Double Dividend in an Endogenous Growth Model with Pollution and Abatement

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Resumen

En un modelo muy estilizado de crecimiento endógeno -con contaminación y actividades privadas de reducción de contaminación (*abatement*) y sin externalidades en producción-, mostramos que el gobierno tiene la posibilidad de explotar la existencia de Efectos Laffer Dinámicos para obtener un Doble Dividendo como resultado de una reforma impositiva medioambiental. Dicha reforma garantiza, además, el cumplimiento de un compromiso previo del gobierno consistente en proporcionar una senda predeterminada de transferencias de suma fija a los consumidores.

Palabras Clave: Doble dividendo, reforma medioambiental verde, actividades de abatement, externalidades medioambientales, impuestos medioambientales, crecimiento endógeno, Efecto Laffer dinámico.

Clasificación JEL: H23, O41, Q28

Abstract

In a very stylized endogenous growth economy with pollution and private abatement activities and without any production externality, we show that the government may exploit dynamic Laffer effects to achieve a double dividend through an environmental tax reform, while fulfilling its commitment to provide an exogenously specified sequence of expenditures in the form of lump-sum transfers to consumers.

Key Words: Double dividend, green tax reform, abatement activities, environmental taxes, environmental externalities, endogenous growth, Dynamic Laffer effect.

JEL Classification: H23, O41, Q28

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1 Introduction

A *green tax reform* -consisting of *increasing* an environmental tax and devoting the proceeds to *decrease* a distortionary tax- is said to yield the strong version of a *double dividend* if it is able to achieve an increase in welfare from environmental amenities (the so-called *green dividend*) as well as from private commodities (the so-called *blue dividend*) [Goulder (1995)]. A general principle for the double dividend to arise is a pre-existing inefficiency in the tax system on non-environmental as well as in environmental grounds. In previous research, a relatively inefficient tax system on commodities or productive factors is considered to distort agents' decisions, taking the competitive equilibrium allocation away from that solving the planner's problem. This literature exploits a *cross-sectional type of tax inefficiency* [Ulph (1992), Bovenberg and de Mooij (1994), Bovenberg and van der Ploeg (1994), Parry (1995), Proost and van Regemorter (1995) or Parry and Bento (2000) consider a static framework, while Bovenberg and Goulder (1996, 1997), Bovenberg and de Mooij (1997), or Heijdra et al. (2006) use dynamic general equilibrium models].

The type of economic structures in which enhancing the efficiency of the tax system as a revenue-raising device has been shown in the literature to lead to a double dividend, incorporate a relatively complex combination of tax structure and economic externalities, which could give the impression that there might be little chance of achieving a double dividend. On the contrary, our main contribution is to show that the double dividend can arise in a simple framework, under a linear technology in which substitution between inputs is precluded, and without any need to introduce an environmental externality in production.[1] The new channel for a double dividend is the correction of a pre-existing *intertemporal* inefficiency of the tax system, emerging from the possibility of obtaining a non-environmental welfare gain by changing the time-profile of tax revenues.

Given a time path for environmental taxes, there exists an *intertemporal inefficiency* in income taxes whenever it is possible to finance the same trajectory of government expenditures with a lower sequence of income tax rates. That possibility exploits the standard negative dependence of the growth rate on the income tax rate in endogenous growth economies. Reducing the income tax rate in an economy on the upward sloping segment of the static Laffer curve will lower revenues. If the government maintains its expenditures as planned, it will have to issue some debt following the tax reform. The increased growth after the income tax cut may, however, allow for eventually retiring the stock of debt outstanding without the need to raise income taxes at any future period, possibly leading to higher non-environmental welfare than under the initial tax structure.

We think of a government considering the possible inefficiency of the current tax structure as a way to finance the sequence of planned expenditures. Specifically, a government having an environmental tax as a second fiscal instrument may design *dynamically feasible green* tax reforms, those that consist of *increasing* the environmental tax and *decreasing* the income tax in such a way that the implied higher future revenues may allow for eventually retiring the debt issued to finance the single-period budget deficits that may arise as a consequence of the tax reform.[2] For that to be possible, the present value of current and

[1] Bovenberg and de Mooij (1997), the closer reference to our work, obtain the double dividend only when the positive externality of environmental quality on productivity is large enough, compared with the production elasticity of pollution as a rival input in production.

[2] Heijdra et al. (2006) study the double dividend hypothesis in an overlapping-generations model without endogenous growth, under a debt financing policy. At a difference of our model, the time path

future revenues under the new tax structure must be at the time of the tax reform at least as large as the present value of current and future expenditures. Our goal is to examine the possibility that, by reducing the cross-sectional and the intertemporal inefficiencies of the tax system simultaneously, this type of reforms may lead to a double dividend.

We consider an AK economy without any production externality. A negative pollution externality in preferences leads to the need for abatement activities, which are carried out by the firms. Abatement is assumed to be a private good which enables firms to increase output without causing more pollution. The government has a planned time path for lump-sum transfers[3] to consumers. The lump-sum nature of government expenditures excludes the possibility of having the positive stimulus that would arise from a positive externality in production, as in Bovenberg and de Mooij (1997).

The possibility to obtain the *blue dividend* as a result of the tax reform depends on the relative size of: *i*) the initial reduction on private consumption, because of a crowding-out effect from investment and abatement, and *ii*) the stimulus on economic growth. On the other hand, the *green dividend* depends on: *i*) the relative values of the elasticities of pollution with respect to capital and abatement, and *ii*) the growth stimulus of the tax reform. The effects of a dynamically feasible green reform on economic growth, initial tax revenues and the interest rate are indeterminate a priori, since they are affected in opposite

for debt is exogenously given, and it is used to redistribute the gains from environmental taxes across generations.

[3]The path of pre-committed transfers can be justified in line with Leeper and Yang (2006, page 2): "While is not uncommon for the [Joint Commitee on Taxation of US] Congress to cut transfers payments when faced with revenue shortfalls [due to tax cuts], the federal government frequently resorts to borrowing instead, postponing the inevitable adjustments in spendings or taxes. The federal debt-GDP ratio climbed from 57.4% in 2001 to 65.7% in 2005 (estimate from Economic Report of the President (2005)), partially due to the series of tax cuts introduced since 2001."

direction by the decrease in the income tax rate and the increase in the environmental tax. It will be more difficult to obtain a dynamically feasible reform the larger the implied decrease in initial tax revenues (because the initial deficits will be larger), the lower the increase in growth (because the increase in the future tax base will be lower) and the larger the raise in interest rates (because the cost of repaying the debt will also be larger).

It is not possible to characterize analytical expressions for these cross-effects even in a simple model economy, so that numerical analysis is needed to analyze the possibility of obtaining a double dividend as result of the tax reform. To this end, the main parameters of the model are calibrated according to stylized facts of actual economies. We obtain a wide range of dynamically feasible green tax reforms that yield the double dividend, even under a given ceiling for debt as a proportion of output. This is important for actual economic policy making, as it is illustrated by the tight restrictions on public indebtedness imposed by the Stability and Growth Pact for the European Union. A sensitivity analysis of the results to changes in parameter values is also carried out. Finally, we show that if the reform leading to the Pigouvian, first-best, tax structure is dynamically feasible and generates a double dividend, then it is the second-best tax reform.

We describe the model economy in section 2. In section 3, we define the proposed green tax reforms. In section 4, we simulate the model and explore the results regarding the possibility of achieving a double dividend. The paper ends with some conclusions.

