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Growth and welfare effects of environmental tax reform and public spending policy

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ABSTRACT

This paper considers the implications of environmental tax reform and public spending policy for growth and welfare. Using a two-sector endogenous growth model where the interactions between health, education, and the environment are taken into account, we show that revenue-positive tax reforms combined with a change in the public spending structure may improve long-run growth and welfare. However, this outcome incurs relatively high welfare cost during the transition phase. This is particularly the case when the spending policy favors education spending.

1. Introduction

Over the recent years, the debate on environmental tax reform has moved on from theoretical discussion to become a practical policy issue in many countries (OECD, 1997, 2010). Several European countries, such as Sweden, Norway, Finland, Denmark, and the Netherlands, implemented environmental tax reforms during the 1990s. More recently, other European countries such as Germany, Italy and the United Kingdom have introduced environmental taxes to reduce their greenhouse gas emissions and raise revenues which may be used in a number way. The public debate on such tax reform is ongoing in other countries, such as France and Switzerland.

For any policy discussion it is absolutely critical to know how the environmental tax revenue is recycled. The key issue is to identify the most appropriate policy for achieving two government goals: (1) lower pollution emissions and (2) high economic growth leading to improved social welfare. In this paper we address some question related to environmental tax reforms. How can tax reform be undertaken without reducing growth and social welfare? Do the transitional and long term effects conflict with each other? What are the associated impacts of a change in public spending structures? These questions are central to public debate, not only in countries where environmental tax reform has been introduced, but also in countries where such reform is still under consideration.

Recent macroeconomic developments have made progress in analyzing the dynamic effects of taxes, particularly within the framework of endogenous growth models.[1] As a consequence, endogenous growth models have often been used to analyze the effects of environmental taxes on the rate of long-term growth. Ricci (2007) provides a comprehensive survey, which presents various impacts of restrictive environmental policy on growth that have been discussed in the literature. A tighter environmental policy can potentially operate through different mechanisms such as investment, education and R&D. Overall, to generate a positive growth effect, many studies incorporate environmental quality into the firm's production function as an externality by assuming that a clean environment would improve the productivity of inputs or the efficiency of the educational system (see for instance Ligthart and van der Ploeg, 1994; Bovenberg and Smulders, 1995; Grimaud, 1999; Hart, 2004; Nakada, 2004; Chen et al., 2009; Paturel, 2009; Aloi and Touremaine, 2011; among others). By developing an endogenous growth model, in which pollution affects human capital depreciation and worker's productivity, Gradus and Smulders (1993, 1996), van Ewijk and van Wijnbergen (1994) and Paturel (2008) show that a tax on emissions, via its effect on learning abilities, promotes long run growth. Using a similar framework, Hettich (1998) and Oueslati (2002) have also highlighted that the labor–leisure choice played a

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[1] Lucas (1990), Devereux and Love (1994), and Stokey and Rebelo (1995), Ortigueira (1998) among others, have focused on the relationship between tax rates and long-term growth rates.

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role in the transmission of the environmental tax effect in a two-sector model of endogenous growth.

The literature on environmental tax has also addressed the so-called "double dividend" issue. The basic idea is whether a switch from different taxes to taxes on polluting goods or production factors can achieve both an improvement in the environment and a reduction in distortions arising from labor or capital taxation.[2] The environmental tax reform allows the government to carry out the operation in a revenue-neutral way, i.e. leaving total tax revenues unchanged. However, environmental tax reform can also be revenue-positive or revenue-negative, depending on how much tax revenue is recycled. In this respect, the environmental tax reform issue has been extensively investigated within the endogenous growth framework (see Bovenberg and Smulders, 1995; Bovenberg and Mooij, 1997; Hettich, 1998; Fullerton and Kim, 2008; Greiner, 2005; Fernandez et al., 2011; among others). Overall, this literature has considered the relationship between environmental tax reform from different aspects and within different endogenous growth frameworks. However, it should be noted that these studies paid relatively little attention to any associated modifications to the public spending structure.[3] In practice, environmental tax reforms are combined with changes in the public spending structure. This is particularly true since governments include the impacts of environmental tax reform within a comprehensive overview of their budget and often wish to allocate additional resources to support productive sectors and/or to increase spending on reducing pollution levels.

The purpose of this paper is to study the effects of tax reform and public expenditure policies within a unified growth model. We use an endogenous growth model with human capital (Lucas, 1988) to assess the effects of environmental tax reform and changes in public spending structure. Thus, we introduce an explicit trade-off between two types of public spending: (1) education spending, which supports the accumulation of human capital, and (2) public abatement spending which aims to improve environmental quality by reducing pollution. Following Gradus and Smulders (1993), we assume that pollution influences agents' abilities to learn. As the learning process is the ultimate engine of growth, reducing pollution can establish a channel through which environmental tax can enhance growth. Moreover, we utilize a numerical approach to compute the entire dynamic transition path towards balanced growth path. The analysis of the dynamic adjustment path enables us to perform welfare calculations. In particular, we make explicit the trade-off between the transitional and long term welfare costs of six policy scenarios, combining environmental tax reforms and changes in the public spending structure.

Our main results can be summarized as follows. We show that tax reform policies may improve growth and social welfare in the long term. Coupled with a change in the structure of public spending, the growth and welfare effects can be amplified. However, these positive effects are achieved at the expense of a reduced growth rate and a relatively high welfare cost during the transition period.

The remainder of the paper is organized as follows. In Section 2 the general model is presented and a market solution is derived. Section 3 discusses the growth and welfare effects of different policies for the use of pollution tax revenues. Section 4 proposes a numerical simulation of different policy scenarios. Here we parameterize the model at the steady state so that it incorporates some macroeconomic stylized facts. We then simulate and comment on the transitional dynamics. Section 5 computes welfare costs for each reform in the transitional and long term. Section 6 summarizes the main findings.

[2] See Goulder (1995), Carraro et al. (1996), Bovenberg and van der Ploeg (1997), Bovenberg (1999) and Giménez and Rodríguez (2010) for a review of the main arguments in this discussion.

[3] To the best of our knowledge, only Kempf and Rossignol (2007) have analyzed the choice of repartition of public spending by a median voter and its impact on growth.

2. The model

We consider a discrete time economy populated with a continuum of identical, infinitely-lived households. Each household owns the stock of physical capital in the economy, K_t, and is endowed with a (normalized) unit time. A proportion of the final product (Y_t) produces a flow of pollution that can be reduced by a public effort towards reducing pollution. The effective pollution flow is assumed to affect individuals' utility and learning process.

2.1. The household

The behavior of the rational household is guided by the maximization of the discounted lifetime utility

$$\mathcal{W}_0 = \sum_{t=0}^{\infty} \beta^t (\log C_t - \phi_P \log P_t) \tag{1}$$

where C_t is consumption and $0 < \beta < 1$ is the discount factor. P_t is the effective pollution flow and ϕ_P represents the weights of pollution in utility. The consumer budget constraint can be written as follows:

$$K_t = \left[1 + \left(1 + \tau_t^K\right) r_t\right] K_{t-1} + \left(1 - \tau_t^H\right) w_t u_t H_{t-1} - C_t + T_t \tag{2}$$

where r_t is the return to physical capital and w_t is the gross wage rate per effective unit of human capital $u_t H_{t-1}$. τ_t^K and τ_t^H are respectively a tax on capital income, and wage tax. T_t represents a lump-sum transfer from the government.

The representative household can increase their human capital stock H_t, by devoting time to schooling $(1 - u_t)$. We assume that this activity takes place outside the market, and new human capital can be acquired by spending time. According to the formulation of Gradus and Smulders (1993), we consider that effective pollution causes human capital to depreciate at a faster rate. This reflects the potential effect of pollution on health that negatively affects the process of human capital accumulation.[4] Let us denote the influence of pollution on the learning process as ηP_t, where $\eta > 0$. Thus, the law of motion for human capital is given by

$$H_t = [1 + B_t(1 - u_t) - \eta P_t] H_{t-1}. \tag{3}$$

$B_t > 0$ represents human capital productivity, which is assumed to depend on public efforts to support education. That is, we define

$$B_t = \widetilde{B}\left(\frac{E_t}{Y_t}\right)^{\xi} \tag{4}$$

where $\widetilde{B} > 0$ is a constant scale parameter, E_t is public education spending and $0 \leq \xi \leq 1$ captures the productivity of public education spending. The assumption that human capital productivity depends on public education expenditure is consistent with the goal of public education policy in practice, as well as with many theoretical works (see for instance Glomm and Ravikumar, 1992; Blankenau, 2005; Angelopoulos et al., 2011).

2.2. Firms and pollution

The economy comprises a large number of identical and competitive firms. They rent capital and hire effective labor from the households at

[4] See Zivin and Neidell (2013) for a comprehensive survey on the relationship between pollution and human capital.

rental price r and wage rate w respectively. They use the following constant-returns Cobb–Douglas technology

$$Y_t = AK_{t-1}^{\alpha}(u_t H_{t-1})^{1-\alpha} \tag{5}$$

where $A > 0$ and $0 < \alpha < 1$.

According to Luptacik and Schubert (1982), we consider that pollution is a by-product of output. To simplify, we assume that one unit of output production leads to one unit of pollution emissions, which is taxed at the rate $\tau^p > 0$. Thus, firms have to pay τ^p per unit of output. Firms are assumed to maximize their market value, which is equal to the appropriately discounted sum of profit flows, the latter is given by

$$\pi_t = (1-\tau^p)Y_t - r_t K_{t-1} - w_t u_t H_{t-1}. \tag{6}$$

Profit maximization implies that in equilibrium, firms pay for each production factor at its marginal productivity.

$$r_t = (1-\tau^p)\frac{\alpha Y_t}{K_{t-1}} \tag{7}$$

$$w_t = (1-\tau^p)\frac{(1-\alpha)Y_t}{u_t H_{t-1}}. \tag{8}$$

Pollution is considered to be a flow variable, hence the model can predominantly be applied to pollutants which dissolve rather quickly. This corresponds to several air pollutants in big cities, such as nitrogen dioxide and particulate matter, which are seriously harmful to human health. We assume that pollution flow can be reduced by means of public abatement activities (D_t) which in turn consume a proportion of output, in line with the flow resource constraint.

Following Gradus and Smulders (1993), among others, we consider that the effective pollution (P_t) can take the following form:

$$P_t = \left(\frac{Y_t}{Dt}\right)^{\mu}, \mu > 0. \tag{9}$$

With the form (Eq. (9)), the effective pollution does not grow without bound and is constant at the steady state.[5] See Bretschger and Smulders (2007) and Ricci (2007) for a survey of the various alternative forms of environmental externality in endogenous growth models.

2.3. The government

Government revenue comes from taxes on capital income (τ_t^K), wages (τ_t^H) and pollution (τ_t^p). All government tax revenues (Z_t) are used to cover abatement expenditure (D_t), education spending (E_t) and lump-sum transfers (T_t). We assume that the government balanced its budget in every period, thus avoiding any burden associated with government debt. Each type of public spending is essential.

