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Uncertainty and the Double Dividend Hypothesis

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Summary

This paper examines the double dividend hypothesis in the presence of labour income uncertainty. Empirical evidence shows that uncertainty over labour income is particularly significant in developing, while not negligible in developed countries. Under uncertainty, and assuming incomplete capital markets, the tax system plays a role in providing social insurance and a green tax reform influences its effectiveness. We show that the increase in environmental tax reduces consumption risk while the balanced budget decrease in labour income tax increases income risk. We find that the total welfare effect of a green tax reform differs substantially from the case of certainty. The critical parameters determining the existence of a second dividend are the lump sum transfers, the relative substitutability of the two goods for leisure and the initial tax rates relative to their optimal that determine also the response of labour supply to a change in the tax mix.

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1 Introduction

Economists have long been advocating the use of environmental policies that provide economic incentives, on the basis of efficiency. More recently, it has been argued that the efficiency benefits of market based policies that generate revenue, such as environmental taxation, may extend beyond the environmental area if revenues are used to decrease existing distortionary taxes, such as labour income taxes.

In this paper we extent the literature on revenue neutral environmental tax shifts by introducing idiosyncratic uncertainty over income. Our analysis is founded on the results of both theoretical and empirical literature showing that labour supply decisions are affected quite strongly by the presence of uncertainty.[1] Based on this evidence, it has been argued that some positive level of labor income taxation is optimal since it reduces uncertainty. Uncertainty about labor income is likely to be particularly significant in developing countries, especially where private insurance is unavailable, but it is not unimportant in developed ones.

Income fluctuations are more common and larger in developing relative to developed countries. Townsend (1995) provides evidence from three developing economies indicating that risks are mostly of the idiosyncratic nature and that only few individuals are able to diversify this risk. Developing and low income nations cope with hardship mainly through the use of informal insurance systems (for example, household might take children out of school during bad economic times or depend on reciprocal gift giving arrangements). Recent evidence indicate that these informal insurance arrangements, although they provide some assistance, they are in general weak and more formal insurance systems through either publicly managed programs or private markets can improve the social safety net of the economy (Townsend (1994), Morduch (1999a)). Furthermore, financial markets are not well developed to allow individuals to access capital during bad economic times. Microfinance is a promising new institution that offers funding to low income people to under-

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[1] *At the theoretical level, Eaton and Rosen (1980a) and more recently Menezes and Wang (2005), have shown that labor supply can decrease in response to an increase in wage rate uncertainty if risk aversion is significant. Ormiston and Schlee (1994) show that an increase in wage uncertainty always lowers aggregate hours of work and increases expected wage rate in competitive labour markets provided workers are risk averse. Floden (2006) examines ways in which labour supply can be used to self-insure against labour income uncertainty. At the empirical level, Low (2005) finds that younger workers with higher uncertainty over income, work longer hours than old workers and Parker et. al. (2005) finds that self-employed workers, facing higher uncertainty, work longer hours as well. However, this response of labour supply to uncertainty is for self-insurance purposes and the longer work hours come at the expense of lower average wages.*

take new entrepreneurial activity and reduce poverty but this alternative also faces a number of problems (Morduch (2006) and Morduch (1999b)). Chetty and Looney (2006) show that even when we observe smooth consumption patterns in low income countries, social insurance could be beneficial since in many cases "...the smoothness of consumption is the result of high risk aversion and not efficient private insurance markets." (Chetty and Looney (2006), p. 2352)

At the theoretical level, Varian (1980) views redistributive taxation as social insurance. Redistributive taxation does not only generate a more equitable income distribution but it also improves the allocation of risk bearing. Taxing uncertain income, transfers some of the risk to the budget constraint and when risks are idiosyncratic in nature, the aggregate tax revenue becomes certain which can be re-distributed back to individuals in the form of lump sum transfers. A green tax reform policy that uses pollution tax revenues to reduce further the labour tax could exacerbate the social insurance system especially in developing nations where the role of labour taxes is limited.[2] Therefore, the analysis of green tax reforms under uncertainty could contribute to the debate on the double dividend hypothesis, especially in the case of developing countries, where, apart from the high income uncertainty, policy makers have to address significant and growing environmental problems.

The interdependency of environmental taxes with other existing taxes was first examined by Sandmo (1975). However, it was not until the early 90s, that the proposal to use environmental taxation revenues in reducing labour income taxes appeared in the literature. Since labor income taxation is distortionary under certainty, its reduction yields a positive welfare effect which has been termed the *revenue recycling effect* (see for example, Oates (1993) and (1995), Pearce (1991), Repetto et al. (1992)). However, increases in environmental taxes lead to higher prices, and thus, to a reduction in real wages yielding a negative welfare effect which has been termed as the *tax-interaction term*. Because of the increase in prices, the incentive to work may fall even though labor income taxation is reduced. The overall effect depends on the departure of the existing taxes from their optimum.[3] If the green tax reform moves existing taxes towards their optimum, there is a "gross

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[2] *As noted by Bird and Zolt (2005), even in the current tax systems of developing countries, the personal income tax system plays a small role in redistributing income and providing social insurance. Furthermore, many developing countries use currently environmental taxes to generate revenue for environmental investments instead of reducing labour taxes (Bluffstone (2003)).*

[3] Ballard, Goddeeris and Kim (2005) have shown that the existence of a second dividend also depends on the specification of the preferences' structure. See also Kim (2002).

benefit" and the green tax reform yields a double dividend. That is, there is a welfare benefit in addition to the expected environmental benefit which is termed as the *Pigouvian effect*. The Pigouvian effect measures the reduction in the consumption of the polluting good due to the marginal increase in the environmental tax, multiplied by the marginal social benefit (marginal environmental damage minus the tax). However, it has been shown that, under certain reasonable assumptions, the tax-interaction tends to dominate the revenue recycling effect, and therefore, there is a "gross cost".[4] In such cases, the sign of the total welfare effect depends on the magnitude of the *Pigouvian effect* relative to the "gross cost". Regardless of whether a second dividend emerges or not, environmental taxes or auctioned permits have an advantage over grandfathered permits if the revenues are used to reduce distortionary taxes.[5]

The green tax reform literature has also examined the effect of revenue recycling policies on equity and unemployment.[6] The literature indicates that green tax reform could possibly reduce involuntary unemployment. In terms of equity, it has been shown that a green tax reform can adversely affect the income distribution, reducing the possibility of achieving a second dividend.[7] Apart from equity considerations, another reason that justify labor income taxation is the provision of social insurance. Eaton and Rosen (1980a) have shown that, when there is uncertainty over labor income and individuals are risk averse, a tax on labor income is optimal, even in the presence of lump sum taxation, since it reduces uncertainty. Therefore, a combination of uniform lump sum taxation and labor income taxation is optimal. Furthermore, Eaton and Rosen (1980b) find that under uncertainty it is optimal to increase the progressivity of the tax system. Despite the criticism that this line of work has received,[8] it is clear that labor income

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[4] See Bovenberg and de Mooij (1994) and (1997), Bovenberg and Goulder (1996), Goulder (1995) and (1996) , Parry (1995) and (1996), Christiansen (1996) and Goulder, Parry and Burtraw (1997). See also the literature review papers by Goulder (1995) and Bovenberg (1999).

[5] See the recent study by Parry (2003).

[6] Bovenberg (1999) and De-Mooij (2000) provide extended reviews of the literature on equity issues.

[7] More recently Layard (2006) argues that income taxation could have a corrective aspect, assuming that people put excessive work effort in an attempt to increase their income relative to the average. Assuming that individuals' utility decreases on average income, the optimal income tax is positive.

[8] For example Lundholm (1992), critised Eaton and Rosen's (1980b) assumption that consumers are (ex ante) homogeneous. According to Lundholm, under this assumption the tax is a substitute for market insurance. Instead, Lundholm argued that consumers should differ in productivity type.

taxation is not completely distortionary under labor income uncertainty.

Although the literature has examined the effects of the green tax reform on equity and unemployment issues, to the best of our knowledge, there is no work examining the welfare effects of the green tax reform in the presence of labour income uncertainty. In the present paper we undertake this task.

The introduction of labour income uncertainty in the model implies that the government has a role in correcting this distortion, especially when private insurance markets are not complete, or, as in some developing countries, not even present. Therefore, under uncertainty the tax system –labour income and environmental tax– can play a corrective role by reducing the dispersion of net income and consumption among individuals. In doing so, both taxes provide some type of insurance, in addition to their respective primary roles (collecting revenues to finance the public good and reducing the environmental externality respectively).

When considering a green tax reform within this framework, one should take into account its effect on the insurance provision mechanism as well. In this paper, we mark this effect as social insurance effect. In Section 4, we decompose this effect into three components. First, the increase in the pollution tax reduces consumption risk, and thus, adds a positive welfare effect. Second, the balanced budget reduction of the labour income tax increases the risk creating thus, a negative welfare effect. The sum of these two effects is positive if the two consumption goods (one that pollutes and the other that does not) are equal substitutes for leisure, or the polluting good is a stronger substitute for leisure. On the contrary, if the polluting good is a sufficiently weaker substitute for leisure relative to the non-polluting good, the net of these two effects on welfare is ambiguous and could be negative. Third, the reduction of labor income taxation increases income risk and in doing so it affects the response of labour supply. When the insurance effect of labour income taxation is added to the income effect on labour supply, the wedge between the income and the substitution effect is shortened and under certain conditions, the response of labour supply to labour income taxation could even become positive. Thus, the marginal cost of labour taxation weakens or it could even become a marginal welfare benefit, yielding a shift in the signs of the revenue recycling and tax interaction effects.

The total, not including the Pigouvian, welfare effect of the green tax reform is ambiguous and depends on the relative substitutability of the dirty and clean good for leisure and the response of labour supply to a change in the tax mix. This, in turn, depends on the departure of the initial taxes from their second best optimum. In Section 5 we show that under uncertainty, the optimal value of labour income tax is positive even in the presence of lump-sum taxes, and that the optimal environmental tax exceeds marginal

environmental damages. Optimal taxation is analyzed within a second best framework. If before the green tax reform labour income tax is above its optimal level while the environmental tax is below its optimal level, then a green tax reform could increase welfare. However, the green tax reform could result in welfare losses if the labor income tax is below its first best and the environmental tax is close to its first best, assuming that lump-sum taxes/transfers are also available.[9]

The rest of the paper is organized as follows. In the two sections that follow we specify the model and the structure of households' decision making. In Section 4 we examine the interaction between labor and environmental taxation under uncertainty. In Section 5 we analyze optimal taxation within a second best framework. Section 6 contains the discussion of results and concluding remarks.