2 The Model

The model economy consists of a large number of infinitely-lived identical households, a single firm and a government. There is no uncertainty in the model. The representative household obtains income each period from interest on savings as well as from transfers received from the government. We assume that population does not grow and, without loss of generality, we normalize its size to one. Hence, variables in the model can be regarded as economy-wide aggregates, or in per capita terms. Household's utility depends positively on consumption and negatively on aggregate pollution: $U(C_t, P_t) = \frac{\left(C_t P_t^{-\eta}\right)^{1-\sigma} - 1}{1-\sigma}$, where C_t, P_t are the levels of consumption and pollution, $\sigma > 0$ is the inverse of the intertemporal elasticity of substitution and $\eta > 0$ is the weight of pollution in utility. This utility function is standard in models with environmental externalities (see Smulders and Gradus (1993), Ligthart and van der Ploeg (1994), or Bovenberg and de Mooij (1997), among others).

The household chooses the levels of consumption (C_t) and wealth (W_t) that maximize the discounted utility function, $\int_0^\infty e^{-\theta t}\ U(C_t, P_t)\ dt$, subject to a sequence of budget constraints, $\dot{W}_t = (1-\tau)\ r_t W_t + T_t + \pi_t - C_t$, given W_0, $\forall t \in [0, \infty)$, where θ denotes the subjective rate of time discount. The return on wealth is r_t , which is subject to a proportional tax rate τ, that can be interpreted as an assets income tax. T_t are lump-sum transfers received from the government, and π_t are dividends received by the representative household as owner of the firm. The household takes the aggregate level of pollution as given.

Solving the household's optimization problem leads to the Keynes-Ramsey rule:

$$\sigma\frac{\dot{C}_t}{C_t}+\eta(1-\sigma)\frac{\dot{P}_t}{P_t}=\left[r_t\left(1-\tau\right)-\theta\right], \tag{1}$$

that determines optimal consumption over time for a given set of tax rates. The usual transversality constraint guaranteeing non-explosive trajectories applies: $\lim_{t\to\infty} e^{-\theta t}\lambda_t W_t = 0$, where λ_t is the Lagrange multiplier for the time t household's budget constraint.

On the other hand, firms produce the single good in the economy using only physical capital (K_t). We assume that the technology is linear (Rebelo (1991))[4]: $Y_t = AK_t$, where A denotes the level of technology. Environmental pollution is regarded as a side product of the production process, and it is increasing in the level of output. Aggregate pollution P_t is a public "bad" which can be reduced by means of abatement activities Z_t which, in turn, consume some output. When abatement activities increase, the stock of capital pollutes less. We assume that P_t and Z_t are both flow variables, so that abatement activities must be renewed each period. The pollution function is:

$$P_t = K_t^{\chi_1} Z_t^{-\chi_2}, \tag{2}$$

where $\chi_1, \chi_2 > 0$ are the elasticities of P_t with respect to physical capital and the abatement activity, respectively. The firm must pay a pollution tax $\tau_{P,t}$ according to the level of pollution P_t.

For simplicity, we assume that the rate of depreciation of physical capital is zero (in line

[4]Despite the lack of realism of an AK technology, we use it because its simplicity precludes substitution among productive factors, making more difficult to achieve a double dividend. Our goal is precisely to see whether a double dividend can arise even in such a simple framework.

with Agell and Persson (2001)). Therefore, letting I_t denote private investment, capital stock accumulates at the rate $\dot{K}_t = I_t$. New output may be transformed into capital, but this process involves adjustment costs. The cost of investment faced by the firm is $\Psi(I_t, K_t) = \left(1 + \frac{\phi}{2}\frac{I_t}{K_t}\right) I_t$, where $\phi \geq 0$ is the adjustment cost parameter (in line with Lucas (1967), Gould (1968) and Treadway (1969)).

The firm maximizes the present value of current and future dividends:

$$\underset{\{I_t, Z_t\}}{Max} \int_0^\infty e^{-\int_0^t r_s ds} \left[AK_t - Z_t - \tau_{P,t} P_t - \left(1 + \frac{\phi}{2}\frac{I_t}{K_t}\right) I_t \right] dt$$

subject to $\dot{K}_t = I_t$, and $P_t = K_t^{\chi_1} Z_t^{-\chi_2}$, given K_0, with first-order conditions:

$$1 = \chi_2 \tau_{P,t} \frac{P_t}{Z_t}, \tag{3}$$

$$r_t = \frac{1}{1 + \phi s_t} \left[A - \chi_1 \tau_{P,t} \frac{P_t}{K_t} + \frac{\phi}{2} s_t^2 + \phi \dot{s}_t \right], \tag{4}$$

where $s_t \equiv I_t / K_t = \dot{K}_t / K_t$ is the investment to capital ratio, as well as the rate of growth rate of physical capital. Condition (3) equates the marginal cost to the marginal benefit to the firm of abatement activities, the latter coming from the reduction in tax payments because of lower pollution. Equation (4) is the arbitrage condition that equates the interest rate to the rate of return on the stock of capital.

Finally, at any point in time the government makes decisions on expenditures, taxation and financing, which are subject to its flow budget constraint:

$$\dot{B}_t + \tau\ r_t W_t + \tau_{P,t}\ P_t = T_t + r_t B_t, \tag{5}$$

which asserts that the government deficit, that is, the aggregate of lump sum transfers (T_t) and interest payments on outstanding debt ($r_t B_t$), net of tax receipts ($\tau\ r_t W_t + \tau_{P,t}\ P_t$), must be financed by issuing additional debt ($\dot{B}_t$).

2.1 The competitive equilibrium

Definition 1 *Given a fiscal policy* $\{\tau, \tau_{P,t}, T_t, B_t\}_{t=0}^{\infty}$*, a competitive equilibrium for this economy is a set of allocations* $\{C_t, W_t, K_t, Z_t, I_t\}_{t=0}^{\infty}$ *and a price system* $\{r_t\}_{t=0}^{\infty}$ *such that: i)* $\{C_t, W_t\}_{t=0}^{\infty}$ *maximize the household utility subject to her budget constraint, taking* $\{W_0\}$ *as given; ii)* $\{K_t, Z_t, I_t\}_{t=0}^{\infty}$ *satisfy the intertemporal maximization conditions, iii) household's wealth is equal to the aggregate of physical capital and the stock of debt outstanding* ($W_t = K_t + B_t$, $\forall t$)*, iv) the government budget constraint is satisfied, and v)* $\{C_t, I_t, Z_t\}_{t=0}^{\infty}$ *satisfy the global constraint of resources:*

$$\left(1 + \frac{\phi}{2}\frac{I_t}{K_t}\right) I_t + C_t + Z_t = AK_t. \tag{6}$$

A balanced growth path (BGP from now) is a competitive equilibrium along which $\{K_t, Z_t, I_t, C_t\}$, as well as the revenues from the pollution tax, all grow at a constant rate γ. Therefore, the environmental tax revenues are a constant percentage of output, $\bar{\tau}_P \equiv \tau_{P,t} P_t / Y_t$.[5] The BGP can then be characterized by the system of equations:

[5] Along a balanced growth path, P_t will grow at a rate $(\chi_1 - \chi_2)\gamma$, while $\tau_{P,t}$ will grow at a rate $[1 - (\chi_1 - \chi_2)]\gamma$.

