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Essays on Interactions Between Environmental and Fiscal Policies: Analytical and Numerical General Equilibrium Analyses

Committee:

Don Fullerton, Supervisor

David A. Kendrick

Peter J. Wilcoxen

Roberton C. Williams III

Stephen P. Magee

Essays on Interactions Between Environmental and Fiscal Policies: Analytical and Numerical General Equilibrium Analyses

by

Seung-Rae Kim, B.S., M.S.

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To My Parents.

Essays on Interactions Between Environmental and Fiscal Policies: Analytical and Numerical General Equilibrium Analyses

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Seung-Rae Kim, Ph.D.
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Supervisor: Don Fullerton

This dissertation is a collection of three essays investigating issues related to environmental fiscal policy and the economy. It focuses on the design and efficiency of market-based environmental regulatory policies under different circumstances, including policy interactions, uncertainty, and endogenous public incentives for technical change. Each essay develops a theoretical or empirical general equilibrium model to study a specific type of policy interaction that affects environmental quality, economic growth, and welfare in a world with other prior distortions.

The first essay extends the literature on the 'double dividend' hypothesis and market-based instrument choice to evaluate the welfare implications of environmental taxes and quotas that apply to polluting intermediate inputs in the presence of other distortionary taxes. It analyzes a static general equilibrium model with non-separable preferences and technology, relatively rare assumptions

in this literature, and then establishes more generalized second-best optimal rules for environmental regulation in a world with pre-existing tax distortions.

The second essay develops a dynamic model of endogenous growth, based on the joint accumulation of private capital and abatement knowledge. It extends previous models to allow for distortionary income taxes for financing both non-productive government spending and public investment in abatement knowledge, focusing on a general treatment of the interactions among sustainable economic growth, the environment, and public finance in a second-best world with distortionary taxes. In this setting, the essay analyzes optimal environmental and fiscal policy rules, and also examines the growth and welfare effects of a tighter environmental policy for sustainable development.

The third essay is a step toward the merger of optimal control models with dynamic CGE models. It demonstrates the usefulness of CGE techniques in control theory application and provides a practical guideline to policymakers in this relatively new field. Moreover, it explores the link between economic stabilization and optimal environmental fiscal policy design in a stochastic dynamic general equilibrium framework. Uncertainty, short-term quantity adjustment process, and sector-specific political preferences (e.g., more stabilization priorities on polluting industries) are taken into account in exploring what time paths of adjustments of the economy would be optimal for the government with explicit policy goals.

Table of Contents

List of Tables

List of Figures

Chapter 1: Optimal Environmental Regulation in the Presence of Other Taxes [1]

1.1 INTRODUCTION

The question of whether the optimal environmental tax in a second-best world lies above or below the social marginal damages from pollution has been the cornerstone of much recent literature. This issue has received a great deal of attention from economists and policymakers over the past decade. As indicated by Pearce (1991), environmental taxes might offer a so-called "double dividend": these taxes not only improve the environment, but might also reduce welfare costs of the overall tax system.[2] One might infer, then, that the second-best optimal pollution tax would be higher than necessary just to correct for the externality.[3] This earlier view in environmental taxation, however, was dramatically reframed by Bovenberg and de Mooij (1994), Goulder (1995), Parry (1995), Oates (1995), Bovenberg and Goulder (1996), Fullerton (1997) and many other authors: in a tax

[1] This chapter was published in 2002, in *Contributions to Economic Analysis &* Policy, Vol. 1: No. 1, Article 4, The Berkeley Electronic Press.

[2] In general, the environmental benefit is called the first dividend and the non-environmental benefit the second dividend. This "double dividend" concept is reviewed at length in Goulder (1995) and Oates (1995). It basically relates to the "environmental tax reform" issue, so the gain depends on the starting point. For example, if the current tax on pollution is below the 'optimal' level, then a reform (the revenue-neutral introduction of new environmental taxes) could raise social welfare.

[3] This strand of literature includes Tullock (1967), Terkla (1984), Lee and Misiolek (1986), and Pearce (1991), Repetto et al. (1992), and Nordhaus (1993).

system with a labor income tax, the second-best optimal pollution tax typically lies below the first-best Pigouvian level. These recent contributions have shown that by raising costs and prices, new environmental taxes decrease the real net return to labor and therefore aggravate the distortions of the pre-existing labor tax. In other words, with other distortionary taxes, environmental regulatory instruments tend to compound those pre-existing distortions, a cost that is recognized as “tax interactions” or “interdependency effects.” According to these interpretations, *pre-existing tax distortions* significantly raise the costs of all environmental policies relative to their costs in a first-best setting. Thus, there has been a fairly general presumption that the optimal environmental tax would be lower than the first-best Pigouvian level (or social marginal damages).[4]

However, most of the recent literature is based on fairly simple models with narrow assumptions and special cases. In particular, these models typically assume weakly separable and homothetic preference structures, which imply that all goods have the same degree of substitutability with leisure.[5] Recall that the pioneering findings by Sandmo (1975) demonstrate that the optimal second-best tax on an externality-generating good is a weighted average of a Ramsey component and a Pigouvian component (social marginal damages). For the

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[4] On this issue, Bovenberg and de Mooij (1994) spawned a sizable body of literature. In particular, Bovenberg and Goulder (1996) calculate that the optimal carbon tax in the U.S. is approximately 68% of the Pigouvian rate. Using a graphical treatment, Parry (1995) also finds that the optimal pollution tax in the U.S. lies 63 - 78% of the Pigouvian rate.

[5] Even though some papers do not require this assumption initially, they typically impose this restriction when deriving their main or additional results. See, e.g., Goulder et al. (1997) and Parry et al. (1999) among others.

Ramsey component, with homothetic separability, any deviation from uniform commodity taxation would always increase the efficiency cost of the tax system from a non-environmental point of view. Thus, the recent results can be considered a re-interpretation of these well-known Ramsey uniform tax results, but with a Pigouvian corrective tax. Note also that according to Corlett and Hague (1953), abstracting from the externality, it could be optimal to tax the good with the lowest compensated cross-price elasticity of demand with leisure, that is, a complement to leisure or at least a weaker-than-average substitute for leisure.[6]

Moreover, technological structures and flexibilities for cleaner production can also affect the economic costs of regulatory instruments. As far as emissions control is concerned, the major focus should be on the use of intermediate inputs and their inter-industry flows, because many actual environmental regulations affect primarily the costs of intermediate inputs.[7] A few studies in the prior literature, including Bovenverg and Goulder (1996) and Parry et al. (1999), have

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6 In this spirit, a recent study by Ballard et al. (2000) uses a simple "numerical" CGE model with two final goods (clean and dirty) and only one input (labor), as corresponds to the analytical model of Bovenberg and de Mooij (1994). They report the possibility that optimal environmental tax rate may exceed the social marginal damages, when the inner nest of the utility function is assumed not to be homothetic. Their numerical simulation illustrates that for even a modest amount of non-homotheticity, Bovenberg and de Mooij's result can be reversed dramatically. Allowing for non-separable labor supply with individual consumption, an econometric CGE model for New Zealand by Diewert and Lawrence (1996) also indicates a negative marginal deadweight loss of tax on motor vehicles (a pollution-related good) in the presence of other taxes. On the other hand, relaxing a different kind of separability (between environment and leisure), recent papers by Schwarz and Repetto (2000) and Cremer et al. (2000) argue that if a cleaner environment can increase labor supply, then the *tax-interaction* critique of the double dividend might not be robust.

7 In most cases, pollution is highly correlated with the use of particular intermediate inputs in production process, and therefore its overall abatement cost depends on the substitution possibilities among inputs or other adjustment of the production process.

made some analytically-tractable contributions on this issue within the context of general equilibrium.[8] However, no attempt has been made to consider the general features of interactions among non-separable utility, production technology, and the optimal environmental taxes.

To explore the optimal configuration of environmental regulatory instruments, it is necessary to trace all of these possible economic channels simultaneously within a single model. Sharing some features of the Parry et al. (1999) approach, this paper employs an analytically-tractable general equilibrium model to derive explicitly the second-best optimal rules for environmental regulation in the presence of other taxes and the non-separable structure of preferences and technology.[9] The model used also examines the role of the key behavioral characteristics of consumption and production as well as the pre-existing tax distortions. This consideration is important because the consequences of many actual environmental regulations depend fundamentally on the substitution possibilities in production, and also because the econometric literature usually does not support the hypothesis that labor supply effects are separable from individual consumption patterns.[10] Results show that the welfare

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[8] These studies extend earlier works by considering pollution taxes imposed on intermediate inputs as well as on consumption goods, even though the central results still rest on the restrictive separabilty assumptions in utility.

[9] While a series of papers by Goulder et al. and Parry et al. always emphasized the significance of pre-existing distortions in welfare effects, they did not proceed to discuss the final derivation of optimal environmental taxes in their analytical models.

[10] For empirical evidence on the non-separability, see, for example, Abbot and Ashenfelter (1976, 1979), Barnett (1979), Blundell and Walker (1982), Browning and Meghir (1991), Alderman and Sahn (1993), Kaiser (1993), and Madden (1995) among many others.

costs could be significantly overestimated or underestimated by models using less general utility and production functions.[11]

This paper makes the following contributions to the literature on optimal second-best environmental regulation. First, it is the first attempt to model analytically the general features of interactions among non-separable utility, production technology, and optimal environmental taxes in a general equilibrium of the second-best. It shows that previous studies that assume separability (e.g., Bovenberg and de Mooij, 1994; Bovenberg and Goulder, 1996; Fullerton, 1997) provide limited estimates of the optimal level of regulation and the potential gains from reform.

Second, incorporating substitution possibilities in the production of dirty outputs, it extends earlier analytical work to establish more generalized second-best rules for the optimal environmental regulation in a general equilibrium setting. Relative to the literature, the role played by the non-separabilities in preferences and technology is also clarified. The results indicate that the condition for the second-best optimal tax rate to exceed the social marginal damages depends *not* just on the difference between the two goods' cross-price elasticities with leisure, but on that difference compared to the tax elasticity of demand for the polluting goods.[12] This implies that the second-best tax on pollution is *not*

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[11] Analogously, Stuart (1984), Ballard (1990) and Fullerton (1991) find that major sources of differences in estimates of marginal excess burden may stem from differences in underlying (model) assumptions rather than uncertainty about the magnitude of various elasticities.

[12] Note that some of earlier papers point out i) that if the dirty good is a relatively weak substitute for leisure, the tax-interaction effect will be smaller and the prospects for a double dividend will improve, or simply argue ii) that the comparison of optimal environmental tax rate to the Pigouvian rate may depend on whether the dirty good is a stronger or weaker than average

always higher than the social marginal damages, even though the dirty output is more of a complement to leisure. This paper also reveals some results about the importance of non-separable labor supply effects in relation to the role of technological substitution in the use of polluting intermediate inputs: the lower the aggregate demand elasticity for the polluting intermediate inputs, the more important is the 'role' of non-separability components in the utility function.

Finally, contrary to the impression given by the extensive prior literature, the results here demonstrate that the level of prior tax distortions has *no* influence on whether the second-best pollution tax is less than or greater than the social marginal damages (even though it still matters for the absolute *size* of the positive or negative deviation of the second-best tax rate from the first-best Pigouvian tax rate). Moreover, under some reasonable parameter conditions, a greater pre-existing tax distortion can increase the optimal level of environmental regulation.

The rest of the paper is organized as follows. Section 1.2.1 and 1.2.2 describe the analytical model with production and emissions to examine the welfare effects of pollution abatement policy changes. Section 1.3 applies this model to derive explicitly the second-best optimal rule of environmental regulation or taxation. Section 1.4 provides the interpretation of results. Section 1.5 discusses the sensitivity of the results to some plausible values of important parameters. The final section offers conclusions.

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substitute for leisure. See, e.g., Bovenberg and Van der Ploeg (1994), Parry (1995), Goulder et al. (1999), Sandmo (2000), Parry and Oates (2000), and Bovenberg and Goulder (2001).

1.2 THE MODEL AND THE ANALYSIS

1.2.1 The Analytical Model of Production and Emissions

In a static, representative agent model, we assume perfect information, perfectly competitive markets, no transaction costs, and a closed economy. Households allocate their hours endowment (H) between leisure demand (l) and labor supply (L), where labor is used to produce two private consumption goods, X and Y, and two intermediate goods, C and D. Here, C represents an aggregate of nonpolluting (or clean) intermediate goods, and D represents an aggregate of all polluting (or dirty) intermediate goods.[13] Labor, the numeraire good, is the only input used by competitive firms to produce each of the two intermediate goods C and D, with per-unit cost q_C and q_D, respectively. The marginal product of labor in each of these two industries is assumed to be constant.[14] Two final goods, X and Y, are also produced by competitive firms under constant-returns-to-scale (CRTS) technology using labor L and the two intermediate goods C and D according to:

$$X = X(C_X, D_X, L_X); \quad Y = Y(C_Y, D_Y, L_Y), \tag{1.1}$$

where aggregated intermediate demand for C is $C_X + C_Y$ and for D is $D_X + D_Y$. The technical substitutability between pollution-generating input D and the other two inputs, C and L, determines emissions abatement possibilities in each industry.

13 This D can be considered as either an aggregate good that is perfectly correlated with pollution emissions or pollution emissions themselves.

14 The production of each intermediate good, C and D, has a linear technology with only one input (say, L_C and L_D, respectively), that is, $C=L_C/q_C$ and $D=L_D/q_D$.

Although both final goods use the pollution-generating input D, we assume that one good X uses it more intensively than the other good Y.[15]

Labor is also used to produce a (non-environmental) public good G, and the marginal product of this labor (L_G) is assumed to be constant. Environmental quality, Q, deteriorates with emissions of pollution (e.g., gaseous, liquid, or solid wastes, noise, and congestion). Environmental quality, Q, is directly related to the total quantity, D, of pollution-generating intermediate goods D_X and D_Y; thus $Q = Q(D) = Q(D_X+D_Y)$ with $Q'(D) = \partial Q/\partial D_X = \partial Q/\partial D_Y < 0$. With a fixed total labor endowment, the resource constraint for the model is

$$H = L + l \quad \text{where} \quad L = L_X + L_Y + L_C + L_D + L_G. \tag{1.2}$$

The representative household utility is

$$U(V(X, Y, l), G, Q). \tag{1.3}$$

Private utility (V) is weakly separable from the two public goods, G and Q.[16]

The model assumes the government provides a fixed quantity of a public good, rather than providing a fixed (real) lump-sum transfer to households.[17]

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15 With no loss of generality, we suppose that $D_X / X > D_Y / Y$. Since X uses proportionally more of the dirty input, we can simply think of X as the dirty good and Y as the clean good.

16 Here, separability between private and public goods implies that the demand functions for l, X, and Y are independent of Q. In this model, it is assumed that G is government expenditure on public consumption. This G is fixed, because we will consider only revenue-neutral changes. Further, since G is fixed, it does not matter how G is used or how G enters utility.

Instead of receiving a fixed lump-sum transfer, each household enjoys fixed nonenvironmental public consumption. Also, each household can earn rents as well as labor income. These rents arise from quantity restrictions on the use of pollution-generating intermediate goods D, such as an emissions quota or nonauctioned permits, as will be discussed in next section. These rents are assumed to be taxed at a given fixed rate. Their presence greatly affects the amount by which the labor tax might have to be adjusted.[18]

1.2.2 Welfare Effects of Pollution Abatement Policy Changes

The government levies a proportional tax t_L on labor income, and also regulates pollution emissions by using either a tax or a non-auctioned quota. A corrective tax t_D can be imposed on the use of pollution-generating intermediate good D. For analytical convenience, this paper models a quota in a way that is analogous to a tax, since taxes and quotas can be converted to each other with some manipulation.[19] In other words, a policy of restricting the quantity of D would raise the shadow price of D by a 'virtual tax', which we call t_D^v, and would generate scarcity rents of amount $\pi^q = t_D^v D$.

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17 When the public good is produced entirely from labor, as in this model, this means that government spending is fixed relative to the price of labor (which is always one since labor is numeraire).

18 In contrast, Parry et al. (1999) and Goulder et al. (1999) assume that these rents are taxed at the same rate as labor income, so that changing the tax rate on labor income affects revenues from rents as well as labor income.

19 Note that this is only true with no uncertainty, as assumed in this model.

Under the quota, with the wedge t_D^v between the demand and supply price of polluting intermediate goods D, the policy-generated scarcity rents π^q ($= t_D^v D$) accrue to households who own firms.[20] These rents become part of the nonlabor income of households. The policy-generated rents may also be taxed, at the fixed rate t_π.[21] The total government revenue, G, consists of labor tax revenues plus the revenues from emissions abatement policies. Thus, the government budget constraint is

$$t_L L + t_D D + t_\pi \pi^q = G, \qquad (1.4)$$

where this $t_D > 0$ only if it is an actual tax t_D, and $\pi^q > 0$ only if a quota with virtual tax t_D^v. Note that the revenues from emissions abatement policies include either direct revenues under tax instruments ($t_D D$) or indirect revenues from the taxation of rents ($t_\pi \pi^q$) under the quota instruments. Since all production functions in this model exhibit constant returns to scale, profits (π^q) equal zero under the emissions tax, but they equal quota rents under the emissions quota.

Denote the household demand prices of X and Y by P_X and P_Y, and normalize the gross wage to unity to get the household budget constraint:

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20 In this case, the demand price for polluting intermediate goods exceeds the marginal private cost (q_D) by t_D^v for each unit of D.

21 The tax rate, t_π, equals one for any case where government captures all the policy-generated scarcity rents, such as by using an emissions tax or sale of permits, and it equals zero for the other extreme case where private households keep all the rents. As indicated in Fullerton and Metcalf (2001), this flexibility for t_π allows alternative cases for maintaining the necessary revenue to pay for G under a quota policy and to explore the fact that the existence of t_π greatly affects the amount by which the labor tax might have to be adjusted.

$$P_X X + P_Y Y = (1 - t_L)\ L + N, \qquad (1.5)$$

where N is nonlabor income, including policy-generated private rents accrued to households. Households choose X, Y, and l (or L) to maximize utility (1.3) subject to their resource constraint (1.2) and budget constraint (1.5), given public consumption, final product prices, the labor tax rate, and environmental levies. This yields first-order conditions for utility maximization:

$$\frac{\partial U}{\partial X} = \lambda P_X\,, \quad \frac{\partial U}{\partial Y} = \lambda P_Y\,, \quad \frac{\partial U}{\partial l} = \lambda(1 - t_L)\,, \qquad (1.6)$$

where λ represents the marginal utility of (nonlabor) income. These first-order conditions and the household budget constraint implicitly define the uncompensated consumption good demand and labor supply functions:

$$X = X(P_X, P_Y, t_L, N); \quad Y = Y(P_X, P_Y, t_L, N); \quad L = L(P_X, P_Y, t_L, N). \qquad (1.7)$$

Now consider the welfare effect of a revenue-neutral tax swap policy involving an incremental environmental regulation change in t_D (or t_D^v), where t_L adjusts to maintain government budget balance.[22] Taking a derivative of the

[22] This kind of methodology has been widely used in the environmental taxation literature since Bovenberg and de Mooij (1994). See, e.g., Goulder et al. (1997), Fullerton (1997), and Parry et al. (1999) among others. It was also discussed in Starrett (1988). In the case where labor is distorted by an existing t_L and existing t_D, we can contemplate an environmental 'tax swap' that raises t_D a small amount, and reduces t_L in a way that is revenue-neutral. In addition, this approach also allows us to discuss optimal tax rates, where *no* such swap can add to welfare ($dU = 0$).

household resource constraint (1.2) with respect to t_D and setting dG = 0 (or equivalently $dL_G = 0$) gives the following aggregation property:

$$\frac{dL}{dt_D}+\frac{dl}{dt_D}=0 \quad or \quad \frac{dL_X}{dt_D}+\frac{dL_Y}{dt_D}+\frac{dL_C}{dt_D}+\frac{dL_D}{dt_D}+\frac{dl}{dt_D}=0\,, \qquad (1.8a)$$

where

$$\frac{dl}{dt_D}=\frac{\partial l}{\partial t_D}+\frac{\partial l}{\partial t_L}\frac{dt_L}{dt_D}+\frac{\partial l}{\partial N}\frac{dN}{dt_D}\,. \qquad (1.8b)$$

Taking a derivative of utility (1.3) with respect to the corrective tax t_D (or t_D^v), substituting in the first-order conditions (1.6), and dividing through by λ, we obtain the following expression for the welfare effects of a revenue-neutral environmental policy change in the tax mix where dG = 0:

$$\frac{1}{\lambda}\frac{dU}{dt_D}=P_X\frac{dX}{dt_D}+P_Y\frac{dY}{dt_D}+(1-t_L)\frac{dl}{dt_D}+\frac{1}{\lambda}\frac{\partial U}{\partial Q}Q'(D)\frac{dD}{dt_D}\,, \qquad (1.9a)$$

where

$$\frac{dX}{dt_D}=\frac{\partial X}{\partial t_D}+\frac{\partial X}{\partial t_L}\frac{dt_L}{dt_D}+\frac{\partial X}{\partial N}\frac{dN}{dt_D} \qquad (1.9b)$$

and where analogous expressions apply for dY/dt_D, dl/dt_D, and dD/dt_D.