The government budget constraint implies that in each period, we have:

$$Z_t = \tau_t^K r_t K_{t-1} + \tau_t^H w_t u_t H_{t-1} + \tau_t^P Y_t = D_t + E_t + T_t. \tag{10}$$

The government can change the budget structure, but should always maintain a minimum allowance for each expense. There is therefore an irreducible level for each type of public expenditure. Let θ_1, θ_2 and $\theta_3 \in]0, 1[$, such as $\theta_1 + \theta_2 + \theta_3 = 1$. That is,

$$E_t = \theta_1 Z_t, D_t = \theta_2 Z_t \text{ and } T_t = \theta_3 Z_t. \tag{11}$$

[5] We assume that $D_t > 0$, insofar as the government is required to deal with polluting activities by maintaining a positive level of abatement expenditures.

Finally, the market clearing condition for the goods market is

$$Y_t = C_t + K_t - (1-\delta_K)K_{t-1} + Z_t. \tag{12}$$

2.4. Characteristics of competitive equilibrium

We now set out the efficiency conditions that determine a competitive equilibrium and derive the analytical solution of the model.

2.4.1. The market solution

Definition 1. A competitive equilibrium for this economy consists of the consequences $\{C_t, Y_t, K_t, H_t, u_t, Z_t, r_t, w_t, \tau_t^P, \tau_t^K, \tau_t^K, P_t\}$ for $t \in [1, \infty)$ and for $0 < \theta_1, \theta_2, \theta_3 < 1$, that satisfy the following conditions.

(a) *Household utility maximization:Maximize Eq. (1) subject to Eqs. (2) and (3)* $\lim_{t\to\infty}\beta^t\lambda_t K_t = \lim_{t\to\infty}\beta^t q_t H_t = 0$.
H_0 and K_0 are given. The variables λ_t and q_t represent respectively the shadow prices of physical and human capital.
(b) Profit maximization (Eq. (6))
(c) Government budget constraint (Eq. (10))
(d) Market clearing condition (Eq. (12))

So as to characterize the competitive equilibrium, let us focus on the different trade-offs faced by the household. After eliminating the shadow prices for physical and human capital, as well as by using Eq. (11), the first order conditions for the household problem can be written as

$$\frac{C_{t+1}}{C_t} = \beta\left[1 + \left(1-\tau_{t+1}^K\right)r_{t+1}\right] \tag{13}$$

$$\frac{C_{t+1}}{C_t} = \beta\frac{\left(1-\tau_{t+1}^H\right)w_{t+1}}{(1-\tau_t^H)w_t}\left(\frac{Z_t/Y_t}{Z_{t+1}/Y_{t+1}}\right)^{\xi}\left\{1 + B\left(\theta_1\frac{Z_{t+1}}{Y_{t+1}}\right)^{\xi} - \eta P_{t+1}\right\}. \tag{14}$$

Eqs. (13) and (14) are Euler conditions determining the optimal accumulation of physical and human capital. These conditions, along with Eqs. (2), (3), (7), (8), (10) and (12) constitute a dynamic system in C, Z, u, K and H which, together with the transversality conditions[6] and initial $K(0)$ and $H(0)$, fully describe the dynamic behavior of the economy along an interior equilibrium.

2.4.2. The balanced growth path

Definition 2. A balanced growth path (or steady state) is an allocation $\{C_t, Z_t, u_t, K_t, H_t, P_t\}$, a price system $\{r_t, w_t\}$, and taxes τ^K, τ^H and τ^p satisfying Definition 1, such that for some initial conditions $K(0) = K_0$ and $H(0) = H_0$, the paths $\{C_t, Z_t, K_t, H_t\}$, grow at a constant rate g, and u_t and P_t both remain constant.

In order to characterize the balanced growth path, we transform some variables to make them stationary. For analytical convenience we use the following transformed variables: $h_t = H_t/K_t$, $c_t = C_t/K_{t-1}$, $y_t = Y_t/K_{t-1}$, $z_t = Z_t/K_{t-1}$ and $g_t = K_t/K_{t-1}$.

Using this change of variables, substituting out prices r_t and w_t, from Eqs. (7) and (8) and substituting for E_t and D_t from Eq. (11), we obtain the following stationary system.

$$g_t = 1 + y_t - z_t - c_t - \delta_K \tag{15}$$

$$g_t\frac{h_t}{h_{t-1}} = \widetilde{B}\left(\frac{\theta_1 z_t}{y_t}\right)^{\xi}(1-u_t) + 1 - \eta P_t \tag{16}$$

[6] These conditions are standard and entail that the present discounted value of both human and physical capital stocks tends to zero at infinity.

$$g_t \frac{c_{t+1}}{c_t} = \beta\left[1 + \alpha\left(1 - \tau^K_{t+1}\right)(1 - \tau^p_{t+1}) y_{t+1}\right] \tag{17}$$

$$g_t \frac{c_{t+1}}{c_t} \beta \frac{\left(1-\tau^H_{t+1}\right) w_{t+1}}{(1-\tau^H_t) w_t} \left(\frac{z_t}{z_{t+1}} \frac{y_{t+1}}{y_t}\right)^{\xi} \left\{1 + \widetilde{B}\left[\theta_1 \frac{z_{t+1}}{y_{t+1}}\right]^{\xi} - \eta P_{t+1}\right\} \tag{18}$$

$$\frac{z_t}{y_t} = \left[\tau^K_t \alpha + \tau^H_t (1-\alpha)\right](1-\tau^p_t) + \tau^p_t. \tag{19}$$

In addition, from Eqs. (9) and (5), we obtain the stationary variables of the output and the effective pollution:

$$y_t = A u_t^{1-\alpha} h_t^{1-\alpha} \tag{20}$$

$$P_t = \left(\frac{y_t}{\theta_2 z_t}\right)^{\mu}. \tag{21}$$

It can easily be shown that the balanced growth path (denoted by an asterisk) takes the following form (see Appendix A):

$$\begin{aligned}
&g^* = \beta\left[1 + \widetilde{B}(\theta_1\Lambda)^{\xi} - \eta(\theta_2\Lambda)^{-\mu}\right]; && y^* = \frac{\widetilde{B}(\theta_1\Lambda)^{\xi} - \eta(\theta_2\Lambda)^{-\mu}}{\alpha(1-\tau^K)(1-\tau^p)} \\
&u^* = \frac{1-\beta}{\beta} \frac{g^*}{\widetilde{B}[\theta_1\Lambda]^{\xi}}; && c^* = 1 + (1-\Lambda) y^* - g^* \\
&P^* = (\theta_2\Lambda)^{-\mu}; && h^* = \left(\frac{y^*}{A}\right)^{\frac{1}{1-\alpha}} \frac{1}{u^*}
\end{aligned}$$

where $\Lambda = z^*/y^* = [\tau^K\alpha + \tau^H(1-\alpha)](1-\tau^p) + \tau^p$. The model's balanced growth path depends on the parameters of public policy through the share of public spending in the final product (Λ), but also on its structure as defined by the choice of the policy parameters θ_1, θ_2, and θ_3. A positive equilibrium growth requires that the net total human capital accumulation should be higher than the effect of pollution on human capital accumulation, i.e. $1 + \widetilde{B}(\theta_1\Lambda)^{\xi} > \eta(\theta_2\Lambda)^{-\mu}$. Table 1 reports the results from comparative statics. Since the comparative statics for the version of the model without pollution are well-understood (Mulligan and Sala-i-Martin, 1993), we concentrate on the effects of policy parameters (see Appendix B).

Note that regardless of the public spending structure and tax system, the share of public spending in the final product has a positive effect on the rate of long-term growth (i. e. $\partial g^*/\partial\Lambda > 0$). In addition, public spending parameters θ_1 and θ_2 have positive effects on growth i.e. $\partial g/\partial\theta_1 > 0$ and $\partial g/\partial\theta_2 > 0$. The lump-sum transfer effect on growth is nil (i. e. $\partial g^*/\partial\theta_3 = 0$). The effects of different tax rates on long-term growth go through Λ. If public expenditures are efficiently mobilized to support education and/or public abatement, then increasing taxes can have a positive effect on long-term growth. It should be emphasized that in our setup, revenue-neutral tax reforms have no effect on the long-term growth rate. In what follows, we limit our analysis to revenue-positive reforms.

The effects that the share of public spending and taxes on time allocated to production are ambiguous and depend on the magnitude of the pollution impact on human capital accumulation. If $\eta P^* > 1$, we deduce that $\partial u/\partial\Lambda > 0$ and $\partial u/\partial\theta_1 > 0$. But if $\eta P^* < 1$, the sign of $\partial u/\partial\Lambda$ depends on the parameters of human capital accumulation and $\partial u/\partial\theta_1 < 0$. Since h^* depends on u^*, we obtain the same ambiguity. Note also that all parameters of tax and spending policies have a negative effect on the level of consumption in equilibrium. This reflects the crowding out effect on consumption related to public spending and taxes. Finally, the level of pollution declines with augmentation of the share of public spending in the final product (i. e., $\partial P/\partial\Lambda < 0$) and the increase in abatement $\partial P/\partial\theta_2 < 0$, but is insensitive to variations of θ_1 and θ_3.

Table 1
Policy parameter effects.

		g^*	y^*	u^*	c^*	P^*
$\Lambda, \tau^P, \tau^K, \tau^H$	+	+	?	?	–	–
θ_1	+	+	?	?	–	0
θ_2	+	+	+		–	–
θ_3	0	0	0	0	0	0

3. Recycling the pollution tax revenue

In this section, we investigate the growth and welfare effects of different policies for the use of pollution tax revenue. Basically, we consider two main options. The first is to use the pollution tax revenues to change the structure of public spending by increasing education spending, abatement expenditures or lump-sum transfers. This option implies that the tax system remains unchanged. The second option is to make various tax reforms by using pollution tax revenues to reduce either wage tax or profit tax. In practice both option can be combined, which leads to several possibilities. However from an analytical perspective, it would be useful to consider both strategies separately and compare their effects on growth and welfare.

3.1. Growth effects

3.1.1. Growth effects of public spending policy

In a first case, the government can use the revenue generated by environmental taxation to increase a single type of public spending. As the growth-effect of the transfer share (θ_3) is nil, we restrict our analysis to two spending policies. Alternatively, the government can increase spending on either education or abatement, while leaving the tax system unchanged. The following proposition restates and compares the growth-effects of both spending policies.

