Journal of Environmental Economics and Management 71 (2015) 90–108

Contents lists available at ScienceDirect

Journal of Environmental Economics and Management

journal homepage: www.elsevier.com/locate/jeem

# Pigou meets Mirrlees: On the irrelevance of tax distortions for the second-best Pigouvian tax ☆

Bas Jacobs [a,b,c,*], Ruud A. de Mooij [c,d,e]

[a] Department of Economics, Erasmus School of Economics, Erasmus University Rotterdam, PO box 1738, 3000 DR Rotterdam, The Netherlands
[b] Tinbergen Institute, The Netherlands
[c] CESifo, Germany
[d] International Monetary Fund, United States
[e] Oxford University Centre for Business Taxation, United Kingdom

ARTICLE INFO

*Article history:*
Received 12 June 2012
Available online 29 January 2015

*JEL Classificaton:*
D62
H21
H23

*Keywords:*
Marginal cost of public funds
Optimal environmental taxation
Optimal redistribution
Externalities

ABSTRACT

This paper extends the Mirrlees (1971) model of optimal income redistribution with optimal corrective taxes to internalize consumption externalities. Using general utility structures and exploring both linear and non-linear taxes, it is demonstrated that the optimal second-best tax on an externality-generating good should not be corrected for the marginal cost of public funds, since it equals one in the optimal tax system. In the optimum, distortions of income taxes are equal to marginal redistributional gains. If the government does not have access to a non-distortionary marginal source of finance, the marginal cost of public funds can be either larger or smaller than one depending on subjective preferences for income redistribution. The optimal second-best corrective tax is then either higher or lower than the Pigouvian level. The findings in this paper generalize and amend prior results based on representative-agent models, shedding new light on the weak double-dividend hypothesis, and on the welfare gains of recycling revenue from environmental taxes.



## Introduction

Pigou (1920) taught us that the optimal tax to address a negative environmental externality is equal to the marginal external damage from the polluting activity. However, the optimality of the Pigouvian tax has been challenged by the theory of second best. In particular, in the presence of distortionary taxes, the marginal environmental damage from pollution

☆ This paper is dedicated to our dear friend and colleague Jenny Ligthart who passed away far too early. She made important contributions to the literature on environmental taxation. We will remember her devotion to teaching and research. We are grateful to the editor, Daniel Phaneuf, and two anonymous referees for excellent comments and suggestions for improvement. We also would like to thank Aart Gerritsen, Arnold Heertje, Michael Keen, Ian Parry, Rick van der Ploeg, Tony Venables and participants of seminars held at Oxford University, Konstanz University, the International Monetary Fund, and the 66th IIPF congress held in Uppsala for useful comments and suggestions. The views expressed in this paper are those of the authors and do not necessarily represent those of the IMF or IMF policy. All remaining errors are our own.

* Corresponding author at: Department of Economics, Erasmus School of Economics, Erasmus University Rotterdam, PO box 1738, 3000 DR Rotterdam, The Netherlands.

*E-mail address:* bjacobs@ese.eur.nl (B. Jacobs).
*URL:* http://people.few.eur.nl/bjacobs (B. Jacobs).

http://dx.doi.org/10.1016/j.jeem.2015.01.003

should be divided by the marginal cost of public funds to determine the optimal second-best corrective tax (Sandmo, 1975; Bovenberg and van der Ploeg, 1994b). As the marginal cost of public funds typically exceeds one in the presence of pre-existing tax distortions, the optimal second-best corrective tax should thus be set below the Pigouvian level (Bovenberg and de Mooij, 1994). For example, if the social cost of carbon (SCC) were estimated at say $33 per tonne,[1] the Pigouvian principle would suggest that a carbon tax of $33 per tonne is optimal. However, with a marginal cost of public funds of say 1.3, second-best theory would guide us to an optimal carbon tax of only $25 per tonne.

The notion that the optimal corrective tax should be adjusted for the marginal cost of public funds, as in Sandmo (1975) and Bovenberg and van der Ploeg (1994b), is based on models that assume a representative agent.[2] These models rule out non-individualized lump-sum taxes to make the optimal-tax problem second best in nature, which is often justified by referring to distributional issues. However, if all agents are identical, there are no distributional issues, and also no economic reasons why non-individualized lump-sum taxes should be ruled out. Making second-best considerations meaningful thus requires a model with heterogeneous agents.

This paper extends the analysis of optimal second-best corrective taxation by adopting a general model where agents differ in their earnings ability, thus extending Mirrlees (1971) and Atkinson and Stiglitz (1976) to include environmental externalities. Our model differs from the representative-agent models in two critical ways. First, individuals are heterogeneous in their earnings ability, which is private information. The optimal-tax problem is second best as the government cannot use individualized lump-sum taxes to redistribute income from high-ability to low-ability agents. Second, in contrast to representative-agent models, the government may have access to a non-individualized lump-sum tax, which is a non-distortionary marginal source of public finance. This instrument renders the marginal cost of public funds equal to one in the optimum. Income taxes are still used as part of the optimal tax system, as they not only create deadweight losses due to distortions in the labor market, but also welfare gains due to a more equal income distribution. In the optimal tax system, these two effects on welfare exactly offset each other.

Allowing for heterogeneous agents and redistributional concerns changes the second-best result of an optimal corrective tax being lower than the Pigouvian rate. Indeed, if the tax system is optimized, the corrective tax should not be adjusted for the marginal cost of public funds. Intuitively, the marginal unit of tax revenue is valued equally by the government and the private sector so that a better environmental quality does not compete with other public goods, such as income redistribution or raising public revenue. We demonstrate that our main result – corrective taxes should not be adjusted for the marginal cost of public funds – holds irrespective of whether taxes are linear or non-linear and for completely general utility functions. We derive the properties on the utility function under which first-best Pigouvian tax rules for externality-generating goods apply in second-best both for linear and non-linear tax systems. We also demonstrate that the corrective non-linear tax is flat as long as marginal environmental damages are constant and preferences are weakly separable between labor and other commodities. Finally, we present our optimal tax rules in terms of sufficient statistics, i.e., elasticities, earnings distributions, and social welfare weights, which can be determined empirically.

To clearly disentangle the roles of, on one hand, agent heterogeneity and, on the other hand, non-individualized lump-sum transfers, we solve the optimal linear tax structure for the special case where the government cannot optimize non-individualized lump-sum transfers. We show that the marginal cost of public funds can then be either larger or smaller than one, depending on whether the government redistributes too much or too little income. Hence, in such a constrained second-best optimum, the optimal pollution tax might be either higher or lower than the Pigouvian level. The representative-agent model, from which many results in the literature are derived, is then nested as the case where distortionary taxes do not have any redistributional benefits. Indeed, the marginal cost of public funds then always exceeds one, since it captures only efficiency losses and no distributional benefits of taxation.

Our findings also shed new light on the debate of the double dividend of green tax reforms, see also the reviews by Goulder (1995), Bovenberg (1999), Sandmo (2000), and Schöb (2003). This literature explores whether an increase in pollution taxes, while using the proceeds to cut distortionary labor taxes, can raise both environmental and non-environmental welfare. In its 'weak' form, the double-dividend hypothesis compares the welfare effects of an environmental tax reform where revenue is recycled through reductions in either distortionary or lump-sum taxes.[3] A number of studies have emphasized that the revenue-recycling effect of the reform renders a weak double dividend likely, because reducing distortionary taxes is preferred to reducing non-distortionary lump-sum taxes, see e.g. Parry (1995) and Goulder et al. (1997).

Our model shows that one should not only look at the revenue-recycling effect, but also account for the so-called 'distributional effect' that is associated with distortionary taxation. Whether a weak double dividend occurs depends on the balance of the revenue-recycling and distributional effects. In the optimal tax system, the two exactly offset each other, so that the revenue-raising capacity of corrective taxes does not make them useful to cut distortionary labor taxes. Indeed,

[1] Estimates of the SCC show a wide range. A recent review by US government agencies (IAWG, 2013) arrives at an estimate of $33 in 2010, based on 2007 US dollars and a discount rate of 3 percent. However, some studies claim that the SCC are much higher (Stern, 2007).

[2] See for surveys, e.g., Goulder (1995), Fullerton and Metcalf (1998), Bovenberg (1999), Sandmo (2000), Goulder and Bovenberg (2002), and Fullerton et al. (2010).

[3] The other, so-called 'strong' double dividend states that, relative to the initial equilibrium, an environmental tax reform increases both environmental and non-environmental welfare. If the initial tax system is optimized from a non-environmental point of view, there can be no welfare gains from a non-environmental perspective and, therefore, no strong double dividend. For a review of this literature, see the studies cited in footnote 2.

labor-tax distortions are present for distributional reasons and the excess burden of labor taxation equals its distributional gain in the optimal tax system. With the marginal cost of funds being one, cutting distortionary labor taxes does not raise social welfare more than increasing lump-sum transfers. Only if deadweight losses exceed the distributional benefits of labor taxes – which is always the case in representative agent models, since distributional gains are set to zero – will the weak double dividend hold.

Before presenting our analysis, Section Contributions to the literature discusses in more detail how this paper contributes to the existing literature on optimal second-best corrective taxes. Section Model presents the model. Section Optimal linear taxation derives the optimal tax system under linear policy instruments, while Section Optimal non-linear taxation does the same under non-linear instruments. Section Conclusions and policy implications discusses policy implications and concludes. Step-by-step derivations of all results are available in the online Appendix to this paper.

## Contributions to the literature

A large part of the literature on second-best corrective taxation uses representative-agent models to show that, in the presence of distortionary taxes, the first-best Pigouvian tax is no longer the optimal corrective tax. Rather, the marginal environmental damage from pollution should be divided by the marginal cost of public funds to obtain the optimal second-best corrective tax (Sandmo, 1975; Bovenberg and van der Ploeg, 1994b). The reason is that corrective taxes distort the composition of consumption from a non-environmental perspective, thereby exacerbating pre-existing distortions in the labor market. Accordingly, the corrective tax should be set below the Pigouvian tax if the initial tax system is distortionary, as it implies that the marginal cost of public funds exceeds one. In this connection, Bovenberg and de Mooij (1994, p.1085) conclude: “In the presence of preexisting distortionary taxes, the optimal pollution tax typically lies below the Pigouvian tax, which fully internalizes the marginal social damage from pollution”.

An extensive corrective-tax literature has expanded the analysis of second-best taxation within the representative-agent framework. Most of this literature is discussed and summarized in Goulder (1995), Fullerton and Metcalf (1998), Bovenberg (1999), Sandmo (2000), Goulder and Bovenberg (2002), and Fullerton et al. (2010). For example, some studies have demonstrated that if the government fails to set optimal taxes, e.g. by letting fixed factors go untaxed, or by setting sub-optimal non-corrective taxes, it is no longer clear in which direction the optimal second-best corrective tax should be modified compared to the first-best Pigouvian tax, see, for example, Bovenberg and van der Ploeg (1994a), de Mooij and Bovenberg (1998), Ligthart and van der Ploeg (1999), Parry and Bento (2000), and Bento and Jacobsen (2007). The literature also provides examples in which markets fail (e.g. due to involuntary unemployment), see also Bovenberg and van der Ploeg (1996), Koskela and Schöb (1999) and Holmlund and Kolm (2000). In this case, the modifications to the Pigouvian tax are again ambiguous. Finally, Liu (2013) argues that, since some environmental taxes are more difficult to evade, a green tax reform might simultaneously benefit the environment and reduce overall tax evasion.

The present paper belongs to the literature that extends the analysis of optimal second-best corrective taxation to a heterogeneous-agent framework. Compared to earlier studies in this area, it contains at least five contributions. First, this paper adds to Kaplow (2012). However, Kaplow does not look at optimal taxes but at tax reforms. He assumes that, when corrective taxes are changed, the non-linear income tax schedule can always be adjusted to completely neutralize the distributional impact of the corrective tax. By assuming weakly separable preferences between labor supply and other commodities, such a benefit-absorbing tax change does not generate incentive effects on labor supply. Neither labor-tax distortions nor distributional effects should thus affect the optimal corrective tax in second best.[4]

Kaplow's approach has a number of shortcomings, however. First, he must assume weakly separable preferences, otherwise the benefit-absorbing change in the non-linear tax schedule need not be incentive compatible so that the tax reform cannot be implemented, see also Laroque (2005), Gahvari (2006) and Jacobs (2009). Hence, Kaplow's approach cannot be generalized to non-separable preferences. Second, while the tax system is sub-optimal to start with, Kaplow assumes that the non-linear income tax schedule can be changed at each and every income level. This begs the question why the government does not optimize the tax schedule in the first place. If there are indeed valid, but unspecified reasons why non-linear tax schedules cannot be optimized, then for the same unspecified reasons it may not be feasible to implement perfect benefit-absorbing tax changes. Finally, as a related point, Kaplow's analysis cannot be generalized to linear tax schedules. The reason is that linear taxes cannot be perfectly tailored to neutralize all distributional effects of corrective taxes. In the real world, tax systems are often restricted to be piece-wise linear, making the analysis of restricted tax systems relevant.

