affected also by public investment. In particular, lower public investment raises pollution if $\sigma_m < \sigma_y$. In that case, compared to capital, pollution is a better substitute for public investment. The demand for abatement rises with the level of pollution, abatement subsidies and pollution taxes (see (II.3)).

Relations (II.7) and (II.8) reveal that the economy grows faster if and only if the interest rate increases. This is because a higher interest rate is associated with a higher after-tax return to capital, which stimulates savings and investment. According to (II.9), consumption rises if profits increase. Consumption is affected also by the income and intertemporal substitution effects associated with changes in the interest rate. In particular, if the intertemporal elasticity of substitution (σ) exceeds unity, the intertemporal substitution effect dominates and consumption declines on account of a higher interest rate.

Table II: The model in relative changes

Output

$$\tilde{y} = \delta \tilde{s} + \gamma \tilde{a} + \alpha \gamma \tilde{P} + \eta \tilde{E} \quad (\text{II.1})$$

Pollution

$$[1 + \alpha(1 - \sigma_y)]\tilde{P} = \frac{\delta(\sigma_m - \sigma_y)}{\sigma_m(\delta + \beta)}\tilde{s} - (1 - \sigma_y)(\tilde{t}_p + \tilde{T}_a) + \sigma_y(\tilde{r} - \tilde{t}_p) \quad (\text{II.2})$$

Abatement

$$\tilde{a} = \tilde{P} + \tilde{T}_a + \tilde{t}_p \quad (\text{II.3})$$

Rate of return to capital

$$\tilde{y} = \frac{\delta(\sigma_m - \sigma_y)}{\sigma_m(\delta + \beta)}\tilde{s} + (1 - \sigma_y)\eta\tilde{E} + \sigma_y[\tilde{r} + \tilde{T}_y] \quad (\text{II.4})$$

Dividends

$$s_d\tilde{d} = -s_i\tilde{i} + (1 - T_y)[\delta\tilde{s} + \gamma\tilde{T}_a - \tilde{T}_y - \alpha\gamma\tilde{t}_p - \epsilon\eta\tilde{P}] \quad (\text{II.5})$$

Profits

$$s_w\tilde{w} = s_d\tilde{d} + s_i\tilde{i} - rs_k\tilde{r} \quad (\text{II.6})$$

Growth rate

$$\tilde{\pi} = \tilde{i} \quad (\text{II.7})$$

Household savings

$$\tilde{i} = \frac{r}{r - \theta}\tilde{r} \quad (\text{II.8})$$

Household budget constraint

$$s_c\tilde{c} = s_w\tilde{w} + (1 - \sigma)rs_k\tilde{r} \quad (\text{II.9})$$

Government Budget constraint

$$(1 - T_y)\tilde{T}_y + T_y\tilde{y} + T_p^*\tilde{t}_p + T_p^*\tilde{P} = (1 - T_a)s_a\tilde{T}_a + T_a s_a\tilde{a} + s_s\tilde{s} \quad (\text{II.10})$$

Environmental Quality

$$\tilde{E} = -\epsilon\tilde{P} \quad (\text{II.11})$$

Goods-market equilibrium (Walras Law)

$$s_i\tilde{i} = \tilde{y} - s_c\tilde{c} - s_a\tilde{a} - s_s\tilde{s} \quad (\text{II.12})$$

Capital letters (X) denote levels of a variable, while lower-case variables (x) denote levels as a ratio of the capital stock (K), i.e. $x = X/K$ for $x = y, s, a, t_p, d, v, w, i, c$ and $\tilde{x} = \tilde{X} - \tilde{K}$.

Elasticities

$$\beta = \frac{\frac{\partial Y}{\partial K} K}{Y}, \quad \delta = \frac{\frac{\partial Y}{\partial S} S}{Y}, \quad \gamma = \frac{\frac{\partial Y}{\partial A} A}{Y}, \quad \alpha \gamma = \frac{\frac{\partial Y}{\partial P} P}{Y}$$

$$\epsilon = -\frac{\partial e}{\partial P} \frac{P}{e} > 0, \quad \eta = \frac{\partial j}{\partial E} \frac{E}{j} > 0$$

Taxes

$$\tilde{T}_a = \frac{dT_a}{1-T_a}, \quad \tilde{T}_y = \frac{dT_y}{1-T_y}, \quad \tilde{T}_p = \frac{dT_p}{T_p}$$

Shares

$$\begin{array}{llll} s_a = A/Y & s_d = D/Y & T_p^* = T_p P/Y & s_w = W/Y \\ s_s = S/Y & s_c = C/Y & s_i = I/Y & s_k = K/Y \\ s_v = V/Y & & & \end{array}$$

Relations between the shares:

$$\begin{array}{ll} \text{Dividends} & s_d = (1-T_y) - (1-T_a)s_a - T_p^* - s_i \quad ; \quad s_d = (r-\pi)s_v \\ \text{Profits} & s_w = s_d + s_i - rs_k = (1-T_y)(\delta-\alpha\gamma) \\ \text{Household Budget Constraint} & s_c = s_w + (r-\pi)s_k \quad ; \quad s_c = s_d \\ \text{Definition of investment} & s_i = \pi s_k \\ \text{Government Budget Constraint} & s_s + T_a s_a = T_y + T_p^* \\ \text{Goods-Market Equilibrium} & s_i = 1 - s_s - s_a - s_c \end{array}$$

Production elasticities

$$\begin{aligned} (1-T_y)\gamma &= (1-T_a)s_a \\ (1-T_y)\alpha\gamma &= T_p^* \\ (1-T_y)\beta &= rs_k \end{aligned}$$

Determinant

$$\Delta^* = \sigma^* [rs_k + s_w + (\epsilon\eta - \alpha\gamma)] + (1-\sigma^*)(1-T_y)(1-\gamma)(1+\alpha)$$

Welfare

The welfare effects of small policy changes can be measured by the marginal excess burden. It amounts to the additional consumption that needs to be provided to the household to keep utility (after the policy shock) at its initial level. Hence, a negative value for the marginal excess burden corresponds to a rise in welfare. The marginal excess burden $\tilde{\lambda} = d\lambda/C$ amounts to (see appendix B):

$$\begin{aligned}
\tilde{\lambda} = & - \left[\frac{\alpha \gamma - \epsilon \eta}{s_c} - \epsilon \phi \right] \tilde{P} - \frac{T_y - T_a}{1 - T_a} \frac{\gamma}{s_c} \left[\tilde{a} + \frac{\pi}{r - \pi} \tilde{\pi} \right] \\
& - \frac{\delta - s_s}{s_c} \left[\tilde{s} + \frac{\pi}{r - \pi} \tilde{\pi} \right] - \frac{T_y \beta}{s_c} \frac{\pi}{r - \pi} \tilde{\pi}
\end{aligned} \tag{2.2}$$

All coefficients at the right-hand side (RHS) of (2.2) represent wedges between the marginal social costs and the marginal social benefits of an activity. If benefits exceed costs at the margin, an increase in such activity enhances welfare.⁸ For the growing variables A, S and K we see that not only changes in current levels matter for welfare, but also the present value of future changes (indicated by the change in the growth rate).

The first term at the RHS of (2.2) stands for the welfare effect of a change in pollution, which is a non-growing variable. First, as a private input into production, pollution exerts a positive effect on output, which is represented by $\alpha\gamma$. Second, by worsening environmental quality, pollution imposes an adverse production externality, captured by $\epsilon\eta$. The overall effect on productivity is positive only if $\alpha\gamma - \epsilon\eta > 0$, i.e. if the positive output effect of additional pollution as a rival input for the individual firm exceeds the negative external (non-rival) productivity effect of aggregate pollution. Finally, pollution yields an adverse consumption externality (see the second term between the first square brackets).