Considering an emissions tax or a quota that creates a wedge of t_D (or t_D^v) per unit between the supply and demand price of intermediate goods D, in this model, the marginal general equilibrium change in final product prices (through the channels of the output-substitution and input-substitution effect) is the same as the ratio of intermediate goods D input to final output; i.e., $dP_X/dt_D = D_X/D$ and $dP_Y/dt_D = D_Y/D$.[23] In addition, the equilibrium quantity of externality-generating intermediate goods D can be expressed as a function of the policy variables. That is, $D(t_D, t_L, N) = D_X(t_D, t_L, N) + D_Y(t_D, t_L, N)$, where $dD/dt_D < 0$.

Taking a derivative of the production function for each consumption good, X and Y, and for each intermediate good, C and D in (1.1) with respect to t_D (or t_D^v), where public consumption is exogenously given, and using the first-order conditions for the profit maximization of private sector gives

$$P_X \frac{dX}{dt_D} = q_C \frac{dC_X}{dt_D} + (q_D + t_D)\frac{dD_X}{dt_D} + \frac{dL_X}{dt_D}, \tag{1.10a}$$

$$P_Y \frac{dY}{dt_D} = q_C \frac{dC_Y}{dt_D} + (q_D + t_D)\frac{dD_Y}{dt_D} + \frac{dL_Y}{dt_D}, \tag{1.10b}$$

$$q_C \frac{dC}{dt_D} = \frac{dL_C}{dt_D}, \tag{1.10c}$$

$$q_D \frac{dD}{dt_D} = \frac{dL_D}{dt_D}. \tag{1.10d}$$

Combining (1.10a) through (1.10d), aggregating over each industry sector, and substituting into the resource aggregation property (1.8a) yields

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[23] Given perfect competition and CRTS technology in (1.1), totally differentiating the zero profit conditions in the final good sector X and dividing through by the product price gives $dP_X X / P_X + dX = q_C dC_X/P_X + (q_D+t_D)dD_X/P_X + dt_D D_X/P_X + dL_X/P_X$. Also, totally differentiating (1.1) and combining with the first-order conditions ($\partial X/\partial L_X = 1/P_X$, $\partial X/\partial C_X = q_C/P_X$, and $\partial X/\partial D_X = (q_D+t_D)/P_X$) yields $dX = (q_C/P_X)\, dC_X + [(q_D+t_D)/P_X]\, dD_X + (1/P_X)\, dL_X$. These two relationships imply that $dP_X X/P_X = dt_D D_X/P_X$, finally yielding the expression for X (for Y, the same procedure applies). Note here that $dq_C = dq_D = 0$ since the marginal product of labor (numeraire) in each of the two intermediate industries is assumed to be constant in our model (see footnote 14 above).

$$P_X \frac{dX}{dt_D} + P_Y \frac{dY}{dt_D} = t_D \frac{dD}{dt_D} - \frac{dl}{dt_D}. \tag{1.11}$$

Substituting (1.11) into (1.9a) and collecting terms offers the following 'double dividend' components (in dollars) in a second-best world:

$$\frac{1}{\lambda}\frac{dU}{dt_D} = -\tau_P \frac{dD}{dt_D} + \left(t_D \frac{dD}{dt_D} + t_L \frac{dL}{dt_D} \right), \quad \text{where } \tau_P \equiv -\frac{1}{\lambda}\frac{\partial U}{\partial Q} Q'(D). \tag{1.12}$$

Here, τ_P represents the first-best Pigouvian tax level that fully internalizes the marginal external damage (MED) from *D*. While the first term ($-\tau_P dD/dt_D$) in the right-hand side in (1.12) implies the (marginal) *environmental welfare gain*, the other two terms, $t_D\, dD/dt_D$ and $t_L\, dL/dt_D$, can be referred to as the (marginal) "*non-environmental welfare effects*" (but distortionary).[24] Notice here that the third term ($t_L dL/dt_D$) is the (marginal) *policy-swap effect*, including both the revenue recycling and tax interaction effects stemming from the revenue-neutral tax swap. This third term is more complicated to interpret because this extra component of the revenue-neutral swap might be ambiguous in the real world. In a first-best world with no other taxes, the social optimum can be achieved obviously where t_L = 0 and t_D = τ_P (= MED). However, with pre-existing

[24] Alternatively, the first and second term ($= -\tau_P dD/dt_D + t_D\, dD/dt_D$) in the right-hand side in (1.12) is the (marginal) *primary welfare gain*, representing the effects of a corrective tax on the externality-generating intermediate goods, *D*. This 'primary welfare gain' actually captures the 'environmental welfare gain' ($-\tau_P dD/dt_D$) *net* of the primary resource cost ($t_D\, dD/dt_D$). (Even if it is beyond the optimum value, an increase in t_D yields a better environment, -(*MED*) dD/dt_D.)

distortionary taxes, the policy instru-ment would need to account for other distortions.

To unravel this, focus on this third term, the *policy-swap effect*. It compounds the recycling of additional tax revenue and interactions among taxes. In order to establish the sign and magnitude of this term, we define the following concept relating to the burden from the preexisting labor tax. This concept will be especially useful in expressing the interaction effect between newly-introduced taxes and pre-existing taxes, as discussed in the literature by Parry (1995), Hakonsen (1998), and Goulder and Williams (1999). As used in these earlier works, first, define

$$M \equiv \frac{-t_L \partial L / \partial t_L}{L + t_L \partial L / \partial t_L}. \qquad (1.13a)$$

This M is the (partial equilibrium) efficiency cost per additional dollar of labor tax revenue raised to finance government consumption expenditure. Further, it can also be expressed as:

$$M = M(t_L, \varepsilon^U) = \left[1 - [t_L/(1-t_L)]\varepsilon^U\right]^{-1} - 1, \qquad (1.13b)$$

where ε^U is the uncompensated labor supply elasticity with respect to the net wage rate. Then, as in that earlier literature, the *marginal cost of public funds* (MCPF) equals M plus one, that is, the additional deadweight loss from the distortionary tax plus the direct cost of removing a dollar from the private sector.[25]

Totally differentiate the government budget constraint (1.4) to decompose the policy-swap effect, set $dG = 0$, and use (1.7) and (1.8) to obtain

$$\frac{dt_L}{dt_D} = -\frac{D + t_D dD/dt_D + t_L \partial L/\partial t_D}{L + t_L \partial L/\partial t_L} = -\frac{(1+M)}{L}\left\{D + t_D dD/dt_D + t_L \partial L/\partial t_D\right\} \quad (1.14)$$

Next, use (1.13) above and the relationship (1.14) between dt_L and dt_D, and substitute the Slutsky equations and symmetry property, where additional emissions tax revenue is replaced through cuts in marginal preexisting labor tax rates and government spending is held constant. Then, the third term, the *policy-swap effect*, in (1.12) can be expressed as:[26]

$$t_L \frac{dL}{dt_D} = M\left(\frac{dD}{dt_D}\right)t_D + MD\phi \qquad \text{in the emissions tax case;} \qquad (1.15a)$$

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25 If the preexisting labor tax rate t_L is positive and labor supply is not backward bending ($\varepsilon^U > 0$), then $M > 0$ and, therefore, the MCPF > 1.

26 Using (1.13a) and (1.14) into the second term of (12) yields $t_L\ dL/dt_D = t_L\ \partial L/\partial t_D + t_L(\partial L/\partial t_L)(dt_L/dt_D) = M\ (D + t_D\ dD/dt_D) - ML\{(\partial L/\partial P_X)(D_X/D) + (\partial L/\partial P_X)(D_Y/D)\}/(\partial L/\partial t_L)$. Substituting the Slutsky equations into the last term, making use of the Slutsky symmetry property and rearranging in terms of t_D, we obtain (1.15). In this case, note that total differentiation of (1.2), on the same level of subutility $V(X, Y, l)$, gives $\partial L^c/\partial t_L = -[P_X/(1-t_L)][\partial X^c/\partial(1-t_L)] - [P_Y/(1-t_L)][\partial Y^c/\partial(1-t_L)]$; and, from the Slutsky symmetry property, $\partial L^c/\partial P_X = \partial X^c/\partial(1-t_L)$ and $\partial L^c/\partial P_Y = \partial Y^c/\partial(1-t_L)$, where superscript c denotes a compensated price effect. For similar derivations in other studies, see Parry et al. (1999) and Goulder and Williams (1999).

$$t_L \frac{dL}{dt_D{}^v} = t_\Pi M\left(\frac{dD}{dt_D{}^v}\right) t_D{}^v + MD(\phi + t_\Pi - 1) \quad \text{in the quota case,} \quad (1.15b)$$

where

$$\phi = \phi(\varepsilon^c_{X\ell}, \varepsilon^c_{Y\ell}, \eta; s_X, h_X) \equiv \left[1 - \frac{h_X \varepsilon^c_{X\ell} + h_Y \varepsilon^c_{Y\ell} + \eta}{s_X \varepsilon^c_{X\ell} + s_Y \varepsilon^c_{Y\ell} + \eta}\right] = \frac{(s_X - h_X)(\varepsilon^c_{X\ell} - \varepsilon^c_{Y\ell})}{s_X \varepsilon^c_{X\ell} + s_Y \varepsilon^c_{Y\ell} + \eta}.$$

Here, ε^c_{Xl} and ε^c_{Yl} are compensated cross elasticities of demand for *X* and *Y* with respect to the price of leisure; η is the income elasticity of labor supply; h_X ($=D_X/D$) and h_Y ($=D_Y/D$) are each sector's share of total pollution-generating intermediate goods *D* in the structure of production; and s_X ($= P_XX/(P_XX+P_YY)$) and s_Y ($= P_YY/(P_XX+P_YY)$) are the expenditure shares of the *X* and *Y* in the value of total output.[27] Notice that $\phi = \phi$ (ε^c_{Xl}, ε^c_{Yl}, η; s_X, h_X) incorporates both the structures of production technology and preferences and the cross-price effects of final consumption goods with leisure, while $M = M$ (t_L, ε^U) reflects the pre-existing labor distortion in this equation. Now, this term ϕ can be referred to as a measure reflecting the difference between the cross-price effects with leisure.[28] For example, ϕ equals zero when *X* and *Y* are equal substitutes for leisure (ε^c_{Xl} equals ε^c_{Yl}). Further, if h_X is greater than s_X (*X* is relatively dirty), then ϕ is greater

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[27] The last equality after (1.15b) follows because $S_Y = 1-S_X$ and $h_Y = 1-h_X$.

[28] The term ϕ can be interpreted as the *degree of relative complementarity* between pollution-intensive consumption and leisure, as in the literature. More generally, it reflects how much the average good produced from the taxed polluting intermediate good (weighted by input shares) is *more* of a complement to leisure than the average consumption good (weighted by expenditure shares). In fact, ϕ varies "significantly" with the differences in the structural and behavioral parameters of country-specific consumption and production patterns.

than zero when X is a complement or weaker substitute for leisure than Y (ε^{c}_{Xl} is less than ε^{c}_{Yl}), and otherwise is less than zero. Note here that environmental regulation on the polluting intermediate goods affects the labor/leisure decision "indirectly," and the non-separable labor supply effects depend on the complementarities with leisure of the consumption goods that are "produced from" the intermediate goods.

Much of the double-dividend debate hinges on whether the *policy-swap effect* in (1.15) is positive such that the use of a higher t_D (with revenue to cut t_L) would result in more labor supply and positive effect on utility in (12). As seen on the left-hand side of (1.15), this *policy-swap effect* is a linear function of t_D (or t_D^v). The sign of the coefficient (=slope) on t_D (or t_D^v) in the first term on the right-hand side is negative, and the sign of the intercept in the second term is ambiguous since ϕ is only in the intercept. Note that the (partial) derivative of the *policy-swap effect* of each regulatory instrument in (1.15) with respect to the environmental tax rate does not depend on the relative complementarity between pollution-intensive goods and leisure (ϕ). In this case, the negative *policy-swap effect* would be generated for any levels of environmental regulation, as long as the intercept term is not positive.[29] In prior papers, separability implies that final

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[29] We can also decompose the *policy-swap effect* (1.15) that stems from revenue-neutral tax swap into the following two components:

$$t_L\, dL/dt_D = M\,(D + t_D dD/dt_D) - MD(1-\phi) \quad \text{in the emissions tax case;} \qquad (1.15a')$$

$$t_L\, dL/dt_D^{\,v} = t_\Pi M\,(D + t_D^{\,v}\, dD/dt_D^{\,v}) - MD(1-\phi) \quad \text{in the quota case,} \qquad (1.15b')$$

where, as in the literature, the *revenue-recycling* component is in the first term and *tax-interaction* component is in the second. In these terms, if the latter component outweighs the former, then the *policy swap effect* would be negative.

goods X and Y have equal cross-price elasticities with leisure, and so $\phi = 0$, the intercept term is zero, and the *policy-swap effect* is necessarily negative. In such a case, raising t_D cannot generate positive non-environmental effects.

Comparing the two regulatory instruments in (1.15), we can observe that non-auctioned quotas would be less efficient than emissions taxes, unless the policy-generated rents are fully taxed ($t_\pi = 1$) or the quotas are sold by government at a price of t_D^v. Without full capture of rents, the government may need to raise the labor tax more and exacerbate the labor market distortion. In (1.15b), the efficiency effect of recycling revenue under the emissions quota is the fraction t_π of that under the emissions tax, since it is indirectly generated only through the taxation of quota rents.[30] This implies that differences in efficiency outcomes of emissions taxes and quotas arise from how the policy-generated scarcity rents are absorbed and recycled by the government, as well as from the costs of pre-existing tax distortions.

1.3 Optimal Second-best Tax Rates

Even though the degree of substitution with leisure plays a critical role in designing the optimal tax structure, most analytical and numerical studies in the literature are based on (weakly) separable preferences between goods and leisure

30 The M (or MCPF) in (1.15b) is different from that in Parry et al. (1999), since increasing t_L affects tax revenues from only labor income. They assumed that rent income is taxed at the *same* rate as labor income.

and homothetic preferences over consumption goods together.[31] In these earlier studies, the optimal second-best tax rate is typically around 70 - 80% of the first-best Pigouvian tax rate (MED), since the cost that is recognized as "tax-interactions" always outweighs the benefit from revenue-recycling.[32]

Under the ordinary case with $\varepsilon^c_{Xl} > 0$ and $\varepsilon^c_{Yl} > 0$ in (1.15), we can impose some separability assumptions on household utility (1.3), as in most earlier studies. For example, assume that $F(X, Y)$ is an aggregate of X and Y that is separable from leisure, l, such that $U = U(\ V(\ F(X, Y), l), G, Q)$ as in much of that literature. Then X and Y are equal net substitutes for leisure (i.e., $\varepsilon^c_{Xl} = \varepsilon^c_{Yl}$). Those assumptions imply $\phi = 0$. In this restricted case, the tax-interaction effect in (1.15') equals M times D regardless of the value of s_X and h_X, and thus the total *policy-swap effect* is just M (dD/dt_D) t_D. Hence, the *policy swap effect* is always negative when t_D is positive. Solving for the second-best optimal pollution tax in (1.12) gives

$$t_D^{\ *} = \frac{\tau_P}{(1+M)}, \quad \text{where } \tau_P = MED \equiv -\frac{1}{\lambda}\frac{\partial U}{\partial Q}Q'(D), \tag{1.16}$$

as noted by the prior literature on this issue (e.g., Sandmo, 1975; Bovenberg and van der Ploeg, 1996; Bovenberg and Goulder, 1996). Since $M > 0$, the optimal

31 Weak separability means that changes in the price of leisure do not affect the allocation of consumption over different commodities. The homothetic sub-utility implies linear Engel curves and all unitary expenditure elasticities for private consumption commodities.

32 For more details, see Bovenberg and de Mooij (1994), Goulder (1995), Parry (1995), Bovenberg and van der Ploeg (1996), and Bovenberg and Goulder (1996, 2001). Their key point behind these results is that the optimal tax rates depart from the Pigouvian rates to the extent that the MCPF differs from unity.

emissions tax is always less than the first-best Pigouvian level, that is, $t_D{}^* < \tau_P$(= MED).

In general, however, ϕ is not restricted to zero. The optimal level of environmental regulation could be affected by the structural parameters of preferences and technology as well as pre-existing tax distortions. The *policy-swap effect* term in (1.15a) has negative slope, as a function of t_D, and ambiguous intercept, which depends on ϕ. Further, using (1.15a), we can also express the welfare impact in (1.12) with respect to t_D as:

$$\frac{1}{\lambda}\frac{dU}{dt_D} = -(1+M)\left(-\frac{dD}{dt_D}\right) t_D + MD\phi + \left(-\frac{1}{\lambda}\frac{\partial U}{\partial Q}Q'(D)\right)\left(-\frac{dD}{dt_D}\right), \quad (1.17)$$

where the sign of the coefficient on t_D in the first term on the right-hand side is negative and the sign of the intercept in the second term is ambiguous. Set (1.17) equal to zero to find the level of optimal regulation as:

$$t_D{}^* = \frac{MD\phi + \tau_P(-dD/dt_D)}{(1+M)(-dD/dt_D)} = \frac{\tau_P}{1+M} + \frac{MD(-\phi)}{1+M}\frac{1}{dD/dt_D}. \quad (1.18)$$

Here, adding on the primary welfare cost due to the environmental tax's distortion on labor, $\tau_P/(1+M)$, the second-term term on the far right-hand side in (1.18) accounts for the secondary welfare cost, compounded by the economy's key behavioral characteristics such as the preference and technology parameters in ϕ. Now, let $\varepsilon_D\left(\equiv -(dD/dt_D)(t_D/D)\right)$ be the (aggregate) demand elasticity for the polluting intermediate inputs D with respect to its tax rate.[33] Then we can further rearrange the optimal second-best tax rate on polluting intermediate goods in (1.18) as:

$$t_D^{\ *} = \frac{\tau_P}{(1+M)\left(1 - \frac{M\phi}{1+M}\frac{1}{\varepsilon_D}\right)} = \frac{\tau_P}{1+M\left(\frac{\varepsilon_D - \phi}{\varepsilon_D}\right)} \equiv \Omega\tau_P, \qquad (1.19)$$

where $\Omega \equiv \left[1 + M(\varepsilon_D - \phi)/\varepsilon_D\right]^{-1}$. This term Ω can be interpreted as the inverse of the *modified MCPF*. It depends on: (i) the marginal efficiency cost, $M = M(t_L, \varepsilon^U)$, which depends on both the pre-existing tax rate on labor, t_L, and the uncompensated labor supply elasticity, ε^U, (ii) the relative degree of complementarity between output from the polluting sector and leisure, ϕ, and (iii) the aggregate demand elasticity for the polluting intermediate inputs into production, ε_D.[34]

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33 Embedded in this parameter, the environmental tax on polluting intermediate goods has a *substitution effect* that reduces pollution per unit of output of each good (which depends on technologies), and an *output effect* that reduces the level of output of each good (which depends on how the change in t_D affects the price of D and on the price elasticities of demand for the two outputs).

34 In emissions quota case for (1.12) and (1.15b'), the same procedure as in (1.17) and (1.18) gives the analogous expression for the optimal second-best level of emissions quota on polluting intermediate goods, in terms of the corresponding 'virtual tax':

$$t_D^{\ v}* = \frac{\tau_P}{(1+t_\Pi M)\left(1 + \frac{M(\phi - t_\Pi)}{1+t_\Pi M}\frac{1}{\varepsilon_D}\right)} = \frac{\tau_P}{(1+t_\Pi M) + M(\phi - t_\Pi)\frac{1}{\varepsilon_D}} \equiv \Omega^v\tau_P, \qquad (1.19')$$

As demonstrated in (1.19), the optimal environmental tax depends substantially on the relative degree of substitution between the dirty output and leisure (ϕ) *and* on the aggregate demand elasticity for the taxed polluting intermediate inputs (ε_D), as well as on the pre-existing labor market distortion (t_L). As in the prior literature, the optimal (second-best) tax rate is primarily adjusted downward when divided by (1+M), to account for the pre-existing tax on labor income. However, it is further adjusted in our model, to allow for the behavioral interactions among preference and technology parameters in ϕ, the elasticity parameter ε_D, and the pre-existing distortion M.

In particular, we can easily know in (1.19) that since $\varepsilon_D > 0$, then $t_D^* < \tau_P$ if $\phi < \varepsilon_D$. In other words, the usual result that $t_D^* < \tau_P$ does *not* require that $\phi \leq 0$ (i.e., that X is not a relative complement to leisure), but only that $\phi < \varepsilon_D$. The dirty input (D) might still be taxed less than MED even if $\phi > 0$, just so long as ϕ is not greater than ε_D. On the contrary, $t_D^* > \tau_P$ if $\phi > \varepsilon_D$. Therefore, the *generalized second-best optimal policy rule*, (1.19), also reveals that the possibility of whether t_D^* is below or above τ_P hinges critically on the parameter relationships of preferences and technology, rather than the size of the pre-existing tax distortion (t_L).[35]

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where $\Omega^v \equiv \left[(1+t_\Pi M) + M(\phi - t_\Pi)/\varepsilon_D\right]^{-1}$. Comparing (1.19') with (1.19), one will observe that the quotas do not yield the same welfare effects as the taxes, unless the policy-generated rents are fully taxed (t_π=1) or the quotas are sold by government at a price of t_D^v.

[35] Note that much of the prior literature has argued that this possibility (or the associated existence of a double dividend) depends critically on the role of pre-existing other distortionary taxes. However, according to our result in (1.19), the welfare consequences from environmental tax reform could vary significantly across countries, with the country-specific characteristics in the

1.4 INTERPRETATION OF THE ANALYTICAL RESULTS

The result from the previous section shows the critical role of the relationship between complementarities or non-separabilities (in the structure of preferences and technology) and the configuration of optimal tax rates, as invoked in Corlett and Hague (1953) and Deaton (1981).[36] This consideration is of great importance for the explorations of the controversial hypothesis regarding whether the optimal tax on pollution in a second-best world is higher or lower than the social marginal damages of pollution. This question, as an important political issue in the environmental tax reform debate, has attracted a great deal of attention over the past decade in the economics literature.