Proposition 1. *Growth effects of change in public spending structure*

(i) *Spending policy 1: Fully utilize the environmental tax revenue to increase education spending, while maintaining abatement and transfer payments, increases the long-term growth rate, i.e.*

$$\left.\frac{dg^*}{d\tau^P}\right|_{d\theta_2 = d\theta_3 = 0}^{d\theta_1 > 0,} > 0.$$

(ii) *Spending policy 2: Fully utilize the environmental tax revenues for increasing abatement expenditure, while maintaining education spending and transfer payments, increases the long-term growth rate, i.e.*

$$\left.\frac{dg^*}{d\tau^P}\right|_{d\theta_1 = d\theta_3 = 0}^{d\theta_2 > 0,} > 0.$$

(iii) *Comparison between policy 1 and policy 2 depends on the relative importance of the pollution effect on human capital accumulation, with respect to the effect of education spending, i.e.*

$$\left.\frac{dg^*}{d\tau^P}\right|_{d\theta_2 = d\theta_3 = 0}^{d\theta_1 > 0} - \left.\frac{dg^*}{d\tau^P}\right|_{d\theta_1 = d\theta_3 = 0}^{d\theta_2 > 0} \begin{cases} > 0, & \xi\Lambda\widetilde{B}(\theta_1\Lambda)^{\xi-1} > \eta\mu\Lambda(\theta_2\Lambda)^{-\mu-1} \\ < 0, & \text{otherwise} \end{cases}.$$

Proof. See Appendix C. ■

Both spending policies have a positive growth effect. Policy to increase abatement is more growth enhancing if the effect of reducing pollution on health $(\eta\mu\Lambda(\theta_2\Lambda)^{-\mu-1})$ is higher than the effect of education spending on the productivity of human capital accumulation $\left(\xi\Lambda\widetilde{B}(\theta_1\Lambda)^{\xi-1}\right)$ and vice versa. Thus, this condition depends on parameters of human capital accumulation. In countries where pollution has a high impact on learning abilities, the mobilization of budgetary resources to reduce pollution allows for the best results in terms of growth. However, in other cases, it would be possible for the mobilization of government resources to increase support for education to lead to better results in terms of long-term growth. Proposition 1 highlights the relative importance of public spending productivity in the improvement of human capital accumulation and ultimately growth rate. This depends on the parameters ξ, $\widetilde{B}$, η and μ.

3.1.2. Growth effects of environmental tax reforms

We now investigate the impacts of two types of tax reforms associated with the implementation of a pollution tax. First, we examine the effects on growth of funding a reduction in the tax on wages through environmental taxation, while maintaining the profits tax at a constant rate ($d\tau^K=0$). Second, the effects on growth of a reduction in the tax on profits is analyzed in the context of maintaining existing levels of tax on wage ($d\tau^H=0$). Both tax reforms are considered as revenue-positive reforms, which require $d\Lambda>0$.

The following proposition sets out the effects of these two reforms on the long term growth rate, when the government keeps the public spending structure unchanged.

Proposition 2. *Growth effects of environmental tax reforms without change in the structure of public spending.*

(i) *Tax Reform 1: Using environmental tax revenues to reduce tax on wages and increase public spending, while maintaining profit tax unchanged, increases the long-term growth rate, i.e.:*

$$\left.\frac{dg^*}{d\tau^P}\right|_{d\tau^K=0}^{d\tau^H<0,\ \ d\Lambda>0} >0.$$

(ii) *Tax Reform 2: Using the environmental tax revenues to reduce tax on profits and increase public spending, while maintaining wage tax unchanged, increases the long-term growth rate, i.e.:*

$$\left.\frac{dg^*}{d\tau^P}\right|_{\tau^H=0}^{d\tau^K<0,\ \ d\Lambda>0} >0.$$

(iii) *Comparison of the growth-effects of Reform 1 and Reform 2 depends on the output elasticities of physical capital (α), i.e.,*

$$\left.\frac{dg^*}{d\tau^P}\right|_{d\tau^K=0}^{d\tau^H<0, d\Lambda>0} - \left.\frac{dg^*}{d\tau^P}\right|_{d\tau^H=0}^{d\tau^K<0, d\Lambda>0} \begin{cases} >0, & \text{if } \alpha<1/2 \\ <0, & \text{otherwise} \end{cases}.$$

Proof. See Appendix C. ■

Proposition 2 establishes that Reforms 1 and 2 are both growth-enhancing. Moreover, Reform 1 is more growth-enhancing than Reform 2, when the output elasticities of physical capital are lower than that of human capital (i.e. $\alpha<1-\alpha$, which needs $\alpha<1/2$). Note also that increasing public spending ($d\Lambda>0$) without tax reforms would be sufficient to improve long-term growth (i.e. $dg^*=\frac{\partial g}{\partial\Lambda}\frac{\partial\Lambda}{\partial\tau^P}d\tau^P>0$). This is because increased public spending positively affects the productivity of human capital accumulation.

3.2. Welfare effects

Using Eq. (1) and the transformed variables, the welfare along the balanced growth path is given by[7]:

$$\mathcal{W}_0=[\log c-\phi_P\log P]\sum_{t=0}^{\infty}\beta^t+\log g\sum_{t=0}^{\infty}t\beta^t. \tag{22}$$

By using the following approximations $\sum_{t=0}^{\infty}\beta^t=\frac{1}{1-\beta}$ and $\sum_{t=0}^{\infty}t\beta^t=\frac{\beta}{(1-\beta)^2}$, we deduce from Eq. (22)

$$\mathcal{W}_0=\frac{\log c-\phi_p\log P}{1-\beta}+\frac{\beta\log g}{(1-\beta)^2}. \tag{23}$$

The different policies discussed above affect welfare through consumption, growth rate and pollution. The following proposition establishes the welfare effects of spending policies.

Proposition 3. *The welfare effect of public spending policy without tax reform ($d\tau^H=d\tau^K=0$).*

(i) *Both spending Policies 1 and 2 are welfare-improving, if the growth effects and/or pollution-effects of θ_1 or θ_2 are higher than their negative effects on consumption, i.e.*

$$\left.\frac{d\mathcal{W}}{d\tau^P}\right|_{d\theta_2=0}^{d\theta_1>0,} \times\begin{cases} >0, \text{if } \frac{\partial g}{\partial\theta_1}\frac{\partial\mathcal{W}}{\partial g}>-\frac{\partial c}{\partial\theta_1}\frac{\partial\mathcal{W}}{\partial c}, \text{which requires } g>\frac{\beta^2}{(\beta+\Lambda-1)(1-\beta)}c \\ <0, \text{otherwise}\end{cases}$$

and

$$\left.\frac{d\mathcal{W}}{d\tau^P}\right|_{d\theta_1=0}^{d\theta_2>0} >0, \times\begin{cases} >0, \text{if } \frac{\partial g}{\partial\theta_2}\frac{\partial\mathcal{W}}{\partial g}+\frac{\partial P}{\partial\theta_2}\frac{\partial\mathcal{W}}{\partial P}>-\frac{\partial c}{\partial\theta_2}\frac{\partial\mathcal{W}}{\partial c}, \\ \quad \text{which requires} \left[\frac{\beta}{1-\beta}\frac{1}{g}-\frac{\Lambda+\beta-1}{\beta}\frac{1}{c^*}\right]\frac{\partial g}{\partial\theta_2}+\frac{\phi_p\mu}{\theta_2}>0 \\ <0, \text{otherwise}\end{cases}.$$

(ii) *Comparison of the welfare effects of spending policies 1 and 2 depends on the relative importance of pollution effect on health with respect to the effect of education spending, i.e.*

$$\left.\frac{d\mathcal{W}}{d\tau^P}\right|_{d\theta_2=0}^{d\theta_1>0,} - \left.\frac{d\mathcal{W}}{d\tau^P}\right|_{d\theta_1=0}^{d\theta_2>0} \begin{cases} >0, \text{if } \xi\Lambda\widetilde{B}(\theta_1\Lambda)^{\xi-1}>\eta\mu\Lambda(\theta_2\Lambda)^{-\mu-1} \\ <0, \text{otherwise}\end{cases}.$$

Proof. See Appendix D. ■

Spending policies may have a positive effect on welfare if their effects on growth and pollution are high enough to offset the negative effects on consumption. Thereby, positive welfare effects related to spending policy 1 requires that the long run growth rate (g) be sufficiently higher than the stationary level of consumption (c). This condition means that the economy is expected to grow at a rate sufficiently high to compensate for any drop in consumption due to the implementation of the environmental tax. However, in the case of spending policy 2, this condition is relaxed due to the welfare positive effect of lower pollution. Moreover, if the effect of education spending $\left(\xi\Lambda\widetilde{B}(\theta_1\Lambda)^{\xi-1}\right)$ is higher than the pollution effect on human capital accumulation $(\eta\mu\Lambda(\theta_2\Lambda)^{-\mu-1})$, spending policy 1 is more welfare improving than spending policy 2 and vice versa.

[7] We have by definition $C_t=cK_{t-1}$ and the equilibrium growth rate can be written $g=K_t/K_{t-1}\Rightarrow K_t=g^{t+1}K_{-1}$.We normalize $K-_1=1$.

Proposition 4. *The welfare effects of environmental tax reforms without change in public spending structure.*

(i) *Both Reform 1 and Reform 2 are welfare-improving, if the effects of public spending on growth and/or pollution are high enough to offset the negative effects of Λ on consumption, i.e.:*

$$\frac{d\mathcal{W}}{d\tau^P}\Bigg|_{\substack{d\tau^H<0, d\Lambda>0\\ d\tau^K=0}}>0 \text{ and } \frac{d\mathcal{W}}{d\tau^P}\Bigg|_{\substack{d\tau^K<0, d\Lambda>0\\ d\tau^H=0}}>0, \text{if } \frac{\partial\mathcal{W}}{\partial g^*}\frac{\partial g^*}{\partial\Lambda}+\frac{\partial\mathcal{W}}{\partial P^*}\frac{\partial P^*}{\partial\Lambda}>\frac{\partial\mathcal{W}}{\partial c^*}\frac{\partial c^*}{\partial\Lambda}.$$

(ii) *Comparison of growth-effects on Reforms 1 and 2 depends on the output elasticity of physical capital and that of human capital, i.e.*

$$\frac{d\mathcal{W}}{d\tau^P}\Bigg|_{\substack{d\tau^H<0, d\Lambda>0\\ d\tau^K=0}}>0-\frac{d\mathcal{W}}{d\tau^P}\Bigg|_{\substack{d\tau^K>0, d\Lambda>0\\ d\tau^H=0}}\begin{cases}>0, & \text{if } \alpha<1/2\\ <0, & \text{otherwise}\end{cases}.$$

If the output elasticity of physical capital is lower than that of human capital (i.e. $\alpha < 1 - \alpha$), then Reform 1 is more welfare-enhancing then Reform 2.

Proof. See Appendix D. ■

The previous propositions allow to establish analytically the conditions required for positive effects on growth and welfare of various tax reforms and spending policies. An important lesson from these analytical developments is that the government may achieve better performance in terms of growth and welfare by combining environmental tax reform with a change in the public spending structure. However, it should be noted that a policy which favors an increase in public spending on abatement is not necessarily the best in terms of growth and welfare. In the next section, we simulate different policy scenarios combining them to estimate welfare costs in the transient and long term.

4. Simulation analysis

We derive a full numerical solution for the model. The objective is to illustrate transitional and long-term effects of different policy scenarios combining tax reforms and spending structure changes. Before proceeding with estimating the effects on growth and welfare, we parameterize the model in order to reflect the best most developed economies, then we discuss the policy scenarios that are being considered.