$$\frac{Z_t}{K_t} = A\chi_2\bar{\tau}_P, \tag{7}$$

$$r = \frac{1}{1+\phi\gamma}\left[A(1-\chi_1\bar{\tau}_P) + \frac{\phi}{2}\gamma^2\right], \tag{8}$$

$$\frac{\dot{K}_t}{K_t} = \frac{\dot{Z}_t}{Z_t} = \frac{\dot{C}_t}{C_t} = s = \gamma = \frac{1}{\tilde{\sigma}}\left[(1-\tau)r - \theta\right], \tag{9}$$

$$\frac{C_t}{K_t} = A(1-\chi_2\bar{\tau}_P) - \left(1+\frac{\phi}{2}\gamma\right)\gamma, \tag{10}$$

$$P_t = P_0\ e^{(\chi_1-\chi_2)\gamma t} = K_0^{\chi_1-\chi_2}\ \left(A\chi_2\bar{\tau}_P\right)^{-\chi_2}\ \ e^{(\chi_1-\chi_2)\gamma t}, \tag{11}$$

where $\tilde{\sigma} \equiv \sigma + (\chi_1 - \chi_2)\,\eta(1-\sigma)$, which reduces to the inverse of the intertemporal elasticity of substitution of consumption when pollution does not enter in the utility function or under the standard assumption in the literature that $\chi_1 = \chi_2$. We assume that $\bar{\tau}_P < 1/\chi_1$, because it guarantees that the interest rate is positive in the absence of adjustment costs (see (8)). This condition on $\bar{\tau}_P$ always holds under empirically plausible values of χ_1.

In spite of the presence of adjustment costs, the next proposition shows that the same condition guaranteeing a positive interest rate also implies that the BGP lacks any transitional dynamics.

Proposition 1 *Under condition $\tilde{\sigma} > \frac{1-\tau}{2}$: i) There exists a positive interest rate along the BGP, and ii) The solution to the competitive equilibrium lacks any transitional dynamics.*
Proof*: see appendix.*

We will only consider parameterizations with $\tilde{\sigma} > 1$, guaranteeing that the after-tax real interest rate is larger than the rate of economic growth[6], and consequently, that time

[6]From (9), we have that $(1-\tau)r > \gamma \Leftrightarrow \theta > (1-\tilde{\sigma})\gamma$, which always holds if $\tilde{\sigma} > 1$.

aggregate utility is bounded. From Proposition 1, this condition also guarantees that the competitive equilibrium takes the form of a BGP[7]. This condition will hold under the standard assumptions $\sigma > 1$, $\chi_2 = \chi_1$. It will also hold if $\chi_1 > \chi_2$, provided the difference between both parameters is small.[8]

3 Green tax reform experiments

In our model economy, higher environmental taxes will tend to reduce after-tax productivity, lowering the incentives for capital accumulation and negatively influencing long-run growth, while the income tax cut will yield the opposite effects. Hence, the final effect on growth of the tax reform is indeterminate. The following proposition shows[9] that if the green tax reform is designed to leave a balanced budget the first period it is introduced[10] (this is the standard tax reform considered in the literature), growth will permanently decrease and hence, the blue dividend will not emerge. Furthermore, since we assume that the government has a pre-committed path of transfers, such tax reforms would not be feasible: the new path for revenues would fall every period below the path of transfers to consumers.

Proposition 2 *In our model economy, a green tax reform that leaves a balanced budget the first period it is introduced, will permanently reduce growth.* ***Proof****: see appendix.*

[7] It is straightforward to show that if $\tilde{\sigma} > 1$, the BGP of the planner's problem also lacks any transitional dynamics (applying proof of prop. 1 to planner solution).

[8] Pollution would decrease over time regardless of the environmental tax policy implemented whenever $\chi_1 < \chi_2$, a case which we exclude from analysis.

[9] The analytical result is available only for the case without adjustment costs ($\phi = 0$), although it can also be seen to arise numerically for $\phi > 0$.

[10] The larger revenues from the environmental source -due to the pollution tax *rise*- exactly offset the lower revenues from non-environmental sources -due to the assets income tax *cut*.

This result shows that achieving a blue dividend in our model economy would require a tax reform unavoidably leading to an initial fall in revenues.[11] Since expenditures are given, the consequence of such tax reform is an initial budget deficit. Hence, to achieve a double dividend the government must be allowed to issue some debt. Only then could a financially feasible tax reform be able to increase economic growth, while achieving a green and a blue dividend simultaneously. Given a time path of pre-committed government expenditures, a green tax reform is said to *be dynamically feasible* if it leads to a tax mix of income and environmental tax rates satisfying the present value government budget constraint. These are tax reforms leading to an increase in the base by enough to allow for eventually retiring the debt that was issued to cover the budget deficits produced at the time of the tax reform.[12]

The possibility to obtain the *blue dividend* as a result of the reform depends on the effect on the rate of growth, as well as on the effect on private consumption at the period of the reform. The level of consumption falls immediately after that tax reform because of a crowding-out effect from abatement and investment. On the other hand, the *green dividend* depends on the elasticity of pollution with respect to capital relative to the elasticity of pollution with respect to abatement, as well as on the effect on growth.[13] As mentioned

[11] To enhance growth, the income tax cut must be larger -for a given environmental tax rise- than in the situation considered in proposition 2, implying that revenues will fall with respect to the baseline case.

[12] The definition of a dynamically feasible green tax reform above relates to what is known in the literature as a dynamic Laffer effect. Such effect may arise in endogenous growth economies in which the rate of growth of output depends negatively from income tax rates. An income tax cut, accompanied of some debt issuing can then be self-financed because of the implied increase in the future tax base, as explained above. [See Ireland (1994), Pecorino (1995), Milesi-Ferreti and Roubini (1998), Agell and Persson (2001) or Novales and Ruiz (2002), all of them for non-environmental economies].

The initial need for debt financing shows that our tax reforms initially lead to lower fiscal revenues, which are eventually compensated over time. In that sense, we could also talk of dynamic Laffer effects.

[13] If $\chi_1 = \chi_2$, then $P_t = (A\chi_2\bar{\tau}_P)^{-\chi_2}$, and the environmental gain is ensured for any tax reform that consists of increasing the pollution tax rate. But if $\chi_1 > \chi_2$ and the growth rate increases after the reform,

in the introduction, it is not possible to characterize analytical expressions for these cross-effects even in our simple economy, so that numerical analysis is needed to analyze the possibility of obtaining a double dividend as result of the tax reform.

We define the *green* and *blue* dividends in terms of welfare gains, similarly to definitions used in the literature on dynamic general equilibrium models (Chamley (1981), Lucas (1987), Cooley and Hansen (1992) or Judd (1997)). We start by computing the total welfare effects (TWE) associated to a green tax reform, measured by the change in consumption (as a percentage of output) that an individual would require each period to be as well off under the initial situation as under the new tax structure. To isolate the blue dividend (BD), we also compute the change in consumption needed to have the same level of welfare under the initial and the new tax structure, this time assuming that the time path of pollution remains the same as before the tax reform. We compute the green dividend (GD) similarly, assuming in this case that the time path of consumption is the same as before the tax reform. The decomposition of TWE into BD and GD is nonlinear, so that TWE can not be obtained by adding BD and GD. See appendix for more details. As in the literature on dynamic Laffer effects, the set of dynamically feasible tax reforms must be numerically characterized. Hence, the analysis of double dividend is also numerical.

the pollution path starts below the path before the reform -due to the incentive on abatement activities resulting from the increase in the pollution tax rate-. After a finite number of periods, the level of pollution will exceed the level of pollution corresponding to the initial tax mix due to the increase in growth. The sign of the discounted effect on environmental welfare must be numerically computed.

