INCOME TAXATION, ENVIRONMENTAL EMISSIONS, AND TECHNICAL PROGRESS

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ABSTRACT

This paper examines the implications of environmental externalities for income tax design in a growing economy. We describe a model with endogenously generated knowledge, in which technical progress reduces the emissions generated by production activities. In this setting, the lack of internalization of environmental externalities results in an above-optimal long-run rate of growth and leads to an inefficient input mix. If emission taxes are infeasible, differential income tax sheltering of physical and knowledge investment can be effective as a second-best remedy. Simulation results from a calibrated model, under a uniform specification of intertemporal and intratemporal substitution possibilities, indicate that the intertemporal allocative effects associated with environmental externalities could dominate intratemporal distortions; hence, income tax reform could outperform indirect tax reform as a second-best Pigouvian instrument, and perform well in comparison with a first-best instrument, even in economies where environmental emissions are sectorally concentrated.

JEL CLASSIFICATION: H21, O31, Q20.

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1. INTRODUCTION

The debate over tax policies and environmental protection has traditionally focused primarily on indirect taxation: carbon taxes, as a response to the problem of global warming (Goulder (1992), Poterba (1993)), automotive taxes to curtail local emissions (Borenstein (1993)), tax-refund schemes and other tax incentives for recycling (Dinan (1993), Fullerton and Kinnaman (1994)). This emphasis on indirect taxes as environmental remedies is also reflected in the structure of most tax systems. Although many countries use energy taxes and other environment-related indirect tax instruments, few countries also have provisions in their income tax codes which relate to environmental protection (Jenkins and Lamech (1992)); and, in those countries that do, these provisions tend to be quite narrow in scope.

This paper examines the implications of environmental externalities for second-best income tax design in a growing economy. There are two main channels through which lack of internalization can affect resource allocation: through its impact on the size and composition of output, and through its impact on the input mix and on asset accumulation. The first type of effect is what has traditionally been stressed in the environmental policy debate; which explains the usual emphasis on indirect tax instruments. More recently, however, the policy debate has begun to focus on the role of innovation in environmental protection (e.g., Carraro and Siniscalco (1994)). This has coincided with a shift in focus in the tax policy debate towards questions of growth and investment, following suggestions that, in growing economies, the intertemporal allocative effects of public policies could be quantitatively more important than their intratemporal impacts (King and Rebelo (1990)).

Here, we argue that, in an economy with endogenous technical progress, if innovation and pollution abatement are positively linked, the allocative implications of environmental externalities with respect to input and investment decisions over time may well dominate their allocative effects with respect to output and consumption decisions within periods. Thus, although income taxation cannot be used to correct intersectoral distortions induced by differential emissions across sectors, income tax reform could nevertheless be effective as a second-best corrective device.

To illustrate this point, we develop a model with endogenous technical progress and production-consumption externalities, in which emissions can be abated by switching to cleaner, more knowledge-intensive technologies. We show that the lack of internalization of environmental emissions leads to above-optimal capital stocks, as well as to a non-optimal output mix. Full internalization of externalities by means of an emission tax raises welfare and lowers the long-run rate of economic growth. Differential tax sheltering of physical and non-physical investment, whereby income from physical capital is taxed more heavily relative to income from knowledge investment, can be employed as a second-best Pigouvian remedy.[1]

A calibrated version of the model is employed to analyze the impacts of three different types of unanticipated tax changes, namely, the introduction of a first-best emission tax, second-best indirect tax reform, and second-best income tax reform. We compute optimal tax reform paths and associated welfare impacts, and find that, un-

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[1]Much of the earlier research on tax reform and environmental emissions has focused on the efficiency gains arising from equal-yield environmental tax reform in the presence of distortionary taxes (the "double dividend" conjecture); see, for example, Goulder (1992). Our analysis is limited to the design of second-best tax instruments of environmental protection and abstracts from any trade-offs associated with the presence of revenue requirements.

der a uniform specification of intertemporal and intratemporal substitution possibilities, if the linkage between emissions and innovation is sufficiently strong, second-best income tax reform outperforms indirect taxation, and performs well in comparison with a first-best instrument, even if emissions are sectorally concentrated.

The plan of the paper is as follows. Section 2 discusses the linkage between environmental emissions and technical progress, and its implications for environmental tax policies. Section 3 presents a model with environmental emissions and endogenous technical progress, and discusses how in this framework income taxes can be used as a second-best Pigouvian remedy. Section 4 describes the calibrated model and reports on results of numerical simulations. Section 5 presents our conclusions.