4.1. Benchmark parameterization

The purpose of this parameterization is to calculate the values of the initial steady state SS0, referred to here as the benchmark case. We cannot really hope to be as precise as those who employ the same model without pollution, since we lack strong empirical evidence concerning the nature of environmental preferences and pollution impacts on human capital accumulation (Eq. (3)). Nevertheless, to the greatest possible extent, we follow the recent literature and determine the values of certain parameters in accordance with some stylized macroeconomic facts. The data used in this study are obtained from the OECD database, which includes: (i) Main Economic Indicators (MEI) and (ii) the International Sectorial Database (ISDB).

The parameter values are: (i) preference parameters: β and ϕ_P, (ii) technology parameters α, A, B, μ, η and ξ, and (iii) public policy parameters: τ^K, τ^H, τ^P, θ_1, θ_2 and θ_3. To calibrate the model, we work as follows. We consider that the economy is initially on the equilibrium growth path where pollution is not taxed ($\tau^P = 0$). To compute the steady state variable values, we resort to the common parameter values

Table 2
Parameter values.

Parameter	Value	Definition
$A > 0$	0.1	Technological progress in goods production
$B > 0$	0.1	Technological progress in human capital production
$g > 0$	1.01	Growth rate
$0 < \alpha < 1$	0.25	Productivity of capital
$0 < \beta < 1$	0.98	Rate of time preference
$0 < \Lambda < 1$	0.4	Public spending share in the output
$0 < \theta_1 < 1$	0.35	Share of education spending in the output
$0 < \theta_2 < 1$	0.1	Share of abatement in the output
$0 < \theta_3 < 1$	0.55	Share of transfer
$\xi > 0$	0.5	Productivity of education spending
$\mu > 0$	0.1	Elasticity of pollution with respect to Y/D
$\eta > 0$	0.012	Pollution impact on health

Table 3
Steady state solution.

	h	c	y	u	d	e	P
Initial steady state (SS0)	10.058	0.117	0.213	0.272	0.0085	0.0298	1.379

already used in the two-sector endogenous growth models. In accordance with the ISDB dataset, we set $\alpha = 0.25$ and $\beta = 0.98$.[8] Additionally, the calibration is carried out so as to capture the share of GDP allocated to public spending (Λ) at 40%, which corresponds to the average level of public spending in OECD countries (MEI). The environment-related expenditure is estimated to be approximately 2.3–5.8% of GDP in OECD countries. We then set average rates $e/y = \theta_1\Lambda = 14\,\%$ and $d/y = \theta_2\Lambda = 4\,\%$. Taking this as a proxy for industrialized economies, the growth rate is 1% and profit tax $\tau^K = 0.35$. The values of the scale factor $A = 0.1$ and $B = 0.1$ were chosen to ensure that u and τ^H were close to the values observed in the OECD countries. The numeric values for the model's parameters are reported in Table 2.

The steady state solution implied by this calibration is reported in Table 3. As can be seen, the proportion of consumption in the final output $c/y = 0.55$ is close to the data average observed in the OECD countries.

4.2. Policy scenarios

There is a wide variation in the use of revenues generated by environmental taxation. According to Sumner et al. (2009), half of the environmental taxes implemented to date return revenues to the government or to entities subject to the tax in order to offset the increased tax burden, while the remainder is used to fund either specific pollution reduction programs or government budgets. Some policies apply a portion of revenues for each purpose. For example, in some countries the revenue from environmental taxation is not hypothecated and contributes to the general public budget without being linked to a specific area of expenditure (e.g., in Norway and Finland). In others, it is used to reduce social security contributions (e.g., Germany and the United Kingdom), personal income taxes (e.g., Denmark, Sweden and the Netherlands) or employment charges (e.g., Italy). In Denmark, environmental tax revenue is used in part to compensate polluters. However, in the United Kingdom, it is used to subsidize investment in clean technologies.[9] In sum, the revenue generated by environmental taxation, can be used to fund offsetting reductions in (1) taxes on labor, (2) taxes on capital, or (3) public spending.

Based on this variety of experiences of environmental tax reform, we consider successively the effect on the steady state of six scenarios that

[8] The discount rate, $1/\beta$ is equal to 1 plus the ex-post real interest rate. We use the ex-post real interest rate from MEI.

[9] For an empirical survey of environmental tax reform see Cansier and Krumm (1997), Ekins and Speck (1999), OECD (1997, 2010), and European Environment Agency (2011).

Table 4
Policy scenarios.

	Tax reform 1	Tax reform 2
	$d\tau^H < 0, d\tau^K = 0$	$d\tau^K < 0, d\tau^H = 0$
Unchanged public spending structure ($d\theta_1 = d\theta_2 = 0$)	Scenario 1	Scenario 4
Increasing education spending ($d\theta_1 > 0, d\theta_2 = 0$)	Scenario 2	Scenario 5
Increasing abatement spending ($d\theta_2 > 0, d\theta_1 = 0$)	Scenario 3	Scenario 6

capture the most plausible policies. We retain both Reforms 1 and 2 as discussed in the previous sections, where the government introduces a pollution tax ($\tau^P = 0.1$) and use its revenues to reduce either the tax on wages or on profits. In both cases we consider a reduction of 10% with respect to the benchmark tax values. Then, both tax reforms are considered within different public spending scenarios. First, we consider the case where the government does not alter the structure of public spending. Next, we consider two possible cases where the public spending changes to increase either expenditure on education or on public abatement. In both cases we also retain a decrease of 10% compared to the value of the benchmark values of θ_1 and θ_2.

In total we analyze the effects of six possible scenarios combining various tax reforms and changes to budgetary policies. For each scenario, we examine the long-term and transitional effects of each tax reform with regard to three public spending policies. Table 4 summarizes the scenarios considered.

4.3. Simulation results

All policy scenarios alter the initial steady state corresponding to the benchmark (SS0) and initiate transitional dynamics towards a new steady state. Table 5 shows the results of changes in the steady state for each scenario.

All scenarios improve long-term growth to varying degrees. The reason for this is that the various reforms alleviate tax burdens on production factors and allocate more resources to the engine of growth, i.e. the accumulation of human capital. As can be seen in Table 3, each of the different scenarios involves a change in h, u and c/y. These changes may be explained by two fundamental economic mechanisms. The first concerns the modification in the allocation of resources between consumption, investment and public spending. Environmental tax can be seen as a levy on available resources within the economy, which induces a decline in the consumption proportion of GDP. To counteract the lack of welfare resulting from the drop in consumption, households spend more of their time in education $(1 - u)$. The result of such time reallocation is an enhancement in productive capacity and therefore better long-term growth. The second mechanism reflects the transformation of the production function, which becomes more intensive in terms of human capital.

Regardless of the envisaged tax reform, the increase in the share of education spending (scenarios 2 and 5) gives the best performance in terms of long-term growth. This is simply due to the direct effect of education spending on the productivity of human capital accumulation (see: Eqs. 3 and 4). However, the impacts on pollution are most marked when tax reform is accompanied by an increase in the share of public spending on abatement (scenarios 3 and 6).

Table 3 only shows the long-term results, when the economy reaches its new steady state. However, before achieving this steady state, the different variables follow different transitional paths. The analysis of the transition process can be useful for understanding the transitional effects of these different policy scenarios. In order to compute the transitional dynamics we log-linearize the dynamic system (Eqs. (15)–(21)) to make the equations approximately linear in

Table 5
Long-term effects of policy scenarios.

		g	P	h	u	c/y
Initial steady state (SS0)		1.010	1.379	10.058	0.272	0.553
Tax Reform 1	Scenario 1	1.0116	1.3692	10.5325	0.2628	0.5142
	Scenario 2	1.0153	1.3692	14.1772	0.2408	0.5074
	Scenario 3	1.0119	1.3445	10.7286	0.2629	0.5135
Tax Reform 2	Scenario 4	1.0114	1.3703	8.7798	0.2638	0.5107
	Scenario 5	1.0151	1.3703	11.8265	0.2417	0.5029
	Scenario 6	1.0117	1.3455	8.9446	0.2639	0.5100

the log-deviations from the steady state.[10] After doing this, we solve the recursive equilibrium law of motion via an undetermined coefficient method. Starting from this solution, the time series can easily be reconstituted from the initial steady state (SS0). We summarize all transitional dynamics using two sets of figures. Figs. 1 and 2 show the different transitional dynamics generated by the different scenarios of tax reform presented above. In each figure we plot the trajectory of some key variables (g, P, h, u, c/y and z/y) to highlight the economic mechanisms that come into effect after the implementation of each scenario. The simulation of the transitional dynamics starts in period $t = 0$, where the government, without forewarning, implements an environmental tax reform. Each policy scenario shocks the initial steady state (SS0) and induces an instantaneous reaction for all economic variables. These reactions show the transitional dynamics within the economy before reaching a new steady state.

In the first set of figures (Fig. 1), we simulate the transitional dynamics induced by tax Reform 1 with and without changes in the composition of public spending. The second set of figures (Fig. 2) concerns Reform 2. We note several differences in transitional dynamics, which lead us to study the transitional effects of tax reforms. The pace at which the economy reaches the new steady state is the result of the interaction between many economic trade-offs. Clearly, transitional dynamics reflect three main mechanisms. Firstly, there is a crowding-out effect caused by the implementation of the environmental tax. The implementation of the environmental tax can be considered as a levy on the resources available within the economy. Thus, with increased government spending, the consumption proportion of GDP declines. Secondly, a factorial reallocation effect occurs, which changes the intensity of physical capital and/or human capital in the final product. This mechanism is enhanced by reducing one of the two distortionary taxes. Third, a reallocation of the available time takes place leading to an increase in time devoted to education. Let us note the differences between the transitional dynamics of the two tax reforms. Although the transitional-term variations have the same sign, their magnitude is quite different.

Interestingly, when the government uses environmental tax revenue to reduce taxation on wages (Reform 1), the economy experiences an immediate sharp decrease in growth, regardless of the scenario considered (Fig. 1.a). However, the use of environmental tax revenue to reduce taxation on profits (Reform 2) delivers an immediate increase in growth (Fig. 2.a). These opposite effects on growth can be explained by the mechanisms of resource reallocation during the transition dynamics. Indeed, the transitional dynamics of the human capital stock per unit of physical capital (h) reflects the factor substitutability, making production more or less intensive in its use of human capital. Apart from scenarios 4 and 6, h grows monotonically (Figs. 1.c and 2.c). The reason for this is that in Reform 2, the tax burden on physical capital is reduced, thereby disadvantaging its substitution in favor of human capital. However, the opposite effect occurs if the reform is associated with increased spending on education (Reform 5).

[10] We follow the method proposed by Uhlig (1995) for solving nonlinear dynamic stochastic models. Although our model is deterministic, the method used by Uhlig (1995) was adapted to calculate the recursive equilibrium law of motion.