In this model, the sign of the *policy-swap effect* of tax reforms in (1.15) is closely related to determining the relationship between the optimal environmental tax rate, t_D,* and the social marginal damages, τ_P. Equation (1.19) shows how this relationship depends on preference and technology parameters in both ϕ and ε_D. To demonstrate this graphically, Figure 1 shows ϕ on the vertical axis and ε_D on the horizontal axis. The solid 45-degree line with positive slope in this figure represents the com-binations of these two parameters where t_D^* is exactly the social marginal damages, τ_P.

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structure of preferences and production technology (i.e., *not* just with the country-specific nature of prior tax distortions).

36 As implied in Corlett and Hague (1953), Sandmo (1976), and Hanemann and Morey (1992), the separability assumption (focused on the complementarity with leisure) can result in misleading conclusions concerning the impact of price changes on welfare, because changes in the prices and expenditure bring about overall reallocations between labor supply and individual consumption patterns.

Theoretically, in the upper portion of Figure 1, a modest set of combinations of the key parameters where $\phi > \varepsilon_D$ generate the cases where $t_D^* > \tau_P$ (since the *modified MCPF* < 1 or $\Omega > 1$ in (1.19) regardless of the degree of pre-existing tax distortion, *M*).[37] On the other hand, if $0 < \phi < \varepsilon_D$, then $t_D^* < \tau_P$ (note that here $t_D^* < \tau_P$, even though $\phi > 0$). This implies that for reasonable parameter values, the second-best tax on pollution is *not* necessarily higher than the social marginal damages, even when the dirty output is more of a complement to leisure. Finally, it could also be that the pollution-intensive good is more of a leisure substitute than the average good ($\phi < 0$), in which case the cost of environmental regulation is even higher than the prior literature suggests ($t_D^* << \tau_P$).

The conventional result in the prior literature with homothetic separability (eq. 1.16) is restricted to the case where the pollution-intensive good is an *average* substitute for leisure ($\varepsilon^c_{Xl} = \varepsilon^c_{Yl}$) and thus $\phi = 0$. In this case, optimal emissions tax rates are always below the rates suggested by the Pigouvian principle (i.e., *modified MCPF* > 1, or $\Omega < 1$), even when revenues from emissions taxes are employed to cut other distortionary taxes. Specifically this corresponds to the dotted horizontal line in Figure 1.1.[38]

[37] The necessary assumptions are that the pollution-intensive good *X* is a weaker-than-average substitute for leisure or a relative complement to leisure ($\phi > 0$), *and* that the intermediate demand for dirty inputs is somewhat inelastic.

[38] Examples include Bovenberg and de Mooij (1994), Bovenberg and Goulder (1996), Fullerton (1997), Goulder et al. (1997, 1999), Fullerton and Metcalf (2001), and Parry et al. (1999) among many others.

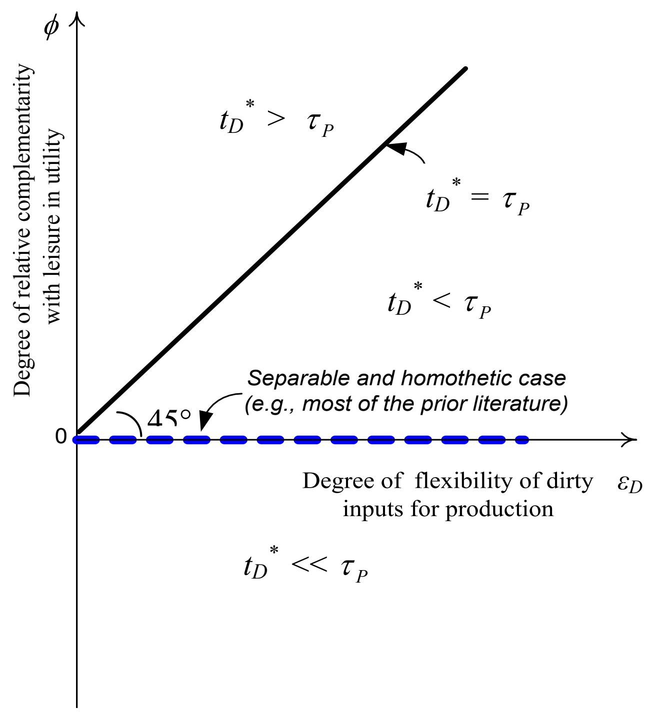

Figure 1.1 Optimal Environmental Taxation in the Behavioral-Parameter Space

However, without clear evidence that labor supply and commodity demands are separable, any welfare cost estimates that assume separability are not fully general. Note that the null hypothesis of separability of leisure from consumption is usually rejected in the econometric literature. Since the responsiveness of consumer and producer behavior to changes in after-tax prices is the main determinant of the size of the welfare cost, it is crucial in policy evaluation how we set out the assumptions on the structure of preferences and technology in an economy. When we relax the separability assumptions, the analytical result of (1.19) explicitly shows that the question of whether the second-best pollution tax is higher or lower than the social marginal damages is inconclusive. Figure 1 illustrates how the answer to the above question depends on the combinations of two key summary parameters, ϕ and ε_D (assuming that the government is on the normal side of the Laffer curve for taxation).[39] In this case, only the relative size of the two key parameters matters. Contrary to the impression given by much of the literature, this result also shows that the answer is *independent* of the presence of pre-existing tax distortions, M. That is, whether t_D^* is above or below τ_P does *not* depend on the size of t_L, if t_L is not zero.

[39] The definition of ϕ in (1.15) shows how it summarizes other preference and technology parameters. Also, ε_D depends on substitution technology in production, and indirectly on preference parameters such as the elasticities of demand for any product that uses D in production. On the other hand, where the Laffer curve is downward-sloping, the model in this paper is not stable. Therefore, this paper assumes that Ω must be positive to ensure that the government is on the normal side of the Laffer curve for taxation. The condition for this is $\phi / \varepsilon_D < (1+M)/M$. Note also that the plausible value for M is about 0.3 or less (as will be discussed in Section 1.2.5).

Note also that the area of each region on this parameter-space in Figure 1 does not represent the probability of whether t_D^* is greater or less than τ_P (unless the probability distribution is 'uniform' on this space). To determine the likelihood that t_D^* exceeds τ_P, the probability distribution of the relevant parameter values would need to be empirically estimated. Moreover, some numerical experiments using econometrically estimated CGE models or Monte Carlo simulation studies would be especially useful to quantify the "empirical" significance of the non-separable structure of preferences and technology, and to explore how much the point estimate for t_D^* in (1.19) deviates from the separable case.[40]

In short, the role played by the non-separable structure of preferences and technology is clarified here, concerning the controversial second-best taxation issue. Relative to the existing literature, the pre-existing tax distortion (t_L or M) does not play a critical role in determining whether or not the optimal pollution tax is below the first-best rate. However, note that the degree of pre-existing distortions still matters for the absolute size of the (positive or negative) deviation between the second-best rate and the first-best Pigouvian rate. The results indicate that the importance of the behavioral responses and characteristics in an economy should not be underemphasized relative to the pre-existing conditions for the initial tax system. In practice, this consideration would be especially important in

40 To do this, we can use 'flexible functional form' techniques (*i.e.*, techniques that do not impose *unwarranted* priori restrictions on elasticities of substitution between the outputs or inputs in models of consumer and producer behavior). For this kind of applications, see Jorgenson and his co-author's works, Hazilla and Kopp (1990), Diewert and Lawrence (1996), and McKitrick (1998).

extrapolating the implications from one country-specific analysis to another country.

1.5 SOME NUMERICAL EXAMPLES (SENSITIVITY ANALYSIS)

The preference structure in the utility function (1.3) allows for a variety of different assumptions about the cross-price elasticities for final consumption goods with respect to leisure and the labor supply elasticity. Also, the share of pollution-intensive consumption in total consumption can vary in (1.15). Thus, it would be interesting to see how sensitively the optimal second-best tax rates responds to the key preference and technology parameters. This section presents some illustrative numerical results.

First, consider some plausible magnitudes for the parameters in (1.19) from the empirical literature. For the United States, the plausible parameter values we adopt are t_L = 0.4, and ε^U between 0.1 and 0.3.[41] Then the pre-existing labor distortion parameter M is between 0.07 and 0.25. For ε_D, the demand elasticity for polluting intermediate inputs with respect to the tax rate t_D, we again use values of between 0.1 and 0.3. These span a range somewhat broader than most empirical estimates.[42]

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[41] The values we adopt are from the relevant literature such as Stuart (1984), Browning (1987), Russek (1996), and Fuchs, Krueger and Poterba (1998).

[42] In the case of energy as a polluting intermediate input, most estimates for the own-price demand elasticity in the literature are (slightly) below unity (e.g., Pindyck, 1979; Berndt and Wood, 1979; Griffin and Gregory, 1981; Jorgenson and Wilcoxen, 1993). We take a value between 0.5 and 1.5 for the price-elasticity $(dD/dt_D)(1+t_D)/D$ from the literature. We then multiply by the tax-inclusive tax rate, $t_D/(1+t_D)$ to get ε_D, since ε_D in our model is a tax-elasticity. If t_D is about 0.2 in the U.S., then $t_D/(1+t_D)$ is 1/6, so the corresponding ε_D in (1.19) would range at most between 0.1and 0.3.

Figure 1.2 displays the sensitivity of the optimal second-best tax rate to a plausible range of values for the three key behavioral parameters: i) the relative degree of complementarity between pollution-intensive goods and leisure (ϕ), ii) the aggregate demand elasticity for polluting intermediate inputs in production (ε_D), and iii) the uncompensated labor supply elasticity (ε^U). These cases all use the same pre-existing labor tax rate, $t_L = 0.4$. The vertical axis represents the ratio of the optimal second-best tax to the Pigouvian tax ($= t_D^* / \tau_P$), which corresponds to the inverse of *modified MCPF*, Ω, in (19). In the second-best world of this model, ϕ substantially affects the welfare change from the tax system through the policy swap effect, while ε_D primarily reflects the marginal cost of environmental regulation in production. According to our numerical results, the optimal environmental tax rates under interactions with the pre-existing tax system are highly sensitive to the plausible values for the key parameters of the economy.

To maximize social welfare, Figure 1.2a and Figure 1.2b show that ϕ and ε_D plays a more crucial role in determining whether Ω is greater than unity. Furthermore, Figure 1.2b demonstrates the importance of non-separability in the household utility function: the *lower* the aggregate demand elasticity (ε_D) for the polluting inter-mediate goods, the *more important* is non-separability in the utility function (ϕ). In other words, the optimal tax rate on polluting intermediate goods depends on ε_D (but only if leisure is non-separable). If ε_D gets sufficiently large (*e.g.*, due to substitution into other intermediate inputs, or induced technological change in production), however, then both equation (1.19) and Figure 1.2b show that the optimal environmental tax rate is not so sensitive to ϕ.

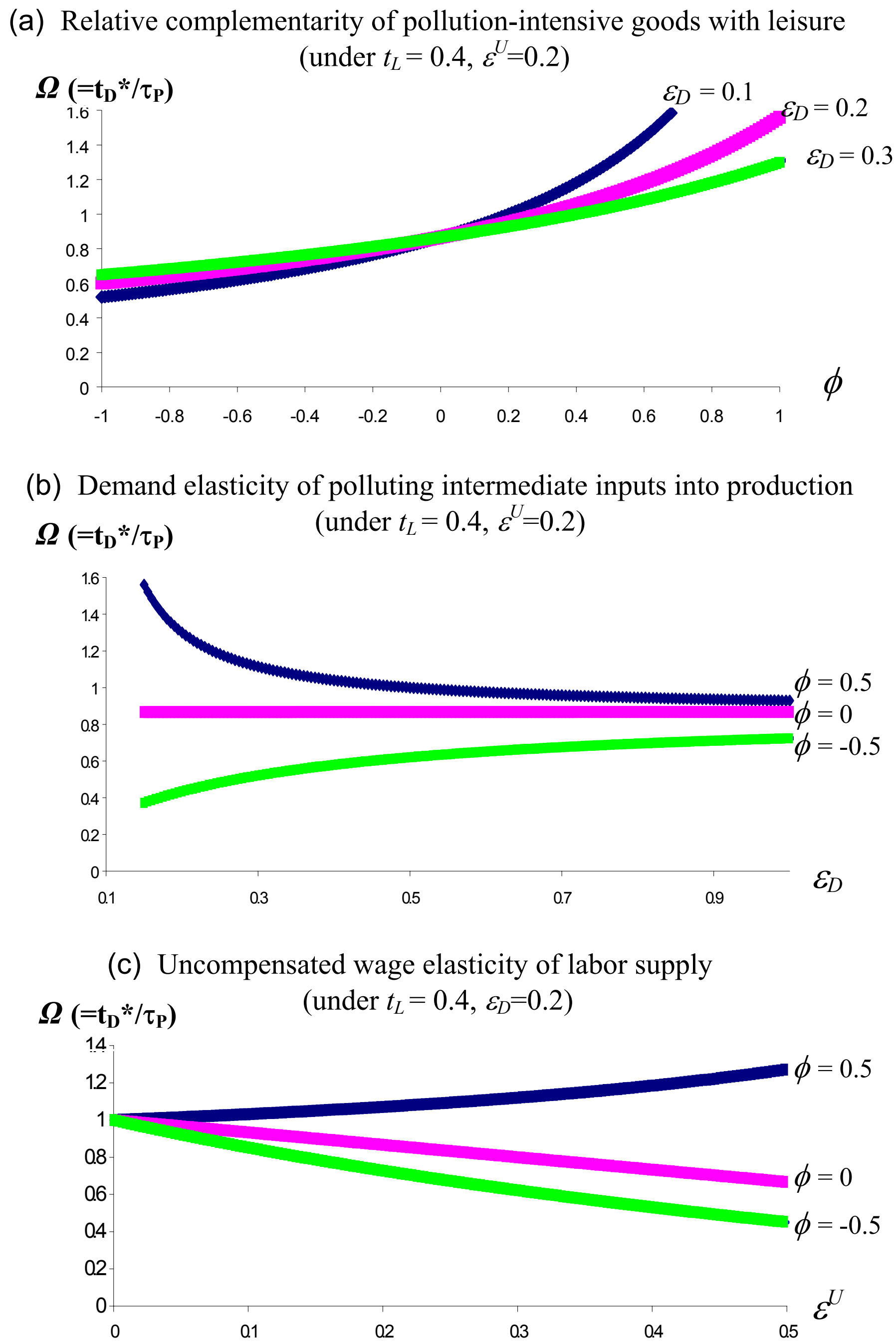

Figure 1.2 Sensitivity Analysis

Figure 1.2c indicates that larger ε^U contributes to additional welfare loss, stemming from the environmental regulation's impact on labor supply as a result of higher output prices and a reduction in the real net wage (e.g., where $\phi \le 0$). In this case, as the supply of taxable labor becomes more responsive to the real net wage, then t_D^* is less than τ_P because the environmental regulation tends to reduce social welfare.

Where the pollution-intensive good is a strong complement to leisure ($\phi > \varepsilon_D$), however, then t_D^* is above τ_P (see the case where $\phi = 0.5$ in Figure 1.2c). When X is a sufficiently stronger complement to leisure, the effect of the higher output price of the dirty good X is to discourage purchase of leisure — that is, to encourage labor supply.

On the other hand, the numerical results of Figure 1.3 illustrate the combined effects of complementarity with leisure (ϕ) and pre-existing distortions (M) on optimal environmental tax rates in a second-best setting. Each curved line in this figure depicts a contour for a particular value for Ω (= the ratio t_D^* / τ_P), *where* ε_D is 'fixed' at 0.2. Higher values for this ratio generally correspond to higher values of ϕ on the vertical axis.

The dotted horizontal line across the middle represents the case of homothetic and weakly separable utility (i.e., ϕ is fixed at zero). Along this horizontal axis, Ω falls as M rises. However, if we consider the whole space in Figure 1.3, where ϕ varies (but ε_D is fixed at 0.2), then Ω could be less sensitive to M. For instance, where ϕ is also 0.2, the contour is a horizontal solid line that has $\Omega = 1$ regardless of the degree of pre-existing tax distortion (M). For values of ϕ between 0 and 0.2, the second-best tax on pollution lies *below* the social marginal damages (i.e., $\Omega < 1$) even when the dirty output is more of a complement to leisure. On the other hand, for values of ϕ above 0.2, Ω rises as M rises, in which case a greater labor market distortion in the initial tax system (M) *increases* the optimal level of environmental regulation.[43]

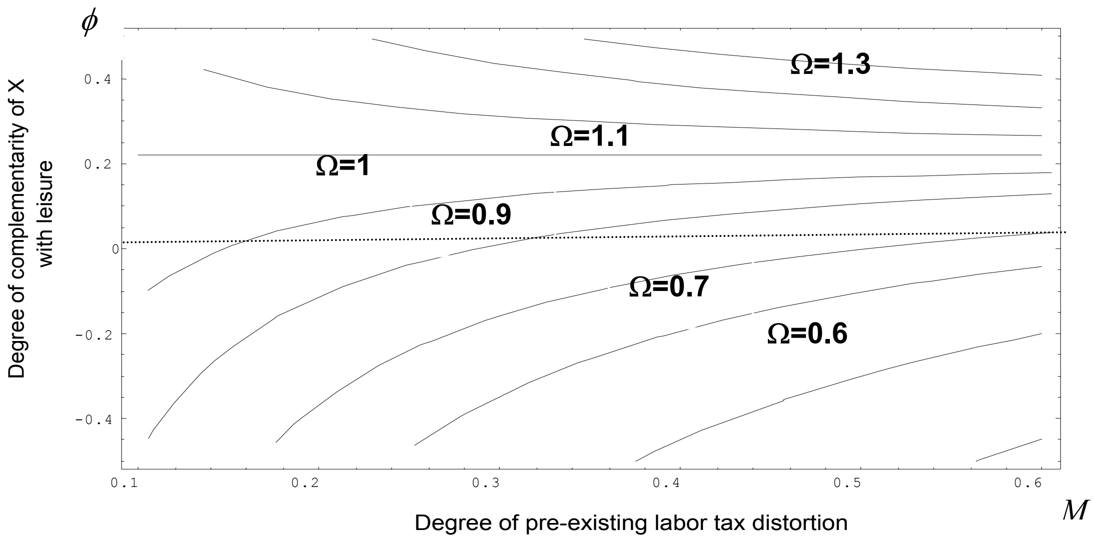

Figure 1.3 Effects of Complementarity with Leisure and Pre-existing Distortions on Optimal Environmental Tax Rates in a Second-Best Setting (under ε_D=0.2)

43 For example, in the literature on agricultural and environmental economics, agricultural outputs and some other leisure-intensive goods (or services) are often considered as belonging to the case with high ϕ, which implies that revenue-neutral tax increases on environmentally-harmful inputs (e.g., fertilizers, chemicals, or wastes) could produce a double dividend. Depending on where an economy is initially located in Figure 1.3, the welfare effects from these specific environmental tax swaps are critically dependent on the slope (or gradient) of the contours (evaluated at the initial starting point of the economy).

1.6 CONCLUSION

Recent studies have suggested that the pre-existing tax distortions in some factor markets play a crucial role in determining the possibility that a tax swap can really increase social welfare. According to this now-extensive literature, the second-best level of environmental taxation typically lies below the first-best Pigouvian level (social marginal damages), unless the uncompensated labor-supply elasticity is negative.

Using a stylized analytical general equilibrium model, this paper extends the emerging literature on optimal environmental regulation in a second-best world. Relative to the previous studies, it explores how the second-best optimal policy rules for environmental taxes and quotas should be set in the presence of other distortionary taxes, relaxing traditional separability assumptions and incorporating general equilibrium interactions between pollution abatement and other economic activities.

The analysis shows that complemetarities or non-separabilities in the structure of preferences and technology play an important role in determining whether the second-best optimal tax on pollution is higher or lower than the Pigouvian rule. One of the main findings of this paper is that the size of pre-existing tax distortions does *not* affect whether the optimal environmental tax rate lies above or below the Pigouvian tax rate — a question that has been a focal point in the recent literature. It also implies that the possibility of double dividends from new environmental taxes could differ markedly across countries, due to country-specific consumption and production patterns (rather than due to the country-specific nature of other pre-existing taxes). In this respect, studies that focus solely on the role of pre-existing tax distortions could be misleading. Future empirical work in this area would be especially useful for policymakers to be able to predict the welfare consequences of new environmental taxes in their countries.[44] Specifically, as mentioned in Section 1.4, this paper clearly suggests the desirability of further experimentation to find out how preferences and technology in the real world deviate from separability assumptions and, thus, how the second-best optimal rules (or point estimates) should change.

The analysis here also indicates that for reasonable parameter values and tax rates, it is possible to have a welfare gain (even if it is a modest welfare gain) from a revenue-neutral environmental regulation reform, where the current tax rate on pollution is below the optimal rate. If the dirty output is a relative complement to leisure, and if the intermediate demand for the taxed polluting inputs is somewhat inelastic, the presence of greater labor distortion in the initial tax system could even raise the welfare gains from environmental tax reform (the optimal pollution tax rises rather than declines with a rise in the marginal cost of public funds). On the other hand, it should also be noted that, in some cases, the second-best tax on pollution is not necessarily higher than the social marginal damages, even when the dirty output is more of a complement to leisure.

