

Health effects and optimal environmental taxes

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Received 24 October 2000; received in revised form 18 July 2001; accepted 23 July 2001

Abstract

The literature on environmental taxation in the presence of pre-existing distortionary taxes has shown that interactions with these distortions tend to raise the cost of an environmental tax, and thus that the optimal environmental tax is less than marginal environmental damages. A recent paper by Schwartz and Repetto (2000) challenges this finding, arguing that the health benefits from reduced pollution will also interact with pre-existing taxes, and may cause the optimal environmental tax to exceed marginal damages.

Schwartz and Repetto's analysis represented health effects implicitly in the utility function. In contrast, the present paper explicitly represents health effects in an analytically tractable general equilibrium model. This model shows that interactions with health effects from pollution actually will tend to *reduce* the optimal environmental tax, contradicting, Schwartz and Repetto's conclusion. This demonstrates the usefulness of explicitly modeling health effects, and it reinforces the general notion that tax-interactions tend to raise the costs of an environmental tax.

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Keywords: Environmental regulation; Pre-existing taxes; Tax interactions; Health

JEL classification: H21; H23; I18; J22

1. Introduction

In recent years, a substantial body of research has focused on the question of how environmental policy should be set in an economy with pre-existing

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distortionary taxes, a question with significant policy importance. This work has shown that interactions with pre-existing taxes raise the cost of environmental taxes. However, it did not account for the effects of health damages from pollution. A recent paper by Schwartz and Repetto (2000) suggests that such health effects may cause the optimal environmental tax to exceed the marginal damage from pollution. The present paper demonstrates that this is not the case.

Previous work has pointed out two contrasting effects on the costs of environmental taxes in the presence of pre-existing distortionary taxes. Some early papers¹ suggested that the cost of a pollution tax could be lower in such a context, because pollution tax revenue could replace revenue from distortionary taxes, and thus produce a welfare gain. This has come to be known as the *revenue-recycling effect*.

More recent papers² demonstrated the existence of an offsetting *tax-interaction effect*. Pollution taxes drive up the price of consumption goods and thus lower the real wage, causing households to work less and consume more leisure. This exacerbates the tax distortion in the labor market, creating an efficiency loss that raises the cost of environmental taxes. These papers also show that this loss is typically — though by no means always³ — larger than the gain from the revenue-recycling effect, and thus that the optimal pollution tax is typically lower than in an economy without such pre-existing taxes; the pollution tax has a narrower base than the labor tax, and thus, all else the same, is less efficient at raising revenue.

However, this literature typically assumes that environmental quality is separable in utility, implying that changes in environmental quality will not affect the labor/leisure decision. Schwartz and Repetto (2000) relax this assumption, and find that if environmental quality is a leisure substitute, the welfare loss from the tax-interaction effect will be diminished or even reversed. Conversely, if environmental quality is a leisure complement, the welfare loss will be increased.⁴ The paper then cites evidence suggesting that the health benefits of reduced pollution will increase labor supply. It concludes that in such cases, the optimal environmental tax will exceed that found by the prior literature, and may exceed marginal pollution damages.

This is an important issue, as health effects represent the largest benefit from

¹See Terkla (1984), Lee and Misiolok (1986), Oates (1993), and Repetto et al. (1992).

²These papers include Bovenberg and de Mooij (1994), Goulder (1995), Parry (1995), Bovenberg and Goulder (1996), Goulder et al. (1999) and Parry et al. (1999).

³The revenue-recycling effect can exceed the tax interaction effect if, for example, the polluting good is a relative complement to leisure, the burden of the pollution tax falls less on capital than that of the pre-existing taxes, or there are large, inefficient income tax deductions. For more detail on these points, see Bovenberg and Goulder (2002).

⁴This point was not new — many papers, starting with Bovenberg and de Mooij (1994), discussed how their results would differ if changes in environmental quality did affect the labor/leisure decision — but Schwartz and Repetto (2000) was the first paper to explore this point in depth.

many environmental regulations. Burtraw and Toman (1998) note that reductions in premature mortality alone typically account for 75 to 85 percent of economic estimates of the benefits of improved air quality. Reduced morbidity accounts for a much smaller, but still significant, fraction; for example, Burtraw et al. (1998) and USEPA (1996) both found that reduced morbidity accounted for roughly 5 percent of the benefit from reducing sulfur dioxide emissions. Thus, if the general-equilibrium effects of lower mortality and morbidity differ substantially from what the prior literature has assumed, this will have broad-reaching implications for the optimal regulation of a wide range of pollutants.