The second term at the RHS of (2.2) reveals that higher current or future abatement improves welfare if the output tax, which acts as an implicit tax on abatement, exceeds the abatement subsidy. Hence, more abatement boosts welfare only if it is taxed on a net basis. In the rest of this paper, we set $T_a = T_y$. Hence, a change in abatement yields no first-order effects on welfare.

The partial welfare effect of higher public investment is captured by the third term at the RHS of (2.2). A rise in public investment improves welfare if the productivity effect of public investment exceeds the share of public investment in output. This condition implies that the marginal product of public investment is larger than unity, i.e. $dY/dS > 1$ or, alternatively, that the marginal social benefits, dY , exceed the marginal social costs, dS . From now on, we assume that $\delta = s_s$. Accordingly, the marginal social benefits and costs of public investment coincide.

The last term at the RHS of (2.2) represents the welfare impact of capital accumulation. The tax on output drives a wedge between the before-tax return to capital (which stands for the marginal social benefits of capital accumulation) and the after-tax return to capital (which measures the marginal social costs of capital accumulation). Hence, if the output tax is positive, a higher rate of capital accumulation (i.e. $\tilde{\pi} > 0$) improves welfare because the benefits in terms of higher future output exceed the costs in terms of current consumption foregone.

3 Effects on growth, pollution and welfare

This section explores the economic, ecological and welfare effects of higher pollution taxes

⁸ Note that these terms represent partial welfare effects as relation (2.2) is not a reduced form.

(i.e. $\tilde{t}_p > 0$). Appendix C solves the model from table II for the special case that $\sigma_m = \sigma_y = \sigma^*$. This section discusses the results for a Cobb-Douglas production function (i.e. $\sigma_m = \sigma_y = 1$), while section 4 examines the more general case in which σ^* is allowed to differ from unity.

Effects on growth and environment

The reduced-form equations for the growth rate, pollution and the tax rate on output are given by:

$$\tilde{\pi} = -\frac{r}{r-\theta} \frac{1}{\Delta} (\alpha\gamma - \epsilon\eta) \tilde{t}_p \quad (3.1)$$

$$\tilde{P} = -\tilde{t}_p - \frac{1}{\Delta} (\alpha\gamma - \epsilon\eta) \tilde{t}_p \quad (3.2)$$

$$\tilde{T}_y = \frac{s_s}{\Delta} (\alpha\gamma - \epsilon\eta) \tilde{t}_p \quad (3.3)$$

where $\Delta = rs_k + s_w - (\alpha\gamma - \epsilon\eta) > 0$.⁹

Expression (3.2) reveals that a pollution tax exerts two effects on pollution. First, pollution decreases proportionally due to input substitution (i.e. the first term at the RHS of (3.2)). Hence, the *composition* of economic activity becomes cleaner. Second, changes in the growth rate affect pollution (see (3.1) and (3.2)). On account of this growth effect, the *level* of economic activity changes. Whether a higher pollution tax raises or reduces the growth rate depends on the difference between, on the one hand, the production elasticity of pollution, $\alpha\gamma$, and, on the other hand, the environmental externality in production, η , multiplied by the elasticity that measures the effect of pollution on environmental quality, ϵ . In particular, if $\alpha\gamma - \epsilon\eta = 0$, a higher pollution tax yields no aggregate productivity effect because the negative effect of lower pollution on the before-tax return to capital ($\alpha\gamma$) is exactly offset by the positive effect on that return of a better environmental quality ($\epsilon\eta$). In this case, the endogenous tax rate on output, T_y , remains unaffected (see (3.3)). The reason is that the higher pollution tax does not yield any additional public revenues: the slope of the Laffer curve is zero. Since both the before-tax return and the output tax are unaffected, the after-tax return to capital, and hence growth (see (3.1)), also remain unchanged. If $\alpha\gamma - \epsilon\eta > 0$, higher pollution taxes reduce the growth rate because the adverse input effect of lower pollution dominates the favorable externality effect, thereby reducing the before-tax return to capital. In this case, the Laffer curve for pollution taxes is downward sloping. Consequently, the government requires a higher tax rate on output in order to meet its revenue constraint. If $\alpha\gamma - \epsilon\eta < 0$, higher pollution taxes raise the before- and after-tax returns to capital and thus

⁹ The determinant, Δ , can be interpreted as the fraction of national income that flows to households. The first term indicates net income from the privately owned capital stock and firm profits. The second term amounts to the net benefits from a lower level of pollution.

stimulate economic growth, thereby allowing for a reduction in the tax rate on output. This result suggests that employing pollution taxes may yield a double-dividend if the environmental externality is large. In that case, higher pollution taxes not only improve the quality of the environment, but also raise tax revenues and boost economic growth. Previous analysis of the double-dividend issue (see e.g. Bovenberg and De Mooij (1994ab) and Bovenberg and Van der Ploeg (1994ab)) have abstracted from production externalities (i.e. $\epsilon\eta = 0$). In that case, a higher pollution tax always implies a net burden on the production sector and thus does not yield a double-dividend as $\alpha\gamma > 0$.

Welfare effects

Armed with the economic and ecological effects, we now turn to the effects on welfare, defined by the marginal excess burden in (2.2). The welfare effects of pollution taxes depend on the effects on only pollution and growth (see (2.2) with $T_a = T_y$ and $\delta = s_s$). By substituting the reduced-form equations for growth and pollution, (3.1) and (3.2), into (2.2), we derive the following solution for the marginal excess burden:

$$\begin{aligned} \tilde{\lambda} = & -\epsilon\phi\tilde{t}_p + \left[\frac{rs_k + s_w}{s_c} - \epsilon\phi \right] \frac{\alpha\gamma - \epsilon\eta}{\Delta} \tilde{t}_p \\ & + \frac{\pi}{r - \pi} \frac{r}{r - \theta} \frac{T_y\beta}{s_c} \frac{\alpha\gamma - \epsilon\eta}{\Delta} \tilde{t}_p \end{aligned} \quad (3.4)$$

The effect of higher pollution taxes on welfare depends on the difference between, on the one hand, the direct amenity effect of lower pollution as indicated by the first term at the RHS of (3.4) and, on the other hand, the social value of the change in the after-tax return to capital. In particular, the second term at the RHS of (3.4) reveals that, on the one hand, a higher after-tax return to capital raises household income from capital and profits (first term between square brackets). On the other hand, a higher after-tax return implies more production and, therefore, more pollution. This harms welfare through the environmental amenity effect (second term between square brackets). The third term at the RHS of (3.4) reveals that a higher after-tax return to capital impacts welfare by raising the growth rate (see (3.1)). This effect depends on the wedge between the marginal social costs and marginal benefits of capital accumulation, implied by the distortionary tax on output.

Overall, relation (3.4) reveals that if a lower pollution level raises the after-tax return to capital (i.e. $\alpha\gamma - \epsilon\eta < 0$), higher taxes on pollution always improve welfare by yielding a double-dividend: they enhance both environmental amenities and productivity and, therefore, growth. If, however, the production externality ($\epsilon\eta$) is smaller than the production elasticity ($\alpha\gamma$), higher pollution taxes reduce the after-tax return to capital. In that case, a trade-off exists between lower economic growth and higher environmental amenities.