General equilibrium, second-best considerations have yielded important policy implications for environmental protection, incorporating the method of

44 It could be done by estimating all of the relevant key structural and behavioral parameters for a particular pollutant by each country, and incorporating them into the generalized second-best optimal rule, equation (1.19).

revenue recycling, the tax interactions with pre-existing distortions in other markets, and the coverage of environmental instruments. This study demonstrates how the Ramsey formula, as a general principle, should be further altered to account for interactions between the key behavioral parameters and the pre-existing distortions in the economy. In particular, the policy scope and implications can be fundamentally changed when we allow for a broad range of economy-wide effects of pollution abatement policies that interact with the distortionary cost of pre-existing taxes in an economy with a non-separable structure of preferences and technology.[45]

To mention some limitations to this paper, it relies on some standard simplifying assumptions about production technology and consumer behavior and thus could be further extended to consider the other effects such as dynamics of capital markets, imperfect competition, uncertainty, internationally-traded goods, and distributional consequences.

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45 The analysis here ignores distributional considerations by assuming the standard representative agent framework, as this procedure enables us to study the efficiency aspects of distortionary taxation in isolation from distributional issues. (In a world of identical consumers, distortionary taxation would in fact seem silly.) In a different light, Kaplow (1996) has questioned the Ramsey paradigm with distortionary taxation, arguing that if we properly tax with distribution and incentive compatibility, then in most cases the MCPF may be still one (as in the case where lump-sum taxation is feasible). In this context, if the offsetting tax adjustment to the income tax offsets both the benefits from correcting the externality and the incidence of the environmental tax, as he argues, then the conventional Pigou (1947)'s conjecture could be still valid.

Chapter 2: Optimal Environmental Investment and Taxation in a Model of Endogenous Growth with Distortionary Taxation [46]

2.1 INTRODUCTION

To ensure that economic growth and the preservation of environmental quality are compatible and socially optimal, it is crucial to understand the interactions among economic activities, technological progress, and ecological processes over time. Environmental policies for sustainable development may be more effective if technological progress in abatement knowledge responds to economic incentives. If so, how can environmental investment and taxation contribute to the productivity of private factors of production and to sustainable economic growth, and how much sustainable development can we expect from a 'clean development mechanism'?

This paper analyzes environmental policy measures within an endogenous growth model with pollution and endogenous accumulation of abatement knowledge. In this model, the economy produces a single final good, and it also accumulates productive assets by devoting some fraction of output to investments that include new abatement knowledge. Environmental quality, modelled as a stock of a renewable resource, acts not only as a public consumption good but also as a productive public input to production. Pollution is inevitable from

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production activities, but it can be reduced by increasing the stock of pollution abatement technical knowledge (e.g., clean technology) and by imposing environmental regulations on production activities (e.g., pollution standards, permit, or taxes).

Recent advances in endogenous growth theories have opened up the possibility of analyzing the growth effects of various policy changes in the long-run. Many endogenous growth models have physical capital, human capital, and non-reproducible inputs such as 'raw' labor, but environmental models can have other inputs that are supplied by nature.[47] In this respect, Bovenberg and Smulders (1995, 1996) extend the model of Lucas (1988) by incorporating two stocks that are "public" inputs to production: the environment and abatement knowledge. Using this endogenous growth model, they argue that a tightening of 'pollution standards' may boost growth, at least in the long-run. They derive optimal environmental policies for internalizing environmental externalities in a sustainable growth framework, but they assume that public environmental R&D activities that generate pollution abatement knowledge are financed through lump-sum taxation; other pre-existing distortionary taxes are not explicitly considered.

Yet it may be important to allow for government activities financed by distortionary taxation in a decentralized competitive market economy. Distortionary taxation can lead to a lower level of long-run per capita income (in the conventional neoclassical growth theory) or to a lower long-run growth rate

[47] Models with nature as an input include Xepapadeas (1993), Tahvonen and Kuuluvainen (1993), Gradus and Smulders (1993), Van Ewijk and Van Wijnbergen (1995), Elbasha and Roe (1996), Bovenberg and Smulders (1995, 1996), and Bovenverg and de Mooij (1997).

(in endogenous growth models). In particular, taxes on private capital income may distort both inter-temporal decisions and inter-asset decisions. As discussed in Rebelo (1991), Rebelo and Stokey (1995), and Jones and Manuelli (1997), taxes on total income or on income from capital lower the rate of saving and growth, while taxes on income from labor or on consumption do not.[48] In a second-best world with revenue requirements and no lump-sum taxes, the distortionary nature of taxes can affect the optimal environmental regulatory instruments. Also, the dynamic fiscal policy effects of shifting from taxes on private capital towards taxes on polluting inputs may be beneficial.

To incorporate the effects of a tighter environmental policy on long-run sustained growth and welfare, this paper uses a dynamic model of endogenous growth based on the joint accumulation of private capital and abatement knowledge capital. The model developed here is an extension of the models explored in Bovenberg and Smulders (1995, 1996), but it departs from their models in the following important ways. First, it allows for distortionary taxes on private capital income to finance both non-productive government spending and public investment in abatement knowledge. The model is thus capable of investigating the role of integrating environmental taxes and other distortionary taxes for optimal environmental and fiscal policy design. By doing so, it establishes the level of 'second-best' optimal environmental and fiscal policy rules under which sustained economic growth and the preservation of environmental quality are compatible and optimal. Second, it provides clear

[48] Taxes on income from labor or on consumption have level effects, but not growth effects.

economic conditions for the relationship between growth and welfare effects of a tighter environmental policy (both environmental investment and emission taxes) for sustainable development in a second-best world. To see the implications for optimal environmental policy rules in the U.S. economy, a numerical analysis is also presented for the case of global warming.

Consequently, our analysis yields some new insights into the growth and environment literature beyond what is obtainable in previous studies. First, unlike the usual growth and taxation literature (e.g., Barro and Sala-i-Martin, 1992, 1995), the rate of optimal environmental investment is greater than its own 'pure' output elasticity, to account for the premium associated with environmental sustainability. Second, contrary to the Bovenberg and Smulders (1995, 1996)'s results, this paper finds that public R&D spending on abatement knowledge may exceed the pollution tax revenues, thereby justifying additional distortionary taxes to finance this public expenditure. Third, under plausible parameter conditions, it could be that the positive long-run growth effects of a tighter environmental policy do not arise — even with endogenous technological progress in abatement technologies and the important productive role of environmental quality.

The rest of this paper is organized as follows. Section 2.2 sets up the model and describes the balanced-growth equilibrium path. Section 2.3 discusses optimal corrective government policies in steady state, with some numerical applications, and it examines growth and welfare effects of a tighter environmental policy in a second-best world. Section 2.4 contains some concluding remarks.

2.2 THE MODEL

This section presents a simple one-sector endogenous growth model with endogenous determination of pollution, environmental quality, and accumulation of private capital and pollution abatement knowledge. The economy produces a single final good.[49] Individual household utility depends on consumption of the final good and on the quality of the environment. This environmental quality is a stock that acts as a nonrival consumption good but also as a public input to production. The economy has three types of assets. The first is private capital (including physical and human capital), and the second is public abatement knowledge (i.e., a nonrival environmental R&D good). Either of these first two types of asset can be accumulated by devoting to it some fraction of output. The third type of asset is environmental quality (i.e., natural capital), which can be augmented only by reductions in pollution − either by reducing production or by investing in the second asset (public abatement knowledge).

2.2.1 Model Assumptions

As in Tahvonen and Kuuluvainen (1991), growth and depletion of the renewable natural resource is modeled according to the following accumulation equation:

[49] The qualitative results are not any different in a two-sector model in which one sector produces final goods and the other produces new abatement knowledge capital.

$$\dot{N} = E(N) - P, \quad \text{where } \partial E / \partial N \gtrless 0 \text{ and } \partial^2 E / \partial N^2 < 0, \tag{2.1}$$

where N denotes the stock of natural capital (or environmental quality), P is pollution, and where the dot over any variable represents the change over time. The first term *E(N)* represents ecological growth through regeneration processes. Natural capital accumulation features diminishing returns ($\partial^2 E / \partial N^2 < 0$), which implies that larger N makes it more difficult to regenerate the complete stock. The second term, P, indicates the deterioration of environmental quality through the extractive use (or harvest) of natural resources in production. As illustrated in Figure 2.1, on a sustainable steady-state path, nature can absorb a maximal amount of pollution without deteriorating, that is, $P = E(N)$. Thus, $E(N)$ represents the absorption capacity of the environment.[50]

The production side of economic activity is described by the following production function and uses of output:

$$Y = A(N)\, F(K, Z) = C + \dot{K} + \delta_K K + q_H \dot{H} + q_H \delta_H H, \tag{2.2a}$$

$$\text{where} \quad Z \equiv H P^{\varepsilon}. \tag{2.2b}$$

[50] For our economy, 'sustainable development' can be defined by $\dot{N} = 0$, and it requires that pollution P is constant in the long run and does not exceed the maximum absorption capacity. Due to the concavity of $E(N)$, we may have two levels of equilibrium N for which $\dot{N} = 0$. One has low N with $\partial E / \partial N > 0$, and the other has high N with $\partial E / \partial N < 0$. With a constant level of pollution P, only the latter equilibrium with $\partial E / \partial N < 0$ is stable, so this study focuses on the latter case. For more details about this, see Neher (1990), Tahvonen and Kuuluvainen (1991), and Bovenberg and Smulders (1995, 1996).

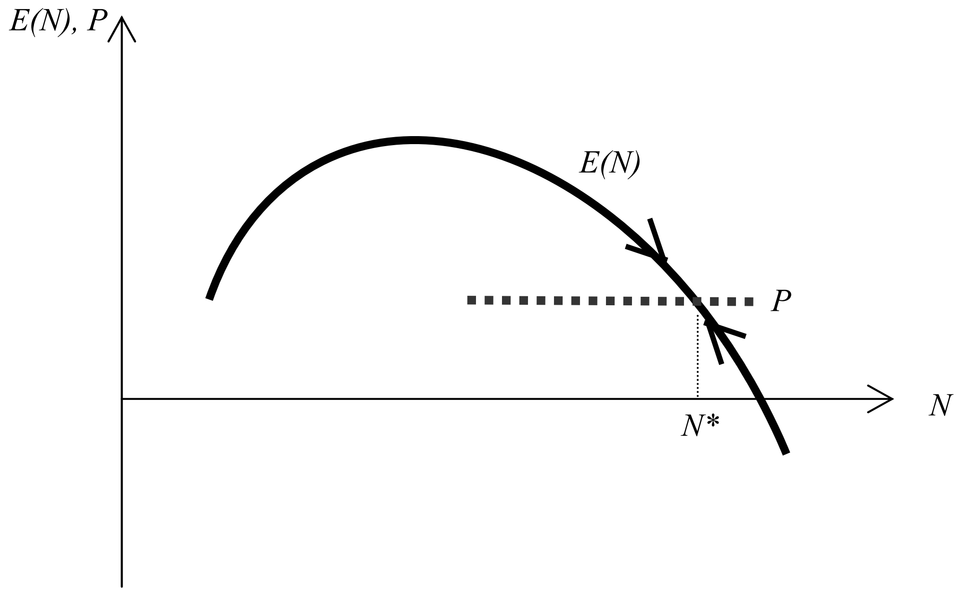

Figure 2.1 The Regeneration of the Environment

Inputs in the production process are private capital (K), "effective" pollution (Z), and nonrival services from the natural environment (captured by N). Private capital (K) includes both physical and other human capital (since H is only knowledge about abatement). Environmental quality, N, is a stock that enters the production function since a higher environmental quality renders the economy more productive. That is, output depends on $A(N)$, which measures the positive 'production externality' associated with the environment as a natural input. $F(\ )$ exhibits constant returns with respect to the two rival inputs, K and Z.[51] The production function is non-decreasing in all arguments and exhibits diminishing returns with respect to each factor alone, while all inputs are essential.[52] This single sector produces a flow of final output that can be consumed (C), invested in accumulating private capital ($\dot{K}$), used by government to generate new public knowledge about pollution abatement techniques ($\dot{H}$), or used for reinvestment to offset depreciations of the two man-made capital stocks ($\delta_K K + q_H \delta_H H$). Here, q_H denotes the shadow price of abatement knowledge relative to private capital (i.e., price at which the output of R&D is sold).

Eq. (2.2a) is the overall resource constraint of the economy. In eq. (2.2b), effective pollution (Z) depends on the stock of available public abatement knowledge (H) and the economy-wide level of actual pollution or extractive use

51 Basically, endogenous growth requires non-diminishing returns to the economy's overall reproducible resources as measured at the aggregate level.

52 Without loss of generality, the model ignores population growth. All variables can be interpreted as expressed per 'raw' labor unit. Also, since we normalize the size of population to unity, individual consumption represents aggregate consumption.

of the environment (P).[53] The exponent term ε in the effective pollution function denotes a pollution-conversion parameter.[54]

2.2.2 The Decentralized Economy

In a decentralized economy with perfect competition, each identical and spatially-homogeneous firm maximizes the firm's value by its choices of investment in private capital K and pollution P (ignoring the environmental production externality of the way P affects N). In equilibrium, all identical firms have the same pollution emissions, which yields the economy-wide concentration level N (e.g., measured as a concentration level, say, μg / ft^3).

The value of a representative firm is the present value V of all future dividends D, where $V = \int_0^\infty e^{-rt} D(Y, \dot{K}, P) dt$, and $D(Y, \dot{K}, P) = Y - \dot{K} - \tau_p P$ is a stream of instantaneous dividends at each time t. Here, τ_p denotes a tax on actual pollution (or price of pollution permits). Pure profits, Π, can be used for dividends or investment but are reduced by normal capital costs. That is, $\Pi = D + \dot{K} - rK$,

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53 This 'effective pollution' input conveys the idea that pollution is a necessary input to production, with its own downward sloping marginal product, but that the same level of input Z can be achieved with less actual pollution P if the firm has access to more abatement knowledge H.

54 This pollution-conversion parameter (ε) reflects mainly country-specific production structures or endowment conditions in a pollution-relevant manner. We will not impose any prior restrictions on the parameter, ε, which affects directly the productivity of pollution itself relative to abatement R&D stock H. Indeed, the difference between the productivities of man-made input H and natural input P plays a crucial role in determining optimal environmental and fiscal policy. The studies by Bovenberg and Smulders (1995, 1996) did not consider this possibility but just assumed $Z = HP$ and $\varepsilon = 1$.

where r is the required rate of return on private capital, gross of tax and gross of depreciation.[55]

Firms set the marginal product of each private input equal to its respective price.[56] Given the total amount of natural capital, N, and public abatement knowledge, H, the optimal allocation of these inputs at any moment in time is governed by:

$$\frac{\partial Y}{\partial K} = A(N)\frac{\partial F}{\partial K} = r \tag{2.3a}$$

$$\frac{\partial Y}{\partial P} = A(N)\frac{\partial F}{\partial Z} H\varepsilon P^{\varepsilon-1} = \tau_p . \tag{2.3b}$$

Thus, firms equate the marginal product of pollution, given the available abatement technical knowledge H, to the marginal cost of pollution (*i.e.*, pollution tax or price of pollution permits).

The representative household utility (or social welfare) W is:

$$W = \int_0^\infty e^{-\theta t} U(C,N)dt, \quad \partial U/\partial C > 0, \quad \partial^2 U/\partial C^2 < 0, \quad \partial U/\partial N \geq 0, \tag{2.4a}$$

where

$$U(C,N) = \frac{(CN^{\phi})^{1-1/\sigma}}{1-1/\sigma} \text{ when } \sigma \neq 1; \text{ and } = ln\, C + \phi\, ln\, N \text{ when } \sigma = 1. \tag{2.4b}$$

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55 Profit or rent accrued to the firm may be attributed to some fixed, non-reproducible factor that is left implicit in the model (such as raw labor).

56 In the absence of adjustment costs, the maximization of the present value (V) of future returns is equivalent to the maximization of profit in each period.

In eq. (2.4a), θ is the pure rate of time preference or utility discount rate. Eq. (2.4b) is a specific instantaneous utility function.[57] The parameter σ measures the intertemporal substitution elasticity, and ϕ measures the environmental preference (or 'consumption externality' associated with the environment).

Consumption and environmental amenities (measured by N) contribute to utility. Households who own private capital receive income from factor rentals (rK), and pay a source-based tax rate τ_K on their private capital income. Also, they earn profits as owners of the firms and obtain lump-sum transfers (G) from government. These income sources are used for consumption or for gross investment in private capital. Hence, the household's flow budget constraint is given by:

$$C + \dot{K} + \delta_K K = (1 - \tau_K)\, r\, K + \Pi + G. \tag{2.4c}$$

The representative household chooses its consumption path and the allocation of its private capital in order to maximize its life-time utility (2.4a) subject to the household budget constraint (2.4c), taking tax rates as given. Ignoring environmental quality in the individual's maximization problem, as it is a nonrival public good, this optimization yields the modified Keynes-Ramsey rule (optimal savings rule) with the growth rate g:

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[57] Preferences must be restricted to ensure the existence of a sustainable balanced-growth path. Growth is balanced in the optimum only if the utility function is of a special form like eq. (2.4b), as discussed in King et al. (1988). This specification implies that the elasticity of marginal utility is constant ($(\partial^2 U/\partial C^2)C/(\partial U/\partial C) = -1/\sigma$) and that the share of amenities in utility is constant ($(N\, \partial U/\partial N)/(C \partial U/\partial C) = \phi$).

$$\theta - (\frac{\partial \dot{U}}{\partial C}) / \frac{\partial U}{\partial C} = (1-\tau_K) r - \delta_K \text{ or } g \equiv \frac{\dot{C}}{C} = \sigma \left[(1-\tau_K) r - \theta - \delta_K + \phi (1 - \frac{1}{\sigma}) \frac{\dot{N}}{N} \right]. \quad (2.5)$$

This equation (2.5), representing the trade-off between consumption and investment, reveals that postponement of consumption must be rewarded by a net-of-tax rate of return that compensates for the pure rate of time preference and the change over time in the marginal value of consumption (including the change in amenities over time).[58]

The government in our economy is assumed to raise revenues by adopting a positive capital income tax rate, τ_K, and a positive pollution tax, τ_P.[59] The revenues from taxation are used to finance government expenditures on public investment ($q_H \dot{H} + q_H \delta_H H$) and on lump-sum transfers to households (G). Further, we suppose that the government fixes the ratio of the lump-sum transfer payments relative to total private capital income, $\varphi \equiv G / rK$. This parameter is used below as a measure of the extent to which distorting taxes are necessary. Assuming a balanced budget at any moment in time, the budget constraint of the government can be written as:

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[58] In a situation of sustainable balanced growth where $\dot{N} = 0$, this equation simply boils down to:

$$\dot{C} / C = \sigma \left[(1-\tau_K) r - \theta - \delta_K \right]. \quad (2.5')$$

As is typical of endogenous growth theory, we require some inequality constraints for the growth rate to be positive ($(1-\tau_K)\, r - \delta_K > \theta$) and for utility to be bounded, which corresponds to the transversality condition ($\theta - g\,(1-1/\sigma) = (1-\tau_K)\, r - \delta_K - g > 0$).

[59] In the long-run equilibrium, N and P are constant while K is growing. Therefore, on a balanced-growth path, the marginal value of pollution, τ_P, must increase at the growth rate g.

$$\tau_K rK + \tau_P P = q_H \dot{H} + q_H \delta_H H + G \,, \text{ or } \tau_K + \tau_P P / rK = \eta + \varphi \,, \quad (2.6)$$

where $\tau_P P / rK$ represents the ratio of pollution tax revenue to private capital income, and where $\eta \equiv (q_H \dot{H} + q_H \delta_H H) / rK$ is the ratio of gross public investment in abatement knowledge to private capital income.

In our model, the sustainable balanced-growth equilibrium path is characterized as a path where environmental quality and pollution remain constant and all other economic variables grow at a common endogenous growth rate g:

$$\dot{N} = \dot{P} = \dot{q}_H = 0 \,, \quad (2.7a)$$

$$\frac{\dot{Y}}{Y} = \frac{\dot{K}}{K} = \frac{\dot{H}}{H} = \frac{\dot{C}}{C} = \frac{\dot{G}}{G} = \frac{\dot{\tau}_P}{\tau_P} = g \,, \quad (2.7b)$$

where g depends on preferences, technology, ecology, and environmental policy. Due to condition (2.7b), the ratios between all the growing variables are also constant. If φ (> 0) is constant, then transfer payment G grows at the common growth rate as well.

For balanced growth to be feasible and sustainable, the production function must meet the following necessary conditions: (i) allocative variables (e.g., C/Y, G/Y) are constant, (ii) the production function features constant returns with respect to the growing man-made inputs K and H, and (iii) the output elasticities of inputs in the production function, eq. (2.2), remain constant over time and their substitution elasticities are smaller than or equal to unity.[60]

However, the nonrival nature of both abatement knowledge capital (*H*) and the environmental quality (*N*) gives rise to externalities, so the decentralized solution in this economy is not optimal from the social point of view. The next section will explore the optimal government policy rules that make the decentralized economy with externalities move along the socially optimal path.