2. ENVIRONMENTAL EMISSIONS, INNOVATION, AND TAX POLICY

The linkage between technical innovation and emission abatement has attracted considerable attention of late. In the environmental policy debate, a number of writers have stressed the role of innovation for emission abatement (Carraro and Siniscalco (1994); Laffont and Tirole (1994)). At the same time, research on economic growth has recently begun to examine the implications of environmental policies for long-run growth (Gradus and Smulders (1993), Bovenberg and Smulders (1993a,b), Bovenberg and de Mooij (1994), Ligthart and van der Ploeg (1994)).[2]

[2]Earlier literature on economic growth and environmental protection focused on a neoclassical growth setting with exogenous long-run growth (Jorgenson and Wilcoxen (1990), Holtz-Eakin and Selden (1992), Tahvonen and Kuuluvainen (1993)).

There are clearly important dynamic dimensions to pollution abatement; it usually requires some form of investment in emissions control equipment, which in turn involves environmental R&D either at the firm level or by specialized suppliers of emission control equipment and services. Furthermore, as is generally the case for R&D efforts, the technologies and ideas developed in a specific field can also find application in other areas (e.g., efforts to devise more fuel-efficient car engines may spawn new materials and procedures which can be applied elsewhere). At the same time, technical developments and R&D not specifically aimed at reducing pollution may generate spillovers for emissions abatement (e.g., even if no taxes were levied on fossil fuels, private agents would still face incentives to look for ways of improving fuel-efficiency in cars).

The preceding discussion suggests that there exists a direct form of output complementarity between emission abatement and overall technical progress in an economy. This conjecture appears to borne by evidence. For example, innovation and energy efficiency generally go hand in hand for a number of consumer products such as cars, domestic appliances, and consumer electronics. And, evidence does suggest that firms respond to environmental regulation and taxes primarily through innovation (Carraro and Siniscalco (1994)).

There is also clear evidence that environmental quality and income levels are generally correlated (Lucas, Wheeler and Hettige (1992), Grossman (1993)). Although such correlation could be ascribed to the presence of stricter environmental standards in richer countries (where higher per capita income levels translate into a higher valuation for environmental quality), purely technological factors are also involved. For example, it has been observed that, income levels being equal, outward-oriented, fast-growing developing economies exhibit a better environmental record than slowergrowing, inward-oriented economies (Low (1992)).[3]

If technological progress and pollution abatement are indeed complementary in this way, the lack of internalization of environmental externalities will affect intertemporal decisions as well as input and investment decisions within periods. Which implies that environmental policies will impact on growth performance, and, conversely, policies that affect the accumulation of knowledge will impact on environmental emissions. In particular, direct taxes, which have been shown to be a central determinant of growth performance (King and Rebelo (1990), Engen and Skinner (1992)), will have effects on emissions and environmental quality.

The implications of tax policies for long-run growth when environmental emissions and economic growth are linked, have been examined by Gradus and Smulders (1993), and by Bovenberg and de Mooij (1994). Both of these studies, however, focus on first-best policies such as emission taxes, which may often be difficult or even impossible to implement. In the case of CO_2, taxation of emissions can be achieved simply by levying taxes on fuel consumption; this is because CO_2 emissions are directly proportional to the quantity of fossil fuels used, independently of the process in which they are used. But this method clearly does not work in other cases; for example, local particulate emissions are not only the result of specific types of inputs being employed, but are also crucially dependent on the choice of process. Thus, in many cases, indirect taxation can only afford a second-best outcome.

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[3]This could be because the lowest-cost processes available to exporters producing for developed country markets happen to be clean technologies developed and adopted in developed countries as a result of stricter environmental standards. Yet, from the point of view of the exporting country, this represents a purely technological effect.

Income taxation can likewise be used as a second-best instrument of environmental protection. And several countries do seem to recognize a role for income tax incentives in the environmental policy mix. Tax credits and immediate expensing are available for environmental R&D in the UK. Canada, France, Germany, Japan, Korea, and Taiwan all have accelerated depreciation provisions for pollution control equipment. In addition, Canada, Korea, and Taiwan, as well as the Netherlands, also grant investment tax credits for pollution abatement equipment or for investment in new technologies (Jenkins and Lamech (1992)).[4] In principle, such provisions directly or indirectly produce incentives for environmental R&D. In practice, tax relief is often limited to qualifying investments that are required in order to comply with regulatory standards, which implies that there are no effects on private choices at the margin.[5]

Moreover, such provisions focus only on pollution-abatement R&D. As we shall show in the following section, when innovation and pollution abatement are directly linked, the lack of internalization of emissions brings about intertemporal substitution as well as inter-asset substitution between physical and non-physical capital. A second-best income tax policy will thus need to address both types of distortions; and this cannot be achieved simply by subsidization of environmental R&D, but requires the use of fiscal incentives with respect to all forms of investment.