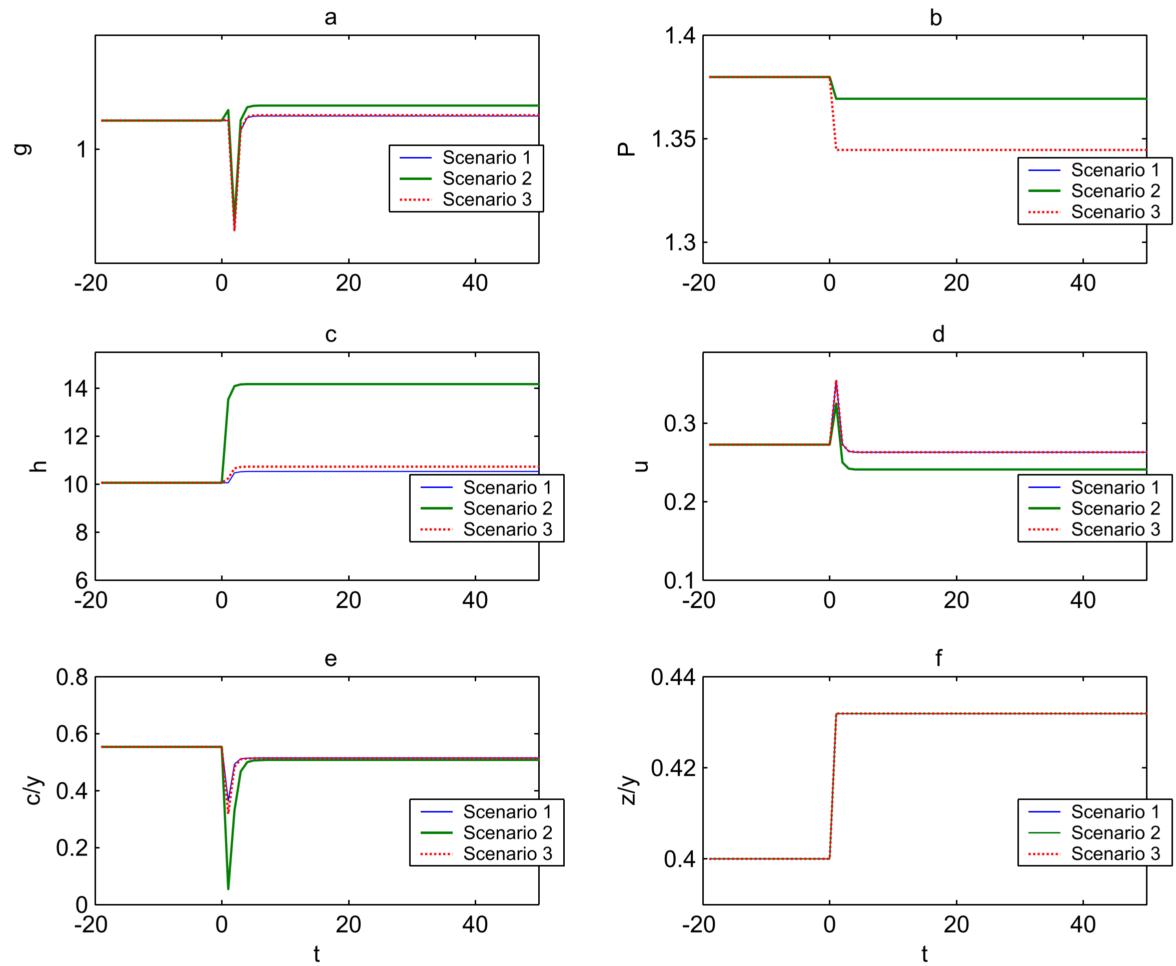

Fig. 1. Transitional dynamics related to tax reform 1.

The effect on the consumption share of GDP (c/y) during the transition may be positive in the cases of scenarios 4 and 6 (Figs. 1.e and 2.e). However, in the other scenarios the crowding-out effect on consumption is observed during the transition. Indeed, c/y decreases immediately and then increases, to progressively reach its new steady state value. Similar but opposite effects are observed for working time (u) (Figs. 1.f and 2.f). Unsurprisingly, we observe the same path for pollution and for the share of GDP on public spending (z/y) for all scenarios (Figs. 1b, 2.b, 1.e and 2.e).

5. Welfare analysis

The task at hand is to provide a measure of the welfare cost associated with our policy scenarios. To achieve this goal, we differentiate welfare as transitional welfare (also referred to as transitional-term welfare) $\mathcal{W}_{1\to2}$ corresponding to the economy's transition from (BC) to a new steady state (NSS), and $\mathcal{W}_2$ welfare related to the NSS. In order to obtain a numerical result, we suppose that the transition from a steady state to another state is achieved within a finite number of periods, and we simply denote T as the date at which we consider that the economy has reached its new rest point.

The total welfare associated with the environmental policy change $\mathcal{W}^{Tot}$ is equal to the sum of utility flows, from $t=0$ to ∞, which can be written as the sum of $\mathcal{W}_{1\to2}$ and $\mathcal{W}_2$:

$$\mathcal{W}^{Tot} = \mathcal{W}_{1\to2} + \mathcal{W}_2. \tag{24}$$

Note that the economy converges only asymptotically to the steady state, and we therefore truncate the transitional dynamics in the effective computation at the horizon T. This horizon is chosen so that for all $t > T$, the difference between the value of physical capital stock at T (k_T) and its value at NSS (k_2) is numerically very small.[11]

Formally, the transitional welfare can be written (see Appendix E for detailed calculations):

$$\mathcal{W}_{1\to2} = \sum_{t=0}^{T} \beta^t \left[\log c_t + \sum_{i=0}^{t-1} \log(g_i) - \phi_P \log P_t \right]. \tag{25}$$

The welfare related to the NSS is given by:

$$\mathcal{W}_2 = \frac{\beta^{T=1}}{1-\beta} \left[\log c_2 + \sum_{i=0}^{T} \log(g_i) - \phi_P \log P_2 + \frac{\beta \log g_2}{1-\beta} \right] \tag{26}$$

and by using Eq. (23) the welfare related to the BC steady state is given by

$$\mathcal{W}_1 = \frac{\log c_1 - \phi_P \log P_1}{1-\beta} + \frac{\beta \log g_1}{(1-\beta)^2}. \tag{27}$$

[11] We tolerate a difference between k_T and k_2 smaller than 10^{-10}.

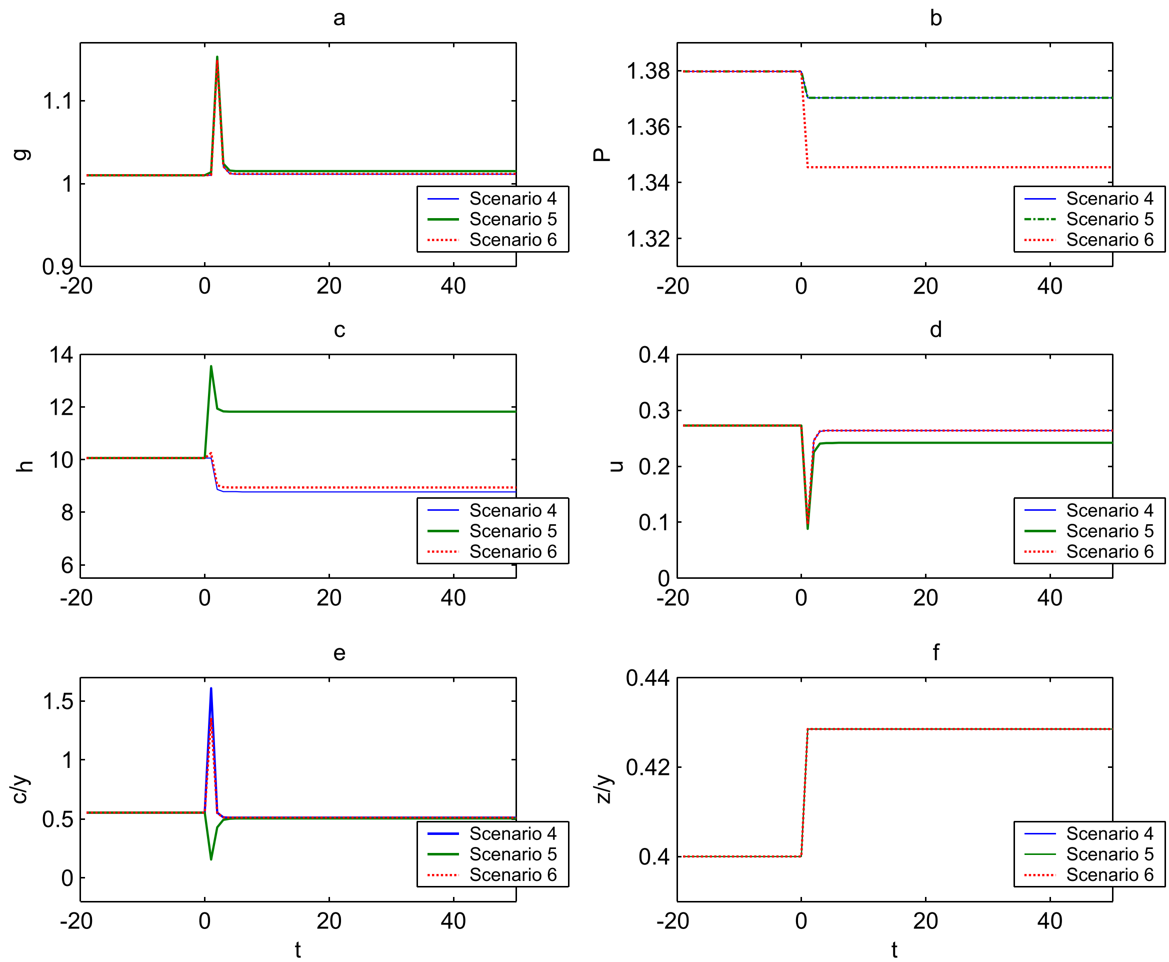

Fig. 2. Transitional dynamics related to tax reform 2.

We now turn to the assessment of the welfare cost implied by the different policy scenarios.[12] We compare the implications of three situations:

(i) First, the economy starts on the benchmark steady-state (without environmental tax). Using Eq. (27), it is a straightforward computational task to derive the permanent consumption flow $\tilde{c}_1$ associated with $\mathcal{W}_1$:

$$\tilde{c}_1 = \exp\left[(1-\beta)\mathcal{W}_1 - \frac{\beta}{1-\beta}\log g_1 + \phi \log P_1\right]. \tag{28}$$

(ii) Second, the economy starts on the benchmark steady state, but the government introduces an environmental tax in $t = 0$. Then the economy experiences a transition before asymptotically reaching a new steady-state. Using Eq. (24), we deduce that the associated permanent consumption flow is $\tilde{c}_2$:

$$\tilde{c}_2 = \exp\left[(1-\beta)\mathcal{W}^{Tot} - \frac{\beta}{1-\beta}\log g_1 + \phi_P \log P_1\right]. \tag{29}$$

(iii) Third, the economy is instantly on its new steady-state implied by the environmental policy. Using Eq. (24), we deduce the associated permanent consumption flow $(\tilde{c}^{rp})$.

$$\tilde{c}^{rp} = \exp\left\{(1-\beta)\mathcal{W}_2 - \frac{\beta}{1-\beta}\log g_1 + \phi_P \log P_1\right\}. \tag{30}$$

Comparing situations (i) and (ii) gives the correct evaluation of the long-run welfare cost λ, as the proportion of benchmark income (y_1) that agents would be willing to sacrifice to stay in the initial steady state, rather than to experience a transition to the new steady state induced by the public policy. Let:

$$\lambda = \frac{\tilde{c}_1 - \tilde{c}_2}{y_1}. \tag{31}$$

Table 6
Long-term effects of policy scenarios.