The present paper reexamines the implications of health effects from pollution. Rather than representing such effects implicitly in the utility function, as Schwartz and Repetto did, it explicitly models two distinct channels through which health damages may affect labor supply — by changing medical expenditures and/or by reducing the household time endowment.⁵

The model confirms that health effects do indeed affect labor supply, and that this results in an additional impact, the *benefit-side tax-interaction effect*.⁶ However, counter to Schwartz and Repetto's results, this effect cannot cause the optimal pollution tax to exceed marginal damages. In fact, for typical parameter values, this effect will cause the optimal pollution tax to be even lower than that indicated by studies which assumed that environmental quality was separable in utility.

To the extent that improved environmental quality causes households to spend less on medical care, households can consume more of other goods, including leisure. That increased leisure creates a general-equilibrium welfare loss, diminishing the benefit of reduced pollution.

In contrast, when pollution causes increased time lost to illness, the sign of the benefit-side tax-interaction effect is ambiguous; both labor and leisure increase, and, while the increased labor leads to a welfare gain, the increased leisure creates an offsetting welfare loss. For typical parameter values, the latter will dominate, leading to a net welfare loss. Furthermore, even if parameter values are such that

⁵The latter could represent lost workdays—time when neither productive work nor enjoyable leisure is possible. If the model were reinterpreted in a life-cycle context, this could also incorporate premature mortality — a reduction in the life-cycle time endowment. Though most of this mortality occurs among the elderly, who are no longer in the labor force, it will still affect labor supply, because reductions in expected lifespan will lead workers to retire at younger ages.

⁶This paper uses the general term “benefit-side tax-interaction effect” even though the health effects considered here represent only one of several possible ways in which environmental quality could affect labor supply. Williams (2000) provides a more general analysis of this effect, considering the case in which pollution affects labor supply through changes in productivity, as well as the health effects considered here. The present paper draws on that work, but focuses exclusively on health effects, allowing it to provide a more complete and realistic analysis of that case. The second-best welfare gain from reduced traffic congestion found by Parry and Bento (2001) represents another example of such a benefit-side effect.

this effect leads to a net welfare gain, the optimal pollution tax will still be unambiguously less than marginal damages. These results differ sharply from Schwartz and Repetto's conclusions, demonstrating the value of explicitly modeling such effects rather than representing them implicitly in the utility function.

The next section of the paper presents an analytically tractable general-equilibrium model that explicitly models health damages, and derives expressions for the optimal level and effect on welfare of a pollution tax. The final section summarizes and concludes.

2. The model

A representative agent model is assumed, where households divide their time endowment (T) between leisure (l) and labor (L), which is used to produce the two consumption goods, X and Y . Households maximize the utility function

$$U(V(l, X, Y), H, G) \quad (1)$$

which is continuous and quasi-concave. G is the quantity of a public good, and H represents consumer health. X , Y , G , and medical care (M) are all produced using labor as the only factor of production. Production exhibits constant returns to scale, and units are normalized such that one unit of labor can produce one unit of any of the four goods.

$$L = X + Y + M + G \quad (2)$$

Environmental quality (Q) equals an exogenous baseline level minus emissions, with units normalized such that the production and consumption of one unit of the polluting good (X) results in one unit of emissions. Good Y is nonpolluting.

$$Q = \bar{Q} - X \quad (3)$$

Pollution has two effects. First, consumer health depends on environmental quality and on the level of medical care consumed.

$$H = H(M, Q) \quad (4)$$

It is assumed that $\partial H / \partial M > 0$, $\partial H / \partial Q > 0$, and $\partial^2 H / \partial M^2 < 0$.

Second, pollution causes households to lose some time to sickness, thus reducing the time they have available for work or leisure. This gives the household time constraint

$$L + l = T - S(Q) \quad (5)$$

where $S(Q)$ represents time lost to sickness, which is decreasing in Q .