2 The model

On the production side, we assume that labour is the only input in the production process of the only two consumption goods D and C. Both production processes exhibit constant returns to scale and the markets for both goods are competitive. We normalize units such that the pre-tax prices of both goods are unity. Good C is assumed to be the environmentally clean good. Production and consumption of good D generate emissions that adversely affect the quality of the environment, π, that is, $\pi = \Pi(D)$ with $\Pi_D < 0$, where $D = \sum D_i$ and D_i is household i's consumption. We further assume that, in the absence of regulation, firms do not internalize any part of the externality and that the marginal product of labour in both industries is independent of environmental quality.

We assume that households face uncertainty over their wages when they decide on their labour supply. Households face different risks, and thus, ex-post earn different wages. The wage of household i is denoted by w_i, with the mean wage rate $\overline{w} = \sum_{i=1}^{n} w_i/n = 1$ normalized to unity. Among the reasons explaining wage uncertainty are: households are searching for jobs but they are not sure which type of job, and thus, what wage, they will get; households are uncertain about their productivity in the job that they will find given their investment in human capital; households face the probability of losing their current jobs in which case there is uncertainty about their wage at the new job. Uncertainty over labour income may arise also due to

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[9]In this paper we utilize uniform lump sum transfers and distortionary taxes as a substitute of market insurance as in the Eaton and Rosen taxation model.

productivity shocks as well as due to imperfect forecasts of inflation.[10] Our paper concentrates on purely idiosyncratic risks, assuming away aggregate risks.[11] We also assume that the market fails to provide insurance due to moral hazard considerations.[12]

The government's function is threefold; to provide a certain amount of public good; a certain level of environmental quality; and insurance against wage uncertainty. To serve these functions, the government uses a proportional tax τ_L, on income inclusive of lump sum transfers, a per unit tax τ_D on D, and uniform lump sum transfers/taxes Ω.[13] Government's budget constraint, expressed in per household terms is:[14,15]

$$\overline{G} = \tau_L \left[\overline{w}(T - l) - \Omega\right] + \tau_D \overline{D} + \Omega \ , \tag{1}$$

where $\overline{G} = \frac{G}{n}$ is the public good per household, $T - l$ is the household's labour supply, with l denoting leisure, and T time endowment. $\overline{w} = \frac{w}{n}$ denotes the mean wage rate of the distribution and $\overline{D} = \frac{D}{n}$ the mean consumption level of the dirty good. Although taxes paid by household i are stochastic,[16] government's budget constraint is non-stochastic, since the government pools together idiosyncratic risks more efficiently.[17]

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[10] For more details see Eaton and Rosen (1980a)

[11] In the case of aggregate risk, the government could provide social insurance through intergenerational risk-sharing arrangement. See for example Gordon and Varian (1988)

[12] See Arrow (1971), Eaton and Rosen (1980a) and Varian (1980).

[13] The labor tax is inclusive of lump sum transfers so that it can be made equivalent to a uniform tax on both commodities. We assume that non-uniform lump sum taxes are not feasible.

[14] The system can be viewed as a commodity tax on the dirty good τ_D and the well known negative income tax that has two parameters, a constant marginal tax rate τ_L and a lump sum transfer, Ω. A negative income tax system is progressive in the sense that average tax rate rises with gross income.

[15] One has to be aware that lump sum transfers and high labor taxes could affect adversely the participation rate into the labor market. See Moffit (1992) for a literature review of the effects of the U.S. welfare system on work incentives.

[16] Household i pays taxes $T_i = \tau_D D_i^* + \tau_L \left[w_i(T - l^*) - \Omega\right]$. The superscript $*$ denotes household's optimal choices as functions of the tax structure and household's wage rate. The tax revenue each individual pays is stochastic since it depends on the random wage rate.

[17] The (strong) law of large numbers guarantees certainty at the aggregate level. The variance of $\overline{w}$ is equal to $var(\sum w_i/n) = \frac{1}{n^2} \sum var(w_i) = \frac{\sigma^2}{n}$ as the number of households increases (n increases), the variance of $\overline{w}$ approaches zero.

3 Individual Decision Making Process

We assume the following structure regarding households' decision making process. Before the realization of the state of nature, households are called to allocate their time endowment between labour and leisure. After uncertainty is resolved, households make their consumption choices. Households solve first the ex-post problem of demand derivation, and then, taking into account the demand for good C and D, they solve their ex-ante labour supply problem. Allowing households to make their decisions in two stages, eliminates the possibility of violating ex post the budget constraint due to wage uncertainty.

3.1 Ex Post Decisions

Given households ex-ante labor supply decision $T - l$, and the ex post wage rate w_i, the optimal choices of goods D and C are derived from the utility maximization problem. Assuming separability between public goods (environmental quality and consumption of the public good) and private choices (of D, C and l), households' utility is,

$$u = U(D, C, l) + V(\Pi(n\overline{D}), n\overline{G}) . \tag{2}$$

The assumption of separability between public goods and private choices, allow us to derive the labour supply response to the change in the tax mix without considering changes in the environmental quality. If however, environmental quality is not separable from leisure and an improvement in environmental quality stimulates labor supply, then a green tax reform is more likely to create a second dividend. On the other hand, if environmental quality and leisure are complements, then a green tax reform will have larger adverse effects on labour supply and the likelihood of a second dividend diminishes. See for example, Schwartz and Repetto (1997). Since the focus of this paper is to analyze the effects of uncertainty on the double dividend hypothesis, we adopt the separability assumption following the main body of the literature. We make the usual assumptions of a twice differentiable, strictly concave utility function, $U(.)$ exhibiting decreasing marginal utility of consumption so that households are risk averse. Each household is subject to the budget constraint:[18]

$$(1 + \tau_D)D + C = (1 - \tau_L)[w(T - l) - \Omega] . \tag{3}$$

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[18]Note that if the labor tax is set at $\tau_L = \frac{\tau}{1+\tau}$ where τ is a proportional tax on the two commodities at equal rates it becomes equivalent to a general comsumption tax. Substituting for τ_L yields $(1 + \tau)(1 + \tau_D)D + (1 + \tau)C = w(T - l) - \Omega$

The first order conditions of households' constrained utility maximization problem yield, $U_D = (1 + \tau_D)U_C$. The solution of the first order conditions yields the optimal consumption choices as functions of the tax rate on labour income, the tax rate on D, the leisure choice and the observed wage rate, that is, $D = D(\tau_D, \tau_L, w_i, l, \Omega)$, and $C = C(\tau_D, \tau_L, w_i, l, \Omega)$. Since the demand functions depend on the wage rate, they differ across individual households.

3.2 Ex Ante Decisions

In the first stage of the game, that is, before the realization of the state of nature, households derive their optimal choice of labour supply from the maximization of the expected utility function subject to the budget constraint, $C = (1 - \tau_L)[w(T - l) - \Omega] - (1 + \tau_D)D$. Substituting the two demand functions, derived in the second stage of the problem, into the expected utility yields,

$$E(u) = E\left[U(D(\tau_D, \tau_L, w_i, l, \Omega), C(\tau_D, \tau_L, w_i, l, \Omega), l)\right] + V(\Pi(n\overline{D}), n\overline{G}) \ .$$

The solution of the constrained maximization problem yields the following first order conditions,[19]

$$E\left[U_C(1 - \tau_L)w\right] = E\left[U_D \frac{(1 - \tau_L)w}{(1 + \tau_D)}\right] = E(U_l) \ . \tag{4}$$

The solution of the first order conditions yields the optimal choice of leisure as a function of the tax rates, that is,

$$l^* = l(\tau_D, \tau_L, \Omega) \ . \tag{5}$$

Finally, we return to the second stage of the game, and substitute the optimal labour choice into the demand functions to derive the optimal choices of goods D and C as functions of the tax rates,

$$D^* = D(\tau_D, \tau_L, \Omega, l^*, w), \quad C^* = C(\tau_D, \tau_L, \Omega, l^*, w) \ . \tag{6}$$

Having determined the optimal choices of households as functions of the tax rates and the uncertain wage rate, we turn in the next section to derive the welfare effect of a revenue recycling policy.

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[19]In deriving equation (4), we use the first order condition of the second stage maximization problem, which implies that, $E[(U_D - (1 + \tau_D)U_C)\frac{\partial D}{\partial l}] = E(0\frac{\partial D}{\partial l}) = 0$.

4 Interaction of labor and environmental taxation under wage uncertainty

We assume that at some initial positive level of τ_L and τ_D the government considers a marginal increase in the environmental tax τ_D within a revenue-neutral policy. The environmental tax is a corrective tax, in the sense that it internalizes an existing externality. In the absence of uncertainty, the proportional labour income tax is distortionary in the sense that it changes the shadow price of leisure. Under certainty, the literature has identified three effects of the revenue recycling policy. The effect of using the revenue from the corrective taxation to reduce the distortionary labour income tax within a revenue-neutral policy, is positive and has been termed the *revenue recycling effect.* However, corrective taxation is not equivalent to lump sum taxation since it results in price increases, and thus, leads to distortions in the labour market, a negative effect that is termed the *tax interaction effect.* If the former effect outweights the latter, environmental taxation generates a *double dividend,* that is, an additional positive effect to the intended improvement in environmental quality, which is termed the *Pigouvian effect.* However, the opposite is more likely to be the case as we discussed in the Introduction.