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[4]As of 1992, the US did not have any special income tax provisions relating to pollution abatement.

[5]In fact, this type of subsidy, by prolonging the economic life of installed capital, might even delay the adoption of new technologies.

3. A MODEL WITH ENDOGENOUS TECHNICAL PROGRESS AND ENVIRONMENTAL EMISSIONS

This section formalizes our preceding discussion by presenting a model with endogenous technical progress and environmental emissions. The engine of growth in the model is investment in knowledge by optimizing agents (as in King and Rebelo (1990)). Production is assumed to generate environmental damage, which we model as a pure flow, but this can be reduced by moving to cleaner, more knowledge intensive technologies. Emissions abatement can then be achieved by accelerating innovation, i.e., by raising the stock of knowledge relative to the stock of physical capital. But, in the absence of any abatement incentives, the implications of different types of assets for environmental emissions will not be taken into account by private investors.

We will begin or discussion by focusing on a one-sector model. Later, this will be extended to allow for sectoral differences in environmental emissions.

Growth and emissions in a one-sector model

We initially assume that there is only one produced good in the economy, which is used both for final consumption and for investment. Production in each period t combines knowledge-augmented labour and physical capital inputs by means of a constant-returns-to-scale technology. Output at time t is

$$Q_t = f\left(NH_t, K_t\right), \tag{1}$$

where K_t is the stock of physical capital at time t, H_t is the stock of knowledge at time t, N is the labour force, which is assumed to be constant over time, and where

f is continuous, strictly quasiconcave and twice differentiable. In this specification, productivity growth is modelled as labour-augmenting technical progress.

There is one infinitely-lived representative agent, whose preferences are assumed to be intertemporally separable, with a constant rate of time preference β:

$$U = \sum_{t=1}^{\infty}(1+\beta)^{-t}U(Z_t), \tag{2}$$

where Z_t is instantaneous consumption at time t, and U is a strictly concave, continuous, instantaneous utility function. In the absence of environmental emissions, Z_t is simply equal to consumption, C_t.

Capital stocks evolve as follows:

$$K_{t+1} = K_t(1-\delta^K) + I_t, \tag{3}$$

$$H_{t+1} = H_t(1-\delta^H) + V_t, \tag{4}$$

where I_t and V_t respectively denote gross investment in physical capital and knowledge, and δ^K and δ^H reflect depreciation. Returns to physical investment and to knowledge investment are thus

$$r_t^K = \frac{\partial Q_t}{\partial K_t} - \delta^K, \tag{5}$$

$$r_t^H = \frac{\partial Q_t}{\partial H_t} - \delta^H. \tag{6}$$

Market clearing in each period requires

$$Q_t = C_t + I_t + V_t. \tag{7}$$

In this model the long-run rate of growth is endogenous. In a steady state, private returns to human and physical investment are equalized

$$r_t^K = r_t^H \equiv \rho, \tag{8}$$

growth is balanced

$$(9) \qquad Q_t/Q_{t-1} - 1 = K_t/K_{t-1} - 1 = H_t/H_{t-1} - 1 = Z_t/Z_{t-1} - 1 \equiv g,$$

and the consumption path is optimal

$$(10) \qquad \frac{U'(Z_t)}{U'(Z_{t+1})} = \frac{1+\rho}{1+\beta}.$$

We model environmental emissions and their linkage with technical progress as follows. Production at time t generates environmental damage equal to D_t, which is assumed to be increasing with output. We also assume that accumulated knowledge has a mitigating effect on emissions, i.e., the higher the stock of knowledge relative to output, the lower the emissions. This relationship can be formalized as

$$(11) \qquad D_t = e(Q_t, H_t),$$

where $\partial e/\partial Q_t > 0$ and $\partial e/\partial H_t < 0$. Net-of-damage consumption is assumed to be simply

$$(12) \qquad Z_t = C_t - D_t > 0.$$

Notice that for balanced growth in all variables to be possible, e must be homogeneous of degree one in its arguments. A specification which satisfies the above requirements is

$$(13) \qquad D_t = \mu \left(\frac{Q_t}{H_t}\right)^{\eta} Q_t = \epsilon_t Q_t,$$

where $\eta > 0$, and ϵ_t represents an emission coefficient (emissions per unit of output). Emissions are thus a linear function of output,[6] and an increasing, constant-elasticity

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[6]As elsewhere in the literature (e.g., in Gradus and Smulders (1993)).

function of the ratio Q_t/H_t. In this specification, emission abatement is a purely dynamic phenomenon. Emissions in each given period can only be curbed by reducing output, but emissions in future periods are affected by current investment choices.