The government levies a corrective tax on good X , and also imposes a tax on labor income. We normalize the gross wage to equal one, yielding the consumer budget constraint

$$(1 - \tau_L)L + I = (1 + \tau_X)X + Y + M \quad (6)$$

where I is lump-sum income, which is assumed to be zero.⁷ For simplicity, we assume that the tax revenue is used to provide a fixed quantity of the public good.⁸

$$G = \tau_L L + \tau_X X \quad (7)$$

Households maximize utility (1) subject to their time constraint (5) and budget constraint (6), taking the quantity of the public good, the tax rates, and the level of environmental quality as given. This yields the first order conditions:

$$U_V V_X = (1 + \tau_X)\lambda; \quad U_V V_Y = \lambda; \quad U_V V_I = (1 - \tau_L)\lambda; \quad U_H \frac{\partial H}{\partial M} = \lambda \quad (8)$$

where λ is the marginal utility of income.

These first-order conditions, together with the other equations given thus far, implicitly define the uncompensated demand functions:

$$X(\tau_X, \tau_L, Q, I); \quad Y(\tau_X, \tau_L, Q, I); \quad I(\tau_X, \tau_L, Q, I); \quad M(\tau_X, \tau_L, Q, I) \quad (9)$$

Now define

$$\eta = \frac{\tau_L \frac{\partial I}{\partial \tau_L}}{L - \tau_L \frac{\partial I}{\partial \tau_L}} + 1 \quad (10)$$

This is the *marginal cost of public funds* (MCPF), the cost to the household of raising a marginal dollar of government revenue through the labor tax. The first term is the marginal deadweight loss per dollar of revenue. Thus, its numerator is the marginal deadweight loss, while the denominator is the marginal revenue, each for a change in the labor tax rate. The cost to households is the deadweight loss plus the revenue; hence the MCPF equals this first term plus one. This is a partial equilibrium definition of the MCPF; it ignores all effects outside the labor market, including changes in the deadweight loss in the market for good X , the revenue from the corrective tax, and environmental quality. We will assume that labor

⁷The budget constraint includes I , even though households do not have any lump-sum income, in order to provide a rigorous expression for income effects later in the paper.

⁸If the tax revenue were instead returned as a lump-sum transfer to households, as in Schwartz and Repetto (2000), the model's results would be unchanged as long as the transfer is held constant in real terms.

supply is not backward-bending⁹ and that marginal revenue from the labor tax is positive, which together imply that $\eta > 1$.

The welfare effect of the environmental tax equals (see Appendix A for derivation)

$$\frac{1}{\lambda} \frac{dU}{d\tau_x} = \underbrace{(\tau_x - \tau_p) \frac{dX}{d\tau_x}}_{dW^P} + \underbrace{(\eta - 1) \left(X + \tau_x \frac{dX}{d\tau_x} \right)}_{dW^R} - \underbrace{\eta \tau_L \frac{\partial l}{\partial \tau_x}}_{dW^I} - \underbrace{\left[(\eta - 1) \tau_L \frac{dS}{dQ} - \eta \tau_L \frac{\partial l}{\partial Q} \right] \frac{dQ}{d\tau_x}}_{dW^{IB}} \quad (11)$$

where τ_p is the marginal damage from pollution¹⁰

$$\tau_p = \frac{1}{\lambda} \frac{\partial U}{\partial H} \frac{\partial H}{\partial Q} - \frac{dS}{dQ} \quad (12)$$

Marginal damages are the sum of the values of the direct utility loss from reduced health (the first term) and the time lost to illness (the second term).¹¹

Expression (11) decomposes the welfare effect into four components.¹² The primary welfare effect (dW^P) is the partial-equilibrium effect of the pollution tax. The revenue-recycling effect (dW^R) is the efficiency gain from using pollution tax revenue to reduce the labor tax rate. Finally, two tax-interaction effects result when changes in households' labor supply decisions interact with the tax distortion in the labor market. The cost-side tax-interaction effect (dW^I), which is by now well-known from the prior literature, results when the pollution tax drives up the costs of producing consumer goods, lowering the real wage and discouraging labor supply. The benefit-side tax-interaction effect (dW^{IB}) expresses the impact of improved environmental quality on labor supply decisions.

Changes in leisure and labor supply have general-equilibrium welfare effects for two reasons. First, changes in labor supply affect the revenue from the income tax. Any fall in labor supply will decrease tax revenue, thus requiring a compensating

⁹Empirical evidence suggests that while male labor supply may be backward-bending (estimates of the male labor-supply elasticity are close to zero), female labor-supply elasticity estimates are much higher, and thus total labor supply is definitely not backward bending. See Fuchs et al. (1998).