Consider now the case that households do not know with certainty the return to their labour effort when they make their labour-leisure decisions. It has been shown that in addition to the distortionary effect associated with revenue generation, taxation has the positive effect of lowering households' risks by pooling them across the economy. Thus, changing the tax structure has an additional effect, hereafter called the *social insurance effect.*

In order to evaluate the social insurance effect, we need to determine the total welfare effect of the revenue recycling policy. That is, we want to account for the direct effect that a change in the environmental tax has on households' optimal choices, as well as the indirect effect generated by the decrease in labour income tax implied by the revenue recycling policy. We proceed by deriving the total change in τ_L by totally differentiating government's budget constraint, equation (1). Since we consider a revenue neutral policy we set $d\overline{G} = 0$, and $d\Omega = 0$ and we obtain:

$$\frac{d\tau_L}{d\tau_D} = -\frac{\overline{D} + \tau_D \frac{d\overline{D}}{d\tau_D} + \tau_L \frac{\partial(T-l^*)}{\partial\tau_D}}{(T-l^*) - \Omega + \tau_L \frac{\partial(T-l^*)}{\partial\tau_L}}, \tag{7}$$

where, $\frac{d\overline{D}}{d\tau_D} = \frac{\partial\overline{D}}{\partial\tau_D} + \frac{\partial\overline{D}}{\partial\tau_L}\frac{d\tau_L}{d\tau_D}$ is the total balanced budget effect of the revenue recycling policy on the dirty good. Assuming that the direct dominates the indirect effect, $\frac{d\overline{D}}{d\tau_D} < 0$. The sign of the relative marginal tax revenue from

the environmental tax (numerator) to labour income tax (denominator) is positive, that is, $\frac{d\tau_L}{d\tau_D} < 0$.

We combine the household's and government's budget constraints from equations (1) and (3), in which we substitute the household's optimal choices, D^*, C^* and l^* to obtain its resource constraint,

$$D^* + C^* + \overline{G} = w(T - l^*) - \tau_L(w - 1)(T - l^*) - \tau_D(D - \overline{D}) . \quad (8)$$

Household's resource constraint is stochastic since it depends on w. The above resource constraint reveals that the government is capable of absorbing risk at a less cost than the individuals. Thus, households face less risk when making their labour decisions. Consider a household that gets a bad draw, that is, $w < \overline{w}$. In the presence of labor taxation, the tax acts as an insurance mechanism in that the individual's income is more than it would be without the labor tax system in place, as the second term in the RHS of (8) indicates. In addition, the bad draw will also reduce consumption of the dirty good below the average consumption level, that is, $D < \overline{D}$, as the third term in the RHS of (8) indicates and the household will again be better off relative to the income level without the tax system. The opposite is true for the households that get a lucky draw. The tax structure reduces the dispersion of net income and consumption.[20]

Households are assumed to maximize their expected utility. Substituting households' optimal choices into the expected utility yields households' expected indirect utility

$$E(W) = E\left[U\left(D^*, C^*, l^*\right)\right] + V\left(\Pi(n\overline{D}), n\overline{G}\right) .$$

We can now derive the total effect of the revenue recycling policy by differentiating the expected indirect utility function with respect to the environmental tax, that is, by specifying the sign of the expression, $\frac{dE(W)}{d\tau_D} = \frac{\partial E(W)}{\partial \tau_D} + \frac{\partial E(W)}{\partial \tau_L}\frac{d\tau_L}{d\tau_D}$. We define $\mu_D = \frac{-nV'\Pi_D}{E(U_C)}$ as the marginal disutility from increasing the consumption of the dirty good per unit of expected marginal utility of the clean good, which for simplicity we term as the *marginal exter-*

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[20]Furthermore, since prior to uncertainty being resolved individuals have the same skills and opportunities, labor taxes satisfy horizontal equity. Ex post individuals' income differs due to luck and thus, there is ex post inequity. However, given that lump sum transfers are available, lucky individuals have a higher average tax bill, while unlucky individuals have a lower average tax bill. This implies that the lucky individuals finance a relatively larger fraction of the public good.

nal damage under uncertainty, and we derive,[21]

$$\frac{1}{E(U_C)}\frac{dE(W)}{d\tau_D} = (\tau_D - \mu_D)\frac{d\overline{D}}{d\tau_D} - \frac{cov\,[U_C, D^*]}{E(U_C)} +$$

$$\rho[\overline{D} + \tau_D\frac{d\overline{D}}{d\tau_D}] + [1 + \rho]\,\tau_L\frac{\partial(T - l^*)}{\partial\tau_D}\ , \qquad (9)$$

where ρ is the *marginal welfare change due to labour taxation per dollar of revenue raised* which is defined in the following equation[22]

$$\rho = \underbrace{\frac{\frac{cov[U_C,w](T-l^*)}{E(U_C)}}{(T - l^*) - \Omega + \tau_L\frac{\partial(T-l^*)}{\partial\tau_L}}}_{\rho_1} + \underbrace{\frac{-\tau_L\frac{\partial(T-l^*)}{\partial\tau_L}}{(T - l^*) - \Omega + \tau_L\frac{\partial(T-l^*)}{\partial\tau_L}}}_{\rho_2}. \qquad (10)$$

The denominator of (10) is the partial equilibrium change in government's revenue due to a marginal change in the labour wage tax rate.[23] The numerator is the welfare change from a marginal change in τ_L.[24]

In the absence of uncertainty, welfare changes because labour-leisure decisions are affected and the labour income tax is distortionary. Under uncertainty, welfare also changes due to the impact of the policy on the insurance system. The welfare effect of the change in the social insurance system, arising from the change in labor taxation, is captured by the second term in equation (9) as well as by changes in ρ.

We examine first the effect that the induced changes of the insurance system have on ρ. First, since labor taxation falls as a result of the revenue recycling policy, the social insurance effect due to the absorption of income risk weakens. This is indicated by the covariance term in the numerator of ρ, which is negative, that is, $cov\,[U_C, w] < 0$, which implies that $\rho_1 < 0$.

Second, the value of ρ_2 depends on the response of labour supply to a change in τ_L, that is, on the sign of $\frac{\partial(T-l^*)}{\partial\tau_L}$. Under certainty, the response of households' choice of leisure to a decrease in labor taxation can be decomposed into an income and a substitution effect. When labor taxation decreases, after-tax income increases and thus, households move toward a

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[21]For some details in the derivation of (9) see Appendix 1.

[22]In the case of certainty, ρ collapses to ρ_2 which equals the M term in Goulder et al. (1997), page 712, equation (14).

[23]It is a partial equilibrium effect due to the omission of the effect of labour taxation on the dirty good. This effect is included in the total effect of the policy on the dirty good.

[24]Note that within this framework of tax incidence analysis we examine uncompensated changes, that is, we consider both income and substitution effects. Thus, the term welfare changes is used within this framework.

higher level of leisure. At the same time though, the shadow price of leisure increases, and as a result, households substitute away from leisure. Thus, the overall effect depends on the relative strength of the income and substitution effects. Within a framework very similar to the one considered in the present paper, Bovenberg and de Mooij (1994) show that the substitution dominates the income effect, that is, $\frac{\partial(T-l^*)}{\partial\tau_L} < 0$, if the elasticity of substitution between leisure and consumption is greater than one.[25] Under this assumption, there is a marginal welfare cost due to labor income taxation, that is, $\rho_2 > 0$.

Under uncertainty, labour income taxation is not by definition sub-optimal and the effect of labor taxation on labour supply has been shown to critically depend on a number of parameters. A decrease in τ_L increases uncertainty which may induce households to choose a higher level of leisure. When this insurance effect is added to the income effect, the likelihood that households increase their labour supply in response to an increase in τ_L is enhanced. The theoretical literature asserts that an increase in wage uncertainty reduces labor supply especially at low initial levels of taxation.[26] Eaton and Rosen (1980a) and (1980b) show that the labour supply response depends on the relative risk aversion and the share of labor income in consumption expenditure. When labor income is the main source of income, the assumption of moderate relative risk aversion just above unity suffices for labor taxation to stimulate labor supply. Within the framework of the present paper we derive similar results. In Appendix 2 we show that, assuming separability between the choices of leisure and the consumption goods, the response of labor supply to an increase in the labour tax is positive if the household's relative risk aversion parameter exceeds unity, and the after tax income elasticity for good D is low. In such cases, that is when $\frac{\partial(T-l^*)}{\partial\tau_L} > 0$, an increase in τ_L unambiguously yields a marginal welfare benefit, i.e. $\rho_2 < 0$.

Therefore, in the presence of uncertainty, $\rho_1 < 0$, while $\rho_2 \gtrless 0$ if $\frac{\partial(T-l^*)}{\partial\tau_L} \lessgtr 0$. A sufficient condition for $\rho = \rho_1 + \rho_2 < 0$ is that $\frac{\partial(T-l^*)}{\partial\tau_L} > 0$ and the necessary condition is that $\left|\frac{cov[U_C,w](T-l^*)}{E(U_C)}\right| > \left|\tau_L\frac{\partial(T-l^*)}{\partial\tau_L}\right|$.

Note that under uncertainty, $1 + \rho = \frac{(T-l^*)-\Omega+\frac{cov[U_C,w](T-l^*)}{E(U_C)}}{(T-l^*)-\Omega+\tau_L\frac{\partial(T-l^*)}{\partial\tau_L}}$ equals the

13

marginal cost of public funds (MCPF). Under certainty, in the absence of externalities ($\tau_D^* = 0$), and assuming that lump sum taxes are available, revenue raised for public good provision does not require distortionary taxation ($\tau_L = 0$). In such case, the MCPF equals unity. In case that labor income taxation is used ($\tau_L > 0$) and assuming $\frac{\partial(T-l^*)}{\partial\tau_L} < 0$, then $MCPF > 1$. This result is supported by a large body of literature in public finance.[27]

While the main body of the literature assumes that labour income taxes are completely distortionary, some authors have incorporated into the analysis a measure of the distributional gains from labour income taxation.[28] Sandmo (1998) argued that the MCPF should not only reflect the efficiency losses of taxes due to the distortions they inflict on markets but also the distributional gains obtained. Sandmo showed, in a model with heterogeneous agents, that if the distributional gains are taken into account, the MCPF figure could be less than unity.

In a similar manner, the present paper shows that, in the presence of uncertainty, if the gains from providing insurance are considered, MCPF could also be less than unity. The sufficient and necessary conditions for $MCPF < 1$ are the same as those yielding $\rho < 0$.