Optimal pollution taxes

The pollution tax is set at its optimal level if a marginal change in its rate leaves welfare unaffected, i.e. if the marginal excess burden is zero. In a first-best world where the government has access to lump-sum taxes, the optimal pollution tax is at the Pigovian level, which fully internalizes the environmental externalities in production and consumption (see (2.2) with $T_y = T_a = 0$ and $\delta = s_s$):

$$\epsilon \phi - \frac{\alpha \gamma - \epsilon \eta}{s_c} = 0 \quad (3.5)$$

However, our model is not first-best. In particular, the government does not have access to lump-sum taxation to finance its public goods. To investigate whether, in this second-best world, the government still finds it optimal to set the environmental tax at its Pigovian level, we substitute (3.5) into (2.2) and arrive at:

$$\tilde{\lambda} = - \frac{T_y \beta}{s_c} \frac{\pi}{r - \pi} \tilde{\pi} \quad (3.6)$$

Hence, if $T_y > 0$, raising the pollution tax above its Pigovian level harms welfare if it reduces the growth rate. Indeed, at the Pigovian tax the production elasticity of pollution exceeds the environmental externality in production if environmental amenities are positive (i.e. $\frac{\alpha \gamma - \epsilon \eta}{s_c} = \epsilon \phi > 0$, see (3.5)). Hence, a higher pollution tax reduces the growth rate (see (3.1)). Intuitively, by internalizing the consumption externality of pollution, environmental taxes reduce the productivity of capital and, therefore, harm growth. This drop in growth produces a first-order loss in welfare, as capital accumulation features a gap between its marginal social costs and marginal benefits.

These results demonstrate that pollution taxes aimed at internalizing environmental externalities may, as a side effect, exacerbate pre-existing distortions in the economy.¹⁰ Indeed, in a second-best world, the optimal tax on pollution differs from its first-best level. In particular, the optimal pollution tax lies below the Pigovian level. Bovenberg and De Mooij (1994a) reach similar conclusions when exploring the interaction between environmental and labor-market distortions. They argue that the optimal pollution tax lies below its Pigovian level because pollution taxes exacerbate the distortion in the labor-market.

4 Tax-Shifting

Section 3 assumed a Cobb-Douglas production function. In that particular case, substitution from pollution towards physical capital is relatively easy. Hence, a pollution tax is a rather effective instrument to cut pollution through input substitution. However, the large drop in pollution implies that the base of the pollution tax erodes substantially. Hence, the pollution tax fails to raise revenues so that the distortionary tax on output can hardly be reduced. Indeed, if the growth rate declines, the tax rate on output needs to be even increased (see (3.3)). This section allows the substitution elasticities σ_y and σ_m to be smaller than unity. Accordingly, pollution taxes imply less factor substitution and thus are more effective as a revenue-raising device. Moreover, compared to capital, abatement is a better substitute for pollution. This does better justice to the term 'abatement.' We restrict our analysis to the case that $\sigma_m = \sigma_y = \sigma^*$.

Effects on growth and pollution

The reduced-form equation for pollution amounts to (see appendix C):

¹⁰ If the government sets abatement subsidies or public investment at non-optimal levels, a change in the growth rate may also affect welfare through its impact on these distortions (see (2.2) with $T_a \neq T_y$ or $\delta \neq s_c$).

$$\tilde{P} = - \left[1 - \frac{(1 - \sigma^*)(1 - T_y)(1 - \gamma) \alpha}{\Delta^*} \right] \tilde{t}_p - \frac{\sigma^*(\alpha \gamma - \epsilon \eta)}{\Delta^*} \tilde{t}_p \quad (4.1)$$

where $\Delta^* \equiv \sigma^* [rs_k + s_w - (\alpha \gamma - \epsilon \eta)] + (1 - \sigma^*)(1 - T_y)(1 - \gamma)(1 + \alpha) > 0$

If σ^* equals unity, (4.1) is identical to (3.2). If substitution between the intermediate factors M and N becomes more difficult, pollution taxes are less effective in cutting pollution, as they induce less substitution from pollution towards capital. Nevertheless, relation (4.1) reveals that pollution taxes always reduce pollution, even if σ^* approaches zero.¹¹

The reduced-form for the tax rate on output is given by:

$$\tilde{T}_y = \frac{s_s}{\Delta^*} (\alpha \gamma - \epsilon \eta) \tilde{t}_p - \frac{(1 - \sigma^*)(1 - T_y)(\alpha - \epsilon \eta) \alpha \gamma}{\Delta^*} \tilde{t}_p \quad (4.2)$$

This relationship reveals that if substitution between pollution and capital becomes more difficult (i.e. σ^* becomes smaller), pollution taxes are more efficient as a revenue-raising device. Indeed, even if pollution taxes involve a negative effect on gross productivity (i.e. $\alpha \gamma - \epsilon \eta > 0$), they may nevertheless raise a positive amount of public revenues (which are used to cut the tax rate on output).

The growth rate is given by:

$$\frac{1}{\sigma} s_i \tilde{\pi} = (\alpha \gamma - \epsilon \eta) \tilde{P} - s_w \tilde{w} \quad (4.3)$$

This expression reveals that the growth performance is affected by two factors, namely, first, the net costs of environmental policy borne by the production sector (i.e. the first term at the RHS of (4.3)), and, second, the part of the costs borne by profits (i.e. the second term at the RHS of (4.3)). As explained in section 3, a tighter environmental policy generates an adverse impact on growth if a lower pollution level implies a net burden on the production sector. This is the case if $\alpha \gamma - \epsilon \eta > 0$, i.e. if the negative output effect of a reduction in pollution as a private rival input exceeds the positive effects associated with less adverse production externalities. The second term at the RHS of (4.3) indicates the effect of shifting the tax burden away from the after-tax return towards profits.¹² In particular, lower profits produce a higher growth rate. Intuitively, taxing away a larger share of profit income creates room to cut the distortionary tax rate on output (see (4.2)), thereby raising the return on capital accumulation.

The reduced-form equation for profits is given by:

$$s_w \tilde{w} = - \frac{s_w}{\Delta^*} (\alpha \gamma - \epsilon \eta) \tilde{t}_p - \frac{(1 - \sigma^*)(1 - T_y) [\alpha \gamma - \epsilon \eta + rs_k \alpha]}{\Delta^*} \alpha \gamma \tilde{t}_p \quad (4.4)$$

The first term at the RHS of (4.4) represents the effect of input substitution. It reveals that, through this channel, profits share in the burden of environmental policy on the production sector. In particular, pollution taxes harm profits if the adverse pollution externalities on production are small compared to the input share of pollution as a rival input (i.e. $\alpha \gamma - \epsilon \eta > 0$). The second term

¹¹ If $\sigma^* = 0$, the coefficient in (4.1) can be rewritten as $-(1 - T_y)(1 - \gamma)/\Delta^* < 0$.