¹⁰The prior literature has also referred to this as the Pigouvian tax level, following Pigou's (1920) result that the optimal corrective tax (in a partial-equilibrium model) is equal to marginal damages. The same result would hold in this general-equilibrium model if the labor tax rate were zero.

¹¹Harrington and Portney (1987) provide a discussion of how to value reductions in sick days, changes in defensive expenditures (including medical care), and other health benefits from regulation, though their model differs somewhat from that used here.

¹²Several earlier papers decompose and explain the first three of these effects; see, for example, Goulder et al. (1999) and Parry et al. (1999). Thus, the discussion here focuses primarily on the benefit-side tax-interaction effect, which was equal to zero under those papers' assumptions. For clarity, the discussion here separates the two tax-interaction effects, whereas Schwartz and Repetto (2000) treated them together.

increase in the tax rate and creating an efficiency loss. Second, the labor tax causes leisure to be underpriced relative to its social cost; the private cost of a unit of leisure is equal to the after-tax wage, whereas the social cost (the marginal value product of labor) is equal to the pre-tax wage. As a result, any increase in leisure leads to a general-equilibrium welfare loss. Summing these two elements for the effect of the pollution tax on the labor/leisure decision gives the third term in (11), and a similar sum for the effects of improved environmental quality gives the fourth term.

Prior work (Parry, 1995, for example) has shown that the cost of environmental regulation depends on the relative degree of substitutability between the polluting good and leisure. For simplicity, we consider the neutral assumption that goods X and Y are equal substitutes for leisure, allowing Eq. (11) to be rewritten (see Appendix A for derivation) as

$$\frac{1}{\lambda} \frac{dU}{d\tau_x} = (\eta\tau_x - \tau_p) \frac{dX}{d\tau_x} + (\eta - 1) \left[-\tau_L \frac{dS}{dQ} - \frac{\varepsilon_{LI}}{\varepsilon_L} \left(1 - \frac{\partial M}{\partial I}\right)^{-1} \left(\frac{dS}{dQ} (1 - \tau_L) + \frac{\partial M}{\partial Q} \right) \right] \frac{dQ}{d\tau_x} \quad (13)$$

where ε_{LI} is the income elasticity of labor supply and ε_L is the uncompensated labor supply elasticity. The first term on the right-hand side combines the primary welfare effect, tax-interaction effect, and revenue-recycling effect, while the second term is the benefit-side tax-interaction effect. Examining this second term shows that if an improved environment results in lower spending on medical care, this effect will reduce the benefit of regulation. This is much like an income effect; as households spend less on medical care, they can spend more on other goods, including leisure. That increase in leisure leads to a welfare loss.

In contrast, if an improved environment results in less time lost to illness, then the sign of the benefit-side tax-interaction effect is ambiguous. In this case, both leisure and consumption will increase, as long as neither is an inferior good. The increased labor supply boosts labor tax revenue, creating a welfare gain. But because leisure is underpriced (as discussed earlier), the increased leisure demand creates an efficiency loss. Thus, the sign of this effect is ambiguous, and depends on what fraction of the additional time goes to labor and what fraction goes to leisure.¹³

¹³As in Schwartz and Repetto (2000), if pollution causes households to spend time sick, improvements in environmental quality will increase labor supply. However, contrary to their conclusion, this does not necessarily mean that there will be a gain from the benefit-side tax-interaction effect. It is easy to see the source of the difference in results. In a model in which the total time available for labor and leisure is fixed—as in Schwartz and Repetto’s study—an increase in labor supply requires a decrease in leisure consumption. Explicitly modeling this health impact, however, shows that both labor and leisure will increase in response to reduced pollution, and thus that the sign of the welfare impact is ambiguous.