The above discussion regarding the value of ρ has important implications on both the revenue recycling and the tax interaction effects as it is evident from equation (9). If $\rho < 0$ then, contrary to the case of certainty, the revenue recycling effect is negative (third term in equation (9)). However, the overall increase in revenue exceeds the marginal welfare benefit implying that $-1 < \rho < 0$ and $(1 + \rho) > 0$. Furthermore, since the pollution tax also acts as an insurance device, labor supply might be also stimulated from the increase in the environmental tax, in which case the tax interaction term alternates in sign relative to the case of certainty.[29] Finally, the increase in the pollution tax generates a reduction in consumption risk and hence an additional positive welfare effect as we noted in discussing equation (8). This welfare effect is captured by the second term in equation (9). The covariance term $cov\left[U_C, \left(D^* - \overline{D}\right)\right]$ under risk aversion is negative and thus, welfare increases as a result of increased environmental taxation.[30]

The extent to which a second dividend is realized under uncertainty, depends on the relative magnitude of the three effects we examined above. We now proceed to compare these effects. Substituting $\rho = \rho_1 + \rho_2$ and using the

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[27] Ballard and Fullerton (1992) offers a comprehensive review of the literature. See also Hausman (1985) on the empirical evidence of taxation and labour supply.

[28] See for example Wilson (1991), Dalby (1998) and Sandmo (1998).

[29] See Appendix 2 for the conditions under which this possibility arises.

[30] Risk aversion implies $U_{CC} < 0$. Thus, as D^* increases due to a positive state of nature so does C^* assuming normal goods and as a result U_C falls.

value of the total induced change in τ_L from equation (7), the sum of the tax interaction and revenue raising effects (the last two terms in equation (9)) can be written:

$$-\frac{cov\left[U_C,w\right]\left(T-l^*\right)}{E(U_C)}\frac{d\tau_L}{d\tau_D}+\rho_2[\overline{D}+\tau_D\frac{d\overline{D}}{d\tau_D}]+[1+\rho_2]\,\tau_L\frac{\partial(T-l^*)}{\partial\tau_D}. \quad (11)$$

The first term shows the decrease in insurance benefits arising from the labour income tax reduction. Since the variability of the consumption of the dirty good arises from the variability of the wage rate, the two covariance terms can be connected more closely. In order to get more insight into the covariance effects (first term in equation (11) and second term in equation (9)), assume that the consumption of the dirty good is a linear function of the individual's income level, namely: $D_i^* = \beta[w_i(T-l^*)-\Omega]$, where β is the marginal propensity to consume the dirty good out of gross labour income.[31] Then,

$$-\frac{cov\left[U_C,D^*\right]}{E(U_C)}-\frac{cov\left[U_C,w\right]\left(T-l^*\right)}{E(U_C)}\frac{d\tau_L}{d\tau_D}=-\frac{cov\left[U_C,w\right]\left(T-l^*\right)}{E(U_C)}\left(\beta+\frac{d\tau_L}{d\tau_D}\right).$$
$$(12)$$

The two covariance terms capture the social insurance effects resulting from the green tax reform under uncertainty, except from the effect on $\frac{\partial(T-l^*)}{\partial\tau_L}$. Therefore, these social insurance effects are positive if the propensity to consume the dirty good out of gross labour income is greater than the balance budget reduction in the labour tax arising from a marginal increase in the Pigouvian tax, that is, iff $\beta > \left|\frac{d\tau_L}{d\tau_D}\right|$.

As shown in appendix 3, we can express the term $\beta + \frac{d\tau_L}{d\tau_D}$ in elasticity form,

$$\left(\beta+\frac{d\tau_L}{d\tau_D}\right)=\frac{\frac{\tau_L}{(1-\tau_L)}\overline{D}\left[\epsilon^c_{\overline{D},(1-\tau_L)}-s_{\overline{D}}\,\epsilon^c_{\overline{D},(1-\tau_L)}-s_{\overline{C}}\,\epsilon^c_{\overline{C},(1-\tau_L)}\right]-\tau_D\frac{d\overline{D}}{d\tau_D}}{(T-l^*)-\Omega+\tau_L\frac{\partial(T-l^*)}{\partial\tau_L}},$$
$$(13)$$

where, $\epsilon^c_{\overline{D}(1-\tau_L)}$ is the compensated elasticity of demand for the dirty good with respect to the price of leisure, $\epsilon^c_{\overline{C},(1-\tau_L)}$ is similarly the elasticity of demand for the clean good with respect to the price of leisure. Furthermore, $s_{\overline{D}}=\frac{\overline{D}}{[(T-l^*)-\Omega]}$ and $s_{\overline{C}}=\frac{\overline{C}}{[(T-l^*)-\Omega]}$ are the shares of the dirty and clean good respectively in income including lump-sum transfers. given that $\frac{d\overline{D}}{d\tau_D}<0$,

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[31] This is a reasonable assumption since most standard type of utility functions yield linear relationships with income. Also β would depend on the value of the labour tax and the Pigouvian tax.

a sufficient condition for the social insurance effect to be positive is that $\epsilon^c_{\overline{D},(1-\tau_L)} \geq \left[\frac{\overline{C}}{\overline{C}+\overline{G}-\Omega}\right]\epsilon^c_{\overline{C},(1-\tau_L)}$.[32] If $\overline{G} > \Omega$, that is if the public good is not financed entirely by lump-sum taxes, the social insurance effect is unambiguously positive if D is not a very weak substitute for leisure relative to C. In such cases, the social insurance effect from increased τ_D dominates the decrease in social insurance provision due to the balanced budget reduction in τ_L. If D is a sufficiently weak substitute for leisure, the social insurance effect could be negative depending on the magnitude of $\frac{d\overline{D}}{d\tau_D}$.

The last two terms in equation (11), $\rho_2[\overline{D} + \tau_D\frac{d\overline{D}}{d\tau_D}] + [1+\rho_2]\tau_L\frac{\partial(T-l^*)}{\partial\tau_D}$, present the sum of the tax interaction and revenue raising effects as in the case of certainty. Following similar steps as in Goulder et al (1997) we can write the tax interaction effect as,

$$[1+\rho_2]\tau_L\frac{\partial(T-l^*)}{\partial\tau_D} = -\overline{D}\rho_2\phi_D, \tag{14}$$

where,

$$\phi_D = \phi_D = \frac{\epsilon^c_{\overline{D},1-\tau_L} - \frac{T-l^*}{\Omega}\epsilon_{T-l^*\Omega}}{\left[s_{\overline{D}}\epsilon^c_{\overline{D},1-\tau_L} + s_{\overline{C}}\epsilon^c_{\overline{C},1-\tau_L} - \frac{T-l^*}{\Omega}\epsilon_{T-l^*\Omega}\right]}., \tag{15}$$

".... is a measure of the degree of substitutability between the dirty good and leisure relative to to that between aggregate consumption and leisure." (Goulder et al (1997), p. 713). Substituting expressions (11), (12), (13), (14) and (15) into equation (9) yields,

$$\frac{1}{E(U_C)}\frac{dE(W)}{d\tau_D} = \underbrace{(\tau_D - \mu_D)\frac{d\overline{D}}{d\tau_D}}_{P} - \underbrace{\frac{cov\left[U_C,w\right](T-l^*)}{E(U_C)}\left(\beta + \frac{d\tau_L}{d\tau_D}\right)}_{SI} +$$

$$\underbrace{(1-\phi_D)\rho_2\overline{D} + \rho_2\tau_D\frac{d\overline{D}}{d\tau_D}}_{RR+TI}.$$

For $\epsilon^c_{\overline{D},(1-\tau_L)} > \left[\frac{\overline{C}}{\overline{C}+\overline{G}-\Omega}\right]\epsilon^c_{\overline{C},(1-\tau_L)}$, from equations (13) and (15) we have $\beta+\frac{d\tau_L}{d\tau_D} > 0$ and $\phi_D > 1$. Therefore, if D is not substantially weaker substitute for leisure relative to C, the social insurance effect is positive $SI > 0$ and the

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[32]To derive this condition, substitute the values of $s_{\overline{D}}$ and $s_{\overline{C}}$ into the first term in the numerator of (13) and use the expected resource constraint $\overline{D}^* + \overline{C}^* + \overline{G} = T - l^*$. In the first best world where the public good is financed entirely by lump-sum taxes $(\overline{G} = \Omega)$ the condition holds as an equality $\epsilon^c_{\overline{D},(1-\tau_L)} = \epsilon^c_{\overline{C},(1-\tau_L)}$.

sum of the revenue recycling and tax interaction effects is negative ($RR + TI < 0$) assuming $\rho_2 > 0$, while it is positive ($RR + TI > 0$) assuming $\rho_2 < 0$.

If $\epsilon^c_{D,(1-\tau_L)} = \left[\frac{\overline{C}}{\overline{C}+\overline{G}-\Omega}\right]\epsilon^c_{C,(1-\tau_L)}$, then $\beta + \frac{d\tau_L}{d\tau_D} = 0$ and $\phi_D = 1$. In this case and assuming we start with $\tau_D > 0$, then the social insurance effect is positive (SI>0), while the sum of the revenue recycling and tax interaction effects is negative ($RR + TI < 0$) assuming $\rho_2 > 0$, while it is positive ($RR + TI > 0$) assuming $\rho_2 < 0$. Therefore, if $\rho_2 < 0$ there is a second dividend, while if $\rho_2 > 0$ the existence of a second dividend requires $\left|\frac{cov[U_C,w](T-l^*)}{E(U_C)}\right| > \left|\frac{\partial(T-l^*)}{\partial\tau_L}\right|$. Assuming $\tau_D = 0$, the Pigouvian is the only welfare effect of the green tax reform since $RR + TI = SI = 0$.

For $\epsilon^c_{D,(1-\tau_L)} < \left[\frac{\overline{C}}{\overline{C}+\overline{G}-\Omega}\right]\epsilon^c_{C,(1-\tau_L)}$, we have $\beta + \frac{d\tau_L}{d\tau_D} < 0$ and $\phi_D < 1$. When D is "sufficiently" weak substitute for leisure and $\tau_D = 0$, the social insurance effect is negative, $SI < 0$ and the sum of the revenue recycling and tax interaction effects is positive ($RR + TI > 0$) assuming $\rho_2 > 0$, while it is negative ($RR + TI < 0$) assuming $\rho_2 < 0$. For $\tau_D > 0$ but relatively small, the signs of the three effects remain the same as long as the direct dominates the indirect effect in the numerator of equation (13) and in the $RR + TI$ term.

