Discount Rates and Distortionary Taxation: Using First-Best Decision Rules in a Second-Best World

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ABSTRACT

This paper examines the links between discounting procedures and distortionary taxation in a numerically calibrated model of climate change and the world economy. Under first-best conditions, carbon dioxide emissions would be taxed at a rate equal to the present-value marginal cost that current emissions impose on the future economy, setting the discount rate equal to the marginal productivity of capital. Under second-best conditions, however, substantially lower discount rates are economically justified when emissions tax revenues are used to provide targeted cuts in labor and capital taxes, while significantly higher discount rates are appropriate when emissions tax revenues are released using lump-sum transfers. The paper shows that reliance on first-best decision rules may lead policy-makers to underestimate the environmental taxes that would maximize social welfare. Attaining the optimum, however, requires careful coordination between environmental and fiscal policies.

INTRODUCTION

The view that policy-makers should discount the future at the rate of time preference revealed in private financial markets plays a key role in environmental economics. In the economics of climate change, for example, Manne (1995; see also Nordhaus, 1994) argues that the future benefits of greenhouse gas emissions reductions should be discounted at a rate equal to the real return on private capital, which averaged roughly 6% per year in the mid to late 20th century (IPCC, 1996, ch. 4). In this perspective, the use of lower discount rates would reduce social welfare by causing low-return public projects to crowd out private investments that generated greater social benefits. Under standard assumptions concerning the costs and benefits of climate change, discount rates of this magnitude suggest that relatively modest levels of greenhouse gas emissions abatement are economically warranted (Manne *et al*., 1995; Nordhaus and Boyer, 2000).

The use of high discount rates is criticized by Broome (1992) and Cline (1992), who argue that policy-makers should attach equal weight to the welfare of present and future generations. And as Tol (2003) notes, greenhouse gas emissions abatement would reduce the risk that climate change would impose catastrophic costs on future generations. Since investors accept annual returns of only 1% on safe financial assets, the use of high discount rates is arguably inappropriate in the economics of climate change (Howarth, in press). Not surprisingly, the use of low discount rates supports aggressive steps towards climate stabilization (Chapman *et al*., 1995; Howarth, 1998).

In this paper, we abstract away from questions of intergenerational fairness and risk to focus on a third aspect of the discount rate debate – the influence of distortionary taxes in markets for savings and investment. Since the seminal work of Eckstein (1958), a detailed theoretical literature has emphasized the fact that taxes on income and capital drive a wedge between pre- and post-tax returns on investment (see Lind, 1982). In the presence of taxation, individuals' time preference is revealed by post-tax returns, while pre-tax returns reveal the marginal productivity of capital. While this fact would seem to imply that the discount rate should be set equal to the post-tax rate, this approach can yield inefficiencies if public projects are financed through reductions in more productive private capital formation. Two major solutions have been proposed to address this difficulty. Analysts may either:

1. Choose the discount rate based on a *weighted average* of pre- and post-tax returns (Sandmo and Dreze, 1971).

2. Work with post-tax discount rates while carefully accounting for the opportunity costs that arise when public projects crowd out private investment using the "shadow price of capital" approach (Bradford, 1975; Lind, 1982).

Unfortunately, these approaches can be difficult to employ in practical applications. As Stiglitz (1982) notes, the weighting factors required by the first approach vary from project to project and depend closely on the interaction between the project itself and the economy as a whole. In a similar vein, the shadow price of capital method requires analysts to gauge how a specific public policy would affect private investment. Since these impacts are mediated by people's decisions in capital markets, the method seems to require the use of general equilibrium models. In the face of such complexities, policy analysts often abstract away from this aspect of the theoretical literature, preferring to work with simplified models of resource allocation in the absence of taxation. This approach – which plays a central role in the economics of climate change (IPCC, 1996, ch. 4) – rests on the hope that first-best decision rules can generate policy recommendations that are good enough to support decisions that pertain to complex real-world economies.