¹² Profits can be maintained in equilibrium due to the presence of a fixed factor in production, which constitutes a barrier for new firms to enter the market.

at the RHS of (4.4) shows the effect of shifting the tax burden away from the after-tax return on investment towards profits. If $\sigma^* < 1$, the tax-shifting effect causes the replacement of output taxes by pollution taxes to raise the return on investment by reducing profits, thereby boosting growth. The overall effect on growth is positive if the aggregate burden of environmental policy on the production sector is small (i.e. $(\alpha\gamma - \epsilon\eta)\tilde{P}$ is small) and a large share of this burden can be shifted unto profits (i.e. \tilde{w} is large and negative). By substituting (4.1) and (4.4) into (4.3), we derive the following condition for pollution taxes to boost the growth rate:

$$\frac{\alpha\gamma - \epsilon\eta}{\alpha} < (1 - \sigma^*)T_p^* \quad (4.5)$$

The left-hand side (LHS) of (4.5) represents the net burden of less pollution on the production sector. In particular, if $\alpha\gamma - \epsilon\eta > 0$, a decline in pollution hurts the production sector. The parameter α determines how effective pollution taxes are in cutting pollution. In particular, if α is large, pollution is an important factor of production relative to abatement (i.e. $\alpha\gamma$ is large relative to γ). In that case, substantially lowering pollution is not attractive for firms, as the marginal product of pollution is highly sensitive to the flow of pollution.¹³

The RHS of (4.5) shows the benefits of pollution taxes in terms of shifting the tax burden away from the return on investment towards profits. If $\sigma^* = 1$, the pollution tax and output tax imply the same relative burden on profits and the return on capital accumulation. Hence, an ecological tax reform does not imply a shift toward non-distortionary lump-sum taxation of profits. Accordingly, the tax-shifting effect exerts no positive effect on growth. If $\sigma^* < 1$, however, compared to the output tax, the pollution tax is more effective in raising revenues without depressing the return to investment. The reason is that the tax on pollution is a more effective instrument to tax away profits (and the quasi-rents from pollution, in particular). Thus, compared to an output tax, a pollution tax incorporates a more important lump-sum element. Accordingly, by using the revenues from the pollution tax to cut the distortionary tax on output (see (4.2)), the government shifts the tax burden away from the return on investment towards profits, thereby boosting growth.

On balance, an environmental tax reform produces a double-dividend by improving the environment and stimulating growth if the positive effect of tax-shifting (which allows for a reduction in the wedge between the before- and after-tax return to capital) dominates the negative effect of input substitution on gross productivity associated with more public consumption in the form of more environmental amenities. Also Bovenberg and Van der Ploeg (1994b) find that, if an environmental tax reform shifts the burden of taxation from labor towards the rents from a fixed factor in production, it may boost employment. Similarly, Bovenberg and De Mooij (1994b) demonstrate that environmental taxes can yield a double-dividend, by expanding employment and improving the environment, if the burden of the public sector is shifted from workers towards transfer recipients.

Welfare effects

In section 3 we found that, in the Cobb-Douglas case, the optimal pollution tax is always below the Pigovian tax in the presence of environmental amenities. The reason is that lowering the pollution tax from the Pigovian level always boosts growth and, therefore, enhances welfare. If substitution is more difficult, the welfare effects of raising pollution taxes from its Pigovian level continues to be represented by (3.6). Hence, if pollution taxes succeed in raising growth, they

¹³ In the extreme case that α goes to infinity, pollution is not affected by a rise in the pollution tax. Hence, the costs of pollution taxes, represented by the LHS of (4.5), are zero.

improve welfare. Contrary to the Cobb-Douglas case, pollution taxes may indeed raise the growth rate if $\sigma^* < 1$, even if environmental amenities cause the production elasticity to exceed the production externality (i.e. $\alpha\gamma - \epsilon\eta = \epsilon\phi s_c > 0$). This is because raising pollution taxes may improve the efficiency of taxation by shifting the tax burden from the return on investment towards profits. In particular, the smaller environmental amenities are (i.e. ϕ is smaller), the more likely it will be that a rise in pollution taxes from the Pigovian level stimulates growth and thus improves welfare. Intuitively, in that case additional environmental amenities are small (i.e. pollution does not fall much if σ^* is small) and cheap (i.e. ϕ small). At the same time, the pollution tax acts as an implicit lump-sum tax on profits. Consequently, the optimal tax on pollution exceeds its Pigovian level.

5 Pollution Permits

This section explores the consequences for growth if the government adopts environmental policy instruments that do not charge a price for pollution. In particular, we assume that the government exogenously determines the economy-wide level of pollution, P , by freely providing pollution permits to existing firms.

Appendix D solves the model if the level of pollution (i.e. the number of pollution permits) is exogenous. It reveals that expression (4.3) for the growth rate continues to hold. Hence, a tighter environmental policy (i.e. $\tilde{P} < 0$) reduces the growth rate by depressing the after-tax return to investment if two conditions are met. First, environmental policy should impose a net burden on the production sector (i.e. $\alpha\gamma - \epsilon\eta > 0$). Second, this burden cannot be shifted to profits. With freely issued pollution permits, the reduced-form for profits is given by:

$$s_w \tilde{w} = \frac{\delta}{\beta + \delta} (\alpha\gamma - \epsilon\eta) \tilde{P} \quad (5.1)$$

Expression (5.1) reveals that a reduction of the number of pollution permits (i.e. $\tilde{P} < 0$) reduces profits if and only if environmental policy imposes a net burden on the production sector (i.e. $\alpha\gamma - \epsilon\eta > 0$). This condition differs from the corresponding condition for the case of pollution taxes (i.e. expression (4.4)) if the substitution elasticity, σ^* , differs from unity. In particular, pollution taxes are more likely to reduce profits than freely issued pollution permits if $\sigma^* < 1$. Intuitively, if firms can not easily replace pollution by other inputs, a large share of the burden of pollution taxes is borne by profits. Hence, pollution taxes succeed in shifting the tax burden away from the after-tax return to investment towards profits.

The reduced-form equation for the growth rate is found by substituting (5.1) into (4.3):

$$\tilde{\pi} = \frac{r}{r - \theta} \frac{\alpha\gamma - \epsilon\eta}{(1 - T_y)(1 - \gamma)} \tilde{P} \quad (5.2)$$

Expression (5.2) shows that a double-dividend (i.e. not only a lower level of pollution but also a higher rate of growth) occurs only if a tighter environmental policy confers a net benefit to the production sector, i.e. if the fall in gross productivity on account of less pollution as a rival input into production ($\alpha\gamma$) is dominated by the boost in the gross productivity of capital on account of less adverse production externalities ($\epsilon\eta$). This condition generally differs from the corresponding condition (4.5) for the case in which the government adopts pollution taxes rather than freely issued pollution permits to cut pollution. The reason is that, in contrast to freely issued pollution permits, pollution taxes may shift the tax burden between profits and the after-tax return on investment.

This difference between the growth performance of alternative instruments of environmental policy reveals that the distribution of property rights of the environment may affect not only the distribution of income but also growth. In particular, if the government owns the property rights of the environment, it can adopt instruments that raise public revenues from the sale of the publicly owned environment, e.g. environmental taxes or auctioned pollution permits. However, if the property rights are assigned to polluters, environmental policy instruments should be adopted that do not raise public revenues, such as pollution standards or freely distributed pollution permits.

The ease with which other inputs can substitute for pollution determines whether environmental policy instruments that change the price for pollution are more likely to enhance growth than those instruments that do not. In particular, comparison of (4.5) and (5.2) reveals that, compared to freely issued pollution permits, pollution taxes are more likely to enhance growth if $\sigma^* < 1$. Intuitively, if substitution possibilities are limited, pollution constitutes a relatively inelastic tax base. Hence, pollution taxes are an attractive instrument to raise revenues because profits, rather than the after-tax return to capital accumulation, bear a large part of the burden of these taxes.

If pollution can be easily replaced by other inputs (i.e. $\sigma^* > 1$), in contrast, freely issued pollution permits are more likely to improve growth than are pollution taxes. The reason is that, with easy substitution, the base of the pollution tax is relatively elastic. Accordingly, the pollution tax is a relatively inefficient device to raise revenues. In particular, the burden of the pollution tax is reflected mainly in a lower after-tax return to investment rather than in a lower profit level. Thus, the revenues generated by the pollution tax are relatively expensive in terms of a lower after-tax return on investment. Indeed, for any given amount of revenues and given the environmental objective, the pollution tax hurts the after-tax return to capital more than the output tax because the pollution tax is less effective in taxing away profits.