3.1 Tax experiment

For simplicity, we take the ratio of environmental tax revenues to output as the policy variable.[14] Given an initial tax mix (τ^0,$\bar{\tau}_P^0$), we assume the economy to be initially on a BGP, with a rate of growth γ_0 for all variables. Taking into account that $\bar{\tau}_P \equiv \tau_{P,t} P_t / Y_t$, $W_t = K_t + B_t$, into (5) and the fact that the government is not issuing debt before the tax reform ($B_{t,0} = 0$, $\forall t$), we can write the path for government transfers before the tax reform, $T_{t,0}$, as:

$$T_{t,0} = \left(A\bar{\tau}_P + \tau r \right) K_{t,0} = \left(A\bar{\tau}_P + \tau r \right) K_0 \ e^{\gamma_0 t}. \tag{12}$$

We assume that the government is committed to guarantee such transfers path ($T_{t,0}$), which must be taken into account when the tax mix is designed. In this context, the government considers the possibility that the current tax structure could be inefficient, in the sense that a tax reform might exist that could achieve a double dividend. Such reform will consist of raising the environmental tax ($\bar{\tau}_P^1 > \bar{\tau}_P^0$) at the same time than lowering the income tax ($\tau^1 < \tau^0$). Let us denote by γ_0 the growth rate before the reform and by γ_1, r_1, $K_{t,1}$ the growth rate, the real interest rate and the trajectory for the stock of capital after the green tax reform. We assume that the reform takes place at $t = 0$.

A green tax reform is dynamically feasible in our setup if the present value government budget constraint holds. Using the terminal constraint for debt ($\lim_{t\to\infty} e^{-(1-\tau)rt} B_t = 0$), that will be the case if the present value of expenditures ($\int_0^\infty e^{-r_1(1-\tau^1)t} T_{t,0} dt$) is not larger

[14] Since the stock of capital is predetermined, there is a one-to-one relationship between the environmental tax rate and the ratio of the environmental tax revenue to output:
$\bar{\tau}_P = \left(\chi_2^{\chi_2/(1+\chi_2)} / A \right) K_t^{\frac{\chi_1 - 1 - \chi_2}{1+\chi_2}} \tau_{P,t}^{\frac{1}{1+\chi_2}}.$

than the present value of revenues $\left(\int_0^\infty e^{-r_1(1-\tau^1)t}\left(A\bar{\tau}_P^1+\tau^1 r^1\right)K_{t,1}dt\right)$, i.e., if:

$$\frac{A\bar{\tau}_P^0+\tau^0 r_0}{r_1(1-\tau^1)-\gamma_0}\leq\frac{A\bar{\tau}_P^1+\tau^1 r_0}{r_1(1-\tau^1)-\gamma_1}. \tag{13}$$

Among all such reforms, we only consider those satisfying the condition $\gamma_1 \geq \gamma_0$; this condition is necessary for the blue dividend to arise. Furthermore, together with $\tilde{\sigma} > 1$, it guarantees a finite present value for government revenues and expenditures[15].

Since these reforms generate initial deficits, debt issuing is needed. A high stock of debt outstanding, in terms of output, is not a problem in a deterministic economy like ours, but for the sake of realism, we will limit our attention to tax reforms leading to a maximum stock of debt below 60% of output (the limit imposed in the Stability and Growth Pact of the European Union). To that end, we compute the time period at which the ratio of stock of debt to output is largest (see appendix). The maximum stock of debt is $b_{t^*}=\frac{T_0\left[e^{\left((1-\tau^1)r_1-\gamma_1\right)t^*}-e^{(\gamma_0-\gamma_1)t^*}\right]}{AK_0[(1-\tau^1)r_1-\gamma_0]}-\frac{\left(A\bar{\tau}_P^1+\tau^1 r^1\right)\left[e^{\left((1-\tau^1)r_1-\gamma_1\right)t^*}-1\right]}{AK_0[(1-\tau^1)r_1-\gamma_1]}$, with

$$\begin{aligned} t^* &= -\frac{\ln[\Omega]}{(1-\tau^1)r_1-\gamma_0}, \qquad (14)\\ \text{where } \Omega &\equiv \left[\frac{T_0}{(1-\tau^1)r_1-\gamma_0}-\frac{\left(A\bar{\tau}_P^1+\tau^1 r^1\right)K_0}{[(1-\tau^1)r_1-\gamma_1]}\right]\frac{[(1-\tau^1)r_1-\gamma_1]\,[(1-\tau^1)r_1-\gamma_0]}{T_0(\gamma_0-\gamma_1)}. \end{aligned}$$

The range of parameter values for which (13) is satisfied cannot be analytically determined. However, it is possible to evaluate numerically whether a proposed tax reform satisfies (13) under specific values for the structural and policy parameters. Among them,

[15]Since we only consider parameterizations for which $\tilde{\sigma} > 1$, then $r_1(1-\tau^1)-\gamma_1 > 0$. As $\gamma_0 \leq \gamma_1$, then $r_1(1-\tau^1)-\gamma_0 > 0$. Both conditions guarantee a finite present value for government revenues and expenditures.

we will pay special attention to those implying $b_{t^*} \leq 60\%$.

4 Simulation analysis

4.1 Parameterization and results

We simulate the model economy by choosing benchmark parameter values consistent with stylized facts for actual economies. The tax rate on pollution before the reform is set so that the environmental tax revenues to output ratio ($\bar{\tau}_P^0$) is 2.7%, the average value reported for European Union (eu25) in Eurostat. The parameter $\chi_2 = 0.3704$ is chosen so that the abatement spending to output ratio replicates the 1% level observed for actual economies (see statistics in Eurostat[16]). The initial income tax rate (τ_0) is 23%. The inverse of the intertemporal elasticity of substitution (σ) is 1.1, and the parameters related to pollution are $\eta = 0.2$, $\chi_1 = \chi_2$ (so that the level of pollution does not grow). The adjustment cost parameter is $\phi = 3$. Additionally, $A = 0.0441$ and $\theta = 0.0056$ so that the after-tax real rate of interest ($(1-\tau_0)r_0$) is 3.2% and growth (γ_0) is 2.4% per year, in line with values usually reported for the US economy.[17] Without loss of generality we assume $K_0 = 1$.

For a given increase in the pollution tax, there is a certain range of cuts in the income tax rate that can be used as part of a feasible tax reform in the sense of allowing for

[16]PAC (Pollution Abatement and Control) expenditures by the private sector as a percentage of GDP (OECD Report based on the 2002 questionnaire on PAC expenditure and revenues). See OECD (2003).

[17]Note that when $\chi_1 = \chi_2$, if $(1-\tau)r > 0$ and $\gamma > 0$, then $\sigma < \frac{(1-\tau)r}{\gamma}$ is needed to guarantee $\theta > 0$. That limits considerably the range of values for σ. Not imposing any condition on interest rates or growth would allow for a wider range of values for σ,but some of them would make more difficult to obtain dynamically feasible green tax reforms (see Novales and Ruiz (2002), for a non-environmental economy).

condition (13) to hold. The intuition is simple. If the income tax cut is too low, the rate of growth decreases. If the income tax cut is too large, the initial deficit will be very large, and condition (13) might fail to hold, even though the increase in growth will also be remarkable. Therefore, there is a range of feasible income tax cuts, the lower limit of that range fulfilling condition (13) as an equality, while the rest lead to a present value budget surplus.