The social rates of return to physical and human capital in this model are

$$s_t^K = \frac{\partial Q_t}{\partial K_t}\left[1-(1+\eta)\mu\left(\frac{Q_t}{H_t}\right)^\eta\right]-\delta^K, \tag{14}$$

and

$$s_t^H = \frac{\partial Q_t}{\partial H_t}\left[1-(1+\eta-\eta/\theta_H)\mu\left(\frac{Q_t}{H_t}\right)^\eta\right]-\delta^H. \tag{15}$$

where θ_H represents the input value share of knowledge in production. In the absence of internalization, the social return to physical capital will lie below the private return. The return to knowledge investment will lie above the long-run private return, ρ, as defined by (8), if

$$\theta_H < \frac{\eta}{1+\eta}. \tag{16}$$

Environmental externalities thus produce an inter-asset substitution effect between physical and non-physical capital as well as intertemporal allocative effects.

Partial income tax sheltering as a Pigouvian remedy

The first-best method to force internalization of environmental externalities consists of directly taxing emissions.[7] Under an emission tax, the net private value of output in each period is

$$W_t = Q_t - \lambda\mu\left(\frac{Q_t}{H_t}\right)^\eta Q_t, \tag{17}$$

[7]Our discussion will focus on tax instruments and will thus abstract from other instruments of environmental protection.

where λ represents the rate of internalization. Net-of-depreciation private rates of return to investment then become

(18)
$$r_t^K = \frac{\partial Q_t}{\partial K_t}\left[1 - \lambda(1+\eta)\mu\left(\frac{Q_t}{H_t}\right)^{\eta}\right] - \delta^K,$$

and

(19)
$$r_t^H = \frac{\partial Q_t}{\partial H_t}\left[1 - \lambda(1+\eta-\eta/\theta_H)\mu\left(\frac{Q_t}{H_t}\right)^{\eta}\right] - \delta^H.$$

Notice that for $\theta_H < \eta/(1+\eta)$ the second term in the square brackets on the right-hand side of (19) will be negative, and thus an emission tax will amount to a subsidy to knowledge investment.

In this model, internalization of environmental emissions raises welfare but generates a negative impact on the long-run rate of return to investment (this can be shown by differentiating the arbitraging condition (8) with respect to λ and K_t). A lower long-run rate of return to investment, in turn, will result (by condition (10)) in a lower long-run rate of economic growth.

If emission taxes are not feasible, income taxation can be used as a substitute corrective device. Let the income tax rate be τ_I. Net-of-depreciation taxable income at time t is then

(20)
$$Y_t = Q_t - \delta^K K_t - \delta^H H_t - \xi^K(I_t - \delta^K K_t) - \xi^H(V_t - \delta^H H_t).$$

where ξ^K and ξ^K are tax parameters representing fractions of physical and non-physical net investment expenditures that are deductible from taxable income (and thus sheltered from taxation).[8] Under this scheme, private net-of-tax returns to

[8]Notice that, in this model, a deduction and a tax credit are fully equivalent.

investment become

$$r_t^K = \left(\frac{\partial Q_t}{\partial K_t} - \delta^K\right)\frac{1-\tau_I}{1-\xi^K\tau_I}, \tag{21}$$

$$r_t^H = \left(\frac{\partial Q_t}{\partial H_t} - \delta^H\right)\frac{1-\tau_I}{1-\xi^H\tau_I}. \tag{22}$$

In the absence of uninternalized environmental emissions, a first-best income tax structure would involve full sheltering of all forms of investment, i.e., $\xi^K = \xi^H = 1$, a scheme which is equivalent to a consumption tax. With uninternalized emissions, differential sheltering of physical and knowledge investment can be used as a second-best substitute for emission taxes. In general, this will involve less than full sheltering of physical capital, as well as preferential treatment of non-physical capital.

If $\theta_H \geq \eta/(1+\eta)$, such a scheme can achieve a first-best outcome. If, however, $\theta_H < \eta/(1+\eta)$, and if ξ^H is restricted to be less than unity, income taxation will only provide a second-best instrument relative to an emission tax. Furthermore, if ξ^K is restricted to be above zero (i.e., if a surtax on physical capital is not available), the maximum rate at which returns to physical investment can be taxed will be τ_I. Finally, even for low values of η, income tax reform may not be able to attain a first-best outcome if time-dependent tax parameters cannot be used during the transition to a new steady state.