The optimal level of pollution permits is found by substituting (5.2) into (2.2) and use $\tilde{\lambda} = 0$:

$$\left[1 + \frac{r}{r - \theta} \frac{\pi}{r - \pi} \frac{T_y}{1 - T_y} \frac{\beta}{\beta + \delta} \right] \frac{\alpha \gamma - \epsilon \eta}{s_c} - \epsilon \phi = 0 \quad (5.3)$$

At the optimal level of pollution permits, the environmental benefits of a marginal reduction in pollution exceed private abatement costs if the environment yields positive environmental amenities (i.e. $\frac{\alpha \gamma - \epsilon \eta}{s_c} - \epsilon \phi < 0$). Intuitively, in this second-best world,

increasing the environmental distortion (by raising pollution above the level where environmental benefits equal abatement costs) reduces the distortion arising from distortionary taxation ($T_y > 0$). In particular, distortionary taxation implies that growth is 'too low': an increase in growth yields a first-order improvement in welfare. If environmental damages of increased pollution equal private costs of pollution abatement, the change in environmental quality yields only second-order welfare effects. However, an increase in pollution boosts growth (if environmental amenities cause the private costs of pollution abatement to exceed the positive productivity effects of less pollution). Accordingly, a marginal increase in pollution above the level where marginal environmental costs equal the marginal reduction in abatement costs boosts welfare: it yields a first-order gain as a result of the growth wedge but only a second-order loss as a result of the environmental wedge.

6 Conclusions

This paper has explored the consequences of an environmental tax reform for economic growth, pollution and welfare in a second-best framework in which the government has to employ distortionary taxes to finance public spending. Our analysis uncovered two channels through which

an environmental tax reform may yield a double-dividend, i.e. not only improve environmental quality but also stimulate economic growth. The first channel, discussed in section 3, is a positive environmental externality on production associated with the role of the environment as a public production factor. Previous analyses of the double-dividend issue modelled the environment as a public consumption good, rather than as a public production factor. In that case, environmental policy always implied a net burden on the production sector of the economy, as the benefits accrued only to the household sector. Accordingly, these analyses have ignored this channel through which a double-dividend can occur (see, e.g., Bovenberg and De Mooij (1994ab) and Bovenberg and van der Ploeg (1994ab)). However, the role of the environment as a public production factor does not overturn the result derived by Bovenberg and de Mooij (1994a) that the optimal pollution tax is lower than the Pigovian tax. As long as the environment produces some environmental amenities as a public consumption good, the Pigovian tax exceeds the optimal pollution tax, which internalizes the adverse pollution externalities on consumption. Intuitively, at the optimal tax level, the pollution tax reduces growth, thereby worsening distortions due to the absence of lump-sum taxation.

The second channel through which an environmental tax reform may boost growth is a shift in the tax burden away from the return on capital accumulation towards profits. In particular, section 4 showed that a pollution tax may improve the efficiency of the tax system as a revenue-raising device by taxing away the quasi-rents from pollution. This second channel operates only if substitution between pollution and other inputs is difficult so that the base of the pollution tax is inelastic.

The role of the environmental tax as a lump-sum tax on rents suggests the importance of how environmental policy assigns property rights to the environment. If the property rights are assigned to polluters, the quasi-rents from pollution accrue to the owners of the firms rather than to the government. Accordingly, a double-dividend cannot occur if the environmental externality in production is relatively small so that a decline in pollution imposes a net cost on the production sector. If the government owns the environment, in contrast, it can use the revenues from the sale of this public resource (i.e. the revenues from pollution taxes or the auctioning off of pollution permits) to cut distortionary taxes. In this case, a tighter environmental policy implies a capital loss for profit earners if substitution away from pollution is difficult. Hence, part of the burden of environmental policy on the production sector is borne by profits rather than the after-tax return to investment. If the tax-shifting away from the after-tax return towards profits is large enough, an ecological tax reform may enhance growth, even if environmental policy implies a net burden on the production sector. Similar results were derived by Bovenberg and de Mooij (1994b) and Bovenberg and van der Ploeg (1994b) in a static framework. Bovenberg and de Mooij showed that an environmental tax reform may boost employment if environmental taxes are allowed to erode the real value of income transfers. Similarly, Bovenberg and van der Ploeg demonstrated that employment may expand if environmental taxes act as an implicit way to tax away profits due to the presence of a fixed factor in production.

This paper shows, however, that a pollution tax, compared to other environmental policy instruments that do not charge a price for pollution, is not always a more efficient instrument to cut pollution. In particular, if substitution between pollution and other inputs is easy, freely issued pollution permits rather than pollution taxes best protect the after-tax return to investment. Intuitively, with easy substitution, the pollution tax is a relatively inefficient device to raise revenues. In particular, the revenues generated by environmental policy instruments damage the after-tax return more and profits less than would revenues generated by the output tax.

In a second-best world with both environmental distortions and tax distortions, the optimal environmental tax typically differs from the Pigovian level. In particular, we demonstrated that the optimal environmental tax may exceed its Pigovian level if the government has no access to more direct ways to tax rents. Intuitively, in the absence of an explicit lump-sum tax on profits, the pollution tax acts an implicit way to tax rents. The conditions for the optimal environmental tax to

exceed the Pigovian level are twofold. First, environmental amenities are unimportant so that a cut in pollution is relatively cheap in terms of losses in the productivity of capital. Second, the pollution tax should be rather ineffective in cutting pollution. Under these two conditions, the shifting of the burden of public spending and environmental amenities to the owners of the firm offsets the costs of additional environmental amenities, thereby alleviating the net burden on investors. Hence, the after-tax return on investment, and with it growth, rise.

References

Bovenberg, A.L. and R.A. de Mooij, 1994a, 'Environmental levies and distortionary taxation,' *American Economic Review*, vol. 94, no.4, pp. 1085-89.

Bovenberg, A.L. and R.A. de Mooij, 1994b, 'Environmental policy in a small open economy with distortionary labor taxes: a general equilibrium analysis,' in Ierland, E.C. van (ed.), *International Environmental Economics*, Elsevier, Amsterdam.

Bovenberg, A.L. and F. van der Ploeg, 1994a, 'Environmental policy, public finance and the labour market in a second-best world,' *Journal of Public Economics*, 55, 349-90.

Bovenberg, A.L. and F. van der Ploeg, 1994b, 'Consequences of environmental tax reform for involuntary unemployment and welfare,' CentER Discussion Paper 9408, Tilburg University.

Bovenberg, A.L. and S. Smulders, 1995, 'Environmental quality and pollution-saving technological change in a two-sector endogenous growth model,' *Journal of Public Economics* (forthcoming).

Butter, F.A. den, and M.W. Hofkes, 1993, 'Sustainable development with extractive and non-extractive use of the environment in production,' Discussion Paper 93-194, Tinbergen Institute.

Goulder, L.H., 1995, 'Effects of carbon taxes in an economy with prior tax distortions: An intertemporal general equilibrium analysis,' *Journal of Environmental Economics and Management* (forthcoming).

Gradus, R. and S. Smulders, 1993, 'Pollution abatement and long-term growth,' CentER Discussion Paper no. 9373, Tilburg University.

Ligthart, J.E. and F. van der Ploeg, 1994, 'Environmental quality, public finance and sustainable growth,' in Carraro, C. and J. Filer (eds.), *Control and game theoretic models of the environment*, Birkhauser.

Marrewijk, C. van, F. van der Ploeg and J. Verbeek, 1993, 'Is growth bad for the environment: pollution, abatement and endogenous growth,' Policy Research Working Paper 1151, World Bank, Washington DC.