This paper avoids all these restrictions by analyzing optimal corrective taxes with general preference structures, allowing for both linear and non-linear tax schedules, and without adjusting the (linear or non-linear) tax schedules to fully neutralize the distributional impact of corrective taxes. Our result that the optimal second-best corrective tax should not be corrected for the marginal cost of public funds is similar to Kaplow (2012), but it does not require a benefit-absorbing tax change in the non-linear tax schedule. Indeed, our finding relies on an envelope property that the distortionary costs and the distributional benefits of taxes offset each other when the tax system is optimized. This also explains why our results do

[4] Kaplow (2012) is related to the arguments provided in Kaplow (1996, 2004), Laroque (2005) and Gauthier and Laroque (2009), who analyze distortionary taxation and optimal public goods provision (rather than externalities).

not require any form of separability in the utility function, since the marginal cost of public funds remains one even when preferences are non-separable. Moreover, we derive that the optimal corrective tax under linear instruments should generally include the distributional impact of corrective taxes, but nevertheless does not need to be corrected for pre-existing tax distortions. And, we show that the optimal linear corrective tax might be equal to the first-best Pigouvian tax.

Second, this paper follows Pirttilä and Tuomala (1997), Cremer et al. (1998), and Micheletto (2008) who also adopt an optimal-tax approach with heterogeneous agents. Like these authors, we find that no correction of the Pigouvian rule is needed with weakly separable preferences, even with labor-market distortions arising from redistributive income taxation.[5] However, their optimal-tax rules are formulated in terms of incentive-compatibility constraints. This makes it difficult to analytically derive general properties of optimal corrective tax schedules. In contrast, this paper follows Saez (2001) and Jacobs and Boadway (2014) to obtain explicit and simple second-best non-linear tax expressions in terms of sufficient statistics: elasticities, earnings distributions, and social welfare weights, which can all be linked to empirical estimates and to the representative-agent models. This approach also enables us to analytically prove that the marginal cost of funds equals one in the optimal non-linear tax system.[6]

A third contribution of this paper is relative to Pirttilä (2000), who analyzes optimal linear corrective and income taxes with redistribution. Following Jacobs (2013), we use an economically more appealing definition for the marginal cost of public funds than Pirrtillä, which is based on the social marginal value of income of Diamond (1975). In contrast to Pirttilä (2000), we demonstrate that the marginal cost of public funds should not play a role in the optimal second-best policy rules for corrective taxes. Moreover, we derive analytical characterizations for optimal linear income and corrective taxes, and the conditions under which the optimal linear corrective tax corresponds to the first-best Pigouvian tax in second-best settings with distortionary income taxation.

As a fourth contribution, this paper explores the robustness of our main findings to various modifications of the utility function and to whether taxes are linear or non-linear. The literature has identified non-environmental reasons why the optimal corrective tax might differ from the Pigouvian rule. First, commodity taxes should optimally be differentiated for efficiency reasons if some commodities are more complementary to leisure than others, cf. Corlett and Hague (1953) and Atkinson and Stiglitz (1976). In that case, corrective taxes may help to alleviate tax distortions in the labor market. Indeed, West and Williams (2007) find evidence that gasoline is a relative complement to leisure, offering scope for such taxes to exceed the Pigouvian rate. Second, when the income tax is restricted to be linear, the tax on polluting consumption can optimally be used for distributional reasons alongside the income tax, cf. Atkinson and Stiglitz (1976) and Pirttilä (2000). If polluting commodities are consumed relatively more by the poor, then the optimal corrective tax may be set below the Pigouvian level. Proost and Mayares (2001) and Williams (2005), for example, use an applied framework to assess optimal corrective taxes to serve distributional goals. Third, changes in environmental quality can either affect labor-supply distortions or the distribution of income, thus further modifying the optimal corrective tax. For example, Williams (2002) explores the role of interactions between environmental quality and labor supply through health and productivity effects. Our analysis captures all these modifications and shows that the main result – no correction for the pre-existing tax distortions – does not depend on specific assumptions regarding the utility function. The paper furthermore derives exact conditions on the utility structure that ensure that the optimal second-best corrective tax equals the first-best Pigouvian rule.

A final contribution of this paper is that it analyzes non-linear corrective taxes alongside the optimal non-linear income tax. This allows us to explore the conditions under which a flat-rate Pigouvian tax is in fact optimal. The existing literature has only looked at linear corrective taxes, which for many consumption goods is a necessary condition as individual commodity purchases are not observed – making non-linear taxes impossible to implement. However, for a number of important polluting consumption goods, such as domestic gas and electricity consumption, it is feasible to levy non-linear taxes, because these commodities cannot easily be transported or stored so that arbitrage is difficult or even impossible. The Netherlands, for instance, levies a non-linear energy tax based on an individual's domestic consumption of electricity and gas.[7] We show that flat-rate corrective taxes are optimal and equal to the Pigouvian tax if the social marginal damage of consuming one unit of the polluting consumption good is constant across individuals and if preferences are weakly separable between commodities and labor supply.

## Model

This paper employs a static model that consists of heterogeneous individuals and a government. Individuals maximize utility by supplying labor and consuming non-polluting ('clean') and polluting ('polluting') commodities. The government maximizes social welfare by setting income taxes and corrective taxes on the polluting good. Without loss of generality, a

[5] Cremer et al. (1998) assume that environmental quality is separable from other commodities. This paper allows environmental quality to enter utility without imposing any form of separability, like in Pirttilä and Tuomala (1997).

[6] This finding is similar to Jacobs and Boadway (2014) who demonstrate that the marginal cost of public funds is one under optimal non-linear income and commodity taxation. Jacquet and Lehmann (2013) find the same when the government optimizes non-linear income and participation taxes.

[7] In 2013, the Dutch government levies a graduated tax of 0.1862 euro/m$^3$ for gas use below 170,000 m$^3$ per year until 0.0115 euro/m$^3$ for gas use exceeding 10,000,000 m$^3$ per year. Similarly, there is a tax of 0.1165 euro/kWh on electricity use below 10,000 kWh, which declines to 0.0005 euro for businesses using more than 10,000,000 kWh per year. Moreover, there a tax credit of 319 euro for electricity, see Dutch Ministry of Finance (2013).

partial-equilibrium setting is assumed in which prices are fixed.[8] The model is introduced under the assumption of linear policy instruments. Formally, the informational assumptions for this instrument set are that the government is able to observe aggregate labor incomes and aggregate consumption of polluting goods. Later, this assumption is dropped by allowing for non-linear instruments, which require observability of labor earnings and consumption of polluting goods at the individual level.

*Households*

There is a total mass of individuals equal to $N$. Individuals may differ by a one-dimensional parameter $n \in \mathcal{N} = [\underline{n}, \overline{n}]$, where $n$ is used to denote the individual's earning ability ('skill level'). All labor types are assumed to be perfect substitutes in aggregate production. As a result, the wage rate per efficiency unit of skill is constant and normalized to unity. The density of individual types is denoted by $f(n)$ and the cumulative distribution function by $F(n)$. All individual-specific variables are indexed with subscript $n$.

Each individual $n$ derives utility from clean commodities $c_n$, polluting commodities $q_n$, and a better environmental quality $E$. In addition, the individual derives disutility from supplying labor $l_n$. The utility function $u_n$ is strictly quasi-concave and identical across individuals:

$$u_n \equiv u(c_n, q_n, l_n, E), \quad u_c, u_q, -u_l, u_E > 0, \quad u_{cc}, u_{ll}, u_{qq}, u_{EE} < 0, \quad \forall n. \tag{1}$$

The subscripts refer to the argument of differentiation, except where the subscript denotes ability $n$. All goods are assumed to be non-inferior. It is assumed that the utility function satisfies the single-crossing conditions, which are needed to implement non-linear taxes, see also Section Optimal non-linear taxation. In addition, we assume that the marginal utility of income is decreasing.[9] No further structure on the cross derivatives of the utility function is imposed and the specification allows for general cross-substitution patterns between consumption of clean and polluting goods, labor supply and environmental quality.

Households spend their net labor earnings and government transfers on consumption of clean and polluting goods. Gross labor earnings $nl_n$ are subject to tax rate $t$, polluting goods $q_n$ are subject to tax rate $\tau$, and individuals receive a non-individualized lump-sum transfer $T$ (or pay a lump-sum tax if $T<0$). The individual budget constraint therefore reads as follows:

$$c_n + (1+\tau)q_n = (1-t)nl_n + T, \quad \forall n. \tag{2}$$

Given the presumed absence of non-labor incomes, the tax on the clean commodity is redundant, and, therefore, set to zero.[10] Each individual maximizes utility subject to their budget constraint. Consumption of polluting commodities causes a classical negative externality in a manner that is outlined in detail below. Households thus take environmental quality $E$ as given when deciding on their consumption plans.

Optimal choices of labor and consumption are governed by the following first-order conditions:

$$\frac{-u_l}{u_c} = (1-t)n, \quad \forall n, \tag{3}$$

$$\frac{u_q}{u_c} = 1+\tau, \quad \forall n. \tag{4}$$

The marginal rate of substitution between labor and consumption in Eq. (3) equals the net wage rate. A larger tax rate on labor earnings induces substitution towards leisure. According to Eq. (4), the individual optimally decides upon the allocation of resources between polluting and clean consumption goods. A higher corrective tax discourages the consumption of polluting goods.

The indirect utility function is designated by $v_n \equiv v(T, t, \tau, E) \equiv u(\hat{c}_n, \hat{q}_n, \hat{l}_n, E)$, $\forall n$, where hats denote optimized consumption of each commodity and labor supply. Application of Roy's identity produces the following derivatives of the indirect utility function: $\partial v_n/\partial T = \lambda_n$, $\partial v_n/\partial t = -\lambda_n nl_n$, $\partial v_n/\partial \tau = -\lambda_n q_n$, and $\partial v_n/\partial E = \lambda_n u_E/u_c$, $\forall n$, where $\lambda_n$ stands for the private marginal utility of income.

[8] Almost all of the papers in the literature fix the marginal rates of transformation between all commodities at one. Hence, all prices are constant, and allowing for general equilibrium provides no additional insights, see e.g., Bovenberg and de Mooij (1994) and Bovenberg and van der Ploeg (1994b). Moreover, our partial-equilibrium results fully generalize to general-equilibrium settings with non-constant prices, since optimal second-best tax rules in general equilibrium are identical to the ones in partial equilibrium as long as there are constant returns to scale in production and all labor types are perfect substitutes, see also Diamond and Mirrlees (1971).

[9] Decreasing marginal utility of income is not automatically implied by the assumption $u_{cc}<0$. For example, the marginal utility of income is constant and equal to one when the utility function is weakly separable in commodities, i.e. $u(\upsilon(c_n, q_n), l_n, E)$, and sub-utility $\upsilon(c_n, q_n)$ is linear homogenous. See also Corollary 2.

[10] Fullerton (1997) shows that the alternative normalization with a zero labor tax raises the optimal commodity taxes on clean and polluting consumption in a uniform way (which is equivalent to an income tax).

*Environmental quality*

Environmental quality ($E$) is modeled as a pure public good. It is specified as a linear function of aggregate consumption of polluting goods:

$$E \equiv E_0 - \alpha N \int_{\mathcal{N}} q_n \, \mathrm{d}F(n), \quad E_0, \alpha > 0, \tag{5}$$

where $E_0$ denotes the exogenously given initial stock of environmental quality. The linearity of the specification for environmental quality is without loss of generality, since the utility function features diminishing marginal utility of environmental quality. The latter assumption ensures increasing social marginal damages from pollution. Alternatively, one can also interpret Eq. (5) as the production technology of environmental quality.

*Government*

The government maximizes a Bergson–Samuelson social welfare function, which is a sum of concave individual utilities:

$$N \int_{\mathcal{N}} \Psi(u_n) \, \mathrm{d}F(n), \quad \Psi'(u_n) > 0, \;\; \Psi''(u_n) \le 0. \tag{6}$$

If $\Psi'(u_n) = 1$, the social welfare function is utilitarian. If $\Psi'(u_n) = 0$, except for the lowest skill level, the social welfare function is Rawlsian.

Total tax revenues from the labor-income tax and the corrective tax should be equal to total outlays on non-individualized transfers $NT$, and an exogenous revenue requirement $R$:

$$N \int_{\mathcal{N}} (tnl_n + \tau q_n) \, \mathrm{d}F(n) = NT + R. \tag{7}$$

## Optimal linear taxation

The Lagrangian for maximizing social welfare is given by (where the whole expression has been divided by the population size $N$ to save on notation)

$$\begin{aligned} \max_{\{T,t,\tau,E\}} \mathcal{L} \equiv & \int_{\mathcal{N}} \Psi(v_n(T,t,\tau,E)) \, \mathrm{d}F(n) \\ & + \eta \left( \int_{\mathcal{N}} (tnl_n + \tau q_n) \mathrm{d}F(n) - T - \frac{R}{N} \right) - \mu \left( \frac{E - E_0}{N} + \alpha \int_{\mathcal{N}} q_n \mathrm{d}F(n) \right). \end{aligned} \tag{8}$$

The Lagrange multiplier $\eta$ denotes the marginal social value of public resources and the Lagrange multiplier $\mu$ denotes the marginal social cost per capita (measured in social welfare units) of providing a better environmental quality $E$. The optimization program (8) is solved for the optimal linear tax on labor income $t$, the linear pollution tax $\tau$ and the non-individualized lump-sum transfer $T$.