Environmental emissions and the output mix

The preceding discussion has focused on a single-sector economy. In reality, we typically observe emissions to be concentrated in certain sectors. When emissions are associated with specific products, lack of internalization will not only lead to an inefficient input mix but it will also cause the output mix to be non-optimal. In order to address this type of misallocation, targeted taxation of different products is required. Below, we extend our model to examine this issue.

Let us assume that two goods are produced in the economy, good 1 and good 2, in quantities Q_t^1 and Q_t^2, and that consumption and investment (both physical and non-physical) consist of a composite of these two goods, M_t, defined as

$$M_t = m\left(Q_t^1, Q_t^2\right), \tag{23}$$

where m is linearly homogeneous, quasiconcave and twice differentiable. If only the production of good 1 generates emissions, environmental damage is

$$D_t = \epsilon_t Q_t^1. \tag{24}$$

To keep things simple, we will assume that factor intensities are identical in the two sectors, and, without loss of generality, choose physical units so that the marginal rate of output transformation between the two products is unity. We can then write

$$Q_t^1 + Q_t^2 = Q_t. \tag{25}$$

Social returns to investment are

$$s_t^K = \frac{\partial Q_t}{\partial K_t}\left[1 - \gamma_t(1+\eta)\mu\left(\frac{Q_t}{H_t}\right)^{\eta}\right] - \delta^K, \tag{26}$$

and

$$s_t^H = \frac{\partial Q_t}{\partial H_t}\left[1 - \gamma_t(1+\eta-\eta/\theta_H)\mu\left(\frac{Q_t}{H_t}\right)^{\eta}\right] - \delta^H, \tag{27}$$

where γ_t is the fraction of good 1 output in total output:

$$\gamma_t = \frac{Q_t^1}{Q_t^1 + Q_t^2}. \tag{28}$$

In the absence of environmental taxes, the relative price of the two goods will be unity, and the equilibrium level of γ_t will be defined by the first-order condition

$$\frac{\partial M_t / \partial Q_t^1}{\partial M_t / \partial Q_t^2} = 1. \tag{29}$$

Equating the marginal rate of substitution between good 1 and good 2, to the ratio of social marginal costs (inclusive of environmental damage) we obtain

$$\frac{\partial M_t / \partial Q_t^1}{\partial M_t / \partial Q_t^2} = 1 + \epsilon_t. \tag{30}$$

Internalization of emissions will thus cause Q_t^1 to fall relative to Q_t^2, and result in a lower γ_t.

Notice, however, that with identical factor intensities, the output mix is completely independent of the tax treatment of factor returns. Thus, a non-discriminatory instrument such as a general factor tax, or an income tax with differential sheltering of assets as the one described above, will be unable to affect output decisions, and will only afford a second-best outcome in comparison with an emission tax.[9]

Differential indirect taxation of good 1 and good 2 can be used to correct output choices within periods. For example, a unit tax equal to ϵ_t on good 1 in combination with a zero tax on good 2 would drive γ_t to its socially optimum value. But such a tax scheme has no effect on the input mix, and is thus unable to address the inter-asset and intertemporal distortions arising from the externality.[10]

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[9]If factor intensities differ across sectors, differential taxation of factors will also have sectoral impacts. These, in turn, will add to or detract from the effectiveness of income tax reform depending on whether the polluting sector is capital intensive or knowledge intensive.

[10]If factor intensities differ across sectors, sectoral taxes will also affect the input mix.

4. ASSESSING THE EFFECTIVENESS OF SECOND-BEST INCOME TAX REFORM

Whether or not income tax reform can be an effective instrument of environmental protection is fundamentally an empirical question. We can note, however, that the recent literature on taxation and endogenous growth has shown that the intertemporal allocative effects of public policies can be quantitatively more important than their intratemporal impacts. In the context of our analysis, this would suggest that the efficiency effects associated with the inter-asset distortion between physical and non-physical capital brought about by environmental externalities could dominate the efficiency effects associated with distortions in the output mix. Which implies that income tax reform could be a relatively effective second-best remedy, even when emissions are sectorally concentrated.

To illustrate this point, we use a numerical version of the two-sector model described in the previous section. We calibrate model parameters so as to capture a number of basic stylized facts characterizing the structure of real-world developed economies, and employ it to compute optimal tax reform paths and associated growth and welfare impacts.[11] We examine, in turn, first-best tax reform (i.e., the introduction of emission taxes), second-best indirect tax reform, and income tax reform.