		$\phi_p = 0.1$		$\phi_p = 1$		$\phi_p = 4.5$	
		λ	λ_{dyn}	λ	λ_{dyn}	λ	λ_{dyn}
Tax Reform 1	Scenario 1	−0.020	1.1774	−0.025	2.587	−0.042	6.752
	Scenario 2	−0.143	3.591	−0.148	3.926	−0.170	7.111
	Scenario 3	−0.035	1.898	−0.049	2.697	−0.108	6.769
Tax Reform 2	Scenario 4	−0.038	1.773	−0.042	2.581	−0.058	6.738
	Scenario 5	−0.161	3.580	−0.166	3.911	−0.186	7.093
	Scenario 6	−0.053	1.898	−0.067	2.691	0.126	6.754

[12] Conceptually, we adapt a method developed by Lucas (1990). For a detailed description of the method see Gomme (1993).

λ is the welfare loss (gain) of switching from the benchmark steady state to the new steady state. In this case, transient movements are correctly taken into account.

Comparing cases (i) and (iii) gives the (incomplete) evaluation of the long-run welfare cost λ_{rp}, as the amount of income that agents would be willing to sacrifice to stay in the initial steady state rather than being located instantly on the balanced-growth path defined by the policy scenario. This cost is measured by

$$\lambda_{rp} = \frac{\widetilde{c}_1 - \widetilde{c}^{rp}}{y_1} \tag{32}$$

λ_{rp} is the welfare loss of switching from the benchmark steady-state to the new one, without undergoing any transient movements, which consequently are omitted from this calculation.

The residual amount of welfare costs due to transitional effects is deduced from Eqs. (31) and (32). Let

$$\lambda_{dyn} = \lambda - \lambda_{rp} = \frac{\widetilde{c}^{rp} - \widetilde{c}_2}{y_1}. \tag{33}$$

We now propose to compute total and transitional welfare costs (λ, λ_{dyn}) for the six policy scenarios studied previously. Our results are reported in Table 6. We vary ϕ_P in an admissible set of values (0.1; 1; 4.5). All scenarios present a negative welfare cost in the long term, which means that all of the tax reforms led to a welfare benefit in the long term, regardless of the spending policy being pursued. These welfare benefits are more important for tax reforms that are coupled with a change in the public spending structure (scenarios 2, 3, 5 and 6). The best results in terms of long run welfare gain are obtained in the cases where the tax reform is associated with an increase in the share of public expenditure on education. We also note that given the low value that households place on environmental quality, the size of this welfare gain is very small. As can be seen in Table 4, the welfare gain in the long run increases with the pollution weight in preferences. In economies with a heightened awareness of environmental degradation, the welfare gain related to tax reforms may be more important.

However, during the transient movements all scenarios present a positive welfare cost. This cost is particularly important for scenarios 2 and 5. Tax reforms which aim to use the revenue from environmental tax to reduce tax on profits and to increase the proportion of education spending, have a relatively high cost during the transition period. It should also be noted that λ_{dyn} rises with the increasing weight of the pollution in the preferences under either of the above noted scenarios.

6. Conclusion

In this paper we have investigated the transient and long term behavior of an economy in response to different environmental tax reforms associated with a change in public spending structure. The endogenous growth model *a la Lucas* is modified by including pollution flow as an externality, which affects both preferences and human capital accumulation. We also introduce an explicit trade-off between two types of public spending: education spending and abatement expenditure. This framework has allowed us to shed light on the mechanism of resource reallocation within the economy and, also, to investigate the responsiveness of growth and welfare to different policy scenarios.

The analysis shows that environmental tax reforms may have a positive impact on growth and welfare in the long run. Moreover, we show that, regardless of spending policy, reducing tax on wages has a more positive impact on growth than cutting tax on profits. Nevertheless, the welfare effect depends on the parameters of the model, particularly the relative effects that expenditure on education or on reducing pollution have on the accumulation of human capital. When environmental tax reform is associated with a change in the structure of public spending, the effects on growth and welfare remain positive, but their magnitude changes. While increasing education spending has a greater impact on stimulating growth, the increase in abatement spending may give the best results in terms of welfare, especially if the effect of pollution on learning is greater than the effect of increased education spending on the productivity of human capital accumulation.

Such analytical results relate to long-term effects and do not reflect what happens during the transition period. Based on a numerical approach, we quantified the growth and welfare effects of six policy scenarios combining tax reforms and changes in the public spending structure. While all of these scenarios were found to have a positive effect on long-term growth, their transitional dynamics do not necessarily show a positive effect on growth. This is particularly the case when public policy does not favor the accumulation of human capital (for example, reducing the tax on profits without an associated increase in education spending).

Moreover, we have conducted an analysis of the welfare cost associated with our different policy scenarios. We dissociate the long term welfare cost and the welfare cost related to the transition dynamics. This distinction allowed us to highlight the trade-off between transient and long-term effects related to each policy scenario. While all scenarios have a welfare gain in the long term, they present a relatively high welfare cost during the transition. This is particularly the case when the policy scenario favors education spending.

It is worth noting that the size of welfare gain is very small in absolute terms and the transitional welfare cost is relatively high. Our results suggest that the welfare gain may not after all be a strong argument in favor of the implementation of green tax reform. Our analysis does suggest however that policymakers who are contemplating a green tax reform should give serious consideration to how the extra revenue should be recycled. The best results in terms of long-run welfare gain may be obtained when tax reforms are associated with a change in the allocation of public spending.

Obviously, our results have several limitations. For example what would happen when the government has to pay interest payments on outstanding debt? In many countries, debt repayment is a major public expenditure that should compete with other expenditures. This question is left for further examination.

Appendix A. Steady state solutions

The steady-state values y, c, u and g are obtained by eliminating the index t from the system (Eqs. (15)–(19)) and by substituting out y and P from Eqs. (20)–(21). The steady state system is given by the following equations:

$$g = 1 + (1-\Lambda)y - c \tag{A1}$$

$$g = \widetilde{B}[(1-\theta)\Lambda]^{\xi}(1-u) + 1 - \frac{\eta}{(\theta\Lambda)^{\mu}} \tag{A2}$$

$$g = \beta\left[1 + \left(1-\tau^{P}\right)\left(1-\tau^{K}\right)\alpha y\right] \tag{A3}$$

$$g = \beta\left[1 + \widetilde{B}((1-\theta)\Lambda)^{\xi} - \frac{\eta}{(\theta\Lambda)^{\mu}}\right] \tag{A4}$$

where $\Lambda = \frac{z}{y} = \left[\tau^{K}\alpha + \tau^{H}(1-\alpha)\right]\left(1-\tau^{P}\right) + \tau^{P}$. From Eq. (21), we obtain. $P = (\theta\Lambda)^{-\mu}$ Eq. (A2) gives directly the steady state growth rate of the economy, which depends only on the parameters of the model, including policy parameters. Using Eqs. (A3) and (A4), we deduce that

$$y^{*} = \frac{\widetilde{B}((1-\theta)\Lambda)^{\xi} - \eta(\theta\Lambda)^{-\mu} - \delta_H}{\alpha(1-\tau^{K})(1-\tau^{P})}. \tag{A5}$$

From Eqs. (A3) and (A4), we obtain

$$u^* = (1-\beta)\left\{1 + \frac{1-\delta_H-\eta(\theta\Lambda)^{-\mu}}{\widetilde{B}[(1-\theta)\Lambda]^{\xi}}\right\}. \tag{A6}$$

By using Eqs. (A1)–(A6), we can easily deduce the values of c^* and h^*.

Appendix B. Comparative statics

This appendix derives the comparative static results cited in Table 1. The partial derivatives of Λ with respect to τ^P, τ^K and τ^K are all positive and given by

$$\frac{\partial\Lambda}{\partial\tau^P} = 1-\left[\tau^K\alpha + \tau^H(1-\alpha)\right]; \quad \frac{\partial\Lambda}{\partial\tau^K} = \alpha(1-\tau^p); \quad \frac{\partial\Lambda}{\partial\tau^H} = (1-\alpha)(1-\tau^p). \tag{B1}$$

From Eq. (A4), we deduce the partial derivative of g^* with respect to Λ:

$$\frac{\partial g^*}{\partial\Lambda} = \beta\left[\xi\theta_1\widetilde{B}(\theta_1\Lambda)^{\xi-1} + \mu\eta\theta_2(\theta_2\Lambda)^{-\mu}\right]>0.$$

As $\frac{\partial g}{\partial\Lambda}>0$, we obtain $\frac{\partial g}{\partial\tau^P} = \frac{\partial g}{\partial\Lambda}\frac{\partial\Lambda}{\partial\tau^P}>0$, $\frac{\partial g}{\partial\tau^K} = \frac{\partial g}{\partial\Lambda}\frac{\partial\Lambda}{\partial\tau^K}>0$ and $\frac{\partial g}{\partial\tau^P} = \frac{\partial g}{\partial\Lambda}\frac{\partial\Lambda}{\partial\tau^H}>0$.

The partial derivatives of g^* with respect to θ_1 and θ_2 are respectively given by:

$$\frac{\partial g^*}{\partial\theta_1} = \beta\xi\Lambda\widetilde{B}(\theta_1\Lambda)^{\xi-1}>0 \quad \text{and} \quad \frac{\partial g^*}{\partial\theta_2} = \beta\mu\eta\Lambda(\theta_2\Lambda)^{-\mu-1}>0\,.$$

From Eq. (A3), we deduce $y^* = \frac{\frac{g^*}{\beta}-1}{(1-\tau^K)(1-\tau^p)\alpha}$.

Thus, the partial derivatives of y^* with respect to Λ, τ^H, τ^P and τ^K are given by $\frac{\partial y^*}{\partial\Lambda} = \frac{1}{\beta}\frac{\partial g^*}{\partial\Lambda}>0$; $\frac{\partial y^*}{\partial\tau^H} = \frac{1}{\beta}\frac{\partial g^*}{\partial\tau^H}>0$; $\frac{\partial y^*}{\partial\tau^P} = \frac{\frac{1}{\beta}\frac{\partial g^*}{\partial\tau^p}[\alpha(1-\tau^p)]+\left[\frac{g}{\beta}-1\right]\left[(1-\tau^K)\alpha\right]}{[(1-\tau^K)(1-\tau^p)\alpha]^2}>0$ and $\frac{\partial y^*}{\partial\tau^K} = \frac{\frac{\partial g^*}{\partial\tau^p}[(1-\tau^p)\alpha]+\left[\frac{g}{\beta}-1\right](1-\tau^p)\alpha}{[(1-\tau^K)(1-\tau^p)\alpha]^2}>0$.

The partial derivative of y^* with respect to θ_1 and θ_2 are respectively given by $\frac{\partial y^*}{\partial\theta_1} = \frac{1}{\beta}\frac{\partial g^*}{\partial\theta_1}>0$ and $\frac{\partial y^*}{\partial\theta_2} = \frac{1}{\beta}\frac{\partial g^*}{\partial\theta_2}>0$.