Most papers in the literature substitute for the environmental technology (5) in the indirect utility function. In our formulation environmental quality $E$ is treated as a separate control variable, while the environmental technology is added as a separate constraint in the optimization procedure. Mathematically, our formulation is equivalent to the standard approach.[11] However, our formulation avoids complex optimal-tax expressions, because the multiplier $\mu$ comprises all the distributional and labor-market effects of changes in environmental quality. One can in principle uncover the full optimal-tax expressions by using the first-order condition for $E$ to eliminate the multiplier $\mu$ in the other first-order conditions. As a final note, treating $E$ as a separate control variable does not imply that we implicitly assume that the government has an extra policy instrument – besides corrective taxes – to steer the environmental quality.

The first-order conditions for an optimal allocation are given by

$$\frac{\partial \mathcal{L}}{\partial T} = \int_{\mathcal{N}} \left[ \Psi' \lambda_n - \eta + \eta tn \frac{\partial l_n}{\partial T} + (\eta\tau - \alpha\mu) \frac{\partial q_n}{\partial T} \right] \mathrm{d}F(n) = 0, \tag{9}$$

$$\frac{\partial \mathcal{L}}{\partial t} = \int_{\mathcal{N}} \left[ -nl_n \Psi' \lambda_n + \eta nl_n + \eta tn \frac{\partial l_n}{\partial t} + (\eta\tau - \alpha\mu) \frac{\partial q_n}{\partial t} \right] \mathrm{d}F(n) = 0, \tag{10}$$

[11] To see this formally, denote by $x$ the vector of all the policy variables, $W(x,E)$ the social welfare function, $g(x) = 0$ the government budget constraint, and $k(E) = 0$ the environmental technology. Then, the problem analyzed in (8) can be written in compact form as $\max_{x,E} W(x,E)$ , s.t. $g(x) = 0$, $k(E) = 0$. However, by inverting the environmental technology, we can write $E = k^{-1}(0)$, and substitute this in the objective function to obtain the following maximization problem: $\max_x W(x, k^{-1}(0))$, s.t. $g(x) = 0$. Clearly, both approaches are mathematically equivalent.

$$\frac{\partial\mathcal{L}}{\partial\tau}=\int_{\mathcal{N}}\left[-q_n\Psi'\lambda_n+\eta q_n+\eta tn\frac{\partial l_n}{\partial\tau}+(\eta\tau-\alpha\mu)\frac{\partial q_n}{\partial\tau}\right]\mathrm{d}F(n)=0, \tag{11}$$

$$\frac{\partial\mathcal{L}}{\partial E}=\int_{\mathcal{N}}\left[\frac{u_E}{u_c}\Psi'\lambda_n-\frac{\mu}{N}+\eta tn\frac{\partial l_n}{\partial E}+(\eta\tau-\alpha\mu)\frac{\partial q_n}{\partial E}\right]\mathrm{d}F(n)=0, \tag{12}$$

where the derivatives of the indirect utility function are used in each expression.[12]

In the rest of this section, the optimal income tax, the optimal corrective tax and the optimal provision of environmental quality are derived by employing the Slutsky equations for labor supply, demand for polluting commodities, and demand for environmental quality: $\partial l_n/\partial t=\partial l_n^*/\partial t-nl_n\partial l_n/\partial T$, $\partial q_n/\partial t=\partial q_n^*/\partial t-nl_n\partial q_n/\partial T$, $\partial l_n/\partial\tau=\partial l_n^*/\partial\tau-q_n\partial l_n/\partial T$, $\partial q_n/\partial\tau=\partial q_n^*/\partial\tau-q_n\partial q_n/\partial T$, $\partial l_n/\partial E=\partial l_n^*/\partial E+(u_E/u_c)\partial l_n/\partial T$, and $\partial q_n/\partial E=\partial q_n^*/\partial E+(u_E/u_c)\partial q_n/\partial T$. The asterisks denote the compensated changes of the demand and supply functions. To compute the income effect of the change in environmental quality, Wildasin (1984) shows (for ordinary public goods) that $u_E/u_c$ measures the marginal change in (virtual) income when environmental quality improves by one unit.

*Definitions*

This subsection introduces a number of definitions in order to facilitate the rewriting of the first-order conditions (9)–(12) for the optimal taxes and the optimal level of environmental quality. First, the marginal cost of public funds (MCF) is defined as the ratio between social marginal value of one unit of public income ($\eta$) and the average of the social marginal value of one unit of private income. The literature distinguishes two ways to measure the latter. The traditional literature on the marginal cost of public funds generally takes $\Psi'\lambda_n$ as a measure for the social marginal value of private income of individual $n$, see, for example, Pirttilä (2000).

**Definition 1.** The traditional measure for the marginal cost of public funds (MCF$'$) is defined as

$$\mathrm{MCF}'\equiv\frac{\eta}{\int_{\mathcal{N}}\Psi'\lambda_n\,\mathrm{d}F(n)}. \tag{13}$$

Jacobs (2009) and Jacobs (2013) demonstrate, however, that this traditional definition of the marginal cost of public funds suffers from three defects. First, the traditional marginal cost of public funds for (non-individualized) lump-sum taxes is generally not equal to one in the optimal tax system, even though lump-sum taxes are non-distortionary. Second, the traditional marginal cost of public funds for the distortionary labor income tax is not directly related to the excess burden of the tax (in the absence of distributional concerns). This is because the marginal cost of public funds for the distortionary tax increases in the *un*compensated elasticity of labor supply, rather than the compensated elasticity, which determines the excess burden. Hence, the marginal cost of public funds of the distortionary tax could even be smaller than one if there is a backward-bending labor-supply curve, cf. Atkinson and Stern (1974) and Ballard and Fullerton (1992). Third, the traditional marginal cost of public funds measure is sensitive to the normalization of the tax system. Indeed, for identical allocations the marginal cost of public funds for the lump-sum tax switches from a number smaller than one to a number larger than one if, respectively, the labor tax or the consumption tax is normalized to zero. In addition, at identical allocations, the marginal cost of public funds of a consumption tax is always larger than the marginal cost of public funds of an income tax.

These properties render the traditional marginal cost of public funds less useful for both theory and applied analysis. Fortunately, these problems disappear if the income effects on taxed bases and environmental welfare are included in the definition of the marginal social value of private income, as Diamond (1975) proposes. Intuitively, the social value of a marginal unit of private income should capture all income effects associated with transferring that unit from the public to the private sector. Hence, the *social* value of private income should not only include the direct effect on private utility ($\Psi'\lambda_n$) but also the indirect (income) effects of transferring one unit of income between the government and the private sector.

**Definition 2.** The *social* marginal value of transferring a marginal unit of income to individual $n$ is

$$\lambda_n^*\equiv\Psi'\lambda_n+\eta tn\frac{\partial l_n}{\partial T}+(\eta\tau-\alpha\mu)\frac{\partial q_n}{\partial T}. \tag{14}$$

$\lambda_n^*$ gives the net increase in social welfare (measured in social utils) of transferring a marginal unit of resources to person $n$. It consists of four elements, captured by the respective terms on the right-hand side of (14). First, when the individual receives a marginal unit of income his private welfare rises by $\lambda_n$, and social welfare thus increases by $\Psi'\lambda_n$. This is the traditional measure of the social value of private income. Second, an individual receiving a marginal unit of income reduces labor supply as long as leisure is a normal good. If labor income is taxed ($t>0$), lower labor supply reduces tax revenues. This results in a change of social welfare by $\eta tn\partial l_n/\partial T$. Third, by receiving a marginal unit of income, the individual consumes

[12] We always assume that the solution to the optimal tax problem is interior and that second-order conditions are met.

more polluting commodities if the polluting commodity is a normal good. If polluting commodities are taxed ($\tau>0$), the government receives more revenues, and social welfare expands by $\eta\tau\partial q_n/\partial T$. Finally, the social value of a unit of private income should subtract the value of the larger environmental damage arising from a larger demand for polluting commodities, as represented by $\alpha\mu\partial q_n/\partial T$.

Our preferred definition of the marginal cost of public funds, which we will use in the remainder of this paper, employs the social marginal value of private income according to (14).

**Definition 3.** The Diamond-based measure for the marginal cost of public funds is

$$\mathrm{MCF}\equiv\frac{\eta}{\overline{\lambda}^*}=\frac{\eta}{\int_{\mathcal{N}}\Psi'\lambda_n+\eta tn\frac{\partial l_n}{\partial T}+(\eta\tau-\alpha\mu)\frac{\partial q_n}{\partial T}\,\mathrm{d}F(n)},\tag{15}$$

where $\overline{\lambda}^*\equiv\int_{\mathcal{N}}\lambda_n^*\mathrm{d}F(n)$.

To derive the optimal income tax $t$, the optimal corrective tax $\tau$, and the provision of environmental quality $E$, the Feldstein (1972) distributional characteristics of the income tax, the corrective tax and environmental quality are introduced.

**Definition 4.** The distributional characteristics of labor income $\xi_l$, polluting goods consumption $\xi_q$, and environmental quality $\xi_E$ are

$$\xi_l\equiv-\frac{\int_{\mathcal{N}}\lambda_n^*z_n\,\mathrm{d}F(n)-\int_{\mathcal{N}}\lambda_n^*\,\mathrm{d}F(n)\int_{\mathcal{N}}z_n\,\mathrm{d}F(n)}{\int_{\mathcal{N}}\lambda_n^*\,\mathrm{d}F(n)\int_{\mathcal{N}}z_n\,\mathrm{d}F(n)}=-\frac{\mathrm{cov}\left[\lambda_n^*,z_n\right]}{\overline{\lambda}^*\overline{z}}>0,\tag{16}$$

$$\xi_q\equiv-\frac{\int_{\mathcal{N}}\lambda_n^*q_n\,\mathrm{d}F(n)-\int_{\mathcal{N}}\lambda_n^*\,\mathrm{d}F(n)\int_{\mathcal{N}}q_n\,\mathrm{d}F(n)}{\int_{\mathcal{N}}\lambda_n^*\,\mathrm{d}F(n)\int_{\mathcal{N}}q_n\,\mathrm{d}F(n)}=-\frac{\mathrm{cov}\left[\lambda_n^*,q_n\right]}{\overline{\lambda}^*\overline{q}},\tag{17}$$

$$\xi_E\equiv-\frac{\int_{\mathcal{N}}\lambda_n^*\frac{u_E}{u_c}\,\mathrm{d}F(n)-\int_{\mathcal{N}}\lambda_n^*\,\mathrm{d}F(n)\int_{\mathcal{N}}\frac{u_E}{u_c}\,\mathrm{d}F(n)}{\int_{\mathcal{N}}\lambda_n^*\,\mathrm{d}F(n)\int_{\mathcal{N}}\frac{u_E}{u_c}\,\mathrm{d}F(n)}=-\frac{\mathrm{cov}\left[\lambda_n^*,\frac{u_E}{u_c}\right]}{\overline{\lambda}^*\overline{\frac{u_E}{u_c}}},\tag{18}$$

where $\overline{z}\equiv\int_{\mathcal{N}}z_n\,\mathrm{d}F(n)$, $\overline{q}\equiv\int_{\mathcal{N}}q_n\,\mathrm{d}F(n)$ and $\overline{u_E/u_c}\equiv\int_{\mathcal{N}}u_E/u_c\,\mathrm{d}F(n)$.

$\xi_l$ corresponds to (minus) the normalized covariance of earnings of individual $n$ ($z_n$), and the net social welfare weight $\lambda_n^*$ of individual $n$. $\xi_l$ measures the marginal gain in social welfare (in monetary equivalents), expressed as a fraction of taxed labor income, of marginally increasing revenue with the labor tax. The distributional characteristic is positive because the covariance between labor earnings and welfare weights is negative. Individuals with higher incomes feature lower welfare weights because of diminishing social marginal utility of income. This is caused by diminishing private marginal utility of income and the concavity of the social welfare function. A positive distributional characteristic $\xi_l$ therefore implies that taxing labor income yields distributional benefits. A stronger social preference for redistribution increases the distributional characteristic. Similarly, more pre-tax inequality in labor earnings raises the demand for redistribution.

Equivalently, $\xi_q$ is (minus) the normalized covariance of polluting consumption $q_n$, and the net social welfare weights $\lambda_n^*$. $\xi_q$ gives the marginal gain in social welfare (in monetary equivalents), expressed as a fraction of polluting consumption, of marginally raising revenue with the pollution tax. Generally, this normalized covariance cannot be signed, since it depends on how the demand for polluting commodities covaries with the social welfare weights. If individuals with a high ability (low ability) consume relatively more from the polluting good, the distributional characteristic is positive (negative), i.e., $\xi_q>0$ ($\xi_q<0$).