Oates, W.E., 1994, 'Green taxes: Can we protect the environment and improve the tax system at the same time?,' *Southern Economic Journal* (forthcoming).

Parry, I.H., 1994, 'Pollution taxes and revenue recycling,' mimeo, US department of Agriculture, Washington DC.

Proost, S. and D. van Regemorter, 'Tax reform policies in the presence of a supranational environmental tax: the role of the macro-economic regime and international coordination,' paper presented at the 50th IIPF congress, Harvard, Cambridge MA, August 1994.

Sørensen, P.B., L.H. Pedersen and S.B. Nielsen, 1994, 'Taxation, pollution, unemployment and growth: could there be a "triple dividend" from a green tax reform?,' paper presented at the 50th IIPF congress, Harvard, Cambridge MA, August 1994.

Rebelo, S., 1991, 'Long-run policy analysis and long-run growth', *Journal of Political Economy*, 99, pp. 500-521.

Schöb, R., 1994, 'Evaluating tax reforms in the presence of externalities,' paper presented at the 50th IIPF congress, Harvard, Cambridge MA, August 1994.

Appendix A: Linearizing the factor demand equations

We log-linearize the model around an initial equilibrium. A tilde (\sim) above a variable denotes a relative change, unless indicated otherwise.

Specification of F

$F = f(M,N)$ is homogenous of degree 1 in M and N . Hence, $F/M = f(1,N/M) \rightarrow \phi = \phi(z)$ where $\phi = F/M$ and $z = N/M$. The first-order derivatives of F are:

$$\frac{\partial F}{\partial N} = \phi' \quad (A1)$$

$$\frac{\partial F}{\partial M} = \phi - z\phi' \quad (A2)$$

The substitution elasticity between M and N is defined as:

$$\frac{1}{\sigma_y} = - \frac{\partial \left(\frac{\partial F / \partial N}{\partial F / \partial M} \right) \frac{N}{M}}{\frac{\partial \frac{N}{M}}{\frac{\partial F / \partial N}{\partial F / \partial M}}} = \frac{-z\phi''}{\phi'} \frac{\phi}{\phi - z\phi'} \quad (A3)$$

Specification of M

$M = m(K,S)$ is homogenous of degree 1 in K and S . Hence, $M/K = m(1, S/K) \rightarrow \mu = \mu(s)$ where $\mu = M/K$ and $s = S/K$. The first order derivatives of M are:

$$\frac{\partial M}{\partial S} = \mu' \quad (A4)$$

$$\frac{\partial M}{\partial K} = \mu - s\mu' \quad (A5)$$

The substitution elasticity between K and S is defined as:

$$\frac{1}{\sigma_m} = - \frac{\partial \left(\frac{\partial M / \partial S}{\partial M / \partial K} \right) \frac{S}{K}}{\frac{\partial \frac{S}{K}}{\frac{\partial M / \partial S}{\partial M / \partial K}}} = \frac{-s\mu''}{\mu'} \frac{\mu}{\mu - s\mu'} \quad (A6)$$

From the definitions of the production elasticities, the Cobb-Douglas specification of N and (A4) and (A5), we derive:

$$\gamma = \frac{\partial Y}{\partial A} \frac{A}{Y} = \left[\frac{\partial F}{\partial N} \frac{N}{F} \right] \left[\frac{\partial N}{\partial A} \frac{A}{N} \right] = \frac{\partial F}{\partial N} \frac{N}{F} * 1 \quad (\text{A7})$$

$$\beta + \delta = \frac{\partial Y}{\partial K} \frac{K}{Y} + \frac{\partial Y}{\partial S} \frac{S}{Y} = \frac{\partial F}{\partial M} \frac{M}{F} \left[\frac{\partial M}{\partial K} \frac{K}{M} + \frac{\partial M}{\partial S} \frac{S}{M} \right] = \frac{\partial F}{\partial M} \frac{M}{F} * 1 \quad (\text{A8})$$

Homogeneity of F and M and using (A7) and (A8) implies:

$$\tilde{F} = \gamma \tilde{N} + (\delta + \beta) \tilde{M} = \tilde{N} + (\delta + \beta) [\tilde{M} - \tilde{N}] \quad (\text{A9})$$

$$\tilde{M} = \frac{\beta}{\beta + \delta} \tilde{K} + \frac{\delta}{\beta + \delta} \tilde{S} \quad (\text{A10})$$

where we have used (2.1).

Specification of N and Y

The Cobb Douglas specification for N implies for the relative change in N:

$$\tilde{N} = \tilde{A} + \alpha \tilde{P} \quad (\text{A11})$$

Moreover, the externality of pollution specified in (I.1) implies for the relative change in Y:

$$\tilde{Y} = \tilde{F} + \eta \tilde{E} \quad (\text{A12})$$

Linearizing marginal factor productivity

Armed with this set of definitions and relations, we are able to log-linearize the factor demand equations (I.6), (I.7) and (I.8) for abatement, pollution and capital, respectively. The relative change in the marginal product of abatement is derived by using (A1), (A3) and the Cobb Douglas specification of N in the production function (I.1):

$$\begin{aligned} \frac{\Delta \partial Y / \partial A}{\partial Y / \partial A} &= \frac{\Delta \partial F / \partial N}{\partial F / \partial N} + \eta \tilde{E} + \frac{\Delta \partial N / \partial A}{\partial N / \partial A} = \\ &= - \frac{1}{\sigma_y} (\beta + \delta) [\tilde{N} - \tilde{M}] + \alpha \tilde{P} + \eta \tilde{E} \end{aligned} \quad (\text{A13})$$

The linearized marginal product of pollution is found by using the same relations as for abatement:

$$\begin{aligned} \frac{\Delta[\partial F/\partial P]j(E)}{\partial Y/\partial P} &= \frac{\Delta\partial F/\partial N}{\partial F/\partial N} + \eta \tilde{E} + \frac{\Delta\partial N/\partial P}{\partial N/\partial P} = \\ &- \frac{1}{\sigma_y} (\beta + \delta) [\tilde{N} - \tilde{M}] + \tilde{A} - (1 - \alpha) \tilde{P} + \eta \tilde{E} \end{aligned} \quad (\text{A14})$$

To derive an expression for the relative change in the marginal product of capital, we use (A2), (A3), (A5), (A6) and the specification of the production function (I.1):

$$\begin{aligned} \frac{\Delta\partial Y/\partial K}{\partial Y/\partial K} &= \frac{\Delta\partial F/\partial M}{\partial F/\partial M} + \eta \tilde{E} + \frac{\Delta\partial M/\partial K}{\partial M/\partial K} = \\ &\frac{1}{\sigma_y} \gamma [\tilde{N} - \tilde{M}] + \frac{1}{\sigma_m} \frac{\delta}{\beta + \delta} [\tilde{S} - \tilde{K}] + \eta \tilde{E} \end{aligned} \quad (\text{A15})$$

Linearizing factor demand equations

Using (A13), we linearize the demand for abatement (I.6) as:

$$\frac{1}{\sigma_y} (\beta + \delta) [\tilde{N} - \tilde{M}] - \alpha \tilde{P} - \eta \tilde{E} = \tilde{T}_a - \tilde{T}_y \quad (\text{A16})$$

From (A14), we arrive at the following linearized demand for pollution (I.7):

$$-\frac{1}{\sigma_y} (\beta + \delta) [\tilde{N} - \tilde{M}] + \tilde{A} - (1 - \alpha) \tilde{P} + \eta \tilde{E} = \tilde{T}_p + \tilde{T}_y \quad (\text{A17})$$