2.3 OPTIMAL POLICIES FOR SUSTAINABLE DEVELOPMENT

2.3.1 The Optimal Corrective Government Policies

For the market economy described above, a benevolent government needs to intervene to ensure the optimal provision of the two public goods *N* and *H*. In this case, where lump-sum taxation is not available, it is important to know how the public investment in abatement knowledge is financed and what becomes of the taxes collected. The government must take as given the decentralized optimizing behavior of firms and households, eqs. (2.3) - (2.5), the ecological constraint eq. (2.1), and government budget constraint eq. (2.6), while affecting the allocation of resources among the three type of capital (*K*, *H*, and *N*) through its policy variables (τ_K, τ_P, and H). Then, in this second-best world, the optimizing government must act to satisfy the following arbitrage condition:

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[60] For details on the necessary conditions for balanced endogenous growth, see Rebelo (1991), Bovenberg and Smulders (1995), Smulders and Gradus (1996), Mino (1996), and Greiner and Hanusch (1998) among others.

$$(1-\tau_K)r-\delta_K=\frac{1}{q_H}A\frac{\partial F}{\partial Z}P^{\varepsilon}+\frac{\dot{q}_H}{q_H}-\delta_H=\frac{1}{\tau_P}\left[\frac{\partial U}{\partial N}/\frac{\partial U}{\partial C}+F\frac{\partial A}{\partial N}\right]+\frac{\partial E}{\partial N}+\frac{\dot{\tau}_P}{\tau_P},\ (2.8)$$

which reveals that investments in the three types of capital should be traded off against each other and also against household savings in eq. (2.5).[61] The first equality in eq. (2.8) says that the net return on private investments ($(1-\tau_K)r-\delta_K$) should be equal to the return on investment in abatement knowledge (consisting of the current return in production and a capital gain), given a certain amount of economy-wide pollution level, P.[62] The second equality in eq. (2.8) says that environmental quality N should also earn the same rate of return as public abatement knowledge. The return on environmental quality in eq. (2.8) consists of (i) its contribution to utility (the consumption externality), (ii) its contribution to total factor productivity (the production externality), (iii) its contribution to ecological processes (marginal absorption capacity), and (iv) a

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[61] Under the balanced budget condition, the benevolent government needs to control the accumulation of the three types of capital optimally. First, as in Bovenberg and Smulders (1995, 1996), denote by λ_K, λ_H, and λ_N the (current value) costate variables associated with the accumulation of private capital (K), abatement knowledge capital (H), and natural capital (N), respectively. Then, letting λ_K ($=\partial U/\partial C$) be numeraire, q_H is the shadow price of abatement knowledge relative to private capital (λ_H/λ_K), and τ_p is the shadow price of environmental quality relative to private capital (λ_N/λ_K). From the first-order (dynamic) conditions for the socially desirable path, we can get the canonical forms for H and N: $\lambda_K A[\partial F/\partial Z]P^{\varepsilon}-\lambda_H\delta_H=\theta\lambda_H-\dot{\lambda}_H$ and $\partial U/\partial N+\lambda_K F\partial A/\partial N+\lambda_N\partial E/\partial N=\theta\lambda_N-\dot{\lambda}_N$, respectively. Using the above associated definitions and comparing these canonical conditions with the decentralized path in Section 2.2, we arrive at eq. (2.8): H and N should earn the same net rate of return as K, which commonly corresponds to $\theta-\dot{\lambda}_K/\lambda_K$ (where $\lambda_K=\partial U/\partial C$) in eq. (2.5). That is, they must satisfy the intertemporal arbitrage conditions governing the law of motion of the costate variables.

[62] The wedge between social and private returns on K (due to τ_K), necessary to finance the public R&D, leads to a shortfall of the balanced growth rate compared to a first-best world with lump-sum taxes. For similar optimality conditions for distortionary taxation and public spending, see Barro and Sala-i-Martin (1995, p. 152-157), or Glomm and Ravikumar (1999).

scarcity rent (capital gain). The Hotelling rule states that if the natural resource is exhaustible, the rate of its price increase ($\dot{\tau}_P / \tau_P$) should equal the rate of return on private capital. Hence, eq. (2.8) can be interpreted as a generalized Hotelling rule for renewable natural resource (in the presence of distortionary taxation).

Now, as is usual in this literature, assume a Cobb-Douglas production technology $F(K,Z) = K^{1-\alpha} Z^{\alpha}$, where α $[\equiv (\partial Y / \partial Z) \cdot Z / Y]$ is the aggregate output elasticity with respect to economy-wide effective pollution *Z* (and hence also to abatement knowledge stock *H*).[63] Also, posit a simple relationship $A(N) = N^{\gamma}$, where γ is a parameter that reflects the extent of the production externality from the stock of natural capital.

On the equilibrium balanced-growth path, we can use eq. (2.3b) and the first equality of eq. (8) to show that:

$$\frac{q_H \dot{H}}{\tau_P P} = \left(\frac{1}{\varepsilon}\right)\left(\frac{g}{(1-\tau_K)r - \delta_K + \delta_H}\right). \qquad (2.9a)$$

This reveals that the golden rule for the accumulation of abatement knowledge, *H*, depends on the physical pollution-conversion parameter ε as well as the depreciation parameters, δ_K and δ_H, the growth rate g, and the after-tax market

[63] As is typical in the literature, this specific functional form is adopted here for balanced growth to be feasible, since *K* and *H* grow at the same rate and, therefore, the output elasticities with respect to these inputs are "constant" (see Bovenberg and Smulders, 1995, p.377; Rebelo, 1991, p.508). Due to the constant returns to scale assumption for *F*( ), the aggregate output elasticity of private capital is $1-\alpha$. We also assume $\alpha\varepsilon < 1$ in this model, such that pollution P decreases in τ_p *ceteris paribus*.

interest rate $(1-\tau_K)r$. From the first-order conditions for the firm's maximization problem, eqs. (2.3a) and (2.3b), we also know that the ratio of pollution tax revenue to private capital income is:

$$\frac{\tau_P P}{rK} = \frac{\alpha}{1-\alpha}\varepsilon, \tag{2.9b}$$

which is always constant over time in our economy.

To figure out the optimal structure for fiscal policy, it would be interesting to explore whether the pollution tax revenues ($\tau_P P$) is enough to finance public R&D expenditure on new abatement knowledge ($q_H \dot{H}$). Even though the transversality condition implies that $(1-\tau_K)\, r - \delta_K > g$ (or, utility is bounded) in eq. (2.9a), the relative size of pollution tax revenues and expenditure on new abatement knowledge is ambiguous as long as the pollution-conversion parameter is less than unity ($\varepsilon < 1$). Hence, we know that if $g/((1-\tau_K)\, r - \delta_K + \delta_H) > \varepsilon$ in (2.9a), then public R&D spending on abatement knowledge may exceed the pollution tax revenues, thereby requiring additional, possibly distortionary, taxes to finance this public expenditure. This additional tax can be measured by $\tau_K - \varphi$, the *extent* to which τ_K exceeds the level necessary to pay for G:[64]

$$\tau_K - \varphi = \left(\frac{\alpha}{1-\alpha}\right)\left(\frac{g+\delta_H}{(1-\tau_K)r - \delta_K + \delta_H} - \varepsilon\right). \tag{2.9c}$$

[64] Substituting eqs. (2.9a) - (2.9b) into eq. (2.6) and using $\dot{H} = gH$ yields eq. (2.9c).

Note that our result is in contrast to the result in Bovenberg and Smulders (1995, p.380). In their simple model, Bovenberg and Sumlders argue that the left-hand side of eq. (2.9a) is "always below" unity, and thus the pollution tax revenues are more than sufficient to finance R&D spending on the optimal balanced-growth path.[65]

On the other hand, the long-run growth rate of all variables can be determined using eqs. (2.1) - (2.8) above. To reformulate the whole dynamic system of the economy so far into a more simplified framework, define three new "fundamental" variables that are constant along the balanced-growth path: $h \equiv H/K$, $c \equiv C/K$, and $\tau \equiv \tau_p/K$. The Appendix derives conditions for the optimal balanced-growth equilibrium values $(h^*,\ c^*,\ N^*,\ \tau^*)$, governed by the government budget constraint eq. (2.6), the dynamic equilibrium conditions in eq. (2.7), and the inter-asset arbitrage conditions in eq. (2.8):[66]

$$h^* = E(N^*)^{\frac{1-\alpha\varepsilon}{\alpha}} N^{*\frac{-\gamma}{\alpha}} \left(\frac{\tau^*}{\alpha\varepsilon}\right)^{\frac{1}{\alpha}} \tag{2.10a}$$

$$c^* = \left[\frac{1}{1-\alpha} - (\frac{\alpha\varepsilon}{1-\alpha} + \tau_K{}^* - \varphi)/h^*\right] r^* + \delta_H - \delta_K \tag{2.10b}$$

65 In other words, as a golden rule for the stock of knowledge, they point out that the government should earmark only "part" of the pollution tax revenues for developing abatement knowledge capital.

66 For simple exposition, without loss of generality, we assume that the relative price of K and H, q_H, is normalized to unity in the long-run steady-state equilibrium.

$$\left[\sigma(1-\tau_K{}^*)-(\frac{\alpha\varepsilon}{1-\alpha}+\tau_K{}^*-\varphi)/h^*\right]r^*-\sigma(\theta+\delta_K)+\delta_H=0 \qquad (2.10c)$$

$$\left(-\frac{1}{\tau^*N^*}\frac{\gamma}{1-\alpha}+1-\frac{1}{1-\alpha}+(\frac{\alpha\varepsilon}{1-\alpha}-\varphi)\right)r^*+(1-\frac{\phi}{\tau^*N^*})c^*-\frac{\partial E(N^*)}{\partial N}=0 \qquad (2.10d)$$

where $r^*=\dfrac{1-\alpha}{\alpha\varepsilon}\tau^*E(N^*) \quad (=\dfrac{1-\alpha}{\alpha\varepsilon}\tau^*P^*)$ (2.10e)

$$\tau_K{}^*=1-\left(\frac{\alpha}{1-\alpha}\right)/h^*+\frac{\delta_H-\delta_K}{r^*}. \qquad (2.10f)$$

Note that eqs. (2.10) represent six equations in six unknowns (h^*, c^*, N^*, τ^*, r^*, and $\tau_K{}^*$). They are not linear in those unknowns, however, and so closed-form solutions are not available. Instead, we first offer interpretations and discussions of how these equations can be used to characterize optimal policy instruments, and second, we later provide numerical solutions.

Eqs. (2.10a) and (2.10b) determine the optimal equilibrium ratios to private capital of pollution abatement knowledge ($h \equiv H/K$) and of consumption ($c \equiv C/K$). The modified Keynes-Ramsey rule (describing the optimal savings-investment path for private capital) is reflected in eq. (2.10c), with a wedge between private and social return to private capital in the market economy. Eq. (2.10d) shows the socially-optimal pricing rule for natural capital (N), where the marginal benefit of pollution equals its marginal cost (i.e., deterioration of natural capital). Eq. (2.10e) gives the equilibrium gross-of-tax return to private capital, which is determined by the product of the pollution tax relative to private capital ($\tau \equiv \tau_P/K$) times the absorption capacity of the environment ($E(N)$) along the balanced-growth path. Also, eq. (2.10f) is the arbitrage condition for private capital and abatement knowledge capital. Social optimality requires that government set the levels of corrective policy instruments, τ and τ_K, according to eqs. (2.10).

From the above six equations, we can see that the optimal long-run equilibrium growth path of the economy depends critically on the size of the necessary pre-existing income tax distortion ($\varphi \equiv G/rK$), the intertemporal substitution elasticity (σ), the pure rate of time preference (θ), the environmental preference parameter (ϕ), the environmental production externality parameter (γ), the production elasticity of abatement knowledge (α), the pollution-conversion parameter (ε), the depreciation parameters of man-made capitals (δ_K and δ_H), and the ecological components behind the absorption capacity function $E(N)$.

Eqs. (2.10b), (2.10c) and (2.10d) reveal that, in particular, the size of the necessary distorting income tax, φ, has critical effects on the optimal configurations of the corrective policy instruments in the economy (τ^*, τ_K^*, and h^*). That is, the levels of those optimal corrective government polices must be quite different from what they would be in the Bovenberg and Smulders (1995, 1996)'s first-best world where $\varphi = 0$.

To see how the key parameters described above affect the second-best optimal government policy rules, we would need closed-form solutions for the system of six equations with six unknowns in eqs. (2.10). With no explicit analytical solutions for some of the unknown entities, we next proceed numerically. Hence, to characterize the solutions in more detail, a numerical sensitivity analysis is undertaken for the case of global warming and sustainable development.[67]

2.3.2 A Numerical Simulation: The Case of Global Warming

Optimal corrective policy rules in our model induce the market equilibrium path to match the socially-efficient path. What level of policy rules should then be adopted to maximize social welfare, including concerns about global warming, and how do the long-run growth outcomes under optimal policy rules react to changes in the set of economic and natural parameters in the economy? These questions often arise in environmental policy debates over greenhouse gases (GHGs) abatement.

In choosing "central" parameter values, we rely primarily on values that are frequently used in the relevant literature. The parameter values chosen from Barro and Sala-i-Martin (1995) and Bovenverg and Smulders(1995, 1996) are: α = 0.24, σ = 0.67, δ_K = 0.08, δ_H = 0.05, and θ =0.03. The absorption capacity function $E(N)$ is specified by a form $\beta N(1-N)$, where $N \in$ (0.5, 1), and the embedded ecological parameter β is chosen as 0.04 from Nordhaus (1994, Ch.3) such that a steady state exists with positive ratios (e.g., C/Y).[68] The parameter φ is set to 0.25, to account for the revenue required for non-productive government

67 The numerical simulation was performed using the GAMS/MINOS5 algorithm (Brooke et al., 1992).

68 For the case of global warming and GHGs, we assume that the environmental quality N is set to be the difference between the catastrophic level of GHGs concentration ($\overline{S}$) and its current accumulation level ($S = \int_{-\infty}^{t} P_t dt$), while the carrying capacity is normalized to unity. The economy here is also assumed to be above the point of maximum sustainable yield (which occurs at N =0.5).

spending (transfer payments). The remaining parameter values are chosen so that the model can reproduce plausible growth rates for the U.S. economy. The central values for those variables are chosen as $\gamma = 0.77$, $\phi = 0.70$, and $\varepsilon = 0.75$, but each is also varied to test the effects of higher and lower values.

In Table 2.1, Row A uses those "central" parameter values and shows the outcome for optimal policy rates in the normalized U.S. economy. The value of τ =14.50, defined as the ratio of the two growing variables τ_P and K, is the rate of pollution taxation or pollution tax intensity for the normalized economy (calibrated to the U.S.). The value of optimal environmental investment rate H/K is 0.619, greater than Barro's(1990) conjecture (i.e., $\alpha/(1-\alpha)$=0.315), even with no prior tax distortions (φ = 0), on the balanced-growth equilibrium paths. Note here that Barro's conjecture ignores prior tax distortions. When we look below in row B1a for values in *our* model with no prior tax distortions, however, we get H/K=0.401, much closer but still higher than Barro's 0.315. The increase from Barro's 0.315 to this value (0.401) seems to reflect not only its own 'pure' output elasticity but also the additional premium for environmental sustainability.

Rows B1a and B1c imply that an increase in the requirement for nonproductive government spending φ (from 0 to 0.35) raises the optimal values for both the environmentally-motivated tax on pollution and the tax on private capital income, while it lowers the optimal long-run growth rate of the economy (from 0.0554 to 0.0047). An increase in φ implies a higher tax on capital income, which makes the accumulation of private capital more costly relative to

Table 2.1 Sensitivity Analysis of Optimal Steady-State Values to Key Parameters (Global Warming Example)

	τ	τ_K	N	H/K	C/K	g
A. Central case	14.50	0.358	0.898	0.619	0.064	0.0238
B. Environment-related parameters						
1. Size of prior tax distortion (φ)						
a. No distortion (0)	8.63	0.068	0.827	0.401	0.022	0.0554
b. Central case (0.25)	14.50	0.358	0.898	0.619	0.064	0.0238
c. High distortion (0.35)	22.64	0.502	0.934	0.854	0.086	0.0047
2. Environmental preference (ϕ)						
a. Low concern (0.3)	12.90	0.355	0.880	0.615	0.066	0.0248
b. Central case (0.7)	14.50	0.358	0.898	0.619	0.064	0.0238
c. High concern (1.5)	16.38	0.360	0.911	0.623	0.062	0.0225
3. Environmental productivity (γ)						
a. Low externality (0.3)	11.08	0.340	0.843	0.586	0.077	0.0351
b. Central case (0.77)	14.50	0.358	0.898	0.619	0.064	0.0238
c. High externality (1.2)	20.12	0.373	0.932	0.647	0.056	0.0162
4. Pollution-conversion factor (ε)						
a. Lowered 20 percent (0.6)	14.07	0.364	0.893	0.615	0.076	0.0295
b. Central case (0.75)	14.50	0.358	0.898	0.619	0.064	0.0238
c. Raised 20 percent (0.9)	15.04	0.352	0.901	0.624	0.053	0.0181
5. Ecological capacity factor (β)						
a. Lowered 20 percent (0.032)	21.84	0.371	0.921	0.644	0.057	0.0169
b. Central case (0.04)	14.50	0.358	0.898	0.619	0.064	0.0238
c. Raised 20 percent (0.048)	11.32	0.349	0.883	0.604	0.069	0.0284
C. General parameters						
1. Intertemporal substitution (σ)						
a. Low (0.33)	6.79	0.235	0.751	0.505	0.110	0.0178
b. Central case (0.67)	14.50	0.358	0.898	0.619	0.064	0.0238
c. High (0.90)	17.70	0.377	0.917	0.645	0.057	0.0212
2. Time preference rate (θ)						
a. Lowered 20 percent (0.024)	16.97	0.372	0.913	0.638	0.059	0.0242
b. Central case (0.03)	14.50	0.358	0.898	0.619	0.064	0.0238
c. Raised 20 percent (0.036)	13.17	0.345	0.884	0.604	0.069	0.0225

other types of capital such as abatement knowledge or natural capital. In order to satisfy the arbitrage rules among the three types of capital in eq. (2.8), the pollution tax and the knowledge intensity of production have to increase. Increases in the taxes on pollution and on private capital income lead to a better environmental quality but lower stock of private capital, and to a higher ratio of consumption to private capital (due to the increased transfer payments and decreased net return to private capital).

If consumers care more about the environment (i.e., as ϕ increases from 0.3 to 0.7 or 1.5 in rows B2a to B2c), then the optimal abatement knowledge intensity of production, H/K, and natural capital stock, N, both increase at the expense of private capital and consumption. The same outcomes occur with an increase in the productivity externality of the environment, γ (from 0.3 to 0.77 or 1.2 in rows B3a to B3c). In these cases, a higher ϕ or γ calls for more ambitious environmental policy and slower economic growth in the optimum steady-state.

A comparison of the results in rows B4a and B4c shows that the pollution-conversion parameter, ε, has effects similar to those of ϕ or γ. Effects on τ_K are different, however. As implied in eq. (2.9c), an increase in ε (from 0.6 to 0.9) leads to a decrease in τ_K (from 0.364 to 0.352).[69] More importantly, it is shown that the welfare maximizing 'mix' of the environmental and capital taxes, τ versus τ_K, depends substantially on the pollution-conversion parameter that affects the output elasticity of pollution. That is, we can see that, making the difference

[69] Note that eq. (2.9c) shows that $\tau_K - \varphi$, the extent to which τ_K exceeds the level necessary to pay for lump-sum transfers ($\varphi = 0.25$), decreases with ε.

between the productivities of man-made input H and natural input P in the economy, ε plays a critical role in integrating environmental and distortionary taxes for how revenues are raised.

The ecological parameter, β, affects the marginal absorption capacity through the assumption that $E(N) = \beta N(1-N)$. It thus plays a critical role in how the economy and the environment interact. The results in rows B5a and B5c indicate that an increased β (from 0.032 to 0.048) makes it easier for the economy to achieve a higher sustainable growth (from 0.0169 to 0.0284) with less stringent environmental policies (τ decreases from 21.84 to 11.32, and τ_K falls from 0.371 to 0.349).

Panel C in Table 2.1 looks at other parameters, those not related to the environment. As seen in rows C1a and C1c, society with a higher intertemporal substitution elasticity, σ, optimally invests more in productive assets, since it is flexible enough to put off consumption to a later date. To invest in more abatement knowledge and improved environmental quality, the government requires a higher environmental levy (τ). In the case of extremely low σ, the capital income tax could fall below the rate needed to pay for lump-sum transfers ($\tau_K < \varphi$).[70]

Finally, rows C2a and C2c show that an increase in the pure rate of time preference, θ, reduces private investment and the stock of environmental quality (N) in the optimum steady-state. Impatient societies tend to invest less in productive assets, thereby leading to a lower long-run growth rate.

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[70] For example, in row C1a, $\tau_K - \varphi = 0.235 - 0.25 = -0.015$.

2.4 GROWTH AND WELFARE IMPLICATIONS OF TIGHTER ENVIRONMENTAL POLICIES

How are growth and welfare affected by a tighter environmental policy in the presence of the externalities and distortionary taxation? Will a tighter environmental policy inevitably reduce economic growth even if it increases social welfare? In a world of endogenous growth, environmental policy may have permanent effects on the productivity of the economy. If pollution taxes are sub-optimally low, for example, then pollution is excessive natural capital is underaccumulated, which affects production.

Suppose that a market economy has its "initial" balanced-growth equilibrium path with sub-optimally low environmental quality ($\tau < \tau^{*}$).[71] For analytical tractability, we ignore transitional dynamics off the balanced growth path. On a sub-optimal balanced growth path where $\tau < \tau^{*}$, we know that $dW/d\tau > 0$, by definition. We now derive an expression for $dg/d\tau$ and show that the sign could be positive or negative, so that a welfare-raising pollution policy might raise or lower growth.