For the production function we adopt a Constant-Elasticity-of-Substitution (CES) functional form:

$$(31) \qquad f(NH_t, K_t) = \phi \left[\alpha_L^{1/\sigma}(NH_t)^{(\sigma-1)/\sigma} + (1-\alpha_L)^{1/\sigma} K_t^{(\sigma-1)/\sigma}\right]^{\sigma/(\sigma-1)},$$

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[11]We should note that numerical simulation is the only feasible method of characterizing optimal policies when these are formulated taking into account transitional dynamic effects as well as steady-state effects.

where $0 < \alpha_L < 1$ is a labour share parameter, ϕ is a scaling parameter, and σ is the elasticity of substitution.

For the intratemporal aggregator m we specify a Cobb-Douglas form:

$$M_t = \psi \left(Q_t^1\right)^{\zeta} \left(Q_t^2\right)^{1-\zeta}. \tag{32}$$

The instantaneous utility function is simply

$$U(Z_t) = \ln Z_t. \tag{33}$$

Thus, we assume Cobb-Douglas substitution possibilities for both intratemporal and intertemporal choices.

Parameter values for functional forms are specified as follows. We assume that the economy is initially on a zero-internalization balanced growth path under a 25% income tax with full sheltering of all forms of investment ($\xi^K = \xi^H = 1$) with a 5% yearly net return to investment and a 2% growth rate. This implies $\beta \approx 2.95\%$. The elasticity of substitution σ is specified exogenously, and subsequently varied for sensitivity analysis. The capital-labour ratio is assumed to be 1/3, which yields $\alpha_L = 0.75$. We also let $\delta^H = \delta^K = 0$, which yields $\phi = 0.05$.

To calibrate the parameters of the damage function (13), we exogenously choose a value for η (this is varied parametrically in our simulations), and assume that, in aggregate, the net environmental damage per dollar of total output is ten cents.[12]

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[12]With reference to CO_2 emissions alone, it has been estimated that the tax revenues from a carbon tax sufficient to meet internationally agreed emissions targets could be as large as 5% to 10% of World GDP (Whalley and Wigle (1991)).

This implies $\epsilon_t = 0.1/\zeta$. We can then infer a value for μ as follows:

$$\mu = \epsilon_t / \left(\frac{Q_t}{H_t}\right)^\eta = \epsilon_t/(\psi/\alpha_L)^\eta. \tag{34}$$

We examine a scenario where emissions are sectorally concentrated and assume that ζ is equal to 0.5, i.e., one half of aggregate final demand is responsible for the totality of emissions generated in the economy. This may represent a reasonable upper-bound estimate of concentration for demand-induced emissions in developed countries.[13]

We use this model to compute tax reform paths which maximize intertemporal welfare as defined by (2). We examine three types of reform. First, we analyze the introduction of a first-best emission tax, and subsequently examine the impacts of second-best indirect taxation—whereby a time-invariant, non-negative tax on the dirty good (good 1) is introduced in all periods—and income tax reform—which is characterized by a combination of time-invariant sheltering rates ξ^K and ξ^H. Tax revenues are returned to the representative consumer in lump-sum fashion, and there is no revenue requirement. All tax changes are assumed to be unanticipated.

Figure 1 shows the time paths for selected variables, following the introduction of an emission tax for $\sigma = 1$, and $\eta = 2$. The transition to a new steady-state lasts approximately 15 years. Environmental emissions fall sharply following the introduction of the tax: their rate of growth initially falls by more than two thirds, and then rapidly rises again to the new steady-state growth rate (which is approximately 1.57%). The rates of growth of output and consumption also fall initially below the

[13]For example, the corresponding Gini coefficient for Canada and the US is less than 0.4 (calculated on the basis of an aggregated 1986 ten-sector input-output matrix for Canada and the US, using emissions coefficients from Perroni and Wigle (1994)).