Computation of the derivatives of u^* makes use of Eq. (A6). We obtain $\frac{\partial u^*}{\partial\Lambda} = \frac{(1-\beta)}{\widetilde{B}[\theta_1\Lambda]^{\xi}}\left\{\frac{\mu\eta}{\Lambda}P + [\eta P-1]\xi\theta_1\widetilde{B}[\theta_1\Lambda]^{-1}\right\}$; $\frac{\partial u^*}{\partial\theta_1} = \frac{(1-\beta)}{\widetilde{B}(\theta_1\Lambda)^{\xi}}\left[-\xi\Lambda(1-\eta P)\widetilde{B}(\theta_1\Lambda)^{-1}\right]$ and $\frac{\partial u^*}{\partial\theta 2} = (1-\beta)\frac{\mu\Lambda\eta(\theta_2\Lambda)^{-\mu-1}}{\widetilde{B}(\theta_1\Lambda)^{\xi}}>0$.

By assuming $\eta P>1$ (which requires $\eta>(\theta_2\Lambda)^{\mu}$), we obtain $\frac{\partial u^*}{\partial\Lambda}>0$ and $\frac{\partial u^*}{\partial\theta_1}>0$.

The partial derivative of c^* with respect to Λ is given by $\frac{\partial c^*}{\partial\Lambda} = \left[(1-\Lambda)\frac{1}{\beta}-1\right]\frac{\partial g^*}{\partial\Lambda}-y^*$. By assuming $\beta>1-\Lambda$ (this limitation is consistent with empirical observations), we deduce that $\frac{\partial c^*}{\partial\Lambda}<0$. Hence, we obtain $\frac{\partial c}{\partial\tau^P} = \frac{\partial c}{\partial\Lambda}\frac{\partial\Lambda}{\partial\tau^P}<0$; $\frac{\partial c}{\partial\tau^K} = \frac{\partial c}{\partial\Lambda}\frac{\partial\Lambda}{\partial\tau^K}<0$ and $\frac{\partial c}{\partial\tau^H} = \frac{\partial c}{\partial\Lambda}\frac{\partial\Lambda}{\partial\tau^H}<0$. The partial derivative of c^* with respect to θ_1 is given by $\frac{\partial c^*}{\partial\theta_1} = \left[\frac{1-\Lambda}{\beta}-1\right]\frac{\partial g^*}{\partial\theta_1}<0$, since $\beta>1-\Lambda$. The partial derivative of c^* with respect to θ_2 is given by $\frac{\partial c^*}{\partial\theta_2} = \left[\frac{1-\Lambda}{\beta}-1\right]\frac{\partial g^*}{\partial\theta_2}<0$, since $\beta>1-\Lambda$.

Appendix C. Growth effects of tax and spending policies

Totally differentiating the equilibrium growth rate (Eq. (A4)) and dividing by the positive change in the environmental tax ($d\tau^P>0$), yields

$$\frac{dg}{d\tau^P} = \frac{\partial g}{\partial\Lambda}\left[\frac{\partial\Lambda}{\partial\tau^P} + \frac{\partial\Lambda}{\partial\tau^K}\frac{d\tau^K}{d\tau^P} + \frac{\partial\Lambda}{\partial\tau^H}\frac{d\tau^H}{d\tau^P}\right] + \frac{\partial g}{\partial\theta_1}\frac{d\theta_1}{d\tau^P} + \frac{\partial g}{\partial\theta_2}\frac{d\theta_2}{d\tau^P}. \tag{C1}$$

C.1. Proof of proposition 1

- In the case of spending policy 1, we have $d\tau^K = d\tau^H = d\theta_2 = 0$ and $d\theta_1>0$. Hence Eq. (C1) yields $\frac{dg}{d\tau^P} = \frac{\partial g}{\partial\theta_1}\frac{d\theta_1}{d\tau^P} = \xi\Lambda\widetilde{B}(\theta_1\Lambda)^{\xi-1}\frac{d\theta_1}{d\tau^P}>0$.
- In the case of spending policy 2, we also have $d\tau^K = d\tau^H = d\theta_1 = 0$ and $d\theta_2>0$. Hence Eq. (C.1) yields $\frac{dg}{d\tau^P} = \frac{\partial g}{\partial\theta_2}\frac{d\theta_2}{d\tau^P} = \eta\mu\Lambda(\theta_2\Lambda)^{-\mu-1}\frac{d\theta_2}{d\tau^P}>0$.

By comparing between the results of both spending policies and assuming that $d\theta_1 = d\theta_2$, we obtain

$$\left.\frac{dg^*}{d\tau^P}\right|_{\substack{d\theta_1>0\\ d\theta_2=0}} - \left.\frac{dg^*}{d\tau^P}\right|_{\substack{d\theta_2>0\\ d\theta_1=0}} = \left(\xi\Lambda\widetilde{B}(\theta_1\Lambda)^{\xi-1}-\eta\mu\Lambda(\theta_2\Lambda)^{-\mu-1}\right)\frac{d\theta_1}{d\tau^P}. \tag{C2}$$

The sign of Eq. (C2) depends on the difference between the effect of education spending on human capital productivity $\left(\text{i.e.}\ \xi\Lambda\widetilde{B}(\theta_1\Lambda)^{\xi-1}\right)$ and the effect on health of reducing pollution (i. e. $\eta\mu\Lambda(\theta_2\Lambda)^{-\mu-1}$).

C2. Proof of proposition 2

In the case of Reform 1, we have $d\tau^K = d\theta_1 = d\theta_2 = 0$ and $d\tau^H<0$. Hence Eq. (C1) yields $\frac{dg}{d\tau^P} = \frac{\partial g}{\partial\Lambda}\left[\frac{\partial\Lambda}{\partial\tau^P} + \frac{\partial\Lambda}{\partial\tau^H}\frac{d\tau^H}{d\tau^P}\right]$. As $\frac{\partial g}{\partial\Lambda}>0$ and $\frac{\partial\Lambda}{\partial\tau^P} + \frac{\partial\Lambda}{\partial\tau^H}\frac{d\tau^H}{d\tau^P} = \frac{d\Lambda}{d\tau^P}>0$, we deduce $\frac{dg}{d\tau^P}>0$.

In the case of Reform 2, we have $d\tau^H = d\theta_1 = d\theta_2 = 0$ and $d\tau^K<0$. Hence Eq. (C1) yields $\frac{dg}{d\tau^P} = \frac{\partial g}{\partial\Lambda}\left[\frac{\partial\Lambda}{\partial\tau^P} + \frac{\partial\Lambda}{\partial\tau^K}\frac{d\tau^K}{d\tau^P}\right]$. As $\frac{\partial g}{\partial\Lambda}>0$ and $\frac{\partial\Lambda}{\partial\tau^P} + \frac{\partial\Lambda}{\partial\tau^K}\frac{d\tau^K}{d\tau^P} = \frac{d\Lambda}{d\tau^P}>0$, we deduce $\frac{dg}{d\tau^P}>0$.

By comparing between the results of both reforms and assuming that $d\tau^H = d\tau^K$, we obtain

$$\left.\frac{dg^*}{d\tau^P}\right|_{\substack{d\theta_1=d\theta_2=0,\, d\Lambda>0\\ d\tau^H<0,\, d\tau^K=0}} - \left.\frac{dg^*}{d\tau^P}\right|_{\substack{d\theta_1=d\theta_2=0\ \ d\Lambda>0\\ d\tau^K<0,\, \tau^H=0}} = \frac{\partial g}{\partial\Lambda}\left(\frac{\partial\Lambda}{\partial\tau^H}-\frac{\partial\Lambda}{\partial\tau^K}\right)\frac{d\tau^H}{d\tau^P}. \tag{C3}$$

By substituting Eq. (B1), we deduce from Eq. (C3) that

$$\left.\frac{dg^*}{d\tau^P}\right|_{\substack{d\theta_1=d\theta_2=0,\, d\Lambda>0\\ d\tau^H<0,\, d\tau^K=0}} - \left.\frac{dg^*}{d\tau^P}\right|_{\substack{d\theta_1=d\theta_2=0,\, d\Lambda>0\\ d\tau^K<0,\, \tau^H=0}} = \frac{\partial g}{\partial\Lambda}\frac{d\tau^H}{d\tau^P}(1-2\alpha)\left(1-\tau^P\right)>0. \tag{C4}$$

The sign of Eq. (C4) depends on the value of α with respect to 1/2. According to the empirical literature, we assume that $\alpha<\frac{1}{2}$.

Appendix D. Welfare effects of tax and spending policies

D.1. Proof of proposition 3

- In the case of spending policy 1, we have $d\tau^K = d\tau^H = d\theta_2 = 0$ and $d\theta_1>0$. Totally differentiating the welfare (Eq. (23)), using $\frac{\partial P}{\partial\theta_1} = 0$ and dividing by the positive change in the environmental tax ($d\tau^P>0$), we obtain

$$\left.\frac{d\mathcal{W}}{d\tau^P}\right|_{d\theta_2=0}^{d\theta_1>0,} = \left(\frac{\partial\mathcal{W}}{\partial c}\frac{\partial c}{\partial\theta_1} + \frac{\partial\mathcal{W}}{\partial g}\frac{\partial g}{\partial\theta_1}\frac{d\theta_1}{d\tau^P}\right)\frac{d\theta_1}{d\tau^P}. \tag{D1}$$

Substituting the derivatives of $\mathcal{W}$ with respect to c and g, and the derivative of c with respect to θ_1, Eq. (D1) yields

$$\left.\frac{d\mathcal{W}}{d\tau^P}\right|_{\substack{d\theta_1>0,\\ d\theta_2=0}} = \frac{1}{1-\beta}\left[\left(\frac{1-\Lambda-\beta}{\beta}\right)\frac{1}{c} + \frac{\beta}{1-\beta}\frac{1}{g}\right]\frac{\partial g}{\partial\theta_1}\frac{d\theta_1}{d\tau^P}. \tag{D2}$$

As $\frac{\partial g}{\partial \theta_1}>0$ and $\frac{d\theta_1}{d\tau^P}>0$, we have $\frac{d\mathcal{W}}{d\tau^P}\Big|_{\substack{d\theta_1>0,\\ d\theta_2=0}}>0$ if $\left(\frac{1-\Lambda-\beta}{\beta}\right)\frac{1}{c}+\frac{\beta}{1-\beta}\frac{1}{g}>0$, which requires $g>\frac{\beta^2}{(\beta+\Lambda-1)(1-\beta)}c$. By assuming $1-\Lambda-\beta<0$ and $\beta>1-\beta$, we have $\frac{\beta^2}{(1-\beta)(\beta+\Lambda-1)}>1$. Thereby, a positive welfare effect $\frac{d\mathcal{W}}{d\tau^P}\Big|_{\substack{d\theta_1>0,\\ d\theta_2=0}}>0$ requires that the long run growth rate (g) be sufficiently higher than the stationary level of consumption (c).