MCPF-1	SI effect	RR+IT effect	Total effect
Case 1: Welfare effect if $\epsilon^c_{D,(1-\tau_L)} >$		$\left\|\frac{\overline{C}}{\overline{C}+\overline{G}-\Omega}\right\|$	$\epsilon^c_{C,(1-\tau_L)}$
$\rho_2 < 0$	$+$	$+$	positive
$\rho_2 > 0$	$+$	$-$	ambiguous
Case 2: Welfare effect if $\epsilon^c_{D,(1-\tau_L)} =$		$\left\|\frac{\overline{C}}{\overline{C}+\overline{G}-\Omega}\right\|$	$\epsilon^c_{C,(1-\tau_L)}$ and $\tau_D = 0$
$\rho_2 < 0$	*nil*	*nil*	does not exist
$\rho_2 > 0$	*nil*	*nil*	does not exist
Case 3: Welfare effect if $\epsilon^c_{D,(1-\tau_L)} =$		$\left\|\frac{\overline{C}}{\overline{C}+\overline{G}-\Omega}\right\|$	$\epsilon^c_{C,(1-\tau_L)}$ and $\tau_D > 0$
$\rho_2 < 0$	$+$	$+$	positive
$\rho_2 > 0$	$+$	$-$	ambiguous
Case 4: Welfare effect if $\epsilon^c_{D,(1-\tau_L)} <$		$\left\|\frac{\overline{C}}{\overline{C}+\overline{G}-\Omega}\right\|$	$\epsilon^c_{C,(1-\tau_L)}$ [33]
$\rho_2 < 0$	$-$	$-$	negative
$\rho_2 > 0$	$-$	$+$	ambiguous

Table 1. Total welfare effect under different assumptions about the relative substitutability of the two goods for leisure.

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[33] Assuming that in the case $\tau_D > 0$, the direct dominates the indirect effect.

Table 1 below summarizes the above discussion. In summing up, we find that, in general, the social insurance effect is positive and moves in the same direction as the sum of the revenue recycling and tax interaction effects if $\rho_2 < 0$ and D is a relatively strong (or equal) substitute for leisure yielding a second dividend. If $\rho_2 > 0$ and and D is a relatively strong (or equal) substitute of leisure there is a "gross cost" in terms of $RR + TI$ but this can be offset by the opposing social insurance effect. The only case in which there is a "gross cost" including the social insurance effect is the case that D is a sufficiently weak substitute and $\rho_2 < 0$. These results differ substantially from the case of certainty. The critical parameters determining the existence of a second dividend are the lump sum transfers, the relative substitutability of the two goods for leisure and the initial tax rates relative to their optimal values that determine also the response of labour supply to a change in the tax mix. In the next section we undertake the task of deriving the optimal tax rates.

5   Optimal Taxation

In the previous Section we show that, starting from some positive values of τ_L and τ_D, the welfare effect of a revenue recycling policy depends on the magnitude of the departure of the initial values of taxes from their optimal. The optimal taxes are determined ex ante, that is, before uncertainty is resolved. Due to the presence of two types of distortions (uncertainty and environmental externality) we analyze optimal taxation within a second best framework.

Recall that, within the framework of our model, the government has three functions, namely to provide the public good, protect the environment, and provide insurance against wage uncertainty. The government has three instruments: labor income tax, environmental tax and lump sum transfers in order to achieve the above three goals. Thus, the government chooses τ_L, τ_D and Ω to maximize the household's indirect expected utility subject to the revenue constraint. The Lagrangian corresponding to the government's constrained maximization problem is,

$$\max_{\tau_L, \tau_D, \Omega} L = E(W(\tau_D, \tau_L, \Omega)) + \lambda \left[\Omega + \tau_L \left[(T - l^*) - \Omega \right] + \tau_D \overline{D} - \overline{G} \right] .$$

Assuming an interior solution, the first order conditions yield,[34]

$$X \frac{\partial \overline{D}}{\partial \tau_D}_{v=c} + \tau_L \Psi \frac{\partial (T - l^*)}{\partial \tau_D}_{v=c} = \frac{cov(U_C, D^*)}{(1 - \tau_L) E(U_C)} \frac{\partial \overline{R}}{\partial \Omega}, \qquad (16)$$

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[34]For some details leading to these conditions, see Appendix 4.

$$X \frac{\partial \overline{D}}{\partial \tau_L}_{v=c} + \tau_L \Psi \frac{\partial (T - l^*)}{\partial \tau_L}_{v=c} = \frac{cov(U_C, w)(T - l^*)}{(1 - \tau_L)E(U_C)} \frac{\partial \overline{R}}{\partial \Omega} , \qquad (17)$$

where, $X = \left[\tau_D - \mu_D \left[1 + \frac{\tau_L}{(1-\tau_L)} \frac{\partial (T - l^*)}{\partial \Omega} \right] \right]$, and $\Psi = 1 + \frac{\mu_D}{(1-\tau_L)} \frac{\partial \overline{D}}{\partial \Omega} > 0.$[35] $\overline{R}$ is defined as the average tax revenue per person, and the subscript $v = c$ indicates compensated changes.

Using the above conditions we can determine government's optimal choices. As a benchmark case, we first consider the case of certainty. In this case, and assuming that government has access to lump sum taxes /transfers, the environmental externality is optimally internalized by a Pigouvian tax. The revenues from the Pigouvian tax together with the lump sum taxes support the provision of the public good. That is, the optimal tax structure is $\tau_D^* = \mu_D$, $\tau_L^* = 0$ and $\tau_D \overline{D} + \Omega^* = \overline{G}$. [36,37]

We now return to the case of uncertainty over labour income. In this case it is optimal to set both labour income and environmental taxes positive, that is, $\tau_D^* > 0$ and $\tau_L^* > 0$, while raising any additional revenue from lump sum taxes. Because of the existence of environmental externalities, the optimal environmental tax is positive,[38] and exceeds the marginal external damage, since the environmental tax is also part of the social insurance mechanism. Sandmo (1998) has shown that $MCPF = \frac{1}{\left[1 + \frac{\tau_L}{(1-\tau_L)} \frac{\partial (T - l^*)}{\partial \Omega} \right]} < 1$, in an optimal setting. This is also true in the current setting since the MCPF does not reflect only the efficiency loss but it accounts also for the social insurance gain. As shown in the previous section, MCPF<1. Thus, when public investment is financed on the margin by uniform lump sum taxes it causes labor supply

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[35] Following Ng (1980) we make the assumption that $\Psi > 0$. Ng (1980) notes that, "...Ψ is positive (though less than one) .... unless the externality is so strong that an increase in income actually makes the community worse off." (p. 747).

[36] Setting $\tau_D^* > \mu_D$ and $\tau_L^* = 0$ cannot satisfy the above conditions since the left hand side of the first optimal condition is negative at these values. Furthermore, setting $\tau_D^* = 0$ and $\tau_L^* = 0$ and raising all funds from lump sum taxation cannot satisfy the above conditions since the left hand side of the first two conditions becomes non-zero at these values. If we set $0 < \tau_D^* < \mu_D$ and $\tau_L^* > 0$ then both conditions cannot be satisfied simultaneously since $X < 0$ for all $\tau_D^* < \mu_D$.

[37] Note that the double dividend literature was built under the assumption of no lump sum taxation. In such a case, Bovenberg and De-Mooij (1994) and (1996) argued that $\tau_D < \mu_D$ because the marginal cost of public funds is greater than unity. However, as correctly pointed out by Fullerton (1997) this result stems from the arbitrary normalization of the clean good's price to unity.

[38] In the absense of externalities, equations (11) and (12) yield $\tau_D^* = 0$ and $\tau_L^* > 0$. The optimal value of τ_L^* is given by (12) where $X = 0$ and $\Psi = 1$. In this case, labour income taxation –which is equivalent to a uniform commodity tax on both goods– is set optimally such as to provide social insurance. The remaining required revenues are raised by lump sum taxes.

to increase. This increase in labor effort creates an efficiency gain in terms of increased revenue to finance public goods given the existence of an optimal wage tax. See Sandmo (1998) for a similar analysis. Unfortunately, it is not possible to derive analytical solution for the optimal tax rates.

After determining the optimal tax rates, the government should compare the existing tax rates to their optimal values before it decides wether and to what extent a revenue neutral policy should be implemented. If the initial tax rates are such that the labor income tax is below its optimal level, while the environmental tax is equal to its optimal level, a green tax reform policy will result in welfare losses. On the contrary, if the environmental tax is below its optimal value and the labour income tax exceeds its optimal value, a case which is more possible in reality, a green tax reform will improve welfare.

6   Conclusions

The present paper re-examines the double dividend hypothesis in the presence of labour income uncertainty. We find that starting from some positive level of environmental and labor income taxation and increasing the former while decreasing the latter within a revenue neutral policy has the following effects: First, the increase in environmental taxation yields a positive welfare effect since it reduces consumption risk, in addition to the Pigouvian effect. Second, the reduction in labor income taxation weakens social insurance provision, while in the same time alleviates some of the distortions in the labour market. The net effect depends on the relative substitutability of the dirty and clean good for leisure. If D is (not) a sufficiently weak substitute for leisure relative to C the net effect is negative (positive). Third, the reduction of labor income taxation increases risk and in doing so it affects the response of labour supply which could even become positive. Thus, the reduction in labour income tax could yield a marginal welfare benefit, reversing the signs of the revenue recycling and tax interaction effects. The total welfare effect of the green tax reform is ambiguous and depends on the relative substitutability of the dirty and clean good for leisure and the response of labour supply to a change in the tax mix. This, in turn, depends on the departure of the initial taxes from their second best optimum. We determine that the optimal value of both environmental and labor taxation is positive. If the initial level of the labour income tax is above its optimum, that is, there is overprovision of social insurance, and the environmental tax below its optimum, then a revenue recycling policy will yield a positive welfare effect. However, a revenue recycling policy will result in welfare losses if the initial level of labor tax is below its optimum, that is, there is underprovision of

20

social insurance, while the environmental tax is close or above its optimum. The lower is labour income tax relative to its optimum, and the closer is the environmental tax to its optimum, the larger the welfare losses will be, assuming the availability of lump-sum taxes.