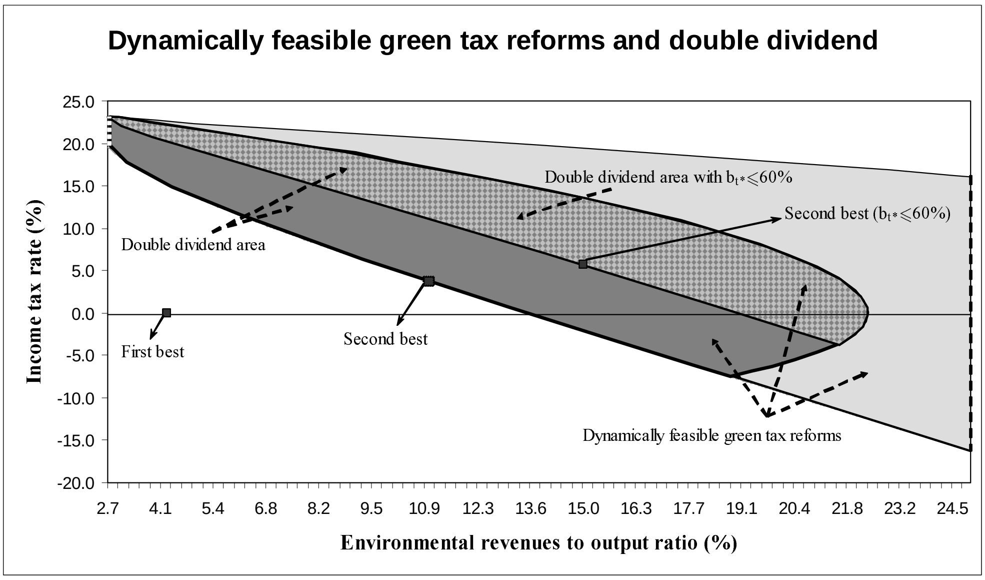

Figure 1 shows the $(\tau^1, \bar{\tau}_P^1)$-pairs resulting from dynamically feasible green tax reforms, those satisfying (13) and $\gamma_1 \geq \gamma_0$. The horizontal axis displays the environmental revenues to output ratio after the reform, starting from $\bar{\tau}_P^0 = 2.7\%$ (the calibrated level). The vertical axis shows the income tax rate after the reform, with the initial tax, $\tau^0 = 23\%$, as an upper bound. The upper limit of the shadowed area in Figure 1 corresponds to the minimum income tax cut that it is dynamically feasible, for every pollution tax rate. The lower limit of the shadowed area corresponds to the maximum income tax cut that yields, for every pollution tax rate, a dynamically feasible reform. This region is open from the left, not including the vertical axis, that corresponds to reforms leaving the environmental tax unaltered, because the green dividend then does not arise. There are dynamically feasible green tax reforms with a rise in pollution tax higher than considered in figure 1, but the double dividend is never present.

The larger the rise in the pollution tax, the larger the increase in environmental tax revenues, so that a given income tax rate cut leads to a lower initial deficit, making easier that the initial debt can be eventually retired. Hence, the lower limit of the shadowed area is decreasing.

Since $\chi_1 = \chi_2$ in our benchmark parameterization, any feasible green tax reform in Figure 1 achieves at least the green dividend ($GD > 0$), because the new pollution path will always lie below the initial pollution path. Among the dynamically feasible green tax reforms, only those inside the darker shadowed and the dotted areas display green tax reforms that also yield a blue dividend. The difference between both regions is that the dotted area contains feasible green tax reforms for which the maximum debt to output ratio does not surpass 60% (that is, $b_{t^*} \leq 60\%$). The blue dividend is not present for those reforms outside those two regions (the pale non-dotted area) because the initial fall in consumption is large relative to the growth stimulus.

A double dividend with a highest level of public debt below 60% of output arises for a wide range of green tax reforms: under the benchmark parameterization, the double dividend can be obtained for levels of the environmental tax revenues to output ratio $\bar{\tau}_P^1 \in (2.7\%, 22.3\%)$. Among them, the highest welfare gain is obtained for a green tax reform changing taxes from the initial levels of $\tau^0 = 23\%$, $\tau_P^0 = 2.7\%$ to: $\tau^1 = 5.6\%$, $\bar{\tau}_P^1 = 15\%$ (*second-best* tax reform *constrained* by the 60% debt ceiling), with: $TWE = 11\%$, made up by a $GD = 4.6\%$ and a $BD = 5.8\%$. The debt constraint is binding.

If we would not impose the 60% upper ceiling on public indebtedness, then we could implement a dynamically feasible green tax reform with substantially larger welfare gains. The green tax reform that yields the maximum welfare consists of changing tax rates form their initial levels to: $\tau^1 = 3.9\%$, $\bar{\tau}_P^1 = 10.9\%$ (non-constrained *second-best* tax reform), with a total welfare gain: $TWE = 14.3\%$ ($GD = 4.6\%$ and $BD = 8.7\%$), but with an excessive stock of debt: $b_{t^*} = 1557\%$.

We think of the Pigouvian tax mix in our framework as the tax scheme that eliminates all tax distortions and externalities (that is, the first-best tax mix). In our model economy, the Pigouvian tax mix will always involve a zero income tax and an environmental tax rate which generates an environmental revenues to output ratio as the one computed in appendix. For our parameterization, the Pigouvian environmental tax generates a pollution tax revenues to output ratio equal to 4.4%. The reform leading to the Pigouvian tax mix is not dynamically feasible, as it is shown in Figure 1 and hence, it is not implementable. Implementing the Pigouvian level for the environmental tax and the lowest feasible income tax, $\tau^1 = 14.8\%$ (that is, the projection of the first-best tax mix on the lowest limit of the dynamically feasible area) is not the second-best tax reform. In fact, the largest welfare gain is obtained through a larger cut in the income tax ($\tau^1 = 3.9\%$) at the expense of a larger pollution tax ($\bar{\tau}_P^1 = 10.9\%$). This reflects the fact that the environmental tax is less distortionary as a revenue-raising device than the income tax.

Finally, Figure 1 allows us to quantify the pre-existing non-environmental inefficiency of the tax system, in particular, the dynamic inefficiency of the time profile of income tax revenues. To that end, we maintain $\bar{\tau}_P^0 = 2.7\%$, and obtain the largest income tax cut which is dynamically feasible (3.4 percentage points), leading to $\tau^1 = 19.6\%$. Such tax cut achieves the largest welfare gain conditioned on $\bar{\tau}_P^0 = 2.7\%$ ($TWE = BD = 3.5\%$), a measure of the dynamic inefficiency of the initial tax system on non-environmental grounds.

4.2 Sensitivity analysis

In Table 1 we show that is possible to find a wide range of dynamically feasible tax reforms yielding a double dividend. Furthermore, we display for every parameter case the second-best tax reforms, that is, the reforms achieving the largest welfare gain, while simultaneously satisfying the debt constraint ($b_{t^*} \leq 60\%$). The values of $\{A, \theta, \chi_2\}$ are adjusted to guarantee that before the tax reform, the economy is characterized by an after-tax rate of interest $R_0 = (1 - \tau_0)r_0 = 3.2\%$, a growth rate $\gamma_0 = 2.4\%$ and an abatement to output ratio equal to 1%. Hence, the sensitivity analysis is carried out for the remaining parameters, $\{\sigma, \phi, \chi_1\}$. We also change the levels of $\{\tau_0, \gamma_0, R_0\}$ because they affect the range of dynamically feasible reforms. We study the effects of changes in η in table 2.