Expression (13) also demonstrates that health effects might lead to a double dividend: a case in which imposing an environmental tax both reduces pollution and raises welfare, exclusive of the environmental benefits (see Goulder, 1995). The second ‘dividend’ — a welfare gain exclusive of environmental benefits — will occur if the benefit-side tax-interaction effect leads to a welfare gain, and that gain is larger than the loss from the (cost-side) tax-interaction effect (net of revenue recycling). The latter is proportional to the environmental tax, and thus, if the benefit-side tax-interaction effect yields a welfare gain, a sufficiently small environmental tax will yield a double dividend.¹⁴

Setting expression (13) equal to zero and rearranging, using $dQ = -dX$, yield an expression for the optimal pollution tax

$$\tau_X^* = \frac{\tau_p}{\eta} + \frac{(\eta - 1)}{\eta} \left[-\tau_L \frac{dS}{dQ} - \frac{\varepsilon_{LI}}{\varepsilon_L} \left(1 - \frac{\partial M}{\partial I}\right)^{-1} \left(\frac{dS}{dQ} (1 - \tau_L) + \frac{\partial M}{\partial Q} \right) \right] \quad (14)$$

The first term on the right-hand side of this equation — marginal damages divided by the marginal cost of public funds — is the optimal environmental tax rate found by the many previous studies (see Bovenberg and Goulder, 2002) that assumed that environmental quality is separable in utility. The second term represents the effect of benefit-side tax interactions.

Is it possible for the optimal pollution tax to exceed marginal pollution damages? For this to be the case, the sum of the two terms in the square brackets in expression (14) must be greater than τ_p . Inspection reveals that this is impossible; the second term is negative, and, while the first term is positive, it is at most equal to $\tau_L \tau_p$.¹⁵

The intuition behind this result is that for the optimal tax to exceed marginal damages, benefit-side tax interactions must magnify the marginal benefit of improved environmental quality by more than cost-side tax interactions (net of revenue recycling) magnify the marginal cost. As discussed earlier, benefit-side tax interactions will lead to a welfare loss if improved environmental quality reduces the demand for medical care, but their effect is ambiguous if improved environmental quality reduces the time lost to illness, thus increasing the time available for labor and leisure. In the latter case, increased leisure leads to a welfare loss, whereas increased labor leads to a welfare gain.

¹⁴This result depends on the precise definition used. If the second dividend is defined as a welfare gain exclusive of both direct and indirect benefits of reduced pollution — thus excluding both the primary effect and the benefit-side tax-interaction effect — then introducing health effects will not produce a double dividend.

¹⁵It is technically possible for the optimal tax to exceed marginal damages if improved environmental quality leads to a substantial rise in medical expenditure, or if leisure is an inferior good. But both of these conditions seem highly unlikely to hold in practice.

But even if all of the additional time goes to increased labor, the welfare gain still cannot offset the increase in costs from cost-side tax interactions. In this case, the marginal labor tax revenue – the source of the benefit-side tax interaction gain—equals the labor tax rate times the value of the marginal time gained (or marginal damages). But the increased marginal cost from cost-side tax interactions, net of the gain from revenue recycling, is the same as if the marginal cost of regulation (equal to the pollution tax) were paid out of government revenue. Thus, if the pollution tax were greater than marginal damages (and the labor tax rate is not over 100%), the cost-side tax interactions would exceed the benefit-side interactions. Consequently, the optimal tax rate must be less than marginal damages.

But can benefit-side tax interactions cause the optimal tax to be above the level suggested by prior work that assumed that environmental quality is separable in utility? For this to be the case, such interactions must magnify the benefits of improved environmental quality: the expression in square brackets must be positive. This is clearly possible, if a cleaner environment reduces time lost to illness, and if a sufficiently large fraction of that time goes to increased labor supply. But estimates of labor supply elasticities suggest that in practice, enough of that time will go to increased leisure to cause a net welfare loss from benefit-side tax interactions. Assuming that the labor tax rate is 0.4, that the uncompensated labor supply elasticity is 0.15, that the income elasticity of labor supply is -0.15 ,¹⁶ and that medical spending is not an inferior good causes the expression in square brackets to be negative, unless improved environmental quality leads to an increase in medical expenditures.

3. Conclusions

This paper has shown that when improved environmental quality reduces spending on medical care, the optimal environmental tax will be lower than that indicated by models that assume that environmental quality is separable from goods and leisure in the utility function. A similar result will hold for typical parameter values when environmental quality affects time lost to illness, though it is possible for the optimal environmental tax to be higher if income effects on leisure demand are very small. In either case, the optimal environmental tax will be below the value of marginal damages from pollution.