The distributional characteristic of the environmental quality $\xi_E$ is defined as the normalized covariance between the social marginal value of private income $\lambda_n^*$ and the marginal willingness to pay for the environment $u_E/u_c$. If mainly high-ability (low-ability) types benefit from a better environmental quality, then $\xi_E>0$ ($\xi_E<0$).

All distributional characteristics reach a maximum of one with the strongest possible distributional concerns, i.e., if the government has Rawlsian social preferences. Distributional characteristics are zero when the government is not interested in redistribution and attaches the same welfare weight $\lambda_n^*$ to all $n$. Similarly, the distributional characteristics are zero if there is no inequality in labor earnings $z_n$ ($\xi_l=0$), demand for polluting goods $q_n$ ($\xi_q=0$) or the willingness to pay for a better environment $u_E/u_c$ ($\xi_E=0$).

Finally, we introduce the compensated elasticities of labor supply and polluting commodities with respect to the policy instruments.

**Definition 5.** The compensated elasticities of labor supply and polluting commodity demand with respect to the income tax, the corrective tax and environmental quality are defined as

$$\varepsilon_{lt} \equiv \frac{\partial l_n^*}{\partial t}\frac{1-t}{l_n} < 0, \quad \varepsilon_{qt} \equiv \frac{\partial q_n^*}{\partial t}\frac{1-t}{q_n}, \quad \varepsilon_{l\tau} \equiv \frac{\partial l_n^*}{\partial \tau}\frac{1+\tau}{l_n}, \quad \varepsilon_{q\tau} \equiv \frac{\partial q_n^*}{\partial \tau}\frac{1+\tau}{q_n} < 0, \quad \varepsilon_{lE} \equiv \frac{\partial l_n^*}{\partial E}\frac{E}{l_n}, \quad \text{and} \quad \varepsilon_{qE} \equiv \frac{\partial q_n^*}{\partial E}\frac{E}{q_n}.$$

The direct tax elasticity of labor supply $\varepsilon_{lt}$ is unambiguously negative, i.e., higher taxes reduce labor supply due to substitution of consumption for leisure. The cross-tax elasticity of polluting consumption cannot be signed. If $\varepsilon_{qt} > 0$ ( $< 0$), higher income taxes will stimulate (discourage) compensated demand for polluting consumption. The direct tax elasticity of polluting consumption, $\varepsilon_{q\tau}$, is unambiguously negative. However, the cross-elasticity of labor supply cannot be signed. If polluting goods consumption reduces labor supply, higher corrective taxes will encourage labor supply ($\varepsilon_{l\tau} > 0$), while if polluting goods consumption boosts labor supply, corrective taxes will discourage work effort ($\varepsilon_{l\tau} < 0$).[13] If improvements in environmental quality raise (reduce) compensated labor supply, $\varepsilon_{lE} > 0$ ($\varepsilon_{lE} < 0$) is obtained. Similarly, if compensated demand for polluting commodities increases (decreases) with a higher environmental quality, $\varepsilon_{qE} > 0$ ($\varepsilon_{qE} < 0$) is found.

*First-best*

To interpret the optimal second-best policy rules, it is useful to derive the first-best outcome. The first-best allocation could be achieved if the government has access to individualized lump-sum taxes. The government would then organize all redistribution through individualized lump-sum taxes until all social marginal welfare weights $\lambda_n^*$ are equalized. Consequently, all redistributional characteristics $\xi$ would become equal to zero. Hence, the government does not rely on any distortionary taxes, and the marginal cost of public funds would be equal to one.

**Proposition 1** (*First-best optimum*). *In first best all redistribution occurs through individualized lump-sum taxes, the marginal income tax rate is set to zero* ($t=0$), *the marginal cost of public funds equals unity* (MCF$=1$), *and the optimal corrective tax satisfies the first-best Pigouvian tax rate*:

$$\tau = \frac{\alpha\mu}{\overline{\lambda}^*}. \tag{19}$$

*Moreover, the Pigouvian tax sustains a first-best level of environmental quality*:

$$N\int_{\mathcal{N}} \frac{u_E}{u_c} \mathrm{d}F(n) = \frac{\mu}{\eta}. \tag{20}$$

**Proof.** Set all social welfare weights equal to $\eta$ ($\lambda_n^* = \Psi'\lambda_n = \eta$), then (10)–(12) yield the results. □

Eq. (19) reflects the first-best Pigouvian tax, which equals $\alpha\mu/\overline{\lambda}^*$. $\mu$ is the social cost measured in social welfare units of reducing aggregate polluting consumption by one unit. By dividing through $\overline{\lambda}^*$, the average social marginal value of private resources, this utility cost is converted into monetary equivalents. A reduction of aggregate polluting consumption by one unit improves the quality of the environment by $\alpha$. Hence, $\alpha\mu/\overline{\lambda}^*$ corresponds to the marginal external cost of one unit of aggregate consumption of polluting commodities.

Eq. (20) is the uncorrected Samuelson rule for environmental quality stating that the sum of the marginal rates of substitution should be equal to the marginal rate of transformation of providing a better environment. $\mu/\eta$ increases if environmental quality is more costly to produce in terms of reducing the consumption of polluting goods.

In order to relate our findings to the earlier literature we subsequently discuss two separate cases. The first case derives the full optimum in second-best, where the government can optimize all its policy instruments, i.e., where first-order conditions (9)–(12) hold simultaneously. The second case derives a constrained optimum in second best, where non-individualized lump-sum taxes are ruled out from the instrument set of the government, i.e. first-order condition (9) might not hold, but (10)–(12) do. These cases allow us to fully trace the role of our two key assumptions: (i) allowing for non-individualized lump-sum taxes and (ii) allowing for heterogeneous agents.

*Second-best – full optimum*

Armed with the Diamond-based measure of the marginal cost of public funds in definition (3), the main proposition of the paper can be established. Each part of the proposition will be interpreted in the sub-sections that follow.

**Proposition 2** (*Second-best full optimum*). *The policy rules for the optimal transfer, income tax, pollution tax and environmental quality are given by*

$$\mathrm{MCF} = 1, \tag{21}$$

[13] The ambiguity in sign of all cross-elasticities is formally derived in the appendix of Jacobs and de Mooij (2011).

$$\xi_l = \frac{t}{1-t}(-\overline{\varepsilon_{lt}}) + \frac{(\tau - \alpha\mu/\overline{\lambda}^*)}{1+\tau}(-\overline{\gamma\varepsilon_{qt}}), \tag{22}$$

$$\xi_q = \frac{t}{1-t}\left(-\frac{\overline{\varepsilon_{l\tau}}}{\overline{\gamma}}\right) + \frac{(\tau - \alpha\mu/\overline{\lambda}^*)}{1+\tau}\left(-\frac{\overline{\gamma\varepsilon_{q\tau}}}{\overline{\gamma}}\right). \tag{23}$$

$$(1-\xi_E)N\int_{\mathcal{N}}\frac{u_E}{u_c}\mathrm{d}F(n) = \frac{\mu}{\eta} + \delta N\left(\frac{t}{1-t}(-\overline{\varepsilon_{lE}}) + \frac{(\tau-\alpha\mu/\overline{\lambda}^*)}{1+\tau}(-\overline{\gamma\varepsilon_{qE}})\right), \tag{24}$$

where $\gamma_n \equiv (1+\tau)q_n/((1-t)nl_n)$ is the net expenditure share of polluting commodities in net labor income, $\overline{\gamma} \equiv [\int_{\mathcal{N}}\gamma_n nl_n \,\mathrm{d}F(n)][\int_{\mathcal{N}} nl_n \,\mathrm{d}F(n)]^{-1}$ denotes the income-weighted average of $\gamma_n$, $\delta \equiv (1-t)\int_{\mathcal{N}} nl_n \,\mathrm{d}F(n)/E$ measures the ratio of net labor income to environmental quality, and $\overline{\varepsilon_{xj}} \equiv [\int_{\mathcal{N}}\varepsilon_{xj} nl_n \,\mathrm{d}F(n)][\int_{\mathcal{N}} nl_n \,\mathrm{d}F(n)]^{-1}$ is the income-weighted average of the elasticity $\varepsilon_{xj}$, $x = l, q$, $j = t, \tau, E$.

**Proof.** Substituting Definition 3 for MCF in the first-order condition of the lump-sum transfer in Eq. (9) yields (21). Substituting the Slutsky equations and the distributional characteristic (16) into the first-order condition for the income tax in Eq. (10), using the definitions for the elasticities, using (21), and rearranging the resulting equation yields (22). Substituting the Slutsky equations and the distributional characteristic (17) into the first-order condition for the commodity tax in Eq. (11), using the definitions for the elasticities, using (21), and rearranging the resulting equation yields (23). Substituting the Slutsky equations and the distributional characteristic (18) into the first-order condition for environmental quality in Eq. (12), using the definitions for the elasticities, using (21), and rearranging the resulting equation yields (24). □

*Optimal non-individualized transfers*

Eq. (21) governs the optimality condition for the non-individualized lump-sum transfer. If the government has access to this non-distortionary marginal source of public finance, the marginal cost of public funds is one in the optimal tax system. In the optimum, the marginal value of resources is equalized in the public and private sector. Hence, a marginal shift of resources from the private to the public sector does not raise social welfare.

Representative-agent models generally exclude non-individualized transfers to make the optimal-tax problem second best. With heterogeneous agents there is no need to do so to obtain a second-best optimal-tax problem. Proposition 1 shows that this has important consequences.

*Optimal income tax*

Eq. (22) equates distributional benefits ($\xi_l$) of higher income taxes, on the left-hand side, with the marginal deadweight loss of the income tax on the right-hand side. If income taxes yield large distributional gains (large $\xi_l$), the optimal income tax is high. The marginal deadweight loss consist of distortions in labor supply ($-(t/(1-t))\overline{\varepsilon_{lt}}$) and distortions in commodity demands ($-((\tau-\alpha\mu/\overline{\lambda}^*)/(1+\tau))\overline{\gamma\varepsilon_{qt}}$). The deadweight loss of the income tax falls with the compensated labor supply elasticity ($-\overline{\varepsilon_{lt}}$). If the demand for polluting goods falls with a larger labor tax ($\overline{\gamma\varepsilon_{qt}} < 0$), the income tax helps to internalize the environmental externality, and should be set higher as long as the corrective tax is below the Pigouvian tax ($\tau < \alpha\mu/\overline{\lambda}^*$). However, if the corrective tax is above the Pigouvian tax ($\tau > \alpha\mu/\overline{\lambda}^*$), a higher income tax exacerbates the non-environmental distortion in consumption, and should be set lower as a result. If $\overline{\gamma\varepsilon_{qt}} > 0$, the opposite reasoning holds.

In the full tax optimum, the marginal cost of public funds is equal to one. Hence, the government only introduces distortions for redistributive or environmental reasons, since all revenue could be raised with non-distortionary taxes. In the optimal tax system, the marginal excess burden of distortionary income taxes, on the right-hand side of (22), is exactly compensated by the social marginal benefits of redistribution, on the left-hand side of (22). When the government does not want to redistribute income ($\xi_l = 0$), and the environmental tax is set at the Pigouvian level ($\tau = \alpha\mu/\overline{\lambda}^*$), then it is optimal not to distort labor supply at all. Intuitively, the distortionary income tax is not required to raise revenue or correct for externalities if non-distortionary lump-sum taxes and corrective Pigouvian taxes are available as well.

*Modified Pigouvian tax*

In analogy to the modified Samuelson rule for the optimal provision of public goods (Atkinson and Stern, 1974), the optimal second-best corrective tax from (23) is labeled the *modified Pigouvian tax*. Eq. (23) equates the distributional benefits of the corrective tax ($\xi_q$) on the left-hand side with the marginal deadweight losses of the corrective tax on the right-hand side. The modified Pigouvian tax increases when it serves as a redistributive device, i.e., if polluting goods are mainly consumed by the high-ability types (i.e., when $\xi_q$ is positive and large). The efficiency costs consist of the marginal deadweight loss in labor supply $-(t/(1-t))\overline{\varepsilon_{l\tau}}/\overline{\gamma}$, and the marginal deadweight loss in the demand for polluting goods $-((\tau-\alpha\mu/\overline{\lambda}^*)/(1+\tau))\overline{\gamma\varepsilon_{q\tau}}/\overline{\gamma} > 0$. Corrective taxes should be set lower (higher) when they reduce (boost) compensated labor supply, i.e., $\overline{\varepsilon_{l\tau}} < 0$ ($\overline{\varepsilon_{l\tau}} > 0$). Intuitively, corrective taxes then exacerbate (alleviate) labor-market distortions.

The optimal corrective tax is not corrected for the marginal cost of public funds, since the latter equals one. Hence, a better environmental quality does not compete with other public goods (income redistribution or revenue raising). Distortions in polluting commodity demands are introduced only if they contribute to redistribution ($\xi_q$), internalizing externalities ($\alpha\mu/\overline{\lambda}^*$) or alleviating labor-supply distortions ($\overline{\varepsilon_{l\tau}} \neq 0$, $t > 0$).