The analysis of the present paper could be extended in different directions. Given the ambiguity of the total welfare effect in a number of instances, it would be interesting to use empirical simulations to determine the sign and the size of the total effect under plausible parameter values. The literature under certainty shows that grandfathered emission permits policies yield lower welfare since they do not generate a revenue recycling effect. It would be interesting to check this result in the case of uncertainty. Finally, as mentioned in the Introduction, recent empirical literature shows that it could be possible that higher uncertainty over income induces employees to work longer hours for self-insurance purposes (Low (2005), Parker et al. (2005) and Floden (2006)). This longer work hours comes at the expense of lower average wages. In this case, taxation can be seen as a substitute to self-insurance. Extending our analysis to this direction might provide some interesting intuition.

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8 Appendices

8.1 Appendix 1: Calculations leading to equation (9):

The government chooses τ_L, τ_D and Ω to maximize the household's indirect utility subject to the revenue constraint. That is, the government's problem is to maximize,

$$E(W(\tau_D, \tau_L, \Omega)) = E(U(D^*, C^*, l^*)) + V(\Pi(n\overline{D}), n\overline{G}) \ ,$$

subject to the government constraint: $\tau_D \overline{D} + \tau_L \overline{w}(T - l^*) + (1 - \tau_L)\Omega = \overline{G}$.

The Lagrangian corresponding to the above problem is:

$$L = E(W(\tau_D, \tau_L, \Omega)) + \lambda \left[(1 - \tau_L)\Omega + \tau_L(T - l^*) + \tau_D \overline{D} - \overline{G} \right] \ .$$

The first order conditions are:

$$\frac{\partial L}{\partial \tau_D} = \frac{\partial E(W(\tau_D, \tau_L, \Omega))}{\partial \tau_D} + \lambda \left[\overline{D} + \tau_D \frac{\partial \overline{D}}{\partial \tau_D} + \tau_L \frac{\partial(T - l^*)}{\partial \tau_D} \right] = 0 \ ,$$

$$\frac{\partial L}{\partial \tau_L} = \frac{\partial E(W(\tau_D, \tau_L, \Omega))}{\partial \tau_L} + \lambda \left[\overline{w}(T - l^*) - \Omega + \tau_L \frac{\partial(T - l^*)}{\partial \tau_L} + \tau_D \frac{\partial \overline{D}}{\partial \tau_L} \right] = 0 \ ,$$

$$\frac{\partial L}{\partial \Omega} = \frac{\partial E(W(\tau_D, \tau_L, \Omega))}{\partial \Omega} + \lambda \left[1 - \tau_L + \tau_L \frac{\partial(T - l^*)}{\partial \Omega} + \tau_D \frac{\partial \overline{D}}{\partial \Omega} \right] = 0 \ ,$$

and

$$\frac{\partial L}{\partial \lambda} = \left[(1 - \tau_L)\Omega + \tau_L(T - l^*) + \tau_D \overline{D} - \overline{G} \right] = 0 \ .$$

Solving the above four equations will yield τ_D^*, τ_L^* and Ω^* and λ^*.

Partially differentiating the indirect utility with respect to the environmental tax yields,

$$\frac{\partial E(W)}{\partial \tau_D} = E \left[U_D \frac{\partial D^*}{\partial \tau_D} + U_C \frac{\partial C^*}{\partial \tau_D} + U_l \frac{\partial l^*}{\partial \tau_D} \right] + nV' \Pi_D \frac{\partial \overline{D}}{\partial \tau_D} \ .$$

From the combined constraint we get,

$$\frac{\partial C^*}{\partial \tau_D} = (1 - \tau_L)w \frac{\partial(T - l^*)}{\partial \tau_D} + \tau_L \frac{\partial(T - l^*)}{\partial \tau_D} + \tau_D \frac{\partial \overline{D}}{\partial \tau_D} - (D^* - \overline{D}) - (1 + \tau_D) \frac{\partial D^*}{\partial \tau_D} \ .$$

Substituting into the indirect utility and utilizing the first order conditions yields,

$$\frac{\partial E(W)}{\partial \tau_D} = -E \left[U_C \left[(D^* - \overline{D}) - \tau_L \frac{\partial(T - l^*)}{\partial \tau_D} - \tau_D \frac{\partial \overline{D}}{\partial \tau_D} \right] \right] + nV' \Pi_D \frac{\partial \overline{D}}{\partial \tau_D} \ ,$$

which can be written as follows,

$$\frac{1}{E(U_C)}\frac{\partial E(W)}{\partial \tau_D} = (\tau_D - \mu_D)\frac{\partial \overline{D}}{\partial \tau_D} - \frac{cov(U_C, (D^* - \overline{D}))}{E(U_C)} + \tau_L\frac{\partial (T - l^*)}{\partial \tau_D} \ ,$$

where $\mu_D = \frac{-nV'\Pi_D}{E(U_C)}$ is defined as the marginal external damage under uncertainty.

Partially differentiating the indirect utility with respect to the labour tax yields,

$$\frac{1}{E(U_C)}\frac{\partial E(W)}{\partial \tau_L} = (\tau_D - \mu_D)\frac{\partial \overline{D}}{\partial \tau_L} - \frac{cov(U_C(w - \overline{w}))(T - l^*)}{E(U_C)} + \tau_L\frac{\partial (T - l^*)}{\partial \tau_L} \ .$$

Partially differentiating the indirect utility with respect to the lump sum taxes yields,

$$\frac{1}{E(U_C)}\frac{\partial E(W)}{\partial \Omega} = (\tau_D - \mu_D)\frac{\partial \overline{D}}{\partial \Omega} + \tau_L\frac{\partial (T - l^*)}{\partial \Omega} \ .$$

Totally differentiating the expected utility with respect to the environmental tax we get,

$$\frac{dE(W)}{d\tau_D} = \frac{\partial E(W)}{\partial \tau_D} + \frac{\partial E(W)}{\partial \tau_L}\frac{d\tau_L}{d\tau_D} \ .$$

Substituting from the above derived values of $\frac{\partial E(W)}{\partial \tau_D}$, $\frac{\partial E(W)}{\partial \tau_L}$, and $\frac{d\tau_L}{d\tau_D}$ from equation (7) into $\frac{dE(W)}{d\tau_D}$ yields, after simple manipulations,

$$\frac{1}{E(U_C)}\frac{dE(W)}{d\tau_D} = (\tau_D - \mu_D)\frac{\partial \overline{D}}{\partial \tau_D} - \frac{cov\left[U_C, (D^* - \overline{D})\right]}{E(U_C)} +$$
$$\rho[\overline{D} + \tau_D\frac{\partial \overline{D}}{\partial \tau_D}] + [1 + \rho]\,\tau_L\frac{\partial (T - l^*)}{\partial \tau_D} \ ,$$

If we substitute $\frac{d\overline{D}}{d\tau_D} = \frac{\partial \overline{D}}{\partial \tau_D} + \frac{\partial \overline{D}}{\partial \tau_L}\frac{d\tau_L}{d\tau_D}$ in the above and we collect terms accordingly we get equation (9) and the definition of ρ in equation (10).

8.2 Appendix 2: Determination of $\frac{\partial (T-l^*)}{\partial \tau_L}$ and $\frac{\partial (T-l^*)}{\partial \tau_D}$ signs:

We can determine the effect of an increase in τ_L on labor supply by differentiating the first order condition of the labour supply determination (ex-ante) problem, equation (4) in the main text,

$$E\left[U_C(C, D, l)(1 - \tau_L)w\right] = E(U_l(C, D, l)) \ .$$

From the budget constraint we have that, $C = M - (1 + \tau_D)D$, where M denotes the after tax income, $M = (1 - \tau_L)[w(T - l^*) - \Omega]$. Assuming separability between the choices of leisure and the consumption goods, the optimal values of the choice variables are $D^* = D(\tau_D, M)$, $C^* = C(\tau_D, M)$, and $l^* = l(\tau_D, \tau_L, \Omega)$. The separability assumption reduces the first order condition to $E[U_C(C)(1 - \tau_L)w] = E(U_l(l))$, which after substituting the budget constraint and the optimal values of the choice variables yields,

$$E[U_C[(1 - \tau_L)[w(T - l^*) - \Omega] - (1 + \tau_D)D^*](1 - \tau_L)w] = E(U_l(l^*)) .$$

Differentiating the above first order condition with respect to the labor tax yields,

$$-E(U_C w) + (1 - \tau_L)E\left[U_{CC}\frac{\partial C}{\partial \tau_L}w\right] + E(U_{ll})\frac{\partial(T - l^*)}{\partial \tau_L} = 0 .$$

Differentiating the budget constraint $C = M - (1 + \tau_D)D(\tau_D, M)$, with respect to the labour tax yields,

$$\frac{\partial C}{\partial \tau_L} = \frac{\partial M}{\partial \tau_L} - (1 + \tau_D)\frac{\partial D}{\partial M}\frac{\partial M}{\partial \tau_L} =$$
$$\left[1 - \frac{(1 + \tau_D)D}{M}\eta\right]\left[-[w(T - l^*) - \Omega] + (1 - \tau_L)w\frac{\partial(T - l^*)}{\partial \tau_L}\right] ,$$

where η is the after tax income elasticity of good D. Substituting the above into the first order condition yields,

$$\left[E(U_{ll}) + (1 - \tau_L)^2E\left[\left[1 - \frac{(1 + \tau_D)D}{M}\eta\right]U_{CC}w^2\right]\right]\frac{\partial(T - l^*)}{\partial \tau_L}$$
$$= E[U_C w] + E\left[U_{CC}w\left[1 - \frac{(1 + \tau_D)D}{M}n\right](1 - \tau_L)[w(T - l^*) - \Omega]\right] ,$$

which reduces to,

$$\frac{\partial(T - l^*)}{\partial \tau_L} = \frac{E\left[U_C w\left[1 - \left[1 + \frac{(1 + \tau_D)D}{C}(1 - \eta)\right]R\right]\right]}{\Delta} ,$$

where $\Delta = \left[E(U_{ll}) + (1 - \tau_L)^2E\left[\left[1 - \frac{(1 + \tau_D)D}{M}\eta\right]U_{CC}w^2\right]\right] < 0$, and $R = -\frac{U_{CC}}{U_C}C$ is the relative risk aversion. The response of labor supply to an increase in the labour tax is positive, if $R > \frac{C}{C + (1 + \tau_D)D(1 - \eta)}$. This condition holds assuming the risk aversion parameter is greater than unity and the after tax income elasticity for good D is low (that is, $\eta \leq 1$).