These results run counter to those found by Schwartz and Repetto (2000). This demonstrates the value of explicitly modeling health effects, rather than assuming a preference relationship, and reinforces the general notion that pre-existing distortionary taxes tend to raise the costs of environmental taxes.

¹⁶These labor elasticities are roughly consistent with those found by Fuchs et al. (1998). A labor tax rate of 0.4 is a standard assumption in the literature; see, for example, Browning (1987).

Acknowledgements

The author would like to thank Larry Goulder, Ian Parry, Lans Bovenberg, Robert Repetto, Jesse Schwartz, and referees for their helpful comments.

Appendix A. Derivation of Eq. (11)

Taking a total derivative of utility with respect to the corrective tax (τ_x), substituting in the consumer first-order conditions, dividing through by λ , and using $dG = 0$ yield

$$\frac{1}{\lambda} \frac{dU}{d\tau_x} = (1 + \tau_x) \frac{dX}{d\tau_x} + \frac{dY}{d\tau_x} + \frac{dM}{d\tau_x} + (1 - \tau_L) \frac{dl}{d\tau_x} + \frac{1}{\lambda} \frac{\partial U}{\partial H} \frac{\partial H}{\partial Q} \frac{dQ}{d\tau_x} \quad (\text{A.1})$$

Taking a total derivative of the production Eq. (2), substituting in a total derivative of the household time constraint (5), and using $dG = 0$ and $dT = 0$

$$\frac{dX}{d\tau_x} + \frac{dY}{d\tau_x} + \frac{dM}{d\tau_x} + \frac{dl}{d\tau_x} + \frac{dS}{dQ} \frac{dQ}{d\tau_x} = 0 \quad (\text{A.2})$$

Subtracting (A.2) from (A.1) and rearranging, using $dQ = -dX$, yields

$$\frac{1}{\lambda} \frac{dU}{d\tau_x} = (\tau_x - \tau_p) \frac{dX}{d\tau_x} - \tau_L \frac{dl}{d\tau_x} \quad (\text{A.3})$$

Taking a total derivative of the household time constraint (5), adding a total derivative of the government budget constraint (7), and rearranging, using $dG = 0$, $dT = 0$, and $(dl/d\tau_x) = (\partial l/\partial \tau_x) + (\partial l/\partial \tau_L)(d\tau_L/d\tau_x) + (\partial l/\partial Q)(dQ/d\tau_x)$ give

$$\frac{dl}{d\tau_x} = \frac{L \frac{\partial l}{\partial \tau_x} - \frac{\partial l}{\partial \tau_L} \left(X + \tau_x \frac{dX}{d\tau_x} - \tau_L \frac{dS}{dQ} \frac{dQ}{d\tau_x} \right) + L \frac{\partial l}{\partial Q} \frac{dQ}{d\tau_x}}{L - \tau_L \frac{\partial l}{\partial \tau_L}} \quad (\text{A.4})$$

Substituting (A.4) and (10) into (A.3) yields Eq. (11)

Derivation of Eq. (13)

The expression for the (cost-side) tax-interaction effect from Eq. (11) is:

$$dW_I = -\eta \tau_L \frac{\partial l}{\partial \tau_x} \quad (\text{A.5})$$

Because the change in the price of good X is equal to the change in the tax rate, the Slutsky equation gives

$$\frac{\partial l}{\partial \tau_x} = \frac{\partial l^C}{\partial \tau_x} - \frac{\partial l}{\partial I} X \tag{A.6}$$

where the superscript ‘C’ denotes a compensated derivative. Similarly,

$$\frac{\partial l}{\partial \tau_L} = \frac{\partial l^C}{\partial \tau_L} - \frac{\partial l}{\partial I} L \tag{A.7}$$

Taking a derivative of the household utility function (1), holding the levels of utility and of environmental quality constant and substituting in the consumer first-order conditions (8) yield

$$\begin{aligned} \frac{\partial l^C}{\partial \tau_L} &= - \frac{\partial l^C}{\partial(1 - \tau_L)} \\ &= \frac{1 + \tau_x}{1 - \tau_L} \frac{\partial X^C}{\partial(1 - \tau_L)} + \frac{1}{1 - \tau_L} \frac{\partial Y^C}{\partial(1 - \tau_L)} + \frac{1}{1 - \tau_L} \frac{\partial M^C}{\partial(1 - \tau_L)} \end{aligned} \tag{A.8}$$