To investigate the growth effects of a tighter environmental policy, substitute eq. (2.10e) into the steady-state version of eq. (2.5) and totally differentiate g with respect to τ. The result is that the long-run balanced-growth rate reacts to changes in pollution taxation in the economy as follows:

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[71] As in Bovenberg and Smulders (1995, 1996), our model does have a balanced growth path, even given sub-optimal pollution taxation, which allows us to analyze the effects of a tighter environmental policy (starting at $\tau < \tau^{*}$) on both growth and welfare. This initial balanced growth path features 'excessive' pollution and, accordingly, the social costs of pollution exceed the social benefits. Specifically, the social rate return on N is greater than the rate of return on K in eqs. (2.8) or (2.10d).

$$\frac{dg}{d\tau} = -\sigma\left(\frac{d\tau_K}{d\tau}\right)r + \sigma(1-\tau_K)\frac{1-\alpha}{\alpha\varepsilon}E(N)\left(1-\eta_{N\tau}/\eta_{NE}\right), \tag{2.11}$$

where $\eta_{N\tau}\left(\equiv (dN/d\tau)(\tau/N)\right)$ is the elasticity of natural capital with respect to the pollution tax and $\eta_{NE}\left(\equiv -(dN/dE)(E/N)\right)$ is the elasticity of natural capital with respect to the absorption capacity of the environment.[72]

Eq. (2.11) implies that the "growth" effect of the tighter environmental policy, where φ is unchanged, has an ambiguous sign and depends crucially on the sign and magnitude of two important components in the economy, $d\tau_K/d\tau$ and $\eta_{N\tau}/\eta_{NE}$.

The first term on the right-hand side in eq. (2.11) represents the marginal '*tax-replacement effect*.' Substitution of environmental taxes for pre-existing distortionary income taxes *ceteris paribus* stimulates economic growth through a less distortionary way of raising revenue. On the normal branch of Laffer curve, raising the pollution tax means a lower capital tax. Since r and σ are positive, the whole first term is positive. The second term on the right-hand side in eq. (2.11) reflects the '*productivity effect*' of a higher τ. If $\eta_{N\tau} < \eta_{NE}$, each component is positive, except that the sign of last component is unknown, then the whole second term is positive, which implies that a higher τ can contribute to the productivity of private factors of production and, thus, to sustainable economic growth.

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[72] Note that $\partial E/\partial N < 0$, according to our assumption regarding dynamically stable equilibrium N, as in footnote 50. The value of the elasticity η_{NE} is not constant along the ecological curve $E(N)$, and it depends critically on the shape of it.

It is typically argued that optimal pollution control hurts economic growth by raising abatement costs.[73] In this model, however, a tighter environmental policy where φ is fixed can have room for stimulating growth as long as it has the 'increased' productivity effect of the pollution tax. Otherwise, a better environmental quality might not be obtained without sacrificing economic growth.

In general, it can be shown that maximizing economic growth is not equivalent to maximizing social welfare even if, for analytical tractability as above, we ignore the transitional dynamics off the balanced growth path.[74] To calculate the welfare effects of a tighter environmental policy starting at time t = 0, first compute the utility functional in eq. (2.4a) on the initial, sub-optimal balanced-growth path (where $\tau < \tau^*$) giving

$$W(\mathrm{g}) = \frac{\left(C(0)N^{\phi}\right)^{1-1/\sigma}}{1-1/\sigma}\frac{1}{\theta - g(1-1/\sigma)}, \text{ if } \sigma \neq 1; \text{ and} \qquad (2.12)$$

$$= \frac{\left(\ln C(0) + \phi \ln N\right)\theta + g}{\theta^2}, \text{ if } \sigma = 1,$$

[73] Most of the prior literature on this issue assumes "exogenous" technological progress that is independent of environmental policy. See, for example, Jorgenson and Wilcoxen (1990), Nordhaus (1994), and Goulder (1995) among many others. In these models, environmental protection has costs that reduce growth.

[74] Note that, as shown by Futagami et al. (1993), if transitional dynamics are taken into account, maximizing economic growth is no longer equivalent to maximizing welfare as well. However, the advantage of limiting the analysis to balanced growth paths is that it enables us analytically to derive clear economic conditions showing how these two goals are different in response to a tighter environmental policy. For a similar analysis on income taxation, see Greiner and Hanusch (1998).

where $C(0)$ is the initial consumption level. With $\theta - g\,(1-1/\sigma) = (1-\tau_K)\,r - \delta_K - g$, we assume this value is positive, so that utility in eq. (2.4a) remains bounded. Substituting eqs. (2.10e) and (2.10f) into the growth rate for C, H, and K on the balanced-growth path yields:

$$C(0) = K(0)\left[\left(\frac{\alpha(1-\varepsilon)}{1-\alpha}+\varphi\right)\frac{1-\alpha}{\alpha\varepsilon}E(N)\tau+\left(\frac{1}{\sigma}-1\right)g+\theta\right], \qquad (2.13)$$

where $K(0)$ is the level of private capital stock at $t = 0$. Insert eq. (2.13) into eq. (2.12), and differentiate $W(\cdot)$ with respect to τ to obtain:

$$\frac{dW}{d\tau} = \frac{K(0)\left(C(0)N^{\phi}\right)^{-1/\sigma_c}}{\theta - g(1-1/\sigma)}\left(\frac{1-\alpha}{\alpha\varepsilon}E(N)\right)\left(\frac{\alpha(1-\varepsilon)}{1-\alpha}+\varphi\right)+\frac{\partial W}{\partial g}\frac{dg}{d\tau}. \quad (2.14)$$

With the assumption $\theta - g\,(1-1/\sigma) > 0$, then the first two components of the first term on the right-hand side in eq.(2.14) are positive and the sign of the whole first part depends upon that of $\alpha(1-\varepsilon)/(1-\alpha)+\varphi$. If ε is less than unity, then the first term is always positive (because $\varphi > 0$). If ε is greater than unity, then the sign is ambiguous. Therefore, we can see that the relative magnitudes of three key parameters (α, ε, and φ) play an important role in determining the link between growth and welfare effects of a tighter environmental policy (i.e., in the signs of $dg/d\tau$ and $dW/d\tau$).[75]

[75] In deciding whether the growth effects of welfare-raising environmental policy is positive or negative, this implies that the critical determinant is the relationship among the above three parameter in the first part on the right-hand side in eq. (2.14).

More importantly, it should be noted that, in eq.(2.14), for a change in the rate of pollution tax on the balanced growth path, maximizing economic growth is not equivalent to maximizing welfare.[76] For instance, we can see that the growth-maximizing rate of pollution tax is always smaller than the welfare-maximizing rate when $\varepsilon < 1$.[77]

It has often been argued in the recent endogenous growth literature that a tighter environmental policy may have positive effects on growth, at least in the long-run (e.g., Bovenberg and Smulders, 1996; Hettich, 2000). As shown in Figure 2.2, however, only very specific conditions may lead to this kind of conclusion.

In Figure 2.2, a tighter environmental policy increases both growth and welfare *only* if $\tau < \tau(g^{max})$. On the other hand, if $\tau(g^{max}) < \tau < \tau(W^{max})$, then a rise in τ raises welfare but decreases growth. In other words, if the initial equilibrium path has $\tau > \tau(g^{max})$, then a welfare-raising increase in the pollution tax does not have positive effect on long-run growth. Beyond the optimum $\tau > \tau(W^{max})$, a further improvement of the environment by a tighter environmental policy is so costly that both growth and welfare decline. However, assuming no transitional dynamics and no prior distortion ($\varphi = 0$), growth and welfare

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[76] Differentiating eq. (2.12) with respect to g, we can see that $\partial W / \partial g > 0$ in eq. (2.14). See, a formal proof on this part, Greiner and Hanusch (1998), p.258.

[77] On the contrary, when $\varepsilon > 1$ and depending on φ, the growth-maximizing rate of pollution tax could exceed the welfare-maximizing rate. Note here that ε summarizes the pollution-related structural information of the economy, while φ reflects the size of pre-existing non-environmental tax distortions.

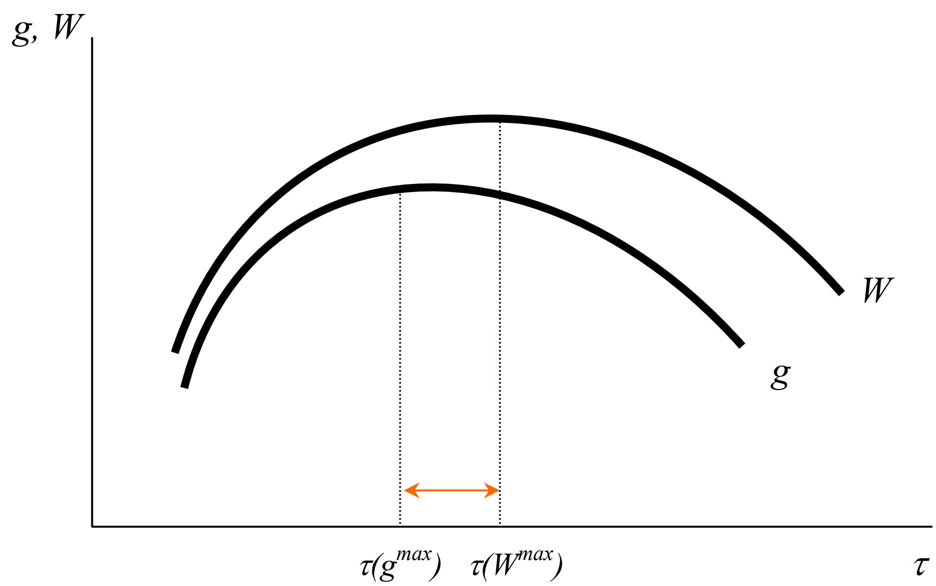

Figure 2.2 Optimal Environmental Policy

maximization could be equivalent goals when $\varepsilon = 1$ (e.g., Barro, 1990; Bovenberg and Smulders, 1995, 1996). [78]

To illustrate the analytical results more specifically, we can calculate the quantitative values of $\tau(g^{max})$ and $\tau(W^{max})$ for the global warming example of the previous section. This numerical simulation for the U.S. economy indicates that, in the central case, but where $\varphi = 0$, the growth-maximizing rate of pollution tax τ is 7.84, which is less than the welfare-maximizing rate of 8.63. The gap between these two values here arises mostly from a difference between the productivities of abatement knowledge and pollution. On the other hand, with all the central case parameters (including $\varphi = 0.25$), the growth maximizing rate of pollution tax is 10.20, which is much less than the welfare maximizing rate of 14.50. In this latter case, the larger gap further reflects the presence of non-productive government spending (i.e., $\varphi > 0$) as well (in a second-best world with distortionary taxation).

2.5 CONCLUSIONS

This paper has developed a one-sector endogenous growth model that combines the so-called 'new' growth theory, distortionary taxation, and

[78] As the more general specification, φ could be negative. In this case, depending on ε, the growth maximizing pollution tax rate could be even greater than the welfare maximizing rate. If $-\overline{\varphi} < \varphi < 0$ (where $-\overline{\varphi}$ is a lower bound on φ), it is also that part of private capital income, which is raised as a fixed "lump-sum tax." The lower bound is determined by the condition that private consumption cannot be negative, depending on the other parameter values of the model economy.

environmental issues. It incorporates abatement knowledge as a productive asset, and it also includes the natural environment as a renewable resource. Accordingly, the economy has three types of assets: private capital, abatement knowledge, and renewable resources. These three assets evolve by the endogenous flows of private savings, public R&D investment, and pollution, respectively. In this framework, our analysis focuses on a general treatment of the interactions among sustainable economic growth, pollution, and public finance in a second-best world with distortionary taxes. We also explore the conditions under which environmental policy has positive effects on both economic growth and welfare.

In the model, we have three main tensions or sets of opposing forces that affect welfare and the long-run rate of economic growth. First, since pollution is an input to production, a lower level of pollution (or of harvesting resources) makes reduces output. Since environmental quality is also a (nonrival) input to production, less pollution also raises environmental quality which raises output. A second tension is between growth and pollution. Growth causes pollution, but growth generates resources for abatement knowledge that may reduce pollution. The improved quality of the environment or the increased stock of abatement knowledge can allow the economy to absorb a larger flow of effective pollution in the steady state. Finally, the economy also has a tension between the positive effects of investment in abatement knowledge and the negative effects from distortionary taxes made necessary by that increase in non-productive government spending.

According to the results, a greater tax distortion (due to more nonproductive government spending) raises the optimal values for environmentally-motivated taxes in balanced growth, while lowering the optimal growth rate of the economy. At the same time, the rate of optimal environmental investment reflects not only its own 'pure' output elasticity but also the additional premium for environmental sustainability in a second-best world, so that the overall abatement knowledge-intensity of production is directed by this policy rule.

On the other hand, this paper shows that, under only very specific conditions, a welfare-improving environmental policy does not inevitably harm economic growth. That is, depending on the starting point (i.e., the extent to which the pollution tax falls short of its optimum), a tighter environmental policy (or revenue-neutral environ- mental tax reform) in a second-best world with prior distortionary taxes could yield a 'win-win' outcome where it improves environmental quality and also enhances long-run economic growth through a less distortionary way of raising revenue. The analysis, however, also demonstrates that the 'win-win' outcome is made less likely by (i) greater (non-environmental) prior tax distortions and (ii) greater difference between the productivities of abatement knowledge (man-made input) and pollution (natural input) in the economy. In other words, it could be that the positive long-run growth effects of a tighter environmental policy do not arise, even with endogenous technological progress in abatement knowledge. It further implies that betting solely on technological breakthroughs by R&D investment on abatement knowledge might not be enough to achieve positive growth effects, unless combined with other government policy instruments such as income tax policy or industrial demand-side management through production restructuring.

An obvious extension of this paper is to study the transitional dynamics of the proposed endogenous growth model of the second-best. Another extension involves the consideration of uncertainty and the learning process in the evolution of the ecological and economic dynamic systems.

Appendix 2.A The Equilibrium Dynamics of the Economy

From eqs. (2.3), (2.4), and (2.6), the growth rates of the two man-made capital stocks are given as: $\dot{H}/H=[\alpha\varepsilon/(1-\alpha)+\tau_K-\varphi]rK/H-\delta_H$ and $\dot{K}/K=[1/(1-\alpha)\ -(\alpha\varepsilon/(1-\alpha)+\tau_K-\varphi)]r-C/K-\delta_K$. Using eq. (2.8), the growth rate of τ_P is: $\dot{\tau}_P/\tau_P=-(\tau_P N/K)^{-1}\ [\phi C/K+\gamma/(1-\alpha)r]-\partial E(N)/\partial N+(1-\tau_K)r-\delta_K$. Then, using the definition of the three new "fundamental" variables (i.e., $h\equiv H/K$, $c\equiv C/K$, and $\tau\equiv\tau_P/K$) that are constant along the balanced-growth path, we can reformulate the whole (transitional) dynamic system of the economy in terms of h, c, N, τ and q_H:

$$\frac{\dot{h}}{h}\left(\equiv\frac{\dot{H}}{H}-\frac{\dot{K}}{K}\right)=\left(\left(\frac{\alpha\varepsilon}{1-\alpha}+\tau_K-\varphi\right)(1+1/h)-\frac{1}{1-\alpha}\right)r+y+\delta_K-\delta_H \tag{2.A.1}$$

$$\frac{\dot{c}}{c}\left(\equiv\frac{\dot{C}}{C}-\frac{\dot{K}}{K}\right)=\left(\sigma(1-\tau_K)+\left(\frac{\alpha\varepsilon}{1-\alpha}+\tau_K-\varphi\right)-\frac{1}{1-\alpha}\right)r+c-\sigma(\theta+\delta_K)+\delta_K$$
$$+\phi(\sigma-1)\frac{E(N)-P}{N} \tag{2.A.2}$$

$$\dot{N}=E(N)-P \tag{2.A.3}$$

$$\frac{\dot{\tau}}{\tau}\left(\equiv\frac{\dot{\tau}_P}{\dot{\tau}_P}-\frac{\dot{K}}{K}\right)=\left(-\frac{1}{\tau N}\frac{\gamma}{1-\alpha}+1-\frac{1}{1-\alpha}+\left(\frac{\alpha\varepsilon}{1-\alpha}-\varphi\right)\right)r+\left(1-\frac{\phi}{\tau N}\right)c-\frac{\partial E(N)}{\partial N} \tag{2.A.4}$$

$$\frac{\dot{q}_H}{q_H}=\left(-\frac{1}{q_H}\left(\frac{\alpha}{1-\alpha}\right)/h+(1-\tau_K)\right)r+\delta_H-\delta_K \tag{2.A.5}$$

where $r=(1-\alpha)\left(\frac{\tau}{\alpha\varepsilon}\right)^{\frac{-\alpha\varepsilon}{1-\alpha\varepsilon}}N^{\frac{\gamma}{1-\alpha\varepsilon}}h^{\frac{\alpha}{1-\alpha\varepsilon}}$ and $P=\left(\frac{\tau}{\alpha\varepsilon}\right)^{\frac{-1}{1-\alpha\varepsilon}}N^{\frac{\gamma}{1-\alpha\varepsilon}}h^{\frac{\alpha}{1-\alpha\varepsilon}}$.

As implied in eq. (2.7), the steady-state equilibrium for the dynamic system in eqs. (2.A.1) - (2.A.5) above can readily be found by setting the five time-derivatives to zero (i.e., $\dot{h} = \dot{c} = \dot{N} = \dot{\tau} = \dot{q}_H = 0$). The absence of non-convexities guarantees the existence of the equilibrium dynamic path. Letting (h^*, c^*, N^*, τ^*) be the optimal balanced-growth equilibrium values of (h, c, N, τ), governed by the inter-asset arbitrage conditions in eq. (2.8), we finally arrive at the equations (2.10a) - (2.10f) in the text. Combining eqs. (2.A.1) and (2.A.3) into eq. (2.A.2) generates the modified Keynes-Ramsey rule (describing the optimal savings-investment path for private capital) as reflected in eq. (2.10c).

Chapter 3: Uncertainty, Political Preferences, and Stabilization: Optimal Control using Dynamic CGE Models [79]

3.1 INTRODUCTION

In recent years there has been growing research interest in converting static computable general equilibrium (CGE) models into dynamic models.[80] This has also raised the possibility that uncertainty could also be added to these dynamic CGE models and the models solved as stochastic control models.

Nonetheless, unlike aggregate macroeconometric models, CGE modeling has been little used with optimal control formulations for stabilization policy analysis. However, as demonstrated in Smith (1993)'s approach, traditional CGE technique can be integrated with optimal control methods. In other words, adding an explicit objective function to the CGE model and minimizing the weighted deviations of the economy from desired levels, allow one to identify how best to achieve explicit goals for society.

This paper is a next step toward the merger of optimal control models with dynamic CGE models. It addresses the question of what time path of adjustment

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[80] Computable general equilibrium (CGE) models are characterized by their price-endogenous features and the inclusion of resource constraints. CGE models are designed to reflect many markets, many institutions, and their interactions, with prices and quantities determined simultaneously while simulating the results of an external shock or a policy change. Moreover, they can focus on the issues of economic structure with government interventions.

of an economy would be optimal for a government with explicit policy goals in the face of uncertainty in the economic system.[81]

The main features of the model employed in this paper are as follows. First, it provides rich dynamics by relaxing the standard neoclassical assumptions in CGE modeling, thereby allowing for more realistic adjustment processes towards long-run equilibrium. Economic phenomena can sometimes be best explained by adjustment processes over time ─ especially in the short- and midterm- run period.[82] Thus, instead of immediate market clearing, the model incorporates price-adjusted mechanisms that allow for some quantity-adjusted components together with cross and feedback effects (e.g., unemployment dynamics in labor markets). Second, unlike the usual control theory applications with aggregate macroeconomic models, the model developed here can be applied to deal with sector-specific policy issues (e.g., more stabilization priorities on polluting industries due to environmental concerns). It can be further used to perform control experiments regarding issues of economic structural reform. Finally, for more realism we incorporate uncertainty and passive learning processes with stochastic components in the dynamic CGE model.[83] Note that the

81 Optimal control theory with CGE approaches would be one of the most appropriate and powerful analytical devices if we can allow for the time path of adjustment towards the new equilibrium in a certain period (even, in response to short-run macroeconomic disturbances due to an unexpected shock) and also incorporate insight with explicit policy weights to reflect the relative importance on various states of the economy.

82 Dynamic general equilibrium modeling usually deals with long-run effects. Considering the weakness of traditional CGE models, note that it is critical how far one can accommodate non-neoclassical features in the CGE framework without giving up its basic characteristics and internal consistency (For details, see Dervis, de Melo, and Robinson, 1982, pp.169-73)

83 The stochastic control framework used here is discussed in detail in Kendrick (1981).

relationships among some particular variables are usually uncertain and the true underlying values for the relevant parameters may be unknown. In such cases the optimality of government policies would be decided with learning about the inherent stochastic world.

Following Johansen (1960)'s linearization method, the dynamic CGE framework is converted to be a stochastic control form amenable to the Duali software (Amman and Kendrick, 1999). Given the variability of an economic system with some stochastic components, this approach can help policy makers determine the timing and extent of government policy intervention.