In the case that the after tax income elasticity of the demand for good D is unity, that is, $\eta = 1$, the sign of the labour supply response to changes in τ_L depends only on the relative risk aversion, as in the case of one good (see Eaton and Rosen (1980a)). We can illustrate this case using a utility function of the form, $U_i = a_1 \frac{D_i^{1-\theta}}{(1-\theta)} + a_2 \frac{C_i^{1-\theta}}{(1-\theta)} + vl + V(\Pi(n\overline{D}), n\overline{G})$, for which $\eta = 1$. Following the same process as above, we derive, $\frac{\partial(T-l^*)}{\partial\tau_L} = (1-\theta)\frac{E[U_C w]}{\Delta} > 0$. Therefore, in this case $\frac{\partial(T-l^*)}{\partial\tau_L} > 0$ if $R = \theta > 1$.

We now turn to derive the response of labour supply to changes in the environmental tax. Differentiating the above first order condition with respect to τ_D yields,

$$E\left[U_{CC}\frac{\partial C}{\partial\tau_D}(1-\tau_L)w\right] + E(U_{ll}(\frac{\partial(T-l)}{\partial\tau_D})) = 0 .$$

Differentiating the budget constraint $C = M - (1 + \tau_D)D(\tau_D, M)$, with respect to the environmental tax yields,

$$\frac{\partial C}{\partial\tau_D} = \frac{\partial M}{\partial\tau_D} - D - (1+\tau_D)\left(\frac{\partial D}{\partial\tau_D} + \frac{\partial D}{\partial M}\frac{\partial M}{\partial\tau_D}\right) =$$
$$(1-\tau_L)w\frac{\partial(T-l^*)}{\partial\tau_D}\left(1 - (1+\tau_D)\frac{\partial D}{\partial M}\right) - D - (1+\tau_D)\frac{\partial D}{\partial\tau_D} .$$

Substituting the above into the first order condition and after simple manipulations yields,

$$\frac{\partial(T-l^*)}{\partial\tau_D} = -(1-\tau_L)\frac{E\left[U_C w R\frac{D}{C}\left(1 + \frac{(1+\tau_D)}{D}\frac{\partial D}{\partial\tau_D}\right)\right]}{\Delta} ,$$

where the first term within the expected value in the nominator is positive, while the second term is negative assuming that $\frac{\partial D}{\partial\tau_D} < 0$ for all states of nature. Thus, $\frac{\partial(T-l^*)}{\partial\tau_D} \lesseqgtr 0$ if the elasticity of the dirty good with respect to the price of the good is $\frac{(1+\tau_D)}{D}\frac{\partial D}{\partial(1+\tau_D)} \lesseqgtr -1$. In the example of constant relative risk aversion we used above, the response of labour supply to changed in τ_D is, $\frac{\partial(T-l^*)}{\partial\tau_D} = -(1-\tau_L)(\theta-1)\frac{E\left[U_C w\frac{D}{C}\right]}{\Delta}$. In this case, the sign of the response of labour supply to changes in the environmental tax depends solely on the value of R, since $\frac{\partial D}{\partial\tau_D} = -\frac{1}{\theta}\frac{D^*}{(1+\tau_D)}$ or the price elasticity of demand for the dirty good which is $\frac{(1+\tau_D)}{D}\frac{\partial D}{\partial\tau_D} = -\frac{1}{\theta} > -1$ if $\theta = R > 1$. Thus $\frac{\partial(T-l^*)}{\partial\tau_D} > 0$, that is the insurance role of environmental taxation has a positive effect on labour supply when individuals have a moderate relative risk aversion parameter.

8.3 Appendix 3. Derivation of $(\beta + \frac{d\tau_L}{d\tau_D})$ and ϕ_D

Substituting the following Slutsky equations,

$$\frac{\partial(T-l^*)}{\partial\tau_D} = \frac{\partial(T-l^*)}{\partial\tau_D}\Big|_{v=c} + \frac{\overline{D}}{(1-\tau_L)}\frac{\partial(T-l^*)}{\partial\Omega} = \frac{\partial\overline{D}}{\partial\tau_L}\Big|_{v=c} + \frac{\overline{D}}{(1-\tau_L)}\frac{\partial(T-l^*)}{\partial\Omega} ,$$

and

$$\frac{\partial(T-l^*)}{\partial\tau_L} = \frac{\partial(T-l^*)}{\partial\tau_L}\Big|_{v=c} + \frac{[(T-l^*)-\Omega]}{(1-\tau_L)}\frac{\partial(T-l^*)}{\partial\Omega} ,$$

into the expression $(\beta + \frac{d\tau_L}{d\tau_D})$, and using the the expression for $\frac{d\tau_L}{d\tau_D}$ from equation (7), yields,

$$\left[\beta + \frac{d\tau_L}{d\tau_D}\right] = \frac{\beta\tau_L\frac{\partial(T-l^*)}{\partial\tau_L}\big|_{v=c} - \tau_L\frac{\partial\overline{D}}{\partial\tau_L}\big|_{v=c} - \tau_D\frac{d\overline{D}}{d\tau_D}}{(T-l^*)-\Omega+\tau_L\frac{\partial(T-l^*)}{\partial\tau_L}} . \qquad ((A3.1))$$

Expressing the first two terms on the numerator of (A3.1) in elasticity form, yields,

$$\left[\beta + \frac{d\tau_L}{d\tau_D}\right] = \frac{\frac{\tau_L\overline{D}}{(1-\tau_L)}\left[\epsilon_{\overline{D},1-\tau_L} - \frac{T-l^*}{T-l^*-\Omega}\epsilon^c_{T-l^*,1-\tau_L}\right] - \tau_D\frac{d\overline{D}}{d\tau_D}}{(T-l^*)-\Omega+\tau_L\frac{\partial(T-l^*)}{\partial\tau_L}} , \qquad ((A3.2))$$

where, $\epsilon^c_{\overline{D},\tau_L} = \frac{(1-\tau_L)}{\overline{D}}\frac{\partial\overline{D}}{\partial(1-\tau_L)}\big|_{v=c}$ is the compensated elasticity of demand for the dirty good with respect to the price of leisure $(1-\tau_L)$ and is positive if the dirty good and leisure are substitutes. Similarly $\epsilon^c_{T-l^*,1-\tau_L} = \frac{(1-\tau_L)}{(T-l^*)}\frac{\partial(T-l^*)}{\partial(1-\tau_L)}\big|_{v=c} > 0$ is the compensated price elasticity of the individual's labour supply with respect to the price of leisure.

Differentiating the expected resource constraint: $\overline{D}+\overline{C}+\overline{G} = (T-l^*)$ with respect the labour taxation while holding utility constant we get:

$$\frac{\partial(T-l^*)}{\partial\tau_L}\Big|_{v=c} = \frac{\partial\overline{D}}{\partial\tau_L}\Big|_{v=c} + \frac{\partial\overline{C}}{\partial\tau_L}\Big|_{v=c} . \qquad ((A3.3))$$

Multiplying through by $(1-\tau_L)$ and expressing these in elasticity form yields,

$$\epsilon^c_{T-l^*,\tau_L} = \frac{\overline{D}}{T-l^*}\epsilon^c_{\overline{D}\tau_L} + \frac{\overline{C}}{T-l^*}\epsilon^c_{\overline{C}\tau_L} . \qquad ((A3.4))$$

Substituting this into the expression $\beta + \frac{d\tau_L}{d\tau_D}$ in equation (A3.2), yields equation (15) in the main body of the paper.

In a similar way we can express in elasticity form the tax interaction effect, as defined in equation (9), $TI = (1 + \rho_2)\tau_L \frac{\partial(T-l^*)}{\partial\tau_D}$. Simple manipulations of the definition of ρ_2 yield,

$$(1 + \rho_2)\,\tau_L = -\frac{\rho_2\left[(T - l^*) - \Omega\right]}{\frac{\partial(T-l^*)}{\partial\tau_L}}.$$

Substituting this into the definition of the tax interaction effect yields,

$$TI = -\rho_2\left[(T - l^*) - \Omega\right]\frac{\frac{\partial(T-l^*)}{\partial\tau_D}}{\frac{\partial(T-l^*)}{\partial\tau_L}}\ ,$$

Utilizing the Slutsky equations from above yields,

$$TI = -\rho_2\left[(T - l^*) - \Omega\right]\frac{\left[\frac{\partial\overline{D}}{\partial\tau_L}\Big|_{v=c} + \frac{\overline{D}}{(1-\tau_L)}\frac{\partial(T-l^*)}{\partial\Omega}\right]}{\left[\frac{\partial(T-l^*)}{\partial\tau_L}\Big|_{v=c} + \frac{[(T-l^*)-\Omega]}{(1-\tau_L)}\frac{\partial(T-l^*)}{\partial\Omega}\right]}.$$

The above expression can be written in elasticity format:

$$TI = -\rho_2\overline{D}\frac{\left[\epsilon^c_{D,1-\tau_L} - \frac{T-l^*}{\Omega}\epsilon_{T-l^*,\Omega}\right]}{\left[\frac{(T-l^*)}{[(T-l^*)-\Omega]}\epsilon^c_{T-l^*,1-\tau_L} - \frac{T-l^*}{\Omega}\epsilon_{T-l^*,\Omega}\right]}.$$

where $\epsilon_{T-l^*\Omega}$ is the elasticity of labour supply with respect to lump sum taxation.