Table 1. Dynamically feasible tax reform yielding double dividend. Sensitivity Analysis

	Double Dividend Range for $\bar{\tau}_P$	$\left(\bar{\tau}_P^{SB}, \tau^{SB}\right)$	γ^{SB}	TWE^{SB}	BD^{SB}	GD^{SB}
Benchmark	**(2.7, 22.3)**	**(15.0, 5.6)**	**2.9**	**11.0**	**4.6**	**5.8**
$\sigma = 1.3$	(2.7, 19.9)	(14.4, 7.4)	2.8	8.3	2.4	5.6
$\phi = 0$	(2.7, 22.2)	(15.2, 6.1)	2.9	10.5	4.2	5.7
$\chi_1 = 0.5 > \chi_2$	(2.7, 22.7)	(15.3, 5.9)	2.8	9.4	3.7	5.2
$\tau^0 = 15\%$	(2.7, 11.7)	(10.2, 5.1)	2.6	4.0	0.2	3.8
$\gamma_0 = 2\%$	(2.7, 17.6)	(14.7, 7.3)	2.4	7.8	0.7	7.0
$R_0 = 4\%$	(2.7, 16.8)	(14.5, 7.3)	2.9	7.7	0.5	7.2

Notes: i) Implementing any second-best tax reform, in column 2, leads to a maximum debt to output ratio of 60%; ii) $SB \equiv$ Second-Best; iii) $\gamma^{SB} \equiv$ Growth rate resulting from the second-best tax reform; iv) *TWE*, *BD* and *GD* are the welfare gains (total, blue and green) as a percentage of output (see definitions in appendix).
v) Benchmark: $\sigma = 1.1$; $\phi = 3$; $\eta = 0.2$; $\chi_1 = \chi_2 = 0.3704$; $A = 0.0441$; $\theta = 0.0056$; $\tau^0 = 23\%$; $\bar{\tau}_P^0 = 2.7\%$; $\gamma_0 = 2.4\%$; $R_0 = 3.2\%$.

Column 1 of Table 1 displays the range for $\bar{\tau}_P$ for which the double dividend results. In all the cases, the lower limit of the interval corresponds to the initial rate ($\bar{\tau}_P^0 = 2.7\%$), obtained from Eurostat data. For example, for the benchmark case, we find that it is possible to increase environmental revenues (as a percentage of output) from 2.7% up to 22.3%. It can be seen that this range is remarkably wide for any of the parameter cases analyzed.

It is easier to obtain dynamically feasible tax reforms (and hence, the double dividend area is wider) : *i*) the larger the intertemporal elasticity of substitution (lower σ), because that increases the growth stimulus of an income tax cut[18] and hence, increases the expansion of future tax base; *ii*) the larger the adjustment cost (ϕ), because the new stock of capital will be productive at a slower rate, generating a lower after-taxes interest rate and leading to a lower debt service; *iii*) when $\chi_1 > \chi_2$, because the pollution path is then increasing and hence, the environmental tax base is also increasing, allowing for larger income tax cuts.

The key parameters conditioning the double dividend area are: the initial income tax rate (τ_0), the initial growth rate (γ_0) and the initial after-tax interest rate (R_0). A decrease in τ_0 or γ_0, or an increase in R_0, would make more difficult to obtain dynamically feasible reforms, and hence, would reduce the possibility to obtain the blue dividend. The lower the initial income tax rate, the lower the possibility to obtain growth enhancing tax cuts and to generate enough revenues to balance the present value government budget constraint. Since θ is adjusted to replicate the calibrated growth rate, the lower the initial growth rate,

[18]Note that for low values of σ, the reduction in the income tax rate increases the after tax interest rate, with an even larger effect on growth (see (9)).

the higher the discount rate θ. A larger θ makes harder to increase growth through tax cuts, thus being more difficult to expand the future tax base. Finally, the larger the initial interest rate, the larger the debt service after the reform and, hence, the more difficult the repayment of outstanding debt.

Columns 2 to 6 displays for every parameterization, the second-best tax reform and the associated growth rate, as well as the total welfare gain and its two components, the blue and green dividends. In all cases, the debt constraint $b_{t^*} \leq 60\%$ has been taken into account and the second-best result implies that such constraint is always binding. In general, the welfare gains are lower the narrower the double dividend area. With respect to the composition of welfare gains, it can be seen that the blue dividend and the green dividend are both sizeable. In the last three rows, in which the range of dynamically feasible reforms is substantially narrower, the blue dividend is seriously harmed with respect to the green dividend.

The objective of table 2 is twofold: i) analyzing how the results are affected by changes in η ; ii) studying the second-best solution when the first-best solution is dynamically feasible. To this end, the η parameter is crucial, since increments in it rise the Pigouvian environmental tax rate, making easier that the Pigouvian tax mix falls inside the region of dynamically feasible green tax reforms.

The first column shows whether the debt constraint is taken into account or not. The second and third columns show the first-best and second-best tax mixes. The fourth column displays the maximum level of debt reached under the second-best policy. Columns 5 to 8 show the growth rate and welfare measures corresponding to implementing the second-best tax reform. Finally, the last column includes the range of $\overline{\tau}_P$ yielding the double dividend.

Tabla 2. The first-best versus the second-best tax mix.

	Debt constraint	$\left(\overline{\tau}_P^{FB}, \tau^{FB}\right)$	$\left(\overline{\tau}_P^{SB}, \tau^{SB}\right)$	b_{t^*}	γ^{SB}	TWE^{SB}	BD^{SB}	GD^{SB}	Double Dividend Range for $\overline{\tau}_P$
Benchmark $\eta = 0.2$	$b_{t^*} \leq 60\%$	**(4.4, 0)**	**(15.0, 5.6)**	**60%**	**2.9**	**11.0**	**4.6**	**5.8**	**(2.7, 22.3)**
$\tau^0 = 23\%$	Unconstrained		**(10.9, 3.9)**	**1557%**	**3.0**	**14.3**	**8.7**	**4.6**	
$\eta = 0.8$	$b_{t^*} \leq 60\%$	(17.1, 0)	(18.6, 0.5)	60%	3.0	38.0	2.9	32.9	(2.7, 22.3)
$\tau^0 = 23\%$	Unconstrained		(17.1, 0)	217%	3.1	38.1	4.1	31.1	
$\eta = 0.7$	$b_{t^*} \leq 60\%$	(15.8, 0)	(10.8, 4.4)	60%	2.7	15.9	0.03	15.9	(2.7, 11.7)
$\tau^0 = 15\%$	Unconstrained		(11.7, 0)	659%	2.8	17.0	0.024	17.0	

Notes: i) *FB*≡First-Best (Pigouvian); *SB*≡Second-Best. ii) *TWE*, *BD* and *GD* are the welfare gains (total, blue and green) as a percentage of output (see definitions in appendix); iii) γ^{SB} ≡Growth rate resulting from the second-best tax reform; iv) b_{t^*} is the largest debt to output ratio on debt path generated by the green tax reform.
iv) Benchmark: $\sigma = 1.1; \phi = 3; \eta = 0.2; \chi_1 = \chi_2 = 0.3704;$ $A = 0.0441; \theta = 0.0056; \tau^0 = 23\%; \overline{\tau}_P^0 = 2.7\%; \gamma_0 = 2.4\%; R_0 = 3.2\%$.