Under the extended general equilibrium features described above, this model can be used to perform several optimal control experiments for economic stabilization with various sector-specific issues in the face of external shocks. Moreover, in the stochastic control experiments the relationship between uncertainty and the efficiency of government polices can be investigated with explicit declaration of their political preferences. It is thus demonstrated that the inclusion of optimal control formulations into stochastic CGE modeling would allow policymakers to use a wide range of policy experiments with careful treatment of uncertainty.

The rest of the paper is organized as follows. The optimal control CGE model is presented in Section 3.2, and some control experiments with industry specific emphases on political preferences and on uncertainty are implemented in Section 3.3. Finally, conclusions are discussed in Section 3.4.

3.2 An Optimal Control CGE Model of the U.S. Economy

3.2.1 General Equilibrium Background of the Model

Building on Smith (1993)'s work, we develop a simple dynamic CGE model that extends the stylized neoclassical CGE structure to allow for the short- or mid-term macroeconomic phenomena such as strains on factor markets. The present model includes decision-making by suppliers, households, government and the foreign sector, and market-clearing conditions, while integrating a traditional CGE modeling technique into a neo-Keynesian macroeconomic framework.

There are two goods, "clean" goods (i=CLN) from pollution-non-intensive industries and "dirty" goods (i=DRT) from pollution-intensive industries.[84] The technology vector is constructed with a constant-returns-to-scale, perfect competition, and Leontief intermediate input demands (V_{ij}). Sectoral supply (X_i^s) is determined by a Cobb-Douglas production technology with a scale parameter A_i and the two primary factors — labor input (F_{Li}^d) and capital input (F_{Ki}^d).

$$X_i^s = A_i\,(F_{Li}^d)^{\beta_i}\,(F_{Ki}^d)^{(1-\beta_i)} \qquad i = CLN, DRT. \tag{3.i}$$

Sectoral demands for primary factors (F_{Li}^d and F_{Ki}^d) are derived from the Cobb-Douglas technologies. Factor demand equations assume that the primary

84 "Clean" goods and "dirty" goods in the model may be viewed as metaphors for two different groups of industries that are subject to different penalties (or priorities) for stabilization. For example, policymakers can give more stabilization penalties on "dirty" industries due to environmental concerns. For a more detailed description of the model, see Kim and Kendrick (2002).

factors are paid the same average rental rate, P_f, and, for each sector, their remuneration is set equal to the value added price or net producer price (net of both indirect taxes τ_i and domestic intermediate input cost shares $\sum_j \alpha_j^d$) times the partial, β_{fi}, of the production function with respect to each factor.

$$F_{fi}^d = \frac{(1-\tau_i - \sum_j \alpha_j^d)\beta_{fi} P_i^d X_i^s}{P_f} \qquad f = L, K \tag{3.ii}$$

Pollution (PE) is also emitted from the production of dirty industries with emissions coefficient (ε).

$$PE = \varepsilon \; X_{DRT}^s \tag{3.iii}$$

In the product markets, the potential net production ($GDPP$) is pre-determined in the economy, depending only on the primary factors endowment and technology level. The equilibrium gap (dr) is defined as the percentage gap between $GDPP$ and the endogenous value of gross domestic product, GDP.[85] This is also simultaneously adjusted to the unemployment rate lur and the ratio of aggregate price index CPI to its reference level, which are all endogenized in this model, taking into account the adjustment costs in factor markets.

[85] This dr is viewed as the ratio of actual deviation from a full-employment neoclassical equilibrium level of the economy. The term 1– dr also implies the effective capacity utilization rate of the economy.

$$lur = lur_n + \rho_1 \; CPI / \overline{CPI} + \rho_2 \; dr \,, \tag{3.iv}$$

where $\rho_1 < 0$, $\rho_2 > 0$ and $dr = (GDPP - GDP) / GDPP$ (3.v)

Endogenizing the short-term adjustment process of prices and wages is critical for analyzing more appropriately the effects of short-term policy changes within the context of optimal control in a certain planning time period. In the model, production and output supply are from profit maximization in accordance with the natural unemployment rate component (lur_n) plus the involuntary unemployment component under a neo-Keynesian regime. Following the spirit of the Phillps curve, this model assumes that the unemployment rate (*lur*), as a wedge between labor supply and demand, is negatively related to the change in *CPI* and positively to the equilibrium gap, as in eq.(iv).[86] Prices and wages are adjusted towards the model closure, along with some rigidities constrained by this "equilibrium gap augmented" Phillips surface.

Domestic composite prices (P_i) are the weighted averages of the domestic prices (P_i^d) and the world prices (P_i^w), with weights based on imports (M_i) and domestic consumption of domestic goods (*Di*).

$$P_i = (P_i^w)^{\vartheta_i} (P_i^d)^{(1-\vartheta_i)} \tag{3.vi}$$

[86] For a similar treatment and discussion on general equilibrium with unemployment, see Patinkin (1966), Hansen (1970) pp.141-47, and Dervis, de Melo, and Robinson (1982).

The consumer price index (CPI) is an average of aggregate prices weighted by private household consumption for each commodity (C_i).

$$CPI = \prod_i (P_i)^{\lambda_i} \tag{3.vii}$$

Labor supply potential is a function of initial labor supply ($\overline{F}_L^s$) times the real wage rate (P_L / CPI) with a real wage elasticity of θ, which is, in turn, adjusted by the unemployment rate.

$$F_L^s = (1 - lur)\overline{F_L^s}\left[\frac{P_L}{CPI}\right]^{\theta} \tag{3.viii}$$

Factor incomes (R_f) are simply the sum of factor demand by domestic production and by the government. Household income (R_Q) is obtained as labor income plus capital income from the value-added (or net) production less direct government tax. Private households allocate their expenditures according to their Cobb-Douglas preferences.

$$C_i = \alpha_{ci} R_Q / P_i \tag{3.ix}$$

Sectoral investment (I_i) is given as a fixed share of total investment.

$$I_i = \alpha_{Ii} I \tag{3.x}$$

Sectoral export (E_i) and import (M_i) depend on the relative price of domestic and world goods with their own price elasticity of demand parameters.

$$E_i = \overline{E}_i (P_i^w / P_i^d)^{\eta_i} \tag{3.xi}$$

$$M_i = \overline{M}_i (P_i^d / P_i^w)^{\mu_i} \tag{3.xii}$$

Capital inflows are the balancing term of the value of imports less the value of exports.

Government revenue (R_G) is the sum of factor taxes, indirect taxes on domestic production and direct taxes from household income. Private household and government saving are the residual of their income less the expenditure on good and services. The government makes purchases of goods and services for each sector, G_i, in real terms.

Sectoral final demand is evaluated as the sum of private and public consumption, investment, and net exports. Thus, gross domestic product (*GDP*) is defined as

$$GDP = \sum_i \left(C_i + I_i + G_i + E_i - M_i \right) \tag{3.xiii}$$

Gross investment (I) is determined by initial investment ($\overline{I}$) times a function of real capital income change with an investment return elasticity of γ. Capital stock (F_K^s) is the depreciated prior period supply ($(1-\delta)\overline{F_{K,-1}^s}$) plus investment from the prior period (I_{-1}) (assuming undifferentiated by source), which is the only inter-temporal linkage in our simple CGE model.

$$F_K^s = (1-\delta)\overline{F_{K,-1}^s} + I_{-1}, \quad \text{where} \quad I = \bar{I}[(R_K / CPI)/\overline{R_K}]^{\gamma} \qquad \text{(3.xiv)}$$

To summarize, the requirements of general equilibrium closure are that in each period the demand for each factor and for each product equal supply:

Labor market clearing

$$\sum_i \frac{(1-\tau_i - \sum_j \alpha_j^d)\beta_{Li} P_i^d X_i^s}{P_L} = (1-lur)\overline{F_L^s}\left[\frac{P_L}{CPI}\right]^{\theta} \qquad \text{(3.xv)}$$

Capital market clearing

$$\sum_i \frac{(1-\tau_i - \sum_j \alpha_j^d)\beta_{Ki} P_i^d X_i^s}{P_K} = (1-\delta)\overline{F_{K,-1}^s} + I_{-1} \qquad \text{(3.xvi)}$$

Product markets clearing

$$X_i^d = X_i^s, \quad \text{where} \quad X_i^d = \sum_j V_{ij} + C_i + I_i + G_i + E_i - M_i \qquad \text{(3.xvii)}$$

To develop this CGE model with simultaneous states, controls and exogenous variables into system equations for a stochastic control version, one can convert the original nonlinear equations into a form amenable to the Duali software (Amman and Kendrick, 1999) which requires a state-space form with all linear relationships expressed in lagged terms. Three main state variables are introduced to use in calculating values from existing endogenous state variables: x = {gross domestic product (*GDP*), employment (*L*), pollution emissions (*PE*)}. This allows us to exploit more realistic policy objectives in the framework of optimal control. The policy or control variables, freeing up in the model, are government expenditures on goods and services: u = {government purchases of commodities (G_i)}. In this open economy, we also have exogenous variables: z = {world prices of commodities (P_i^w)}.

3.2.2 Optimal Control CGE Framework

Based on the CGE model described above, we have developed a small optimal-control CGE model of the U.S. economy. To do this, first, the nonlinear CGE framework is converted to classic system equations for an optimal control model, which will be used to perform various computational experiments. Then, if we add an explicit objective function (or social loss function) such as a quadratic "tracking" criterion function to the stochastic CGE model, it allows one to determine the level of policy (or control) variables to minimize the penalty-weighted squared deviation of the economy from the desired levels. In this case, as demonstrated in Smith (1993), the traditional CGE modeling is a special case of the optimal control problem – one in which the control variables are forced on the model and the resulting states are merely calculated as the CGE simulation. Specifically, for handling the standard CGE simulation within control theory applications such as the Duali, we can set to zero the weights (w_n) on the states variables and set to maximum possible value the weight (λ_m) on the controls.

The underlying CGE model in Section 3.2.1 can be implemented in percentage rates of change using the Johansen (1960)'s method. The principle of this method is a Taylor approximation around the base value to replace all non-linear equations by linear approximations, which are linear function of the log-deviations of variables from their base values. Without loss of the basic general equilibrium properties of the model in section 3.2.1 we can obtain a reduced linearized CGE model [eq. (3.1) thru (3.19)] in Table 3.1 by taking the total derivative of each function and dividing by the base period value. In this case, all variables with the superscript "*" in the equations represent the percentage deviations from the base period values such as the steady-states, means or secular trends. The lagged states variables are indicated by the subscript "-1".

Table 3.1 The Optimal Control CGE Framework

Objective function

$$\min\ J = \sum_t \left[\sum_n w_n (x_{nt}{}^* - \tilde{x}_{nt}{}^*)^2 + \sum_m \lambda_m (u_{mt}{}^* - \tilde{u}_{nt}{}^*)^2 \right] \tag{3.1}$$

Gross Domestic Product

$$GDP^* = \sum_i \Phi_{iQ}(R_Q^* - P_i^*) + \sum_i \Phi_{iG} G_i^* + \sum_i \Phi_{iE} E_i^* - \sum_i \Phi_{iQ} M_i^* + \Phi_I I^* \tag{3.2}$$

Employment

$$L^* = \sum_i \Psi_{iL} F_{Li}^{d\ *} \tag{3.3}$$

Pollution emissions

$$PE^* = X_{DRT}^{s\ *} \tag{3.4}$$

Domestic Commodity Prices

$$P_i^{d^*} = 1/(1-\vartheta_i)P_i^* - \vartheta_i/(1-\vartheta_i)P_i^{w^*} \tag{3.5}$$

Gross Domestic Supply

$$X_i^{s^*} = \sum_f \beta_{fi} F_{fi}^{d^*} \tag{3.6}$$

Factor Demand

$$F_{fi}^{d^*} = P_i^{d^*} + X_i^{s^*} - P_f^{\ *} \tag{3.7}$$

Consumer Price Index

$$CPI^* = \sum_i \lambda_i P_i^{\ *} \tag{3.8}$$

Unemployment Rate

$$lur^* = \rho_1\ CPI^* - \rho_2\ GDP^* \tag{3.9}$$

Labor Equilibrium

$$P_L^{\ *} = \sum_i (\Psi_{iL}/\theta) F_{Li}^{d^*} + CPI^* - \rho_1/[\theta(1+\rho_1)]\ lur^* \tag{3.10}$$

Capital Equilibrium

$$P_K^{\ *} = \frac{\Psi_{CLN,K}}{\delta + \Psi_{CLN,K}}\left\{P_{CLN}^{d\ \ *} + X_{CLN}^{s\ \ *}\right\} + \frac{\delta}{\delta + \Psi_{CLN,K}}\left\{P_{DRT}^{d\ \ *} + X_{DRT}^{s\ \ *}\right\} - \frac{\gamma\Psi_{CLN,K}}{\delta + \Psi_{CLN,K}}\ I_{-1}^{\ \ *} \tag{3.11}$$

Export Quantities

$$E_i^* = \eta_i(P_i^{w^*} - P_i^{d^*}) \tag{3.12}$$

Import Quantities

$$M_i^* = \mu_i(P_i^{d^*} - P_i^{w^*}) \tag{3.13}$$

Factor Incomes

$$R_f^* = P_f^* + \sum_i \Psi_{if} F_{fi}^{d^*} \tag{3.14}$$

Household Income

$$R_Q^* = \sum_i \Gamma_{Qf} R_f^* + \Gamma_{QG} R_G^* \tag{3.15}$$

Government Income

$$R_G^* = \sum_f \Lambda_f R_f^* + \Lambda_G R_G^* + \sum_i \Lambda_i (P_i^{d^*} + X_i^{s^*}) + \Lambda_Q R_Q^* + \Lambda_{KA} I^* \tag{3.16}$$

Gross Investment

$$I^* = \gamma(R_K^* - CPI^*) \tag{3.17}$$

Intermediate Demand

$$V_i^* = \sum_j \upsilon_{ij} X_i^{s^*} \tag{3.18}$$

Output Equilibrium

$$P_i^* = -\frac{1}{\Theta_{iQ}} X_i^{s^*} + \frac{\Theta_{iV}}{\Theta_{iQ}} V_i^* + R_Q^* + \frac{\Theta_{iG}}{\Theta_{iQ}} G_i^* + \frac{\Theta_{iE}}{\Theta_{iQ}} E_i^* - \frac{\Theta_{iM}}{\Theta_{iQ}} M_i^* \tag{3.19}$$

where share parameters evaluated at the base period values are

$$\Phi_{iQ} = \frac{C_i}{GDP}, \Phi_{iG} = \frac{G_i}{GDP}, \Phi_{iE} = \frac{E_i}{GDP}, \Phi_{iM} = \frac{M_i}{GDP}, \Phi_I = \frac{I}{GDP} \;;$$

$$\Psi_{iL} = \frac{F_{Li}^d}{L};\ \Psi_{iK} = \frac{F_{Ki}^d}{K};\ \Gamma_{Qf} = \frac{P_f \sum_i F_{fi}}{R_Q};\ \Lambda_i = \frac{\tau_i P_i^d X_i^s}{R_G};\ \upsilon_{ij} = \frac{V_{ij}}{V_i};$$

$$\Theta_{iQ} = \frac{C_i}{X_i^s}, \Theta_{iV} = \frac{V_i}{X_i^s}, \Theta_{iG} = \frac{G_i}{X_i^s}, \Theta_{iE} = \frac{E_i}{X_i^s}, \Theta_{iM} = \frac{M_i}{X_i^s}.$$

As is typical in the control theory literature, the dynamic evolution of the states variables in the above model can be represented by the state-space form of eq. (3.2) thru eq. (3.19) in matrix notation. In this case, following Kendrick (1981, Chapter 4), sectoral government expenditures, $G_i^* = u_{i,-1}$, are set equal to government obligations of the previous period and the exogenous sectoral world prices, $P_i^{w^*} = z_{i,-1}$, to those of the previous period, so as to write the model in the usual format of control theory. After stacking these new states into the augmented state vector x and doing simple matrix manipulation, we finally get the system equation for our optimal control CGE model:

$$x_{k+1} = A(\theta_k)x_k + B(\theta_k)u_k + C(\theta_k)z_k + \xi_k, \quad k = 0, 1, \cdots, \text{T-1}. \tag{3.20}$$

where x_0 is given, $\xi_k \sim N(0,Q)$, and $\theta_k \sim N(\hat{\theta}_k, \Sigma_{0|0}^{\theta\theta})$. Here ξ_k and θ_k are normally distributed with means and covariances as shown above. System equation (3.20) is a system of first-order difference equations in which the current 26 states are functions of their previous period states, 2 previous period controls and 2 previous period exogenous variables. The additive error term, ξ_k, is normally distributed with mean zero and covariance *Q*. The evolution of uncertain parameters, θ_k, is specified as

$$\theta_{k+1} = D\theta_k + \zeta_k, \qquad k = 0, 1, \cdots, T\text{-}1 \tag{3.21}$$

which permits time-varying random parameters.[87] In general it is difficult to know the relative uncertainty across parameters since there is no general criteria yet to select which of the parameters in *A*, *B* and *C* matrix should be treated as uncertain. However, as will be seen in next section, it would be reasonable to assume that all of the non-zero parameters in the system equations are uncertain.

3.2.3 Data Sources, Calibration, and Stochastic Elements

Considering the exploratory nature of joint stochastic control-CGE models, this paper employs the simplest approach to data sets and model calibration. We used a social accounting matrix (SAM) for the 1989 U.S. economy. This data was basically recompiled from the original SAM database

[87] For a detailed discussion of the structure of the optimal control model, see Kim and Kendrick (2002).

constructed by the U.S. International Trade Commission for analysis of U.S. trade policy. For our purpose, the original 31 industrial sectors in the U.S. SAM, benchmarked to 1989, were amalgamated into two broad sectors: pollution-non-intensive industries (or "clean" industries) and pollution-intensive industries (or "dirty" industries).[88] Two commodities from the two broad industries are the base for CGE modeling. The model for stochastic control CGE experiments described in Section 2.2 was calibrated directly from the U.S. SAM. Thus, for our model, the U.S economy has been divided into a SAM composed of two broad industrial sectors, two factor sectors (labor, capital), one household sector, one investment sector, one government sector, and one sector which represents the rest of the world. The key elasticities of the model not available from the SAM were uncertain but approximately chosen from the relevant literature. The real wage elasticity of θ we adopt is 0.3 for the U.S economy.[89] The investment return elasticity of γ adopted here is 1.1 which is higher than the real wage elasticitities.[90] The parameter values associated with the "equilibrium gap augmented" Phillips surface in eq. (3.9) are $lur_n = 0.05$, $\rho_1 = -0.05$, and $\rho_2 = 0.66$. Thus, in the base case, the model can collapse into the fully neoclassical CGE

[88] In this paper, "clean" industries are those with a relatively low portion of pollution intensities in their production such as services and agriculture, whereas "dirty" industries are those with a relatively large proportion of pollution intensities such as energy and metal processing, petrochemicals, transportation and the other manufacturing products.

[89] See Stuart (1984), Browning (1987), Russek (1996), and Fuchs, Krueger and Poterba (1997).

[90] Reliable estimates of the elasticity of investment with respect to rates of return are relatively difficult to find because of the data problems. However, Engle (1974)'s estimates are useful for our model. The elasticity estimates by Engle (1974) for the four major durable and nondurable industries are 0.64, 1.57, 0.80, and 1.5. The value adopted here is the simple average of these values and it seems somewhat plausible compared to the other estimates reported by Jorgenson and Stephenson (1969).

Table 3.2 Estimated Model and Parameter Values : 26 States, 2 Controls and 2 Exogenous Variabl

26 States / Parameter Matrix of System Equations

X=	A(TINV)=	B=		C=	
GDP	-0.02104	0.80050	0.16544	0.14473	0.86883
L	0.03708	0.10117	0.02166	0.01160	0.10649
PE	0.24541	-0.19883	0.06273	-0.03625	0.32229
PD1	-0.15482	0.47960	0.09889	0.07132	0.50277
PD2	-0.14643	0.59096	0.12255	0.08819	0.62348
XS1	0.15991	0.24528	0.02902	0.03521	0.14396
XS2	0.24541	-0.19883	0.06273	-0.03625	0.32229
FDL1	0.01845	0.16718	0.01028	0.02243	0.04716
FDL2	0.11235	-0.16557	0.06765	-0.03216	0.34620
CPI	-0.14692	0.47456	0.09795	0.09150	0.52052
LUR	0.02167	-0.55348	-0.11438	-0.10037	-0.60101
PL	-0.01337	0.55770	0.11763	0.08410	0.59957
PK	-0.50158	0.67973	0.13569	0.09913	0.68731
E1	0.10063	-0.31174	-0.06428	0.60364	-0.32680
E2	0.24160	-0.97508	-0.20221	-0.14552	0.62126
M1	-0.07741	0.23980	0.04944	-0.46434	0.25139
M2	-0.19035	0.76824	0.15931	0.11465	-0.48948
RL	0.02371	0.65887	0.13928	0.09570	0.70606
RK	0.01650	0.62910	0.12558	0.09174	0.63611
RQ	0.02209	0.64484	0.13335	0.09362	0.67560
RG	0.02988	0.63143	0.13044	0.09053	0.65959
TINV	0.17976	0.17000	0.03040	0.00027	0.12714
V1	0.18149	0.13317	0.03753	0.01717	0.18898
V2	0.21138	-0.02209	0.04931	-0.00781	0.25132
P1	-0.15095	0.46762	0.09642	0.09452	0.49022
P2	-0.12635	0.50994	0.10575	0.07610	0.67510

2 Controls

$$U=\begin{bmatrix} G1 \\ G2 \end{bmatrix}$$

2 Exogenous

$$Z=\begin{bmatrix} PW1 \\ PW2 \end{bmatrix}$$

framework. The elasticities used for the U.S import demand and export supply are chosen to represent the middle ground of published estimates obtained from the most recent studies. For the dirty industries, import and export elasticities are set at 1.3 and 1.65, respectively, while the clean industries have import and export elasticities set at 0.5 and 0.65.[91] Here, trade flows of dirty industry product are more price-responsive than those of clean industries.