Substituting $\epsilon^c_{T-l^*,1-\tau_L} = \frac{\overline{D}}{T-l^*}\epsilon^c_{D,1-\tau_L} + \frac{\overline{C}}{T-l^*}\epsilon^c_{C,1-\tau_L}$ into TI in equation (A3.6) yields,

$$TI = -\rho_2\overline{D}\frac{\epsilon^c_{D,1-\tau_L} - \frac{T-l^*}{\Omega}\epsilon_{T-l^*\Omega}}{\left[\frac{\overline{D}}{[T-l^*-\Omega]}\epsilon^c_{D,1-\tau_L} + \frac{\overline{C}}{[T-l^*-\Omega]}\epsilon^c_{C,1-\tau_L} - \frac{T-l^*}{\Omega}\epsilon_{T-l^*\Omega}\right]},$$

or,

$$TI = -\rho_2\overline{D}\phi_D\ ,$$

where,

$$\phi_D = \frac{\epsilon^c_{D,1-\tau_L} - \frac{T-l^*}{\Omega}\epsilon_{T-l^*\Omega}}{\left[\frac{\overline{D}}{[T-l^*-\Omega]}\epsilon^c_{D,1-\tau_L} + \frac{\overline{C}}{[T-l^*-\Omega]}\epsilon^c_{C,1-\tau_L} - \frac{T-l^*}{\Omega}\epsilon_{T-l^*\Omega}\right]}.$$

31

8.4 Appendix 4. Calculations leading to equations (16) and (17):

The first order conditions of the government's constrained maximization problem with respect to τ_L and Ω yield,

$$\frac{(\tau_D - \mu_D)\frac{\partial \overline{D}}{\partial \tau_L} - \frac{cov(U_C, wl^*)}{E(U_C)} + \tau_L \frac{\partial(T-l^*)}{\partial \tau_L}}{(\tau_D - \mu_D)\frac{\partial \overline{D}}{\partial \Omega} + \tau_L \frac{\partial(T-l^*)}{\partial \Omega}} = \frac{\frac{\partial \overline{R}}{\partial \tau_L}}{\frac{\partial \overline{R}}{\partial \Omega}} \; ,$$

where $\overline{R}$ denotes the average tax revenue per person. This expression can be written as follows,

$$(\tau_D - \mu_D)\left[(1 - \tau_L)\frac{\partial \overline{D}}{\partial \tau_L} - [(T - l^*) - \Omega]\frac{\partial \overline{D}}{\partial \Omega}\right]$$

$$- \mu_D \tau_L \left[\frac{\partial(T - l^*)}{\partial \Omega}\frac{\partial \overline{D}}{\partial \tau_L} - \frac{\partial(T - l^*)}{\partial \tau_L}\frac{\partial \overline{D}}{\partial \Omega}\right]$$

$$+ \tau_L \left[(1 - \tau_L)\frac{\partial(T - l^*)}{\partial \tau_L} - [(T - l^*) - \Omega]\frac{\partial(T - l^*)}{\partial \Omega}\right]$$

$$- \frac{cov(U_C, w)(T - l^*)}{E(U_C)}\frac{\partial \overline{R}}{\partial \Omega} = 0 \quad ((A4.1))$$

The total effects of a change in labor taxation on the dirty good and labor supply are,

$$\frac{\partial \overline{D}}{\partial \tau_L} = \frac{\partial \overline{D}}{\partial \tau_L}\bigg|_{v=c} + \frac{[(T - l^*) - \Omega]}{(1 - \tau_L)}\frac{\partial \overline{D}}{\partial \Omega} \; ,$$

and

$$\frac{\partial(T - l^*)}{\partial \tau_L} = \frac{\partial(T - l^*)}{\partial \tau_L}\bigg|_{v=c} + \frac{[(T - l^*) - \Omega]}{(1 - \tau_L)}\frac{\partial(T - l^*)}{\partial \Omega} \; ,$$

respectively. The subscript $v = c$ indicates compensated changes. Substituting these values into equation (A4.1) yields,

$$\left[\tau_D - \mu_D\left[1 + \frac{\tau_L}{(1 - \tau_L)}\frac{\partial(T - l^*)}{\partial \Omega}\right]\right]\frac{\partial \overline{D}}{\partial \tau_L}\bigg|_{v=c}$$

$$+ \tau_L \left[1 + \frac{\mu_D}{(1 - \tau_L)}\frac{\partial \overline{D}}{\partial \Omega}\right]\frac{\partial(T - l^*)}{\partial \tau_L}\bigg|_{v=c} = \frac{cov(U_C, w)(T - l^*)}{(1 - \tau_L)E(U_C)}\frac{\partial \overline{R}}{\partial \Omega} \; . \quad ((A4.2))$$

The first order conditions of the government's constrained maximization problem with respect to τ_D and Ω yield,

$$\frac{(\tau_D - \mu_D)\frac{\partial \overline{D}}{\partial \tau_D} - \frac{cov(U_C, D^*)}{E(U_C)} + \tau_L \frac{\partial(T-l^*)}{\partial \tau_D}}{(\tau_D - \mu_D)\frac{\partial \overline{D}}{\partial \Omega} + \tau_L \frac{\partial(T-l^*)}{\partial \Omega}} = \frac{\frac{\partial \overline{R}}{\partial \tau_D}}{\frac{\partial \overline{R}}{\partial \Omega}} \; .$$

This expression can be written as follows,

$$
(\tau_D - \mu_D) \left[\frac{\partial \overline{D}}{\partial \tau_D} - \frac{\overline{D}}{(1 - \tau_L)} \frac{\partial \overline{D}}{\partial \Omega} \right]
$$

$$
- \frac{\mu_D \tau_L}{(1 - \tau_L)} \left[\frac{\partial (T - l^*)}{\partial \Omega} \frac{\partial \overline{D}}{\partial \tau_D} - \frac{\partial (T - l^*)}{\partial \tau_D} \frac{\partial \overline{D}}{\partial \Omega} \right]
$$

$$
+ \tau_L \left[\frac{\partial (T - l^*)}{\partial \tau_D} - \frac{\overline{D}}{(1 - \tau_L)} \frac{\partial (T - l^*)}{\partial \Omega} \right]
$$

$$
- \frac{cov(U_C, D^*)}{(1 - \tau_L) E(U_C)} \frac{\partial \overline{R}}{\partial \Omega} = 0 \ . \quad ((\text{A4.3}))
$$

The total effects of a change in environmental taxation on the dirty good and labor supply are,

$$
\frac{\partial \overline{D}}{\partial \tau_D} = \frac{\partial \overline{D}}{\partial \tau_D}_{v=c} - \frac{\overline{D}}{(1 - \tau_L)} \frac{\partial \overline{D}}{\partial M} = \frac{\partial \overline{D}}{\partial \tau_D}_{v=c} + \frac{\overline{D}}{(1 - \tau_L)} \frac{\partial \overline{D}}{\partial \Omega} \ ,
$$

and

$$
\frac{\partial (T - l^*)}{\partial \tau_D} = \frac{\partial l(T - l^*)}{\partial \tau_D}_{v=c} + \frac{\overline{D}}{(1 - \tau_L)} \frac{\partial (T - l^*)}{\partial \Omega} \ ,
$$

respectively. Substituting these values into equation (A4.3) yields,

$$
\left[\tau_D - \mu_D \left[1 + \frac{\tau_L}{(1 - \tau_L)} \frac{\partial (T - l^*)}{\partial \Omega} \right] \right] \frac{\partial \overline{D}}{\partial \tau_D}_{v=c}
$$

$$
+ \tau_L \left[1 + \frac{\mu_D}{(1 - \tau_L)} \frac{\partial \overline{D}}{\partial \Omega} \right] \frac{\partial (T - l^*)}{\partial \tau_D}_{v=c} = \frac{cov(U_C, D^*)}{(1 - \tau_L) E(U_C)} \frac{\partial \overline{R}}{\partial \Omega} \ . \quad ((\text{A4.4}))
$$

The first order conditions of the government's constrained maximization problem with respect to τ_D and τ_L yield,[39]

$$
\frac{(\tau_D - \mu_D) \frac{\partial \overline{D}}{\partial \tau_D} - \frac{cov(U_C, D^*)}{E(U_C)} + \tau_L \frac{\partial (T - l^*)}{\partial \tau_D}}{(\tau_D - \mu_D) \frac{\partial \overline{D}}{\partial \tau_L} - \frac{cov(U_C, w(T - l^*))}{E(U_C)} + \tau_L \frac{\partial (T - l^*)}{\partial \tau_L}} = \frac{\frac{\partial \overline{R}}{\partial \tau_D}}{\frac{\partial \overline{R}}{\partial \tau_L}} \ . \quad ((\text{A4.5}))
$$

Substituting the values of the total effects of a changes in environmental and labour taxation on the dirty good and labor supply from above, equation

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[39]Notice that had there been no lump sum taxes, this would be the only valid ratio.

(A4.5) can be written as follows,[40]

$$
\left[\tau_D - \mu_D\left[1 - \frac{\tau_L}{(1-\tau_L)}\frac{\partial(T-l^*)}{\partial M}\right]\right]\left[((T-l^*)-\Omega)\frac{\partial\overline{D}}{\partial\tau_D}\Big|_{v=c} - \overline{D}\frac{\partial\overline{D}}{\partial\tau_L}\Big|_{v=c}\right]
$$
$$
+\tau_L\left[1 - \frac{\mu_D}{(1-\tau_L)}\frac{\partial\overline{D}}{\partial M}\right]\left[((T-l^*)-\Omega)\frac{\partial(T-l^*)}{\partial\tau_D}\Big|_{v=c} - \overline{D}\frac{\partial(T-l^*)}{\partial\tau_L}\Big|_{v=c}\right]
$$
$$
-\mu_D\tau_L\left[\frac{\partial\overline{D}}{\partial\tau_D}\Big|_{v=c}\frac{\partial(T-l^*)}{\partial\tau_L}\Big|_{v=c} - \frac{\partial\overline{D}}{\partial\tau_L}\Big|_{v=c}\frac{\partial(T-l^*)}{\partial\tau_D}\Big|_{v=c}\right]
$$
$$
-\frac{cov(U_C, D^*)}{E(U_C)}\frac{\partial\overline{R}}{\partial\tau_L} + \frac{cov(U_C, w(T-l^*))}{E(U_C)}\frac{\partial\overline{R}}{\partial\tau_D} = 0 \ . \quad ((A4.6))
$$

The ratio of optimal conditions in equation (A4.4) corresponds to equation (16) in the text, while equation (A4.2) to equation (17) in the text. Equation (A4.6) is not presented in the main text since lump sum taxes are available.

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[40] Ng (1980) optimal condition without the covariance terms can be obtained by setting $\Omega = 0$. We also include in the tax base of income taxation the lump sum compensation to the household. In order to make it equivalent to a general consumption tax

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