*Modified Samuelson rule*

Eq. (24) gives a modified Samuelson rule for the provision of the environmental public good.[14] The left-hand side of Eq. (24) indicates the benefits of a cleaner environment. It is equal to the sum of the marginal rates of substitution between environmental quality and consumption, i.e., the sum of the marginal willingness to pay for a cleaner environment. The difference with the ordinary Samuelson rule in (20) is that distributional characteristic of environmental quality deflates (inflates) the marginal benefits if mainly the rich (poor) benefit from a better environmental quality, i.e., when $\xi_E > 0$ ($\xi_E < 0$). The right-hand side of Eq. (24) gives the marginal cost of a cleaner environment. In the optimum, MCF$=1$, so that the right-hand side does not feature a correction for the marginal cost of public funds. Consequently, tax distortions do not lead to a lower provision of environmental quality.

As in (20), the first term on the right-hand side, $\mu/\eta$, reflects the marginal rate of transformation of producing environmental quality. The second and third terms on the right-hand side of (24) reflect the direct impact of changes in the public good of environmental quality on, respectively, labor supply and polluting consumption, cf. Atkinson and Stern (1974) and Jacobs (2013) for ordinary public goods. If a better environmental quality reduces (increases) compensated labor supply, i.e., $\overline{\varepsilon_{lE}} < 0$ ($\overline{\varepsilon_{lE}} > 0$), the marginal cost of providing a better environment increases (decreases) as long as labor income is taxed. In that case, the government loses (gains) tax revenues from the labor tax if the quality of the environment improves. Similarly, if a better environment would reduce (increase) the compensated demand for polluting commodities, i.e., $\overline{\gamma\varepsilon_{qE}} < 0$ ($\overline{\gamma\varepsilon_{qE}} > 0$ ), the marginal cost of providing a better environment increases (decreases) if environmental externalities are more (less) than fully internalized by the corrective tax, i.e., $\tau - \alpha\mu/\overline{\lambda}^* > 0$ ($\tau - \alpha\mu/\overline{\lambda}^* < 0$).

*Conditions for first-best rules in second-best*

An important special case can be derived where the optimal corrective tax in the second-best equals the first-best expression for the Pigouvian tax. This case most clearly illustrates our main result.

**Corollary 1.** *If preferences are given by*

$$u_n \equiv \upsilon(c_n, q_n) - h(l_n) + \Gamma(E), \quad \upsilon_c, \upsilon_q, h', \Gamma' > 0, \quad \upsilon_{cc}, \upsilon_{qq}, -h'', \Gamma'' < 0, \quad \forall n, \tag{25}$$

*where $\upsilon(.)$ is a linear homogeneous sub-utility function over clean and polluting commodities, then the modified Pigouvian tax equals the first-best Pigouvian tax, $\tau = \alpha\mu/\overline{\lambda}^*$, and environmental quality follows the first-best Samuelson rule, $N\int_{\mathcal{N}}(u_E/u_c)\,\mathrm{d}F(n) = \mu/\eta$.*

**Proof.** Marginal utility of income is constant, due to the linear homogeneity of $\upsilon(\cdot)$, which follows from substitution of the first-order condition $u_q/u_c = 1+\tau$ in the definition for $\lambda_n = u_c$. Therefore, $u_E/u_c$ is constant, so that $\xi_E = 0$, cf. (18). Furthermore, $\varepsilon_{lt} = \gamma_n \varepsilon_{l\tau}$, which follows from totally differentiating the first-order conditions (3), (4), and the utility function (1), and setting the change in utility to zero in order to find the compensated elasticities. Finally, it can be derived that $\int_{\mathcal{N}}(1-\lambda_n^*)((1+\tau)/(1-t))q_n\,\mathrm{d}F(n) = \int_{\mathcal{N}}(1-\lambda_n^*)\gamma_n n l_n\,\mathrm{d}F(n)$, since $(1+\tau)q_n/((1-t)nl_n + T)$ is constant with homothetic preferences and using the first-order condition for $T$ from (9). Substitution of these results in the first-order conditions – Eqs. (10) and (12) – proves the proposition. □

The preferences given in Eq. (25) are quasi-linear in total real consumption $\upsilon(\cdot)$, and income effects in labor supply are absent. Due to the homotheticity of sub-utility $\upsilon(\cdot)$, taxing polluting commodities has no distributional advantage over taxing labor income. Intuitively, consumption of polluting commodities is proportional to labor income. Hence, taxing polluting goods at a higher rate than the Pigouvian tax yields no distributional gains but, compared to the tax on labor income, results in larger distortions in the composition of consumption, thereby harming non-environmental welfare. Similarly, corrective taxes cannot be used to alleviate tax distortions in labor supply, since both clean and polluting goods are equally complementary to leisure. Thus, the consumption tax imposes the same distortions on labor supply as the income tax, while it introduces additional distortions in the optimal composition of consumption. These distortions can be avoided by not taxing polluting commodities at a different rate than the Pigouvian rate. Finally, the absence of income effects ensures that labor supply is independent from environmental quality and that the marginal valuation of environmental quality is the same for all individuals. Hence, environmental quality is neither used to alleviate labor-market distortions nor to improve upon the income distribution. Naturally, optimal allocations differ between first-best and second-best settings.

The restrictions on preferences in Eq. (25) are similar to those in Bovenberg and van der Ploeg (1994b). Using a representative-agent framework, however, they find that the optimal second-best Pigouvian tax should be corrected for the marginal cost of public funds and, therefore, is lower than the Pigouvian tax in the presence of distortionary taxes. This paper shows that this correction disappears when distortionary taxes are optimized to satisfy distributional concerns.

[14] Eq. (24) can be used to solve for $\mu$, which can be substituted in the expressions for the optimal income and corrective taxes. This demonstrates that $\mu$ absorbs the complex distributional and labor-market effects of a change in environmental quality $E$.

*Second-best constrained optimum*

As explained earlier, representative-agent models generally exclude non-individualized lump-sum taxes to make the optimal tax problem second best, usually by referring to distributional concerns. However, these are absent if every agent is the same. Consequently, there are no reasons to introduce tax distortions as all revenue could be raised with non-distortionary, non-individualized lump-sum taxes. This paper explicitly allows for redistributional concerns by considering heterogeneous agents. In doing so we do not need to rule out non-individualized lump-sum transfers to make the problem second-best. Yet, one may wonder to what extent the results in Proposition 1 are driven by (i) the introduction heterogeneous agents giving rise to distributional concerns or (ii) allowing for the non-individualized lump-sum transfer in the instrument set of the government. To explore this issue, the next proposition derives the marginal cost of public funds and the optimal policy rules when the government cannot optimize the lump-sum tax. Hence, first-order condition (9) might not hold and the government solves the system (10)–(12) for a given, and possibly sub-optimal level of transfers.

**Proposition 3** (*Second-best constrained optimum*). *When the government cannot optimize non-individualized lump-sum transfers, the policy rules for the optimal income tax, pollution tax and environmental quality are given by*

$$1-\frac{1}{\text{MCF}}+\frac{\xi_l}{\text{MCF}}=\frac{t}{1-t}(-\overline{\varepsilon_{lt}})+\frac{\left(\tau-\frac{\alpha\mu/\overline{\lambda}^*}{\text{MCF}}\right)}{1+\tau}(-\overline{\gamma\varepsilon_{qt}}), \tag{26}$$

$$1-\frac{1}{\text{MCF}}+\frac{\xi_q}{\text{MCF}}=\frac{t}{1-t}\left(-\frac{\overline{\varepsilon_{l\tau}}}{\overline{\gamma}}\right)+\frac{\left(\tau-\frac{\alpha\mu/\overline{\lambda}^*}{\text{MCF}}\right)}{1+\tau}\left(-\frac{\overline{\gamma\varepsilon_{q\tau}}}{\overline{\gamma}}\right), \tag{27}$$

$$(1-\xi_E)N\int_{\mathcal{N}}\frac{u_E}{u_c}\text{d}F(n)=\text{MCF}\cdot\left[\frac{\mu}{\eta}+\delta N\left(\frac{t}{1-t}(-\overline{\varepsilon_{lE}})+\frac{\left(\tau-\frac{\alpha\mu/\overline{\lambda}^*}{\text{MCF}}\right)}{1+\tau}(-\overline{\gamma\varepsilon_{qE}})\right)\right]. \tag{28}$$

**Proof.** Substituting the Slutsky equations and the distributional characteristic (16) into the first-order condition for the income tax in Eq. (10), using the definitions for the elasticities and rearranging the resulting equation yields (10). Substituting the Slutsky equations and the distributional characteristic (17) into the first-order condition for the commodity tax in Eq. (11), using the definitions for the elasticities and rearranging the resulting equation yields (27). Substituting the Slutsky equations and the distributional characteristic (18) into the first-order condition for environmental quality in Eq. (12), using the definitions for the elasticities and rearranging the resulting equation yields (28). □

*Marginal cost of public funds*

Again, to understand the optimal policy rules in Proposition 3, it is important to discuss the marginal cost of public funds. By rewriting the optimal income tax (26), the marginal cost of public funds in the constrained second-best optimum can be written as

$$\text{MCF}=\frac{1-\xi_l-\frac{\alpha\mu/\overline{\lambda}^*}{1+\tau}(-\overline{\gamma\varepsilon_{qt}})}{1-\frac{t}{1-t}(-\overline{\varepsilon_{lt}})-\frac{\tau}{1+\tau}(-\overline{\gamma\varepsilon_{qt}})}\gtrless 1. \tag{29}$$

The marginal cost of public funds in Eq. (29) depends on three main factors. First, it increases with the deadweight cost of the tax, measured by term in the denominator, i.e. $t/(1-t)(-\overline{\varepsilon_{lt}})+\tau/(1+\tau)(-\overline{\gamma\varepsilon_{qt}})$, which is the sum of the excess burdens in the labor market and the goods market. Second, the marginal cost of public funds decreases if income taxation produces larger distributional benefits, i.e., when $\xi_l>0$ is larger. Third, the marginal cost of public funds decreases (increases) if income taxes generate environmental benefits (costs) by affecting the demand for polluting goods, i.e., when $-\overline{\gamma\varepsilon_{qt}}>0$ ($-\overline{\gamma\varepsilon_{qt}}<0$). Expression (29) clearly demonstrates that allowing for heterogeneous agents is important. In representative-agent models, the exclusion of non-individualized lump-sum transfers generally implies $\text{MCF}>1$, reflecting the excess burden of taxation. With heterogeneous agents, however, this is no longer true. Indeed, the presence of distributional (and possible environmental) benefits of distortionary taxes may render the marginal cost of public funds either larger or smaller than one. See also Jacobs (2013). Intuitively, the marginal cost of public funds reflects the ratio between the social marginal benefits and the total net social costs of raising an additional euro. The latter increase in deadweight losses, but are reduced when there are more favorable effects on the income distribution and the environment.

To see more clearly why the marginal cost of public funds can be either smaller or larger than one, suppose that the corrective tax is set at the Pigouvian level ($\tau=\alpha\mu/\overline{\lambda}^*$). Then, if the distributional benefits $\xi_l$ of the income tax are larger (smaller) than the marginal excess burden $t/(1-t)(-\overline{\varepsilon_{lt}})$, tax systems redistribute too little (much) income, and the marginal cost of public funds is smaller (larger) than one. Only if distributional gains exactly equal the deadweight loss (i.e., $\xi_l = t/(1-t)(-\overline{\varepsilon_{lt}})$), will the marginal cost of funds be equal to one. This is the case when non-individualized lump-sum transfers would – coincidentally – be set at its optimal level.

In order to calculate the marginal cost of public funds in constrained (or sub-optimal) tax systems one needs explicit measures of the distributional benefits of taxes. If economists wish to refrain from making intrinsically political statements regarding the social benefits of income redistribution, they should not make statements whether the marginal cost of public funds is larger or smaller than one, for a given level of social transfers. Indeed, if an economist claims that the marginal cost of public funds of the tax system is in fact larger (smaller) than one, he/she implicitly reveals a political preference for less income redistribution, since the marginal cost of public funds is larger (smaller) than one only if the government redistributes too much (little) income.

Applied policy economists should probably resort to Becker (1983)'s efficient redistribution hypothesis, which argues that the political system exhausts all opportunities to gain voters. Hence, tax systems would indeed be optimized from a political point of view, which, of course, does not need to coincide with a neatly behaved social welfare function adopted by the fictitious benevolent planner in the current paper. Nevertheless, also in that case one can argue that the deadweight losses should be equal to the distributional – or, more correctly, political – gains of distortionary taxes and the marginal cost of public funds would again be equal to one in the full tax optimum.