By adding (A16) and (A17), we find the following relation between abatement and pollution:

$$\tilde{A} = \tilde{P} + \tilde{T}_p + \tilde{T}_a \quad (\text{A18})$$

Combining (A10) and (A18), we derive for abatement and pollution:

$$\tilde{A} = \frac{1}{1 + \alpha} \tilde{N} + \frac{\alpha}{1 + \alpha} [\tilde{T}_p + \tilde{T}_a] \quad (\text{A19})$$

$$\tilde{P} = \frac{1}{1 + \alpha} \tilde{N} - \frac{1}{1 + \alpha} [\tilde{T}_p + \tilde{T}_a] \quad (\text{A20})$$

Finally, (A15) and (I.8) yield for the desired demand for capital:

$$\frac{1}{\sigma_y} \gamma [\tilde{N} - \tilde{M}] + \frac{1}{\sigma_m} \frac{\delta}{\beta + \delta} [\tilde{S} - \tilde{K}] + \eta \tilde{E} = \tilde{r} + \tilde{T}_y \quad (\text{A21})$$

Now we are able to derive the factor-demand equations as presented in table II. First, the rate of return to capital (II.4) is found by substituting (A9), (A10) and (A12) into (A21) to eliminate \tilde{N} , \tilde{M} and \tilde{F} , respectively. Second, relation (II.2) for pollution is found by substituting (A10) and

(A11) into (A16) to eliminate \tilde{N} and \tilde{M} , and then using (II.4) to eliminate \tilde{Y} . Finally, (II.3) is equivalent with (A18).

Appendix B: Welfare Effects

This appendix derives the marginal excess burden as a measure for changes in social welfare. It represents the welfare changes due to various policy measures in terms of consumption.

Utility is defined in (I.9). On the sustainable balanced-growth path private consumption grows at a constant rate, π , while pollution remains constant. Hence, we can rewrite utility as:

$$U = \frac{[C_0 E^\phi]^{1-\frac{1}{\sigma}}}{1-\frac{1}{\sigma}} \int_0^{\infty} e^{[\pi(1-\frac{1}{\sigma})-\theta]t} dt \quad (B1)$$

where C_0 is the initial consumption level. To solve the integral at the RHS of (B1), we require that $\pi(1 - 1/\sigma) - \theta < 0$ so that that utility is bounded. Using (I.11) from table I, we rewrite this condition as follows:

$$\theta - \pi(1 - \frac{1}{\sigma}) = r - \pi > 0 \quad (B2)$$

Solving the integral in (B1) yields the following expression for utility:

$$U = \frac{[C_0 E^\phi]^{1-\frac{1}{\sigma}}}{(1 - \frac{1}{\sigma})(\theta - \pi(1 - \frac{1}{\sigma}))} \quad (B3)$$

For utility to remain constant after a policy shock, we need:

$$0 = dU = \frac{\partial U}{\partial C} dC + \frac{\partial U}{\partial E} dE + \frac{\partial U}{\partial \pi} d\pi \quad (B4)$$

The derivatives at the right-hand side of (B4) can be derived by differentiating (B3) with respect to the respective arguments. This yields:

$$\frac{\partial U}{\partial C} dC = \frac{[C_0 E^\phi]^{1-\frac{1}{\sigma}}}{r - \pi} \tilde{C} \quad (B5)$$

$$\frac{\partial U}{\partial E} dE = \frac{[C_0 E^\phi]^{1-\frac{1}{\sigma}}}{r-\pi} \phi \tilde{E} \quad (\text{B6})$$

$$\frac{\partial U}{\partial \pi} d\pi = \frac{[C_0 E^\phi]^{1-\frac{1}{\sigma}}}{r-\pi} \frac{\pi}{r-\pi} \tilde{\pi} \quad (\text{B7})$$

Substituting (B5), (B6) and (B7) into (B4), we arrive at the following expression for the change in welfare:

$$\tilde{\lambda} + \tilde{C} + \phi \tilde{E} + \frac{\pi}{r-\pi} \tilde{\pi} = 0 \quad (\text{B8})$$

where $\tilde{\lambda} = \frac{d\lambda}{C}$ is the additional consumption that needs to be provided to the household in order to keep utility, after the policy shock, at its initial level. It is denoted as the marginal excess burden.

To arrive at an alternative formulation for the marginal excess burden in (B8), we substitute (II.1) into (II.12) to eliminate consumption. Thus, we find

$$\tilde{\lambda} = -\phi \tilde{E} - \frac{\pi}{r-\pi} \tilde{\pi} - \frac{\delta - s_s}{s_c} \tilde{s} - \frac{\gamma - s_a}{s_c} \tilde{a} - \frac{\alpha \gamma - \epsilon \eta}{s_c} \tilde{P} + \frac{s_i}{s_c} \tilde{i} \quad (\text{B9})$$

By substituting (II.11) into (B9) we can eliminate \tilde{E} . Then we use the relations between the shares in table II to rewrite the coefficient for abatement. By using (II.7), we can eliminate \tilde{i} . Finally, by using the relations between the shares and the definitions of the elasticities at the end of table II we can rewrite the coefficient for growth as in (2.2).

Appendix C: Solution of the model

This appendix solves the model of table II for the case that $\sigma^* = \sigma_m = \sigma_y$ and that the government uses T_y to balance its budget (ex post). We assume that $\delta = s_s$, $T_a = T_y$ and $\tilde{T}_a = \tilde{S} = 0$. This appendix makes extensive use of the relations between shares and the definitions of the production elasticities at the end of table II.

By substituting (II.3) and (II.11) into (II.1), we can write output as:

$$\tilde{y} = [\gamma + \alpha \gamma - \epsilon \eta] \tilde{P} + \gamma \tilde{i}_p \quad (\text{C1})$$

Then we substitute (C1) into (II.4) to eliminate \tilde{y} , use (II.11) to eliminate \tilde{E} and impose $\sigma_y = \sigma_m =$

σ^* . This yields:

$$\sigma^* \tilde{r} = [\gamma + \alpha \gamma - \sigma^* \epsilon \eta] \tilde{P} + \gamma \tilde{t}_p - \sigma^* \tilde{T}_y \quad (C2)$$

Substitution of (C2) into (II.2) to eliminate \tilde{r} , we arrive at the following relation:

$$[(1-\gamma)(1+\alpha) + \sigma^*(\epsilon\eta - \alpha)] \tilde{P} + \sigma^* \tilde{T}_y = - (1-\gamma) \tilde{t}_p \quad (C3)$$

By substituting \tilde{y} and \tilde{a} from (C1) and (II.3) into the government budget constraint (II.10), we find another expression for \tilde{P} and \tilde{T}_y in terms of the exogenous variables:

$$[\alpha \gamma - T_y \epsilon \eta] \tilde{P} + (1-T_y) \tilde{T}_y = - T_p^* \tilde{t}_p \quad (C4)$$

Relations (C3) and (C4) form two linear equations in two endogenous variables. Rewriting them in matrix notation yields:

$$\begin{pmatrix} 1 - T_y & \alpha \gamma - T_y \epsilon \eta \\ \sigma^* & (1-\gamma)(1+\alpha) + \sigma^*(\epsilon\eta - \alpha) \end{pmatrix} \begin{pmatrix} \tilde{T}_y \\ \tilde{P} \end{pmatrix} = \begin{pmatrix} -T_p^* \\ -(1-\gamma) \end{pmatrix} \tilde{t}_p \quad (C5)$$