– In the case of spending policy 2, we have $d\tau^K=d\tau^H=d\theta_1=0$ and $d\theta_2>0$. Totally differentiating the welfare (Eq. (23)) and dividing by the positive change in the environmental tax ($d\tau^P>0$), we obtain

$$\frac{d\mathcal{W}}{d\tau^P}\Big|_{\substack{d\theta_2>0,\\ d\theta_1=0}}=\left(\frac{\partial\mathcal{W}}{\partial c}\frac{\partial c}{\partial\theta_2}+\frac{\partial\mathcal{W}}{\partial g}\frac{\partial g}{\partial\theta_2}\frac{d\theta_2}{d\tau^P}+\frac{\partial\mathcal{W}}{\partial g}\frac{\partial P}{\partial\theta_2}\frac{d\theta_2}{d\tau^P}\right)\frac{d\theta_2}{d\tau^P}. \tag{D3}$$

Substituting the derivatives of $\mathcal{W}$ with respect to c, g and P, and the derivative of c with respect to θ_1, Eq. (D1) yields

$$\frac{d\mathcal{W}}{d\tau^P}\Big|_{\substack{d\theta_2>0,\\ d\theta_1=0}}=\frac{1}{1-\beta}\left[\frac{1}{c}\left(\frac{1-\Lambda-\beta}{\beta}\right)\frac{\partial g}{\partial\theta_2}+\frac{\beta}{1-\beta}\frac{1}{g}\frac{\partial g}{\partial\theta_2}+\phi_p\frac{\mu}{\theta_2}\right]\frac{d\theta_2}{d\tau^P} \tag{D4}$$

$$\frac{d\mathcal{W}}{d\tau^P}\Big|_{\substack{d\theta_2>0,\\ d\theta_1=0}}>0\Leftrightarrow\left[\frac{\beta}{1-\beta}\frac{1}{g}-\frac{\Lambda+\beta-1}{\beta}\frac{1}{c}\right]\frac{\partial g}{\partial\theta_2}+\phi_p\frac{\mu}{\theta_2}>0. \tag{D5}$$

By comparing the results of both spending policies and assuming that $d\theta_1=d\theta_2$, we obtain

$$\frac{d\mathcal{W}}{d\tau^P}\Big|_{\substack{d\theta_2>0,\\ d\theta_1=0}}-\frac{d\mathcal{W}}{d\tau^P}\Big|_{\substack{d\theta_2>0,\\ d\theta_1=0}}=\frac{1}{1-\beta}\left\{\left[\frac{1}{c}\left(\frac{1-\Lambda-\beta}{\beta}\right)+\frac{\beta}{1-\beta}\frac{1}{g}\right]\left(\frac{\partial g}{\partial\theta_2}-\frac{\partial g}{\partial\theta_1}\right)+\phi_p\frac{\mu}{\theta_2}\right\}\frac{d\theta_2}{d\tau^P}. \tag{D6}$$

Note that $\frac{\partial g}{\partial\theta_2}-\frac{\partial g}{\partial\theta_1}=\beta\left(\theta_2\mu\eta(\theta_2\Lambda)^{-\mu-1}-\xi\theta_1\widetilde{B}(\theta_1\Lambda)^{\xi-1}\right)$.

Thus $\frac{d\mathcal{W}}{d\tau^P}\Big|_{\substack{d\theta_2>0,\\ d\theta_1=0}}-\frac{d\mathcal{W}}{d\tau^P}\Big|_{\substack{d\theta_2>0,\\ d\theta_1=0}}$, If $\theta_2\mu\eta(\theta_2\Lambda)^{-\mu-1}>\xi\theta_1\widetilde{B}(\theta_1\Lambda)^{\xi-1}$.

D.2. Proof of proposition 4

– In the case of reform 1, we have $d\tau^K=d\theta_1=d\theta_2=0$ and $d\tau^H<0$. Thus Eq. (D.1) yields

$$\frac{d\mathcal{W}}{d\tau^P}\Big|_{\substack{d\tau^H<0,d\Lambda>0\\ d\tau^K=0}}=\left[\frac{\partial\mathcal{W}}{\partial c}\frac{\partial c}{\partial\Lambda}+\frac{\partial\mathcal{W}}{\partial g}\frac{\partial g}{\partial\Lambda}+\frac{\partial\mathcal{W}}{\partial P}\frac{\partial P}{\partial\Lambda}\right]\times\left(\frac{\partial\Lambda}{\partial\tau^P}+\frac{\partial\Lambda}{\partial\tau^H}\frac{d\tau^H}{d\tau^P}\right). \tag{D7}$$

– In the case of reform 1, we have $d\tau^H=d\theta_1=d\theta_2=0$ and $d\tau^K<0$. Thus Eq. (D.1) yields

$$\frac{d\mathcal{W}}{d\tau^P}\Big|_{\substack{d\tau^H<0,d\Lambda>0\\ d\tau^K=0}}=\left[\frac{\partial\mathcal{W}}{\partial c}\frac{\partial c}{\partial\Lambda}+\frac{\partial\mathcal{W}}{\partial g}\frac{\partial g}{\partial\Lambda}+\frac{\partial\mathcal{W}}{\partial P}\frac{\partial P}{\partial\Lambda}\right]\times\left(\frac{\partial\Lambda}{\partial\tau^P}+\frac{\partial\Lambda}{\partial\tau^K}\frac{d\tau^K}{d\tau^P}\right). \tag{D8}$$

As $\frac{\partial\Lambda}{\partial\tau^P}+\frac{\partial\Lambda}{\partial\tau^K}\frac{d\tau^K}{d\tau^P}>0$, the sign of Eq. (D1) depends on $\frac{\partial\mathcal{W}}{\partial c}\frac{\partial c}{\partial\Lambda}+\frac{\partial\mathcal{W}}{\partial g}\frac{\partial g}{\partial\Lambda}+\frac{\partial\mathcal{W}}{\partial P}\frac{\partial P}{\partial\Lambda}$. The effect of tax reforms on welfare acts through consumption, growth and pollution. If the effects on growth $\left(\left(\frac{\partial g}{\partial\Lambda}+\frac{\partial g}{\partial\theta_2}\right)\frac{\partial\mathcal{W}}{\partial g}>0\right)$ and pollution $\left(-\left(\frac{\partial P}{\partial\Lambda}+\frac{\partial P}{\partial\theta_2}\right)\frac{\partial\mathcal{W}}{\partial P}>0\right)$ offset the negative effect on consumption $\left(\left(\frac{\partial c}{\partial\Lambda}+\frac{\partial c}{\partial\theta_2}\right)\frac{\partial\mathcal{W}}{\partial c}<0\right)$, tax reforms improve welfare, i.e., $\frac{d\mathcal{W}}{d\tau^P}\Big|_{\substack{d\tau^H<0,d\Lambda>0\\ d\tau^K=0}}>0$ and $\frac{d\mathcal{W}}{d\tau^P}\Big|_{\substack{d\tau^H<0,d\Lambda>0\\ d\tau^K=0}}>0$.

By comparing the results of both reforms and assuming that $d\tau^H=d\tau^K$, we obtain

$$\frac{d\mathcal{W}}{d\tau^P}\Big|_{\substack{d\tau^H<0,d\Lambda>0\\ d\tau^K=0}}-\frac{d\mathcal{W}}{d\tau^P}\Big|_{\substack{d\tau^H<0,d\Lambda>0\\ d\tau^K=0}}=\left[\frac{\partial\mathcal{W}}{\partial c}\frac{\partial c}{\partial\Lambda}+\frac{\partial\mathcal{W}}{\partial g}\frac{\partial g}{\partial\Lambda}+\frac{\partial\mathcal{W}}{\partial P}\frac{\partial P}{\partial\Lambda}\right]\{2\alpha-1\}(1-\tau^p)\frac{d\tau^H}{d\tau^p} \tag{D9}$$

$$\frac{d\mathcal{W}}{d\tau^P}\Big|_{d\tau^K=0}^{d\tau^H<0,d\Lambda>0}-\frac{d\mathcal{W}}{d\tau^P}\Big|_{d\tau^K=0}^{d\tau^H<0,d\Lambda>0}>0\Leftrightarrow\alpha>\frac{1}{2}. \tag{D10}$$

Appendix E. Transitional welfare cost

The economy reaches NSS at $t=T+1$. We have the following expression of $\mathcal{W}_2$

$$\mathcal{W}_2=\sum_{t=T+1}^{\infty}\beta^t\left(\log C_t-\phi_p\log P_t\right) \tag{E1}$$

$\mathcal{W}_2$ can also be written as follows

$$\mathcal{W}_2=\beta^{T+1}\sum_{i=0}^{\infty}\beta^i\left(\log C_{T+1+i}-\phi_p\log P_t\right) \tag{E2}$$

where

$$\forall t\geq T+1, C_t=c_2K_{t-1}\Rightarrow\forall i\geq 0, C_{T+1+i}=c_2K_{T+i}$$
$$\forall t\geq T+1, K_t=g_2K_{t-1}\Rightarrow\forall i\geq 0, K_{T+1+i}=g_2K_{T+i}.$$

The economy reaches NSS at $t=T+1$. NSS's capital stock inherited from previous decisions is K_T. Thus $K_{T+1}=g_2K_T$, $K_{T+2}=g_2^2K_T,\ldots$, $K_{T+i}=g_2^iK_T$. Consumption expression writes $C_{T+1+i}=c_2g_2^iK_T$ and $\mathcal{W}_2$ can be written

$$\mathcal{W}_2=\beta^{T+1}\sum_{i=0}^{\infty}\beta^i\left[\log\left(c_2g_2^iK_T\right)-\phi_p\log P_2\right]=\frac{\beta^{T+1}}{1-\beta}\left[\log c_2+\log K_T-\phi_p\log P_2+\frac{\beta\log g_2}{1-\beta}\right].$$

Note that K_T is inherited from the transitional dynamics. Thus, we have $K_0=g_0K_{-1}$, $K_1=g_1g_0K_{-1}$, $K_T=g_Tg_{T-1}\ldots g_1g_2K_{-1}$. More elegantly, one can write

$$\log(K_T)=\log\left(\prod_{i=0}^{T}g_i\right)+\log(K_{-1})=\sum_{i=0}^{T}\log(gi). \tag{E3}$$

Thus, the final expression of $\mathcal{W}_2$, is given by

$$\mathcal{W}_2=\frac{\beta^{T+1}}{1-\beta}\left[\log c_2+\sum_{i=0}^{T}\log(g_i)-\phi_p\log P_2+\frac{\beta\log g_2}{1-\beta}\right]. \tag{E4}$$

We have the following $\mathcal{W}_{1\to 2}$ expression:

$$\mathcal{W}_{1\to 2}=\sum_{t=0}^{T}\beta^t\left(\log(c_tK_{t-1})-\phi_P\log P_t\right). \tag{E5}$$

By using $\log(K_t) = \log(\prod_{i=0}^{t} g_i) + \log(K_{-1}) = \sum_{i=0}^{t} \log(g_i)$, we deduce

$$\mathcal{W}_{1\to 2} = \sum_{t=0}^{T} \beta^t \left[\log(c_t) + \sum_{i=0}^{t-1} \log(g_i) - \phi_P \log P_t \right]. \tag{E6}$$

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