*Optimal policy rules*

There are two fundamental differences between Propositions 2 and 3. The first is that the marginal cost of public funds enters the expressions for the optimal income tax in Eq. (26), the optimal pollution tax in Eq. (27), and the modified Samuelson rule in Eq. (28). $(1-1/\text{MCF})$ in the optimal tax expressions (26) and (27) is a revenue raising term, which is generally referred to as the Ramsey term. If tax revenue makes taxes valuable – as indicated by a high MCF – then the government optimally introduces larger distortions of income taxes and pollution taxes. The Ramsey term $(1-1/\text{MCF})$ vanishes when the government can also optimize non-individualized lump-sum taxes, since MCF$=1$ in that case. Intuitively, the non-individualized lump-sum tax is targeted at revenue raising (at the margin) and no distorting income taxes or pollution taxes are required for that purpose.

A second important difference is that both the distributional gains of the income and pollution taxes ($\xi_l$ and $\xi_q$) and the social marginal damage of polluting goods consumption ($\alpha\mu/\overline{\lambda}^*$) are now divided by the marginal cost of public funds (MCF). Intuitively, when the marginal cost of public funds is larger than one, the government sacrifices both on income redistribution and environmental quality in order to raise more revenue. Hence, the public goods of income redistribution and providing a clean environment directly compete with the public good of raising revenue. However, if the marginal cost of funds is smaller than one, the public goods of income redistribution and providing a clean environment do not compete but are complementary with raising revenue.

That the external cost of pollution, $\alpha\mu/\overline{\lambda}^*$, is deflated with the marginal cost of public funds if the government has no access to non-individualized lump-sum taxes is well-known from the papers in the representative-agent literature, see for example Sandmo (1975) and Bovenberg and van der Ploeg (1994b). These models have emphasized that, since MCF $>1$, pre-existing tax distortions push the optimal second-best corrective tax below its first-best Pigouvian level, as argued as well by Bovenberg and de Mooij (1994). However, from Eq. (27) follows that the second-best corrective tax can be either below or above the modified Pigouvian level, depending on whether the marginal cost of public funds is larger or smaller than one. Consequently, with heterogeneous agents one cannot generally tell in which direction the modified Pigouvian tax should be adjusted when non-individualized lump-sum taxes are not available to the government. When distortionary taxes feature redistributional benefits, and these distributional benefits are larger than the distortions, the marginal cost of public funds is smaller than one, and, hence, the government should pursue a more ambitious environmental policy. This case thus reinforces the general point of this paper. However, if the income tax redistributes too much income, and the marginal cost of public funds is larger than one in the restricted optimum, the optimal pollution tax is driven below the Pigouvian level. That case most closely resembles the models in the representative-agent literature, where the tax system by assumption features too high distortionary taxes, since taxes only generate distortions and no distributional benefits. In the full second-best optimum with non-individualized lump-sum taxes, MCF$=1$, and neither the benefits of redistribution ($\xi_l$ and $\xi_q$) nor the costs of externalities ($\alpha\mu/\overline{\lambda}^*$) are deflated by MCF.

Finally, the cost of providing environmental quality $\mu/\eta$ in Eq. (28) is multiplied with MCF. If the marginal cost of public funds is larger (smaller) than one, the cost of providing a cleaner environment is larger (smaller) than in the full second-best optimum, hence the government reduces (increases) the optimal supply of environmental quality compared to the first-best Samuelson rule.

## Optimal non-linear taxation

In the real world, tax systems are generally non-linear, and it is important to verify whether the results obtained under linear instruments carry over to a setting with non-linear taxes. We therefore analyze non-linear taxes on both income and polluting commodities. This adds to the literature, which only analyzes linear corrective taxes alongside non-linear income taxes (Pirttilä and Tuomala, 1997; Cremer et al., 1998; Micheletto, 2008). Doing so allows us to explore whether linear corrective taxes are sufficient to implement second-best allocations, even when they are not restricted to be linear.

The government can observe total labor income of an individual, $z_n \equiv nl_n$. The non-linear income tax schedule is designated by $T(z_n)$. The marginal tax rate is $T'(z_n) \equiv \mathrm{d}T(z_n)/\mathrm{d}z_n$. Moreover, the government is able to verify consumption of polluting goods at the individual level. Hence, a non-linear commodity tax can be levied. The non-linear tax on the polluting commodity is given by $\tau(q_n)$, where $\tau'(q_n) \equiv \mathrm{d}\tau(q_n)/\mathrm{d}q_n$ stands for the marginal commodity tax. Both tax functions are assumed to be continuous. Compared to the previous Section, the individual's optimization problem is not affected, except that non-linear marginal tax rates replace the linear ones in the first-order conditions for utility maximization (3) and (4). The social welfare function remains identical as well.

To determine the non-linear policy schedules $T(\cdot)$ and $\tau(\cdot)$, a standard mechanism-design approach is employed. First, making use of the revelation principle, the optimal direct mechanism is derived, which induces individuals to reveal their ability truthfully through self-selection. This direct mechanism yields the optimal second-best allocation. Then, this allocation is decentralized as the outcome of a competitive equilibrium by employing the non-linear policy instruments.

Any second-best allocation must satisfy the resource and incentive-compatibility constraints. The economy's resource constraint is[15]

$$N\int_{\mathcal{N}}(z_n - c_n - q_n)\,\mathrm{d}F(n) = R. \tag{30}$$

Since $n$ is not observable by the government, every bundle $\{c_n, q_n, z_n\}$ for individual $n$ must be such that individual $n$ does not want to have another bundle $\{c_m, q_m, z_m\}$ intended for individual $m \neq n$. If utility is written as $u(c_n, q_n, l_n, E) = u(c_n, q_n, z_n/n, E) \equiv U(c_n, q_n, z_n, E, n)$, then incentive compatibility requires

$$U(c_n, q_n, z_n, E, n) \geq U(c_m, q_m, z_m, E, n), \quad \forall m \in \mathcal{N}, \quad \forall n \in \mathcal{N}. \tag{31}$$

By adopting the first-order approach, these incentive constraints can be replaced by a differential equation on utility:[16]

$$\frac{\mathrm{d}u(c_n, q_n, l_n, E)}{\mathrm{d}n} = -\frac{l_n u_l(c_n, q_n, l_n, E)}{n}. \tag{32}$$

Consumption of clean goods is a function $c_n \equiv c(q_n, l_n, u_n, E)$ of the allocation, which is found by inverting the utility function. The government thus maximizes social welfare (6) subject to the resource constraint (30) and the incentive constraints (32). After integrating the incentive-compatibility constraint (32) by parts, the Lagrangian for maximizing social welfare can be formulated as

$$\begin{aligned}\max_{\{l_n, q_n, u_n, E\}} \mathcal{L} \equiv & \int_{\mathcal{N}}\left(\Psi(u_n) + \eta\left(nl_n - c(q_n, l_n, u_n, E) - q_n - \frac{R}{N}\right)\right)f(n)\,\mathrm{d}n \\ & -\mu\left(\frac{E-E_0}{N} + \alpha\int_{\mathcal{N}} q_n\,\mathrm{d}F(n)\right) \\ & + \int_{\mathcal{N}}\left(\theta_n \frac{l_n u_l(c(q_n, l_n, u_n, E), q_n, l_n, E)}{n} - u_n\frac{\mathrm{d}\theta_n}{\mathrm{d}n}\right)\mathrm{d}n + \theta_{\overline{n}}u_{\overline{n}} - \theta_{\underline{n}}u_{\underline{n}},\end{aligned} \tag{33}$$

where $\theta_n$ is the Lagrangian multiplier associated with the differential equation for utility (32). Intuitively, $\theta_n$ equals the marginal increase in social welfare of extracting one unit of income from individuals above $n$. As before, $\eta$ measures the marginal social value of public resources, while $\mu$ is the marginal social cost (in utils) of raising environmental quality per capita $E/N$ with one unit.

The optimal policy rules derived below employ elasticities that are defined and derived in Lemma 1.

**Lemma 1.** *The compensated elasticity of labor supply with respect to the marginal income tax rate is*

$$\varepsilon_{lT'} \equiv \frac{\partial l_n^*}{\partial T'}\frac{1-T'(nl_n)}{l_n} = \frac{u_l/l_n}{u_{ll} + \left(\frac{u_l}{u_c}\right)^2 u_{cc} - 2\left(\frac{u_l}{u_c}\right)u_{cl} + nu_l\frac{T''}{1-T'}} > 0. \tag{34}$$

[15] If the government maximizes social welfare subject to the resource constraint, and all individuals respect their budget constraints, the government budget constraint is automatically satisfied by Walras' law.

[16] This is a valid procedure only if second-order conditions for utility maximization are fulfilled in the optimum allocation. This requires that the following constraint on the second-best allocation holds

$$\frac{\mathrm{d}(U_{\mathbf{X}}/U_c)}{\mathrm{d}n}\cdot\frac{\mathrm{d}\mathbf{X}_n'}{\mathrm{d}n} \leq 0, \ \forall n,$$

where $U(c_n, q_n, z_n, E, n) \equiv U(c_n, \mathbf{X}_n, E, n)$ and $\mathbf{X}_n \equiv [z_n, q_n]$ is the vector of gross income and consumption of polluting goods. See Mirrlees (1976) for a formal proof. This constraint generalizes the Spence-Mirrlees ('single-crossing') and monotonicity conditions to a multi-commodity setting. In the remainder it is assumed that this constraint is always respected, hence the first-order approach is applicable.

*The uncompensated elasticity of earnings with respect to the wage rate is:*[17]

$$\varepsilon^u_{zn} \equiv \frac{\partial z_n}{\partial n}\frac{n}{z_n} = \frac{u_l/l_n + u_{ll} - \left(\frac{u_l}{u_c}\right)u_{cl}}{u_{ll} + \left(\frac{u_l}{u_c}\right)^2 u_{cc} - 2\left(\frac{u_l}{u_c}\right)u_{cl} + nu_l \frac{T''}{1-T'}} > 0. \tag{35}$$

*The compensated elasticity of polluting goods demand with respect to the marginal pollution tax rate is*

$$\varepsilon_{q\tau'} \equiv -\frac{\partial q^*_n}{\partial \tau'}\frac{1-\tau'(q_n)}{q_n} = -\frac{u_q/q_n}{u_{qq} + \left(\frac{u_q}{u_c}\right)^2 u_{cc} - 2\left(\frac{u_q}{u_c}\right)u_{cq} - \frac{\tau''}{1+\tau'}u_q} > 0. \tag{36}$$

*The uncompensated (and compensated) cross elasticity of demand for polluting goods with respect to labor supply, conditional on net income* $\overline{y} \equiv \overline{z} - T(\overline{z})$, *is*

$$\varepsilon^u_{ql}\Big|_{\overline{y}} \equiv \frac{\partial q_n}{\partial l_n}\frac{l_n}{q_n}\Big|_{\overline{y}} = \frac{\left(\frac{u_q}{u_c}u_{cl} - u_{ql}\right)l_n/q_n}{u_{qq} + \left(\frac{u_q}{u_c}\right)^2 u_{cc} - 2\left(\frac{u_q}{u_c}\right)u_{cq} - \frac{\tau''}{1+\tau'}u_q} \gtreqless 0. \tag{37}$$

**Proof.** See online Appendix.

We will express our optimal tax formulae in *ABC*-form as in Diamond (1998). Moreover, the optimal non-linear income tax uses the formulation of Saez (2001) in terms of the earnings distribution $\tilde{F}(z_n) \equiv f(n)$, which has a corresponding earnings density $\tilde{f}(z_n)$. The next proposition characterizes optimal tax policy under non-linear policy instruments.

**Proposition 4.** *The optimal non-linear marginal income tax schedule is given by the ABC-formula*:

$$\frac{T'(z_n)}{1-T'(z_n)} = \underbrace{\frac{1}{\varepsilon_{lT'}}}_{\equiv A_n}\underbrace{\frac{\int_{z_n}^{z_{\overline{n}}}(1-\lambda^*_n)\tilde{f}(z_m)\,\mathrm{d}z_m}{(1-\tilde{F}(z_n))}}_{\equiv B_n}\underbrace{\frac{(1-\tilde{F}(z_n))}{z_n\tilde{f}(z_n)}}_{\equiv C_n}, \quad \forall z_n \neq z_{\overline{n}}, z_{\underline{n}}, \tag{38}$$

*The marginal cost of public funds equals one at the optimal tax system*:

$$MCF \equiv \frac{\eta}{\int_{\mathcal{N}} \Psi'\lambda_n + \eta t n \frac{\partial l_n}{\partial(-T(0))} + (\eta\tau - \alpha\mu)\frac{\partial q_n}{\partial(-T(0))} f(n)\,\mathrm{d}n} = 1. \tag{39}$$

*The optimal non-linear marginal pollution tax is given by*

$$\left(\frac{\tau'(q_n) - \frac{\alpha\mu}{\eta}}{1+\tau'(q_n)}\right)\varepsilon_{q\tau'} = -\frac{T'(z_n)}{1-T'(z_n)}\varepsilon_{lT'}\frac{\varepsilon^u_{ql}\big|_{\overline{y}}}{\varepsilon^u_{zn}}, \quad \forall z_n. \tag{40}$$

*Optimal provision of environmental quality satisfies*:

$$N\int_{\mathcal{N}}\frac{u_E}{u_c}(1+\Delta_n)f(n)\mathrm{d}n = \frac{\mu}{\eta}, \tag{41}$$

*where*

$$\Delta_n \equiv \frac{T'(z_n)}{(1-T'(z_n))}\frac{\varepsilon_{lT'}}{\varepsilon^u_{zn}}\frac{\partial\ln(u_E/u_c)}{\partial\ln l_n}. \tag{42}$$

**Proof.** See online Appendix. □

*Optimal income taxation*

The expression for the optimal non-linear income tax (38) is identical to Mirrlees (1971) and Saez (2001) and does not depend on the presence of the externality. Since the non-linear income tax is well understood in the optimal-tax literature, it will not be discussed further here. The reader is referred to Mirrlees (1971), Sadka (1976), Seade (1977), Tuomala (1984), Ebert (1992), Diamond (1998), and Saez (2001) for extensive analyses of the optimal non-linear income tax.