Solving this linear system by inverting the matrix at the left-hand side of (C5), we find:

$$\Delta^* \begin{pmatrix} \tilde{T}_y \\ \tilde{P} \end{pmatrix} = \begin{pmatrix} (1-\gamma)(1+\alpha) + \sigma^*(\epsilon\eta - \alpha) & T_y \epsilon \eta - \alpha \gamma \\ -\sigma^* & 1 - T_y \end{pmatrix} \begin{pmatrix} -T_p^* \\ -(1-\gamma) \end{pmatrix} \tilde{t}_p \quad (C6)$$

where:

$$\begin{aligned} \Delta^* &= (1-T_y)(1-\gamma)(1+\alpha) - \sigma^*[\alpha \gamma - \epsilon \eta + (1-T_y)\alpha] \\ &= \sigma^* [rs_k + s_w - (\alpha \gamma - \epsilon \eta)] + (1-\sigma^*)(1-T_y)(1-\gamma)(1+\alpha) \end{aligned} \quad (C7)$$

The determinant in (C7) should be positive for the equilibrium to be stable. (C6) yields the reduced-form equations for the output tax and pollution:

$$\Delta^* \tilde{T}_y = s_s (\alpha \gamma - \epsilon \eta) \tilde{t}_p - (1-\sigma^*) T_p^* (\alpha - \epsilon \eta) \tilde{t}_p \quad (C8)$$

$$\begin{aligned} \Delta^* \tilde{P} &= -[rs_k + s_w] \tilde{t}_p - (1-\sigma^*) T_p^* \tilde{t}_p \\ &= -\Delta^* \tilde{t}_p + (1-\sigma^*)(1-T_y)(1-\gamma) \alpha \tilde{t}_p - \sigma^* (\alpha \gamma - \epsilon \eta) \tilde{t}_p \end{aligned} \quad (C9)$$

Substituting (C3) into (II.2) to eliminate \tilde{P} , we find for the interest rate:

$$[(1-\gamma)(1+\alpha) + \sigma^*(\epsilon\eta - \alpha)]\tilde{r} = -(\alpha\gamma - \epsilon\eta)\tilde{t}_p - [1 + \alpha(1 - \sigma^*)]\tilde{T}_y \quad (C10)$$

Hence, pollution taxes reduce the interest rate if $\alpha\gamma - \epsilon\eta > 0$, while higher output taxes are usually associated with a lower interest rate. In order to find the reduced form for the interest rate we substitute (C8) into (C10). After some tedious algebra, we find:

$$\Delta^* \tilde{r} = -(\alpha\gamma - \epsilon\eta)\tilde{t}_p + (1 - \sigma^*)(1 - T_y)\alpha\gamma\alpha\tilde{t}_p \quad (C11)$$

The reduced form for the growth rate is closely related to (C11) (see (II.7) and (II.8)). Similarly, the reduced form for investment is derived from (C11) and (II.8). To arrive at a reduced form equation for abatement, we substitute (C9) into (II.3). By substituting this solution and the reduced forms for output and investment into (II.12), we find consumption. Finally, the reduced form for the marginal excess burden can be derived by substituting the reduced forms for pollution and growth into (2.2).

In order to gain more insight into the effects of pollution taxes on the interest rate, we derive another expression for \tilde{r} . By substituting (II.5) into (II.6) to eliminate \tilde{d} , we find for profits:

$$s_w \tilde{w} = -(1 - T_y)[\tilde{T}_y + \alpha\gamma\tilde{t}_p + \epsilon\eta\tilde{P} + \beta\tilde{r}] \quad (C12)$$

Substituting (C4) into (C12) to eliminate \tilde{T}_y and rearranging terms, we find the following expression for the interest rate:

$$(1 - T_y)\beta\tilde{r} = (\alpha\gamma - \epsilon\eta)\tilde{P} - s_w \tilde{w} \quad (C13)$$

The reduced form for profits is derived by substituting (C9) and (C11) into (C13).

$$\Delta^* \tilde{w} = -(\alpha\gamma - \epsilon\eta)\tilde{t}_p - \frac{\alpha\gamma}{\delta - \alpha\gamma}(1 - \sigma^*)[\alpha\gamma - \epsilon\eta + \alpha r s_k]\tilde{t}_p \quad (C14)$$

The effect of pollution taxes on profits is determined by a substitution-effect (first term at the RHS of (C14)) and a shift effect (second term at the RHS of (C14)).

Appendix D: Pollution Permits

This appendix solves the model of table II if the level of pollution, P , rather than the pollution tax, T_p , is an exogenous policy variable. Furthermore, T_p does not represent a tax but the

shadow price of pollution. Accordingly, the model differs from table II as, on the one hand, T_p does not involve costs for firms in the form of tax payments while, on the other hand, it does not yield public revenues. In particular, the term $T_p P$ disappears from equations (I.3) and (I.12) in table I for dividends and the government budget constraint, respectively. Assuming that $\tilde{s} = \tilde{T}_a = 0$ and $T_a = T_y$, $\delta = s_s$, this involves the following changes for table II:

Dividends

$$s_a \tilde{d} = -s_i \tilde{i} - (1 - T_y) [\tilde{T}_y - (\alpha \gamma - \epsilon \eta) \tilde{P}] \quad (\text{II.5}')$$

Government budget constraint

$$(1 - T_y) \tilde{T}_y = -T_y \tilde{y} + T_a s_a \tilde{a} = -T_y (\alpha \gamma - \epsilon \eta) \tilde{P} \quad (\text{II.10}')$$

where the second expression is found by using (II.1) and (II.3). Substitution of (II.5') into (II.6), we find for profits:

$$s_w \tilde{w} = - (1 - T_y) [\tilde{T}_y - (\alpha \gamma - \epsilon \eta) \tilde{P} + \beta \tilde{r}] \quad (\text{D1})$$

Substituting (II.10') into (D1) to eliminate \tilde{T}_y , we arrive at the following expression for \tilde{r} :

$$(1 - T_y) \beta \tilde{r} = (\alpha \gamma - \epsilon \eta) \tilde{P} - s_w \tilde{w} \quad (\text{D2})$$

Expression (D2) is equivalent to (C14) in appendix C. Hence, this relationship holds, irrespective of whether pollution taxes or pollution permits are adopted as environmental policy instruments.

In order to find the reduced form for the interest rate, we substitute (II.3) into (II.2) to eliminate \tilde{t}_p . This yields the following relation between \tilde{a} , \tilde{r} and \tilde{P} .

$$\sigma^* \tilde{r} = \alpha (1 - \sigma_y) \tilde{P} + \tilde{a} \quad (\text{D3})$$

By substituting (II.10') into (II.4) to eliminate \tilde{T}_y and combining this result with (II.1) to eliminate \tilde{y} , we find another expression between abatement, the interest rate, and pollution:

$$\sigma^* (1 - T_y) \tilde{r} - (1 - T_y) \gamma \tilde{a} = [(1 - T_y) (1 - \sigma^*) \alpha \gamma + \sigma^* (\alpha \gamma - \epsilon \eta)] \tilde{P} \quad (\text{D4})$$

We now substitute \tilde{a} from (D3) into (D4) to arrive at the reduced form for the interest rate:

$$\tilde{r} = \frac{\alpha \gamma - \epsilon \eta}{(1 - T_y) (1 - \gamma)} \tilde{P} \quad (\text{D5})$$

The reduced form for growth is found by means of (II.7) and (II.8). Combining (D5) with (D2), we derive the reduced form equation for profits:

$$s_w \tilde{w} = \frac{\delta}{\beta + \delta} (\alpha \gamma - \epsilon \eta) \tilde{P} \quad (\text{D6})$$