The assumption that the cross-elasticity between X and leisure is equal to the average (weighted by consumption share) over all goods can be written as

$$\begin{aligned} \frac{\partial X^C}{\partial(1 - \tau_L)} \frac{1 - \tau_L}{X} &= \frac{1}{(1 + \tau_x)X + Y + M} \left((1 + \tau_x)X \frac{\partial X^C}{\partial(1 - \tau_L)} \frac{1 - \tau_L}{X} \right. \\ &\quad \left. + Y \frac{\partial Y^C}{\partial(1 - \tau_L)} \frac{1 - \tau_L}{Y} + M \frac{\partial M^C}{\partial(1 - \tau_L)} \frac{1 - \tau_L}{M} \right) \end{aligned} \tag{A.9}$$

Substituting (A.9) and the household budget constraint (6) into (A.8) yields

$$\frac{\partial l^C}{\partial \tau_L} = \frac{\partial X^C}{\partial(1 - \tau_L)} \frac{L}{X} \tag{A.10}$$

Finally, the Slutsky symmetry property gives

$$\frac{\partial l^C}{\partial \tau_x} = \frac{\partial X^C}{\partial(1 - \tau_L)} \tag{A.11}$$

Substituting (A.6), (A.7), (A.10), (A.11) and the definition of η (10) into (A5) yields a simplified expression for the cost-side tax-interaction effect

$$dW^I = -(\eta - 1)X \tag{A.12}$$

The expression for the benefit-side tax-interaction effect from Eq. (11) is:

$$dW^{IB} = - \left[(\eta - 1)\tau_L \frac{\partial S}{\partial Q} + \eta\tau_L \frac{\partial l}{\partial Q} \right] \frac{dQ}{d\tau_x} \tag{A.13}$$

The change in spending on X , Y , and l for a change in I will equal

$$(1 - \tau_L) \frac{\partial l}{\partial I} + (1 + \tau_x) \frac{\partial X}{\partial I} + \frac{\partial Y}{\partial I} = 1 - \frac{\partial M}{\partial I} \quad (\text{A.14})$$

For a change in Q that change will be

$$(1 - \tau_L) \frac{\partial l}{\partial Q} + (1 + \tau_x) \frac{\partial X}{\partial Q} + \frac{\partial Y}{\partial Q} = -(1 - \tau_L) \frac{dS}{dQ} - \frac{\partial M}{\partial Q} \quad (\text{A.15})$$

Weak separability of health in the utility function implies that leisure demand is determined solely by the relative prices of l , X , and Y (which are not affected by changes in Q) and by the amount spent on those goods. Together with (A.14) and (A.15), this implies

$$\frac{\partial l}{\partial Q} = -\frac{\partial l}{\partial I} \left(1 - \frac{\partial M}{\partial I}\right)^{-1} \left(\frac{dS}{dQ}(1 - \tau_L) + \frac{\partial M}{\partial Q}\right) \quad (\text{A.16})$$

The uncompensated labor supply elasticity is

$$\varepsilon_L = \frac{\partial L}{\partial(1 - \tau_L)} \frac{1 - \tau_L}{L} = \frac{\partial l}{\partial \tau_L} \frac{1 - \tau_L}{L} \quad (\text{A.17})$$

and the income elasticity of labor supply is

$$\varepsilon_{LI} = \frac{\partial L}{\partial I} \frac{(1 - \tau_L)L}{L} = -\frac{\partial l}{\partial \tau_L} (1 - \tau_L) \quad (\text{A.18})$$

Substituting expressions (A.14) through (A.16) and the definition of the MCPF (10) into (A.13) and rearranging yield an expanded expression for the benefit-side tax-interaction effect

$$dW^{IB} = -(\eta - 1) \left[\tau_L \frac{\partial S}{\partial Q} + \frac{\varepsilon_{LI}}{\varepsilon_L} \left(1 - \frac{\partial M}{\partial I}\right)^{-1} \left(\frac{dS}{dQ}(1 - \tau_L) + \frac{\partial M}{\partial Q}\right) \right] \frac{dQ}{d\tau_x} \quad (\text{A.19})$$

Substituting (A.12) and (A.19) into (11) yields Eq. (13).

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