[17] The uncompensated elasticity of earnings with respect to the wage rate is always positive given that earnings should be monotonic in skills at the optimal second-best allocation. The labor-supply elasticity with respect to the wage rate could be negative, however, due to off-setting income and substitution effects.

*Marginal cost of public funds*

Eq. (39) shows that, in the optimum, the marginal cost of public funds is again equal to one, like with linear taxes. Note that the intercept of the tax function $-T(0)$ serves the same role as the non-individualized lump-sum tax $T$ under linear instruments. Thus, tax distortions should be equal to distributional and/or environmental gains for all tax rates at each point in the earnings distribution. Our finding thus generalizes Jacobs and Boadway (2014) who demonstrate that MCF=1 in models of optimal commodity taxation in the absence of externalities.

*Modified Pigouvian tax*

The optimal non-linear pollution tax in Eq. (40) equates costs of setting the corrective tax beyond the Pigouvian level on the right-hand side, with the benefits of doing so on the left-hand side. Like before, the optimal corrective tax in Eq. (40) does not depend on measures for the marginal cost of public funds, since MCF = 1 in the optimal tax system. Note also that (40) expresses the modified Pigouvian tax entirely in terms of sufficient statistics: the elasticities and tax rates can all be measured empirically.

Setting environmental taxes above (below) Pigouvian levels could be useful to reduce labor-market distortions if $\varepsilon^u_{ql}|_{\overline{y}} < 0$ $(>0)$.[18] The polluting good $q$ is then less (more) complementary with work than the clean good $c$ is. If $\varepsilon^u_{ql}|_{\overline{y}} < 0$ $(>0)$, the marginal willingness to pay for the polluting commodity decreases (increases) with labor supply, i.e., $\partial \ln(u_q/u_c)/\partial \ln l_n < 0$ $(>0)$, see (37).[19] By reducing (increasing) the conditional demand for polluting goods – i.e. the change in demand holding net income constant – the government indirectly stimulates labor supply, and thereby alleviates the distortions of the income tax. Consequently, the optimal corrective tax in second-best is higher (lower) than the Pigouvian tax if $\tau'(q_n) > \alpha\mu/\overline{\lambda}^*$ $(\tau'(q_n) < \alpha\mu/\overline{\lambda}^*)$.

Taxes on polluting goods should deviate more from the Pigouvian level the larger is the conditional demand elasticity of polluting goods with respect to labor, i.e., the larger is $\varepsilon^u_{ql}|_{\overline{y}}$ in absolute value. Pollution taxes should also deviate more from Pigouvian levels if labor-market distortions are larger, i.e., when marginal excess burden of the income tax $(T'(z_n))/(1-T'(z_n))\varepsilon_{lT'}$ is larger.

$\varepsilon^u_{zn}$ designates the (uncompensated) earnings elasticity with respect to the wage rate. The larger this elasticity, the stronger labor earnings correlate with ability. Moreover, the cross-elasticity of polluting goods with respect to labor supply equals minus the cross-elasticity of polluting goods with respect to ability: $\varepsilon^u_{ql}|_{\overline{y}} = -\varepsilon^u_{qn}|_{\overline{y}} \equiv (\partial q_n/\partial n)n/q_n|_{\overline{y}}$, see the online Appendix. Therefore, the ratio $-\varepsilon^u_{ql}|_{\overline{y}}/\varepsilon^u_{zn} = \varepsilon^u_{qn}|_{\overline{y}}/\varepsilon^u_{zn}$ implicitly determines which good is more useful to tax in order to redistribute income. If labor earnings correlate more heavily with ability than polluting goods do ($\varepsilon^u_{zn}$ increases relative to $\varepsilon^u_{qn}|_{\overline{y}}$), the government relies more on distorting labor supply and less on distorting demand for polluting goods to redistribute income (and vice versa).

In contrast to the case with linear income taxes, corrective taxes are not directly used for redistribution if non-linear income taxes can be used. Since the utility function is identical for all agents, commodity demands are identical for all agents earning the same income. Hence, the demand for polluting goods does not reveal additional information about ability than is already available from observing earnings. As a result, corrective taxation does not help to organize redistribution more efficiently than can be done with the income tax alone. Direct redistribution through income taxation is superior, because it avoids distortions in the demand for polluting goods, while generating the same distortions in labor supply.[20] Of course, reducing the distortions of income redistribution indirectly helps to redistribute more income, see also Jacobs and Boadway (2014).

The last result is similar to the findings of Kaplow (2012), but the interpretation is different. In particular, our result shows that if the government optimizes the tax system, then there should neither be corrections for tax distortions (or: the marginal cost of public funds) nor for the distributional aspects of income taxes in the rule for the modified Pigouvian tax. We demonstrate that this is true, even if the government does not offset the distributional impact of the corrective tax through a benefit-absorbing tax change as in Kaplow (2012). The reason is that tax distortions and distributional gains cancel in the optimum, which is an envelope property of the optimal income tax. Moreover, this also explains why our result holds true even if we assume non-separable preferences or analyze linear income taxes, in contrast to Kaplow (2012).

[18] Browning and Meghir (1991) and Crawford et al. (2010) empirically reject weak separability for the UK. Some externality-generating goods are found to be leisure complements (domestic fuels), while others are leisure substitutes (motor fuels). Pirttilä and Suoniemi (2014) find that a joint expenditure category of housing and energy consumption is a leisure complement in Finland. West and Williams (2007) present evidence that gasoline is a relative complement to leisure.

[19] Note that the term in the numerator of (37) can be written as

$$l_n\left(\frac{u_q}{u_c}u_{cl} - u_{ql}\right) = u_q\left(\frac{l_n u_{cl}}{u_c} - \frac{l_n u_{ql}}{u_q}\right) = -u_q\frac{\partial \ln(u_q/u_c)}{\partial \ln l_n}$$

[20] However, this result disappears if there is also preference heterogeneity, see also Mirrlees (1976) and Saez (2002). If, conditional on earnings, the willingness to pay for polluting commodities (i.e., the marginal rate of substitution of polluting and clean commodities) correlates with skills, corrective taxes (or subsidies) should also be employed for redistributional reasons.

*Modified Samuelson rule environmental quality*

Eq. (41) gives the optimal provision of environmental quality under non-linear instruments. $\Delta_n$ in equation (42) can be interpreted as the 'virtual subsidy' on the provision of environmental quality relative to the first-best policy rule. That is, environmental quality is overprovided compared to the first-best rule, $N\int_{\mathcal{N}} u_E/u_c \, \mathrm{d}F(n) < \mu/\eta$ , if the willingness to pay for a cleaner environment rises with labor supply, i.e., $\Delta_n > 0$ if $\partial \ln(u_E/u_c)/\partial \ln l_n > 0$. Similarly, environmental quality is underprovided compared to the first-best rule, $N\int_{\mathcal{N}} u_E/u_c \mathrm{d}F(n) > \mu/\eta$, if the individual's marginal willingness to pay for a cleaner environment falls with labor effort, i.e., $\Delta_n < 0$ if $\partial \ln(u_E/u_c)/\partial \ln l_n < 0$. Intuitively, in the second-best with labor-market distortions, the government employs environmental quality to indirectly alleviate these distortions by under-providing leisure complements or overproviding leisure substitutes – relative to the first-best policy rule. The government likes to deviate more from the first-best Samuelson rule for environmental quality when labor supply is more heavily distorted, i.e., when marginal excess burden of the income tax $T'(z_n)/(1-T'(z_n))\varepsilon_{lT'}$ is larger. Note, again, that there is no correction for MCF on the right-hand side of (41), since it is equal to one.

*Conditions for first-best policy rules in second-best*

Like in the linear case, we illustrate our main findings by deriving the conditions on the utility function that render the first-best rules for corrective taxes and environmental quality applicable in second-best with distortionary taxation.

**Corollary 2.** *If utility is given by $u(h(c_n, q_n, E), l_n)$, the optimal modified Pigouvian tax follows the first-best Pigouvian rule, and environmental quality follows the first-best Samuelson rule*:

$$\tau' = \frac{\alpha\mu}{\lambda^*} = \alpha N \int_{\mathcal{N}} \frac{u_E}{u_c} \mathrm{d}F(n). \tag{43}$$

**Proof.** If $u(h(c_n, q_n, E), l_n)$ we have $\partial \ln(u_E/u_c)/\partial \ln l_n = \partial \ln(u_q/u_c)/\partial \ln l_n = 0$, which implies that $\varepsilon^u_{ql}\big|_{\overline{y}} = 0$, see (37). Substitution in (40) and (41) yields the result. □

Thus, with the relatively weak assumption that consumption of goods and environmental quality are weakly separable from leisure, the optimal second-best policy rule for corrective taxation and environmental quality are identical to the optimal first-best policy rules. The intuition is that neither pollution taxes nor provision of environmental quality are used to alleviate labor-market distortions or to redistribute more income. Indeed, environmental policy is only targeted at internalizing the environmental externality. Moreover, the optimal marginal corrective tax is constant, i.e., flat, in the case where labor supply is weakly separable from clean and polluting commodities – even though the corrective tax is allowed to be non-linear. The intuition is that the marginal external damage of consuming one unit of the polluting commodity, $\alpha$, is constant across skill types. Hence, linear pollution taxes suffice to internalize all marginal pollution damages.

## 6. Conclusions and policy implications

This paper shows that, if the tax system is optimized to satisfy redistributional objectives, the second-best policy rule for internalizing environmental externalities should not be corrected for the marginal cost of public funds. However, the optimal second-best corrective tax may still differ from its first-best Pigouvian level for other reasons, some of which have been studied in prior literature. For instance, deviations from the Pigouvian tax are generally desirable depending on the complementarity of labor with polluting commodities and with environmental quality. When linear taxes are employed, second-best corrective taxes also depend on their distributional impacts. However, this redistributive role of pollution taxes is not present under optimal non-linear taxation.

If the government can levy non-linear income taxes, the second-best corrective tax is equal to the first-best Pigouvian tax if utility is weakly separable between labor and other commodities. When linear taxes are considered, the optimal corrective tax in second-best is only equal to the Pigouvian tax if utility is weakly separable between consumption goods and leisure, sub-utility over clean and polluting goods is homothetic, and income effects in individual choices are absent.

The results in this paper have important policy implications. For instance, if the marginal cost of public funds is equal to one, public resources are equally scarce as private resources, even though taxes create deadweight losses. Accordingly, countries with highly distortionary tax systems due to a strong preference for equality should not set lower taxes on, e.g., carbon emissions than countries with smaller tax distortions.

The finding that the marginal cost of public funds equals one hinges on in the presence of a non-distortionary marginal source of public finance. We show that, when the government cannot optimize with respect to this instrument, the marginal cost of public funds can be either smaller or larger than one depending on whether the tax system redistributes too little or too much income. By incorporating distributional concerns our findings thus demonstrate that corrections for the second-best Pigouvian tax may be the opposite from what has been suggested by representative-agent models.[21] We nest the

[21] Also if markets or governments fail, it is no longer guaranteed that the marginal cost of funds is one. Again, it is then no longer clear in which direction optimal second-best corrective tax should be modified compared to the first-best Pigouvian tax.

representative-agent model as a special case of our model, where the distributional benefits of distortionary taxes are set equal to zero, and the marginal cost of public funds generally exceeds one.