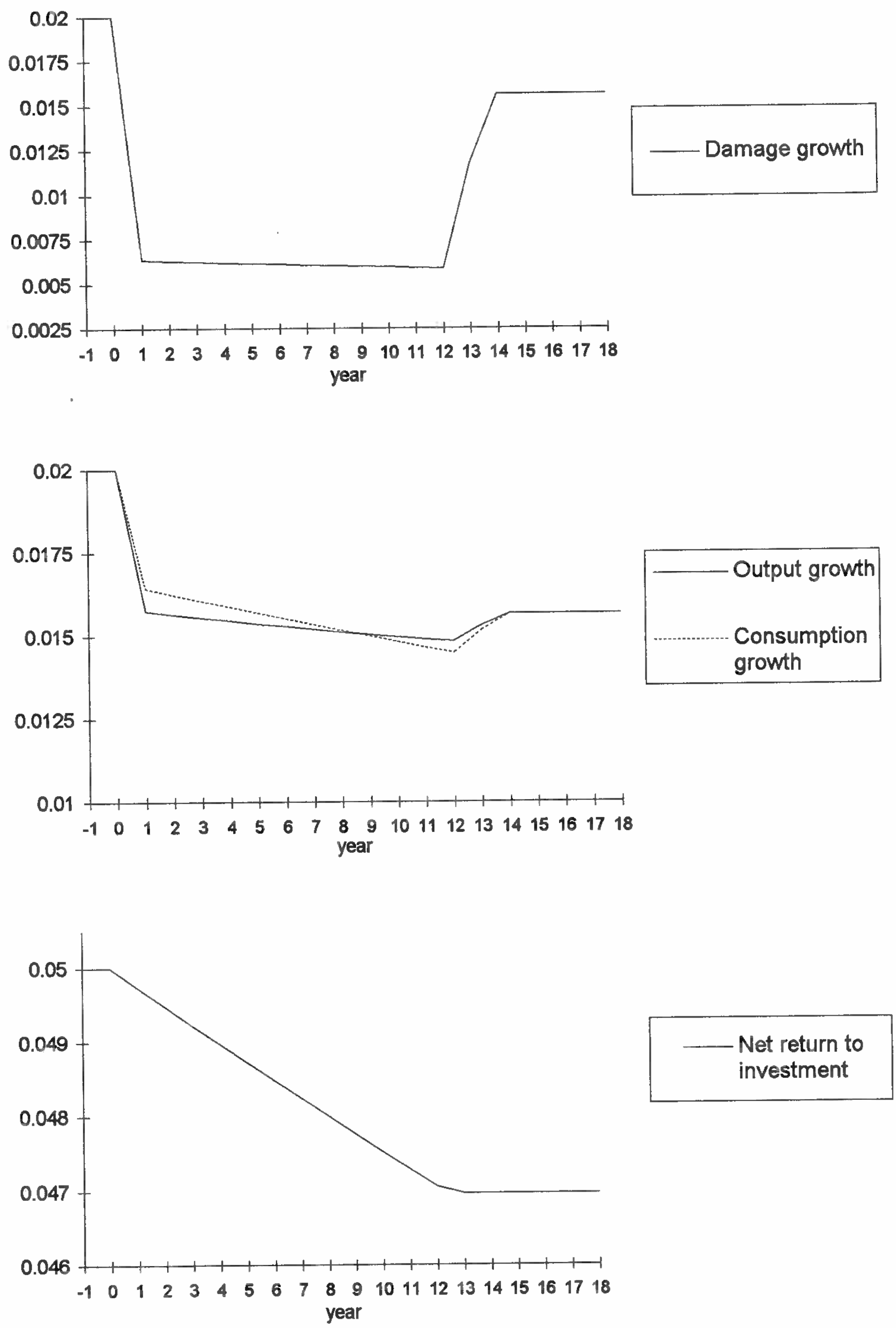

Figure 1: Full internalization: transition path ($\sigma = 1$; $\eta = 2$)

new steady-state rate.

Table 1 reports steady-state growth effects of full internalization, as well as impacts on emissions per unit of output and dynamic welfare impacts for different values of η and σ. Growth impacts are pronounced in all scenarios. Unit emissions fall by more than 30% in some cases. Impacts on emissions increase markedly with an increase in η (which reflects the strength of the linkage between emissions and knowledge). Dynamic welfare impacts, measured in terms of the present value of equivalent variations as a proportion of the discounted flow of future income, are also positively related to η.

Table 2 shows optimal rates of indirect taxation on good 1 and associated steady-state and welfare effects. These are all are independent of σ and η. For our parameterization the optimal rate of indirect taxation on good 1 is 26.22%, and the associated output mix γ is 0.442. Impacts on long-run growth are modest. Dynamic welfare effects are also rather modest when compared with the gains of first-best tax reform (Table 1), especially when η is large.

Table 3 reports second-best rates of tax sheltering for physical and non-physical assets for different values of η, obtained by numerically computing second-best income tax reform paths. A second-best policy requires zero sheltering of physical investment in some cases (implying that a first-best policy would call for an effective tax on physical capital income in excess of 25%). For low values of η, both ξ^H and ξ^K are less than unity, but for higher values of η we obtain corner solutions with $\xi^H = 1$ (implying that a first-best policy would require subsidization of knowledge investment).