We obtain two remarkable findings: *i*) the η parameter does not have any effect on the region of dynamically feasible green tax reforms nor on the region for double dividend tax reforms. This is because when $\chi_1 = \chi_2$, the balanced growth path does not depend on η. However, this parameter will affect the welfare gain. The larger the environmental concern, the larger the agents' willingness to give up a non-environmental welfare gain in favor of a larger environmental welfare gain, which is attained for a larger environmental tax rate; and *ii*) if the reform leading to the first-best or Pigouvian tax mix is dynamically feasible and generates a double dividend, then it is the second-best tax reform (see second row, for $\eta = 0.8$, $\tau_0 = 23\%$, when the debt ceiling is not taken into account). If the reform leading to the Pigouvian tax mix is dynamically feasible but it does not generate a double dividend, then the second-best income tax rate will be zero, i.e., equal to the Pigouvian income tax and the second-best environmental tax will be the largest level that generates a double dividend, given that $\tau^{SB} = 0$ (see third row, for $\eta = 0.7$, $\tau_0 = 15\%$, when the debt constraint is not taken into account).

5 Conclusions

An income tax system is said to be *intertemporally inefficient* whenever it is possible to finance the same trajectory of government expenditures with a lower sequence of income tax rates, potentially leading to a gain in non-environmental welfare. This type of inefficiency has not been previously analyzed in environmental frameworks. A second, *cross-sectional type of tax inefficiency* -widely exploited in the environmental literature- arises when a relatively inefficient tax system on commodities or productive factors takes the competitive equilibrium allocation away from that solving the planner's problem. The contribution of this paper is to show that there are situations in which the two types of inefficiency can be corrected simultaneously.

That a double dividend can sometimes be achieved has already been shown in dynamic economies when there is a sufficiently important negative externality of pollution in production. We show in this paper that such a condition is not necessary for a double dividend to arise. The reason is that an active public sector financing policy that uses debt issuing in combination with tax revenues may easily allow for a higher income tax cut, with a more important stimulus for future growth of the tax base.

Specifically, we have shown in a relatively simple model economy, under reasonable values for the structural parameters and tax rates, that a government committed to a given sequence of lump-sum transfers to the private sector can sometimes implement a dynamically feasible green tax reform that allows for fulfilling its commitment to the private sector while achieving a double dividend. Since the proposed reform includes debt issuing, there is a shift in tax burden from the present to the future (outstanding debt is well-known to be equivalent to lump-sum taxes in a representative agent's general equilibrium models without uncertainty). This is justifiable from an environmental point of view: since present generations bear the cost of the environmental reform while future generations benefit from a cleaner environment, it seems fair that the former are compensated by a decrease of taxes while the latter bear a larger tax burden.

Among the range of tax reforms leading to a double dividend, the one producing the largest welfare gain could use an environmental tax above or below the environmental Pigouvian level. We show that if the reform leading to the Pigouvian, first-best, tax structure is dynamically feasible and generates a double dividend, then it is also the second-best reform.

The implementation of our policy reform could seem very attractive in actual policy making since: *i*) substituting debt for distortionary taxation should get a strong social support for the green reform and, *ii*) the stock of debt outstanding as a consequence of the proposed tax reform may be quite reasonable at each point in time, as a proportion of output.

Introducing uncertainty in the economy would allow us to consider the effects on interest payments and on consumers' expectations of an increase in risk premium due to a sizeable stock of government debt. The extent to which uncertainty makes more difficult the possibility of achieving a double dividend is left for future research. Considering an economic structure with a non-trivial transition to steady-state following a policy intervention may significantly affect the possibility of obtaining a dynamic Laffer effect, and hence, a double dividend, and it is also left as a possible extension of this research.

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7 Appendix

Proof of proposition 1:

i) Positive interest rate:

Let us denote $\psi_1 \equiv \frac{\phi}{\tilde{\sigma}}(1-\tau)\left(1-\frac{1-\tau}{2\tilde{\sigma}}\right)$, $\psi_2 \equiv 1+\frac{\phi\theta}{\tilde{\sigma}}\left(\frac{1-\tau}{\tilde{\sigma}}-1\right)$, and $\psi_3 \equiv A(1-\chi_1\bar{\tau}_P)+\frac{\phi\theta^2}{2\tilde{\sigma}^2}$. Equations (9) and (8) can be collapsed into: $\psi_1 r^2+\psi_2 r-\psi_3=0$, a second degree equation characterizing the interest rate along the BGP:

$$r=\frac{-\psi_2 \pm \left[\psi_2^2+4\psi_1\psi_3\right]^{1/2}}{2\psi_1}. \tag{15}$$

Condition $\bar{\tau}_P<1/\chi_1$ implies $\psi_3>0$, while $\tilde{\sigma}>\frac{1-\tau}{2}$ implies $\psi_1>0$ and the square bracket in the expression for r is positive. Then, expression (15), taken with the positive sign, yields a real, positive interest rate.

ii) The BGP lacks any transitional dynamics:

Using (1), (2), (3), (4), and $\bar{\tau}_P \equiv \tau_{P,t}P_t/Y_t$ it can be shown that:

$$\sigma\left(\frac{\dot{C}_t}{C_t}-\frac{\dot{K}_t}{K_t}\right)+\tilde{\sigma}s_t=\frac{1-\tau}{1+\phi s_t}\left[A(1-\chi_1\bar{\tau}_P)+\frac{\phi}{2}s_t^2+\phi\dot{s}_t\right]-\theta. \tag{16}$$

Using (6) together with $\dot{K}_t = I_t$ and (3) we get

$$\left(\frac{\dot{C}_t}{C_t} - \frac{\dot{K}_t}{K_t}\right) = -\frac{(1+\phi s_t)\dot{s}_t}{A(1-\chi_2\bar{\tau}_P) - \left(1+\frac{\phi}{2}s_t\right)s_t}. \tag{17}$$

From (16) and (17): $\dot{s}_t = \frac{\Gamma_1(s_t)}{\Gamma_2(s_t)}$, where $\Gamma_1(s_t) \equiv \theta + \tilde{\sigma}s_t - \frac{1-\tau}{1+\phi s_t}\left[A(1-\chi_1\bar{\tau}_P) + \frac{\phi}{2}s_t^2\right]$ and $\Gamma_2(s_t) \equiv \frac{\sigma(1+\phi s_t)}{A(1-\chi_2\bar{\tau}_P)-\left(1+\frac{\phi}{2}s_t\right)s_t} + \frac{(1-\tau)\phi}{1+\phi s_t}$.

Note that the steady state for s is stable if $\left.\frac{\partial \dot{s}_t}{\partial s_t}\right|_{s_t=s} < 0$. However,

$$\left.\frac{\partial \dot{s}_t}{\partial s_t}\right|_{s_t=s} \underbrace{=}_{\text{note that } \Gamma_1(s)=0} \frac{\tilde{\sigma} + \phi\theta + \phi s\left(2\tilde{\sigma} - (1-\tau)\right)}{(1+\phi s)\Gamma_2(s)},$$

which is positive if $\tilde{\sigma} > \frac{1-\tau}{2}$. Therefore, only if s_t grows at a constant rate can the transversality condition be guaranteed to hold. Hence, the competitive equilibrium solution will always be on the balanced growth path.■

Proof of proposition 2.