As a corollary, the findings of this paper are also relevant for the welfare effects of environmental tax reform and the so-called 'weak double-dividend hypothesis'. In particular, recycling the revenue from an environmental tax through lower distortionary labor taxes might no longer be superior to recycling this revenue through higher (non-individualized) lump-sum transfers. If the tax system is optimized, the efficiency costs and redistributional gains from income taxes are equal and the marginal cost of public funds equals one. Consequently, it becomes irrelevant whether the revenue from corrective taxes is used to cut distortionary labor taxes or to increase non-individualized lump-sum transfers. If tax systems are not optimal, a weak double dividend does not occur as well if deadweight losses of taxes are smaller than their distributional benefits. The marginal cost of funds is then lower than one. Indeed, only if deadweight losses of taxes exceed their distributional benefits, as is the case in all representative-agent models, a weak double dividend is feasible, because the marginal cost of funds is then larger than one.[22]

These findings may have broader implications for the analysis of instrument choice in environmental policy. In particular, some papers have argued that revenue-raising instruments are superior compared to non-revenue-raising instruments, such as regulation or subsidies (Goulder et al., 1999). This argument rests on the presumption that public resources are scarcer than private funds due to pre-existing tax distortions, i.e., that the marginal cost of public funds is larger than one. However, if the tax system is optimized, we conclude that public funds are not scarcer than private funds, so that revenue raising does not in itself yield a social welfare gain. Intuitively, the fundamental informational constraint in second-best analysis – ability is private information – cannot be relaxed by simply adopting a different policy instrument. As long as quantity controls, regulation or subsidies can sustain the second-best allocation equally well as taxes, revenue-raising instruments are not necessarily superior. Thus, one needs to include additional, instrument-specific constraints in the analysis to assess whether revenue-raising instruments are to be preferred over other instruments.[23]

## Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.jeem.2015.01.003.

## References


Atkinson, Anthony B., Stern, Nicholas H., 1974. Pigou, taxation and public goods. Rev. Econ. Stud. 41 (1), 119–128.

Atkinson, Anthony B., Stiglitz, Joseph E., 1976. The design of tax structure: direct versus indirect taxation. J. Public Econ. 6 (1–2), 55–75.

Ballard, Charles L., Fullerton, Don, 1992. Distortionary taxes and the provision of public goods. J. Econ. Perspect. 6 (3), 117–131.

Becker, Gary S., 1983. A theory of competition among pressure groups for political influence. Q. J. Econ. 98 (3), 371–400.

Bento, Antonio M., Jacobsen, Mark, 2007. Ricardian rents, environmental policy and the 'double-dividend' hypothesis. J. Environ. Econ. Manag. 53 (1), 17–31.

Bovenberg, A. Lans, 1999. Green tax reforms and the double dividend: an updated reader's guide. Int. Tax Public Finance 6 (3), 421–443.

Bovenberg, A. Lans, Mooij, Ruud A., 1994. Environmental levies and distortionary taxation. Am. Econ. Rev. 84 (4), 1085.

Bovenberg, A. Lans, van der Ploeg, Frederick, 1994a. Consequences of environmental reforms for involuntary unemployment and welfare. Environ. Resour. Econ. 12 (2), 137–150.

Bovenberg, A. Lans, van der Ploeg, Frederick, 1994b. Environmental policy, public finance and the labour market in a second-best world. J. Public Econ. 55 (3), 349–390.

Bovenberg, A. Lans, van der Ploeg, Frederick, 1996. Optimal taxation, public goods and environmental policy with involuntary unemployment. J. Public Econ 62 (1–2), 59–83.

Browning, Martin, Meghir, Costas, 1991. The effects of male and female labour supply on commodity demands. Econometrica 59 (4), 925–951.

Corlett, Wilfred J., Hague, Douglas C., 1953. Complementarity and the excess burden of taxation. Rev. Econ. Stud. 21 (1), 21–30.

Crawford, Ian, Keen, Michael, Smith, Stephen, 2010. Value added taxes and excises. In: Mirrlees, James A., Adam, Stuart, Besley, Timothy J., Blundell, Richard, Bond, Steven, Chote, Robert, Gammie, Malcolm, Johnson, Paul, Myles, Gareth D., Poterba, James M. (Eds.), The Mirrlees Review—Dimensions of Tax Design, Oxford University Press, Oxford, pp. 275–422. (Chapter 4).

Cremer, Helmuth, Gahvari, Firouz, Ladoux, Norbert, 1998. Externalities and optimal taxation. J. Public Econ. 70 (3), 343–364.

de Mooij, Ruud A., Lans Bovenberg, A., 1998. Environmental taxes, international capital mobility and inefficient tax systems: tax burden vs. tax shifting. Int. Tax Public Finance 5 (1), 7–39.

Diamond, Peter A., 1975. A many-person Ramsey tax rule. J. Public Econ. 4 (4), 335–342.

Diamond, Peter A., 1998. Optimal income taxation: an example with a U-shaped pattern of optimal marginal tax rates. Am. Econ. Rev. 88 (1), 83–95.

Diamond, Peter A., Mirrlees, James A., 1971. Optimal taxation and public production I: production efficiency. Am. Econ. Rev. 61 (1), 8–27.

Dutch Ministry of Finance. 2013. Belastingen op Milieugrondslag. http://www.rijksoverheid.nl/onderwerpen/belastingtarieven/belastingen-op-milieugrondslag. The Hague: Ministry of Finance.

Ebert, Udo, 1992. A reexamination of the optimal nonlinear income tax. J. Public Econ. 49 (1), 47–73.

Feldstein, Martin, 1972. Distributional equity and the optimal structure of public prices. Am. Econ. Rev. 62 (1), 32–36.

Fullerton, Don, 1997. Environmental levies and distortionary taxation: comment. Am. Econ. Rev. 87 (1), 245–251.


[22] Naturally, outside the optimum there still can be scope for a double dividend of an environmental tax reform, as environmental taxes may be an indirect way to alleviate distortions imposed by other taxes, other market failures, or other government failures.

[23] For example, Fullerton and Metcalf (2001) demonstrate that revenue-raising instruments can skim off scarcity rents of environmental policies without imposing distortions. Revenue-raising instruments are then superior over non-revenue raising instruments. However, if the government can levy a pure rent tax to directly skim off scarcity rents, revenue-raising instruments are no longer superior over other instruments.

Fullerton, Don, Leicester, Andrew, Smith, Steven, 2010. Environmental taxes. In: Mirrlees, James A., Adam, Stuart, Besley, Timothy J., Blundell, Richard, Bond, Steven, Chote, Robert, Gammie, Malcolm, Johnson, Paul, Myles, Gareth D., Poterba, James M. (Eds.), The Mirrlees Review – Dimensions of Tax Design, Oxford University Press, Oxford, pp. 423–547. (Chapter 5).
Fullerton, Don, Metcalf, Gilbert E., 1998. Environmental taxes and the double-dividend hypothesis: did you really expect something for nothing? Chicago-Kent Law Rev. 73, 221–256.
Fullerton, Don, Metcalf, Gilbert E., 2001. Environmental controls, scarcity rents, and pre-existing distortions. J. Public Econ. 80 (2), 249–267.
Gahvari, Firouz, 2006. On the marginal cost of public funds and the optimal provision of public goods. J. Public Econ. 90 (6–7), 1251–1262.
Gauthier, Stephane, Laroque, Guy R., 2009. Separability and public finance. J. Public Econ. 93 (11–12), 1168–1174.
Goulder, Lawrence, Parry, Ian W.H., Burtraw, Dallas, 1997. Revenue-raising versus other approaches to environmental protection: the critical significance of pre-existing tax distortions. Rand J. Econ. 28 (4), 708–731.
Goulder, Lawrence H., 1995. Environmental taxation and the double dividend: a reader's guide. Int. Tax Public Finance 2 (2), 157–183.
Goulder, Lawrence H., Bovenberg, A. Lans, 2002. Environmental taxation and regulation in a second-best setting. In: Feldstein, Martin, Auerbach, Alan J. (Eds.), Handbook of Public Economics, vol. 3., Elsevier, pp. 1471–1545. (Chapter 23).
Goulder, Lawrence H., Parry, Ian W.H., Williams, Roberton C., Burtraw, Dallas, 1999. The cost-effectiveness of alternative instruments for environmental protection in a second-best setting. J. Public Econ. 72 (3), 329–360.
Holmlund, Bertil, Kolm, Ann-Sofie, 2000. Environmental tax reform in a small open economy with structural unemployment. Scand. J. Econ. 7 (3), 315–333.
IAWG (2013), "Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866", Technical Support Document, Interagency Working Group on Social Cost of Carbon, Washington-DC: United States Government.
Jacobs, Bas, 2009. The Marginal Cost of Public Funds and Optimal Second-Best Policy Rules. Erasmus University Rotterdam.
Jacobs, Bas, 2013. The Marginal Cost of Public Funds is One at the Optimal Tax System. mimeo: Erasmus University Rotterdam.
Jacobs, Bas, Boadway, Robin, 2014. Optimal linear commodity taxation under optimal non-linear income taxation. J. Public Econ. 117 (1), 201–210.
Jacobs, Bas, de Mooij, Ruud A, 2011. Pigou Meets Mirrlees: On the Irrelevance of Tax Distortions for the Second-Best Pigouvian Tax. CESifo Working Paper No. 3342. CESifo, Munich.
Jacquet, Laurence, Lehmann, Etienne, Van der Linden, Bruno, 2013. The optimal marginal tax rates with both intensive and extensive responses. J. Econ. Theory 148 (5), 1770–1805.
Kaplow, Louis, 1996. The Optimal supply of public goods and the distortionary cost of taxation. Natl. Tax J. 49 (4), 513–533.
Kaplow, Louis, 2004. On the (ir)relevance of distribution and labor supply distortion to public goods provision and regulation. J. Econ. Perspect. 18 (4), 159–175.
Kaplow, Louis, 2012. Optimal control of externaliteits in the presence of income taxation. Int. Econ. Rev. 53 (2), 487–509.
Koskela, Erkki, Schöb, Ronnie, 1999. Alleviating unemployment: the case for green tax reforms. Eur. Econ. Rev. 43 (9), 1723–1746.
Laroque, Guy R., 2005. Indirect taxation is superfluous under separability and taste homogeneity: a simple proof. Econ. Lett. 87 (1), 141–144.
Ligthart, Jenny E., van der Ploeg, Frederick, 1999. Environmental policy, tax incidence, and the cost of public funds. Environ. Resour. Econ. 13 (2). 187–107.
Liu, Antung Anthony, 2013. Tax evasion and optimal environmental taxes. J. Environ. Econ. Manag. 66 (3), 656–670.
Micheletto, Luca, 2008. Redistribution and optimal mixed taxation in the presence of consumption externalities. J. Public Econ. 92 (10–11), 2262–2274.
Mirrlees, James A., 1971. An exploration in the theory of optimum income taxation. Rev. Econ. Stud. 38 (2), 175–208.
Mirrlees, James A., 1976. Optimal tax theory: a synthesis. J. Public Econ. 6 (4), 327–358.
Parry, Ian W.H., 1995. Pollution taxes and revenue recycling. J. Environ. Econ. Manag. 29 (3), S64–S77.
Parry, Ian W.H., Bento, Antonio M., 2000. Tax deductions, environmental policy, and the 'double-dividend' hypothesis. J. Environ. Econ. Manag. 39 (1), 67–96.
Pigou, Arthur C., 1920. The Economics of Welfare. Macmillan, London.
Pirttilä, Jukka, 2000. A Many-Person Corlett–Hague Tax Rule with Externalities. Oxford Economic Papers 52 (3), 595–605.
Pirttilä, Jukka, Suoniemi, Ilpo, 2014. Public provision, commodity demand and hours of work: an empirical analysis. Scand. J. Econ. 116 (4), 1044–1067.
Pirttilä, Jukka, Tuomala, Matti, 1997. Income tax, commodity tax and environmental policy. Int. Tax Public Finance 4 (3), 379–393.
Proost, Stef, Mayares, Inge, 2001. Marginal tax reform, externalities, and income distribution. J. Public Econ. 79 (2), 343–363.
Sadka, Efraim, 1976. On income distribution, incentive effects and optimal income taxation. Rev. Econ. Stud. 43 (2), 261–267.
Saez, Emmanuel, 2001. Using elasticities to derive optimal income tax rates. Rev. Econ. Stud. 68 (1), 205–229.
Saez, Emmanuel, 2002. The desirability of commodity taxation under non-linear income taxation and heterogeneous tastes. J. Public Econ. 83 (2), 217–230.
Sandmo, Agnar, 1975. Optimal taxation in the presence of externalities. Scand. J. Econ. 77 (1), 86–98.
Sandmo, Agnar, 2000. The Public Economics of the Environment. Oxford University Press, Oxford.
Schöb, Ronnie. 2003. The Double Dividend of Environmental Taxes: A Survey. Working Paper 2003.60. Fondazione Eni Enrico Mattei.
Seade, Jesus K., 1977. On the shape of optimal tax schedules. J. Public Econ. 7 (2), 203–235.
Stern, Nicholas H., 2007. The Economics of Climate Change: The Stern Review. Cambridge University Press, Cambridge and New York.
Tuomala, Matti, 1984. On the optimal income taxation: some further numerical results. J. Public Econ. 23 (3), 351–366.
West, Sarah E., Williams, Roberton C., 2007. Optimal taxation and cross-price effects on labor supply: estimates of the optimal gas tax. J. Public Econ. 91 (3–4), 593–617.
Wildasin, David E., 1984. On public good provision with distortionary taxation. Econ. Inq. 22 (2), 227–243.
Williams, Roberton C., 2002. Environmental tax interactions when pollution affects health or productivity. J. Environ. Econ. Manag. 44, 261–270.
Williams, Roberton C., 2005. An Estimate of the Optimal Second-Best Gasoline Tax Considering Both Efficiency and Equity. mimeo: University of Texas Austin.