Table 4 reports corresponding welfare and growth impacts. Welfare gains are substantially larger than the corresponding gains in Table 2, indicating that, in this example, the intertemporal allocative effects associated with environmental externali-

Table 1: Steady-state impacts and dynamic welfare effects of full internalization

$\sigma = 0.5$	η		
	1	2	4
Terminal K/L ratio	0.311	0.212	0.261
Terminal growth	1.54%	1.55%	1.59%
Terminal change in unit emissions	-1.74%	-9.19%	-23.39%
Dynamic welfare change	2.52%	2.88%	4.08%
$\sigma = 1.0$	η		
	1	2	4
Terminal K/L ratio	0.292	0.260	0.224
Terminal growth	1.55%	1.57%	1.16%
Terminal change in unit emissions	-9.35%	-8.91%	-32.80%
Dynamic welfare change	2.62%	3.22%	4.87%
$\sigma = 1.5$	η		
	1	2	4
Terminal K/L ratio	0.275	0.235	0.213
Terminal growth	1.55%	1.54%	1.64%
Terminal change in unit emissions	-4.61%	-8.68%	-34.51%
Dynamic welfare change	2.72%	3.49%	5.32%

Table 2: Second-best indirect tax reform

Optimal *ad valorem* tax rate on good 1	26.22%
Terminal growth	1.97%
Dynamic welfare change	1.17%

Table 3: Optimal income tax sheltering
of physical and non-physical assets

$\sigma = 0.5$		η	
	1	2	4
Physical investment (ξ^K)	26.9%	0.0%	0.0%
Knowledge investment (ξ^H)	79.4%	90.7%	100.0%
$\sigma = 1.0$		η	
	1	2	4
Physical investment (ξ^K)	28.4%	4.6%	0.0%
Knowledge investment (ξ^H)	79.4%	89.1%	100.0%
$\sigma = 1.5$		η	
	1	2	4
Physical investment (ξ^K)	29.7%	25.0%	31.4%
Knowledge investment (ξ^H)	79.0%	85.3%	93.5%

Table 4: Steady-state impacts and dynamic welfare effects of second-best income tax reform

$\sigma = 0.5$		η	
	1	2	4
Terminal K/L ratio	0.309	0.293	0.289
Terminal growth	1.52%	1.55%	1.65%
Terminal change in unit emissions	-1.96%	-5.53%	-14.08%
Dynamic welfare change	1.69%	2.12%	3.13%
$\sigma = 1.0$		η	
	1	2	4
Terminal K/L ratio	0.287	0.262	0.250
Terminal growth	1.52%	1.56%	1.66%
Terminal change in unit emissions	-3.63%	-11.33%	-25.01%
Dynamic welfare change	1.82%	2.52%	4.16%
$\sigma = 1.5$		η	
	1	2	4
Terminal K/L ratio	0.269	0.293	0.288
Terminal growth	1.53%	1.58%	1.69%
Terminal change in unit emissions	-5.08%	-11.94%	-23.44%
Dynamic welfare change	1.93%	2.73%	4.30%

ties dominate intratemporal distortions. Although efficiency impacts are significantly lower than the figures in Table 1 (the full internalization case), a comparison between the two sets of figures reveals that investment decisions are responsible for a surprisingly large fraction of overall allocative impacts.

We can sum up our numerical findings as follows. In our example, under a uniform specification of intertemporal and intratemporal substitution possibilities, income taxation outperforms indirect taxation as a second-best instrument of environmental protection. Furthermore, although the advantages of an emission tax over a second-best instrument are significant, the bulk of possible efficiency gains can be secured through income tax reform.

5. SUMMARY AND CONCLUSION

This paper has examined the effectiveness of income tax reform as an environmental remedy. We have shown that, when technical progress and emission abatement are directly linked, differential income tax sheltering of physical and non-physical assets can be used to correct the inter-asset and intertemporal distortions induced by environmental externalities. We have also argued that, if this linkage is sufficiently strong, the allocative implications of environmental externalities with respect to input and investment decisions over time could dominate the intersectoral distortions traditionally stressed in the environmental policy literature.

The main conclusion emerging from our analysis is that income taxation seems to have been unduly neglected as an instrument of environmental protection. Although direct taxes are unable to correct intersectoral distortions induced by differential emissions across sectors, income taxation could nevertheless be very effective as a second-best policy instrument. Its contribution to the environmental tax policy mix should therefore be expanded. This could be achieved by untying existing income tax preferences from regulatory regimes, and by broadening their scope to include other forms of knowledge investment beyond environmental R&D, while at the same time restructuring existing tax shelters for competing assets.

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