We consider $\phi = 0$. Let us denote by $rev_{t,0}$ and $rev_{t,1}$ the tax revenues before and after the tax reform. Let us denote by $(\tau^0, \bar{\tau}_P^0)$ and $(\tau^1, \bar{\tau}_P^1)$ the tax mix before and after the tax reform, where $\bar{\tau}_P^1 > \bar{\tau}_P^0$. Let us denote by γ_0 and γ_1 the growth rate before and after the reform. Note that, before the reform: $T_t = rev_{t,0}$, and $rev_{t,i} = \left(\tau^i r_i + \bar{\tau}_P^i A\right) K_0 e^{\gamma_i t}$, where $r_i = A(1-\chi_1\bar{\tau}_P^i)$, $i = 0, 1$, since $\phi = 0$. We assume that the tax reform takes place at $t = 0$. Hence, $rev_{0,0} = rev_{0,1} \Leftrightarrow \tau^0 r_0 + \bar{\tau}_P^0 A = \tau^1 r_1 + \bar{\tau}_P^1 A$; so, given $(\tau^0, \bar{\tau}_P^0)$ and $\bar{\tau}_P^1$:

$$\tau^1 = \frac{\tau^0(1-\chi_1\bar{\tau}_P^0) + \bar{\tau}_P^0 - \bar{\tau}_P^1}{1-\chi_1\bar{\tau}_P^1}. \tag{18}$$

From (9), $\gamma\tilde{\sigma} = (1-\tau)r - \theta$. So, $\gamma_0 - \gamma_1 > 0 \Leftrightarrow (1-\tau_0)r_0 - (1-\tau_1)r_1 > 0 \Leftrightarrow (1-\tau^0)(1-\chi_1\bar{\tau}_P^0) - (1-\tau^1)(1-\chi_1\bar{\tau}_P^1) > 0 \Leftrightarrow (1-\tau^0)(1-\chi_1\bar{\tau}_P^0) - (1-\chi_1\bar{\tau}_P^1) + [\tau^0(1-\chi_1\bar{\tau}_P^0) + \bar{\tau}_P^0 - \bar{\tau}_P^1] > 0 \Leftrightarrow (\bar{\tau}_P^1 - \bar{\tau}_P^0)(1+\chi_1) > 0$ where we have used (18) and $\bar{\tau}_P^1 > \bar{\tau}_P^0$.■

Characterizing the largest stock of debt

We compute the stock of debt at time t as $B_t = \int_0^t e^{-(1-\tau^1)r^1(t-s)}\left[T_{s,0} - \left(A\bar{\tau}_P^1 + \tau^1 r^1\right)K_{s,1}\right]ds$, which, as a percentage of output, is

$$b_t = \frac{T_0\left[e^{\left((1-\tau^1)r^1-\gamma_1\right)t} - e^{(\gamma_0-\gamma_1)t}\right]}{AK_0\left[(1-\tau^1)r^1-\gamma_0\right]} - \frac{\left(A\bar{\tau}_P^1 + \tau^1 r^1\right)\left[e^{\left((1-\tau^1)r^1-\gamma_1\right)t} - 1\right]}{AK_0\left[(1-\tau^1)r^1-\gamma_1\right]}. \quad (19)$$

Maximizing b_t with respect to t , we get (14). Then, the maximum stock of debt, denoted by b_{t^*}, would be obtained by substitution of (14) in (19).

Measures of total welfare gain and blue and green dividend

Let γ_0 and γ_1 be the growth rates before and after the reform. Let $C_{t,0} = C_{0,0}e^{\gamma_0 t}$, $P_{t,0} = P_{0,0}e^{(\chi_1-\chi_2)\gamma_0 t}$ and $Y_{t,0} = Y_{0,0}e^{\gamma_0 t}$ be the paths for consumption, pollution and output under the initial policy $(\tau^0, \bar{\tau}_P^0)$, and $C_{t,1} = C_{0,1}e^{\gamma_1 t}$ and $P_{t,1} = P_{0,1}e^{(\chi_1-\chi_2)\gamma_1 t}$ be the paths followed by consumption and pollution under the new policy $(\tau^1, \bar{\tau}_P^1)$, where, from (10), $C_{0,i} = \left(A(1-\chi_2\bar{\tau}_P^i) - (1+\frac{\phi}{2}\gamma_i)\gamma_i\right)K_0$ and $P_{0,i} = (\chi_2\bar{\tau}_P^i A)^{-\chi_2} K_0^{\chi_1-\chi_2}$, $i = 0, 1$.

Total welfare effect

The total welfare effect of the reform, as a percentage of output is: $TWE = \frac{\lambda C_{0,0}}{Y_{0,0}} \times 100$, where λ *is computed from* $\int_0^\infty e^{-\theta t}\frac{\left((1+\lambda)C_{t,0}\ P_{t,0}^{-\eta}\right)^{1-\sigma}-1}{1-\sigma}dt = \int_0^\infty e^{-\theta t}\frac{\left(C_{t,1}\ P_{t,1}^{-\eta}\right)^{1-\sigma}-1}{1-\sigma}dt.$

Blue dividend

The value of the blue dividend, as a percentage of output, is $BD = \frac{\omega C_{0,0}}{Y_{0,0}} \times 100$, where ω *is computed from* $\int_0^\infty e^{-\theta t} \frac{\left((1+\omega)C_{t,0}\ P_{t,0}^{-\eta}\right)^{1-\sigma}-1}{1-\sigma} dt = \int_0^\infty e^{-\theta t} \frac{\left(C_{t,1}\ P_{t,0}^{-\eta}\right)^{1-\sigma}-1}{1-\sigma} dt.$

Green dividend

The value of the green dividend expressed as percentage on output is: $GD = \frac{\upsilon C_{0,0}}{Y_{0,0}} \times 100$, where υ *is computed from* $\int_0^\infty e^{-\theta t} \frac{\left((1+\upsilon)C_{t,0}\ P_{t,0}^{-\eta}\right)^{1-\sigma}-1}{1-\sigma} dt = \int_0^\infty e^{-\theta t} \frac{\left(C_{t,0}\ P_{t,1}^{-\eta}\right)^{1-\sigma}-1}{1-\sigma} dt.$

If $\omega < 0$ ($\upsilon < 0$) then the blue (green) dividend does not emerge.

Computing the Pigouvian pollution tax

We compare the conditions characterizing the competitive equilibrium with the optimality conditions for the central planner's problem. The central planner solution is an allocation $\{C_t,\, K_t,\, Z_t\}_{t=0}^{\infty}$ that maximizes the lifetime utility of households, subject to the aggregate constraint of resources [(6), together with $\dot{K}_t = I_t$], and the pollution equation (2).

The Euler condition is

$$\sigma \frac{\dot{C}_t}{C_t} + \eta(1-\sigma)\frac{\dot{P}_t}{P_t} = \left[\frac{1}{1+\phi\gamma}\left(A - \frac{\chi_1}{\chi_2}\left(\frac{Z_t}{K_t}\right)_P + \frac{\phi}{2}\gamma^2\right) - \theta\right], \tag{20}$$

where

$$\left(\frac{Z_t}{K_t}\right)_P = \frac{\eta\chi_2}{1+\eta\chi_2}\left(A - \gamma\left(1 + \gamma\frac{\phi}{2}\right)\right), \tag{21}$$

with the P index standing for the planner's solution.

The consumption to capital ratio is

$$\left(\frac{C_t}{K_t}\right)_P = \frac{1}{1+\eta\chi_2}\left(A-\gamma\left(1+\gamma\frac{\phi}{2}\right)\right). \tag{22}$$

The first-best fiscal policy would allow for the efficient allocation of resources to be attained as a competitive equilibrium. Therefore, in order to characterize the first-best tax policy, we compare the growth rate, consumption and abatement ratios to capital for the market solution with those for the central planner solution.

Comparing (1) and (7) with (20) and (21), and using (8), we obtain the Pigouvian pollution and income tax rates: $\bar{\tau}_P^* = \frac{\eta}{A}\left(\frac{C_t}{K_t}\right)_P$ and $\tau^* = 0$.

Finally, it is straightforward to show that if $\tilde{\sigma} > 1$, the BGP of the planner's problem also lacks transitional dynamics (applying the proof of proposition 1 to the solution planner).

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