Table 3.2 represents the coefficients of the estimated matrices *A*, *B* and *C*. In the state-space form, matrix *A* has non-zero values only in a column vector associated with total investment of previous period (*TINV*), since this variable is the only inter-temporal linkage in our simple CGE model. However, any uncertainty contained in each of the above key parameters in the original structural CGE framework would be distributed throughout the final (state-space form) system equations (3.20) during the matrix transformation. Thus the systems equations would also have some estimates of variance and covariance of coefficients as well as the residuals from equations.

3.3 CONTROL EXPERIMENTS

The optimal control CGE model developed in Section 2 provides a full economic specification with both price and quantity equations and it incorporates the speed of evolution of the economic system over time. In addition, it allows for more realistic adjustment processes towards long-run equilibrium, which is

[91] These are the industry-wide average values from the estimates by Reinert and Roland-Holst (1992) and Shiells and Reinert (1993).

important especially for capturing the short- and midterm- run effects of temporary external shocks.

In what follows, we will use Duali to perform some control experiments with the U.S. control-CGE model, focusing on the roles of asymmetric political preferences and uncertainty across industrial sectors. Duali is a specialized software that can receive as inputs the desired paths for target and control variables, weighting penalty matrices, and the state-space representation of the economic model with or without its stochastic specifications. With the help of this software, we can easily compute the optimal feedback rule and the solution paths for the states and controls.

3.3.1 How does the Structure of Sectoral Political Preferences Matter for Macroeconomic Stabilization?

How do changes in the structure of policymaker's political preferences affect the macroeconomic performance of stabilization policy? For instance, the macroeconomic performance can vary with the degree of policymaker's environmental preferences. This section performs some experiments with alternative penalty weight schemes associated with issue of pollution emissions. Specifically, as an illustration, the case of macroeconomic stabilization with sector-specific political preferences (i.e., dirty or clean industries) is compared to the case with no sector-specific political preferences.

For our economy, the policy goal of the economy (in aggregated terms) is to stabilize *GDP*, employment (*L*) and pollution emissions (*PE*) around the base case values, that is around zero, in the face of unexpected shocks. Assume that at period 0, the U.S economy is initially shocked (below its base case values) due to a temporary 5% deterioration in the international price-competitiveness of the dirty industries. Then, the optimal solutions for macroeconomic stabilization with three alternative penalty weight schemes are compared. Figure 3.1 provides the comparison of the optimal control solutions for the cases of (i) more of the political preferences on clean industries (sector1-focused scheme), (ii) more of the political preferences on dirty industries (sector2-focused scheme), and (iii) no sector-specific political preferences (equal scheme).[92]

The graphs in Figure 3.1 show that the optimal control paths for all three schemes outperform the autonomous responses of the economic system. However, the stabilization performance of "sector2-focused scheme" in our experiment is somewhat worse than that of "equal scheme," since more controls on economic activities of the U.S. dirty industries tend to slow down directly the speed of recovery from the initial recession that was centered on the dirty industrial sectors. On the contrary, "sector1-focused scheme" performs better than "equal scheme." We can also see that in the case of "sector1-focused scheme" the fiscal policy of spending on clean goods (*G1*) plays a major role compared to that of dirty goods (*G2*), and *vice versa* in the case of "sector1-focused scheme."

92 The optimal control case with "equal scheme" is undertaken with the equal penalty weight structure on the states (*GDP*, employment and pollution emissions). For the optimal control case "sector1-focused (sector 2-focused) scheme," the penalties on all sectoral activities of the dirty (clean) industries are now set to zero. Also, the model in Duali can be easily implemented to simulate the autonomous response of the model to a change in initial conditions. To do so, change the value of the nonzero elements in the W vector back to zero and and the value of the two elements in the Λ matrix to large numbers such as 9999999. For all cases, check to be sure that all desired paths are set to zero.

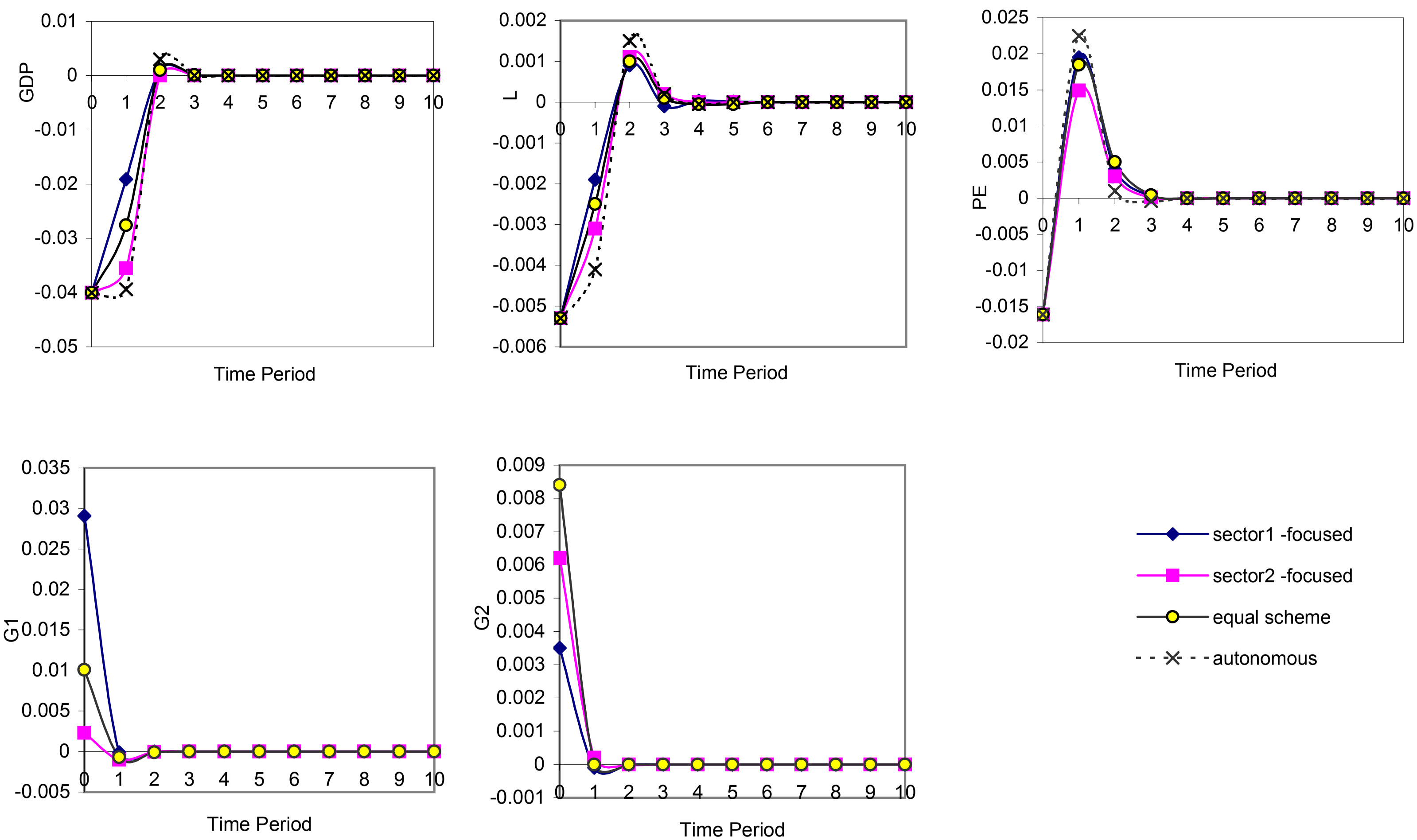

Figure 3.1 Optimal Control Solutions under Alternative Political Preferences Schemes in the CGE Model

The results above imply that the macroeconomic performance of stabilization could vary significantly with sector-specific political preferences (i.e., dirty or clean industries). This consideration would be especially important when policymakers address the issues of industrial, environmental, macroeconomic stabilization concerns simultaneously in an open economy framework.

On the other hand, for a substantial gain in realism, policymakers might need to take uncertainty into account. Indeed, economic models are biased due to the true underlying values of parameters being unknown (multiplicative uncertainty) and all the variances in states is not fully explained by the equations defining these states (additive uncertainty). Note that there are random shocks frequently hitting the economy, and the actual values of the model parameters, variables and initial conditions are never known with certainty.

Thus, the structure of political preferences can also affect the macroeconomic consequences of policy procedures in the face of uncertainty. We performed an experiment of 100 Monte Carlo runs with two different political preferences across industrial sectors, assuming that there is uncertainty associated with all parameters in the *B* matrix with the 20% standard deviations of each of these parameter mean values.[93] For each run, we compute the values of the quadratic tracking function in eq. (3.1). Then, the simulation results are encapsulated in a plot of pairs of criterion values from certainty equivalence

[93] Following Amman and Kendrick (1999)'s approach, for each of the two cases the Monte Carlo runs are done using Duali. In Duali all the random variables regarding additive noise, uncertain parameters, measurement errors and uncertain initial states are generated by Monte Carlo routines using the covariance matrices and the probability distributions.

procedure (CE) and open loop feedback procedure with parameter uncertainty (OLF) across Monte Carlo runs.[94]

Figure 3.2 summarizes the simulation results. Here the 45 degree line indicates when the criterion values of OLF policies are equal to CE policies. Thus a greater number of points above the 45 degree line imply that OLF policy performs better than CE policy. In the first panel of Figure 3.2, for a majority of the Monte Carlo runs the criterion values of OLF is smaller, and thus better, than the criterion value of CE.[95] However, the second panel indicates a similar performance for both control procedures. Therefore, we can see that the macroeconomic performance comparison of policy procedures towards uncertainty could be conditioned on the structure of policymaker's political preferences (i.e., relative penalty weights in criterion functions). However, note that there are no general theoretical results yet regarding the relative performance of CE and OLF, and the results may also depend on differences in the sizes and specifications in a wide variety of models.[96]

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[94] Stochastic control experiments generate a dynamic stochastic environment through random shock generation. These experiments use specific solution procedures: Certainty Equivalence (CE) and Open Loop Feedback with parameter uncertainty (OLF). CE considers only the additive uncertainty and ignores parameter uncertainty, while OLF uses both the mean and covariance values of the parameter estimates with passive learning. For this solution procedure in Duali, see Amman and Kendrick (1999).

[95] Using a simple macroeconomic model, Amman and Kendrick (1999) also found a similar result.

[96] For a detailed discussion, see Kendrick (2002).

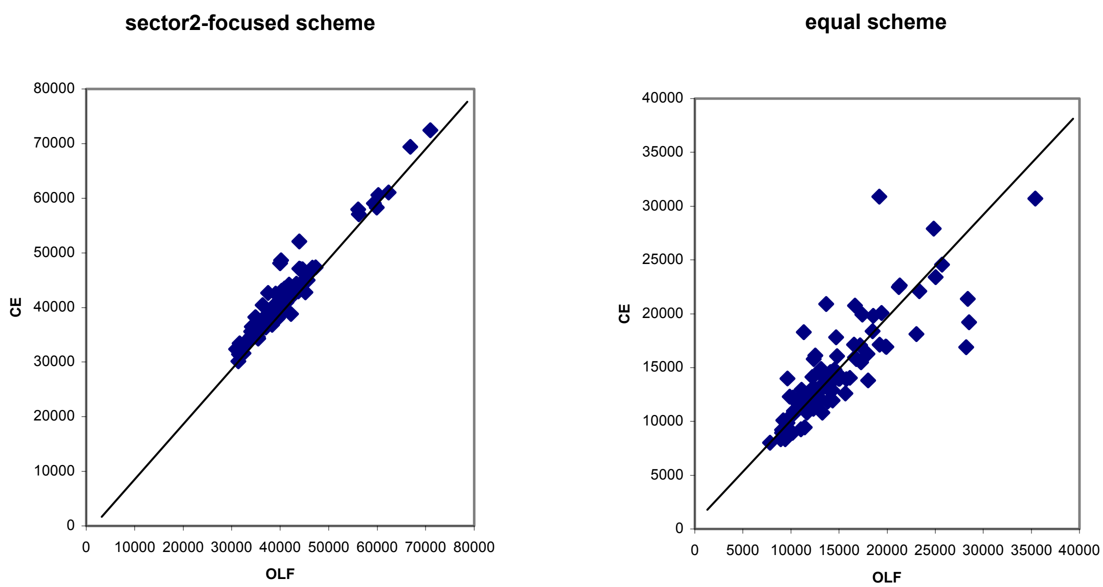

Figure 3.2 Comparison of Criterion Values Across Monte Carlo Runs

3.3.2 How does the Structure of Uncertainty Matter for Sectoral Government expenditures?

How does the existence of parameter uncertainty cause policymakers to use their control instruments as compared to the case of no parameter uncertainty in a dynamic setting. In this section we will investigate the question of whether or not the existence of parameter uncertainty causes policymakers to use their controls in a more conservative fashion as compared to the case of no parameter uncertainty in a dynamic setting. For the cases of models with several states and controls, we cannot obtain the general answer to the above question. The result depends on the unknown covariance matrices associated with all of the states and controls in a complex way.

The policymaker's goal is to stabilize the economy in the face of unexpected temporary shocks. The desired levels of *GDP*, employment (*L*) and total pollution emissions (*PE*) were set to their initial levels in 1989 with equal policy weights for each. As before, we assume that the U.S economy is initially shocked below its base-case value due to the terms-of-trade shocks at period 0 and also that there is uncertainty in connection with six out of the parameters in the *B* matrix with the 20% standard deviations of each of these parameters. The vector of the base case mean values of these uncertain parameters (θ_0) and the variance-covariance matrix of uncertain parameters (Σ_0) are

$$\theta_0 = \begin{bmatrix} b_{11} = .80051 \\ b_{12} = .16544 \\ b_{21} = .10117 \\ b_{22} = .02166 \\ b_{31} = -.19883 \\ b_{32} = .06273 \end{bmatrix}, \quad \Sigma_0 = \begin{bmatrix} .002563 & & & & & \\ & .00109 & & & & \\ & & .00041 & & & \\ & & & .00002 & & \\ & & & & .00158 & \\ & & & & & .00016 \end{bmatrix}.$$

Here, b_{11}, b_{21} and b_{31} are *GDP*, *L* and *PE* parameters associated with government expenditure on clean goods (*G1*), respectively, and b_{12}, b_{22} and b_{32} are the parameters associated with government expenditure on dirty goods (*G2*).

The general equilibrium effects of changing the degree of model uncertainty can be traced to investigate the question of where optimal policies should lie. To investigate the consequences of changing the level of relative uncertainty of the model parameters corresponding to one of the policy variables, the standard deviation of the *G2* parameters, b_{12}, b_{22} and b_{32}, were doubled from 20% to 40%.

Figure 3.3 compares the alternative optimal paths of the policy variables in the case of a doubling in the relative uncertainty of the *G2* parameters.

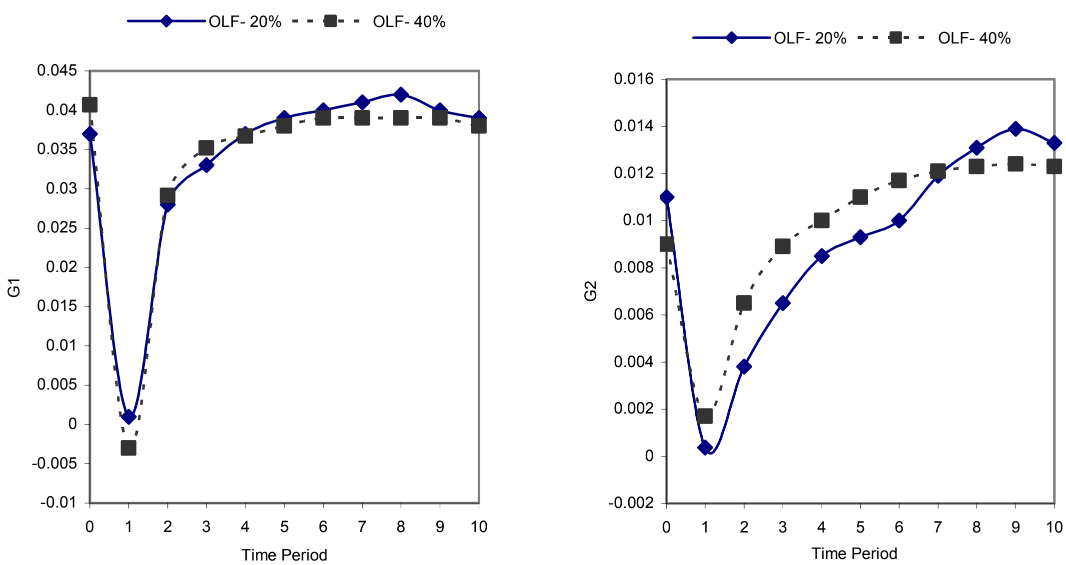

Figure 3.3 Effects of Relative Parameter Uncertainty of Policy Variables

As we can see in the graphs, the new path of *G2* is flatter than before, which implies that a relatively higher uncertainty in the *G2* parameters induces a more cautious use of that policy as a control instrument. On the contrary, government expenditure *G1* with a relatively certain parameters fluctuates more than before and is used more vigorously. This seems plausible but the results would be conditioned on the structure of penalty weights in the criterion functions and differ according to the structure of model assumptions. However, this experiment clearly suggests that policymakers need to consider the relative degree of associated parameter uncertainty among policy variables when choosing levels of policy intervention.

3.3 CONCLUSION

Traditional CGE models have ignored uncertainty ─ even when applied to fields such as environmental modeling that are replete with economic uncertainty. In contrast, many control theory models have focused on the effects of uncertainty. Thus marrying the tradition of CGE and control modeling can result in price-quantity models with explicit dynamics and careful treatment of uncertainty.

In this perspective our paper explores an operational optimal control model of the U.S economy with traditional CGE approaches. It is intended to demonstrate the usefulness of CGE techniques in control theory application and also to provide a practical guideline to policymakers in this relatively new field. First, we develop a small dynamic SAM-based CGE model for the U.S economy.

Then we compute the optimal control paths for the policy and state variables to guide the economy toward its desired goals as compared to the autonomous responses of the system in the face of unexpected shocks. Specifically, as an example, the U.S. control CGE model is used to explore the links between uncertainty, environmental care, and optimal government expenditure policy in a dynamic general equilibrium framework.

Instead of immediate market clearing, the model incorporates price-adjusted mechanisms that allow for some quantity-adjusted components (such as unemployment dynamics in labor markets) together with cross and feedback effects. This consideration is of great importance for short- or mid-term economic stabilization policies against unexpected external shocks. The results indicate that the optimal control solutions could differ not only due to differences in underlying model assumptions or structures, but also depending crucially on uncertainty about the magnitude of various parameters in the economy. In particular, it is also demonstrated that the performance of economic stabilization could vary significantly with asymmetric political preferences and uncertainty across industrial sectors. In such cases, allowing for those components in more general CGE-based economic modeling may identify policies in the inherently stochastic world that may outperform traditional control-theory modeling approaches.

An interesting extension of the paper would be to consider the industry classifications of exportable, importable and non-tradable sectors, and then to analyze some (sector-specific or strategic) international trade policy issues. Another possible extension might include the consideration of monetary variables in the CGE framework, so that we could examine both fiscal and monetary policy in relation to industrial and international trade policy issues. Incorporation of additional inter- temporal linkages such as investment accelerator, durable consumption behavior, or the dynamic Phillips curve would enrich the model dynamics and possible control-theory CGE applications as well.

To mention some limitations of the model in this paper, it relies on the parameter values artificially drawn from the relevant literature rather than consistently estimated in a unified framework of the model. Thus, for more practical implementation of the model, we will need a fairly disaggregated econometric model of the U.S. economy (in reduced form). Further, it depends on the standard simplifying assumptions on the model economy and thus could be extended to consider the other effects of imperfect competition, monetary and financial behaviors, and distributional consequences.

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Vita

Seung-Rae Kim was born in Taegu, Republic of Korea, on October 10, 1966, the son of Nam-Hae Kim and Sung-Ja Shin. After completing high school, he entered Seoul National University, Korea, and completed the degree of Bachelor of Science in Engineering in 1989. Being admitted to the Graduate School of Seoul National University, he received his Master of Science degree in Engineering in 1991. Parts of his Master's thesis were published in an international journal, *Energy Policy*, 1993, and other Korean academic journals. During the following years, he served in the Korean Army, and then was employed as a researcher at the POSCO Research Institute, Seoul, Korea.

In September 1998, he entered the Doctoral program at the University of Texas at Austin, and in May 2000, he earned his Master's degree in Economics. Under the supervision of Dr. Don Fullerton, he completed his doctoral dissertation, *Essays on Interactions Between Environmental and Fiscal Policies*, in January, 2003. While working on his dissertation, he won 2002-2003 *Joseph L. Fisher Doctoral Dissertation Fellowship Award* from Resources for the Future (RFF), Washington, D.C., in an international competition, and part of his dissertation was published in *Contributions to Economic Analysis & Policy*, 2002, Berkeley Electronic Press.

Permanent address: 3366 Lake Austin Blvd., Apt. C, Austin, TX 78703

This dissertation was typed by the author.