This paper explores the validity of this hypothesis in the context of a numerically calibrated model of interactions between climate change and the world economy. Specifically, we adapt Coleman's (2000) model of optimal taxation in the U.S. economy to account for the costs and benefits of greenhouse gas emissions abatement at the aggregate global level. In this model, a tax on labor and capital income is used to finance exogenously defined public expenditures. We consider the time path that arises in this model when climate change policies are chosen using a "first-best" decision rule in which greenhouse gas emissions are taxed at a rate equal to the discounted value of marginal future damages. In this setting, the discount rate is set equal to the marginal productivity of capital as revealed by the pre-tax return on capital investment. This approach would promote economic efficiency in the absence of distortionary taxation (Arrow and Kurz, 1970).

We contrast the results that arise under this "first-best" decision rule with the second-best paths that occur when the discount rate is chosen to maximize the welfare of a representative household. In the context of this model, the first-best decision rule:

1. Substantially *understates* the optimal discount rate that arises when emissions tax revenues are returned to households in the form of lump-sum transfers.

2. Substantially *overstates* the optimal discount rate in the case where emissions tax revenues are used to provide targeted cuts in labor and capital taxes.

Since the discount rate is instrumental in balancing the present costs and future benefits of greenhouse gas emissions abatement, these scenarios differ markedly in terms of their substantive policy recommendations. In particular, the analysis supports the view that environmental taxes can in some cases exacerbate the distortions induced by prevailing fiscal policies (Bovenberg and de Mooij, 1994; Bovenberg and Goulder, 1996; Parry *et al.*, 1999). On the other hand, it also supports Pearce's (1991; see also Jaeger, 2002) argument that relatively high greenhouse gas emissions taxes may be justified when policies are carefully designed to reduce the deadweight cost of taxation.

Interestingly, the literature on second-best environmental taxes has focused mainly on the distortions caused by labor taxes in models of static resource allocation. The public finance literature, however, has shown that reducing capital taxation in dynamic economies can yield particularly large welfare gains (Summers, 1981; Lucas, 1990). Although Shackleton *et al.* (1996) and Bovenberg and Goulder (1997) examine how relieving capital taxes can reduce the perceived costs of greenhouse gas emissions taxes, they do not take the next step of integrating costs and benefits to calculate second-best emissions taxes. The present paper addresses this gap while linking it explicitly to issues of discounting and intertemporal choice.

THE MODEL

We consider a model that is patterned after Coleman's (2000) analysis of optimal tax policies in a competitive, intertemporal economy. Based on a set of empirical assumptions that pertain to the United States, Coleman develops a representative agent model of the interplay between households and producers in the presence of distortionary taxation. In this study we adapt Coleman's model in three principal ways. First, we revise the model's representation of technology and preferences to include the costs and benefits of greenhouse gas emissions and the accumulation of greenhouse gases in the atmosphere. Second, we augment the model to allow for population growth, a factor that was not considered by Coleman. Finally, we recalibrate the model based on a set of stylized facts that apply to the overall world economy. Using this approach, we are able to analyze the welfare effects of greenhouse gas emissions taxes in the presence of pre-existing taxes on labor and capital.

Household Behavior

We assume the existence of a representative household that seeks to maximize the objective function:

$$V = \sum_{t=0}^{\infty} N_t u_t(c_t, l_t, S_t) \boldsymbol{d}^{t} \qquad (1)$$

under conditions of perfect foresight. In this specification, N_t is the population at date $t \in [0, \infty)$, measured in billions of persons; c_t is per capita consumption, measured in U.S. dollars at year 2000 prices; l_t is a measure of labor effort, defined as the proportion of non-sleep hours a typical person spends at work; and S_t is the atmospheric stock of carbon dioxide, a greenhouse gas that adversely affects global climate, measured in billion metric tons of carbon. The utility function $u_t(\cdot)$ is concave, increasing in consumption, and decreasing with respect to labor effort and carbon dioxide levels. The parameter d defines the rate of pure time preference, or the relative weight that households attach to present and future welfare. Time is measured in decades with the period t = 0 interpreted as the interval 2000-2009.

Each member of the household holds the capital wealth k_t (measured in year 2000 dollars) and earns income by renting labor and capital services to the production sector at the wage rate w_t and the interest rate r_t. Governments tax the income earned on labor and capital at the rates t_{lt} and t_{kt} while providing a transfer payment p_t to each individual. Under these conditions, the household faces the budget constraint:

$$c_t + k_{t+1} - k_t = (1 - t_{lt})w_t l_t + (1 - t_{kt}) r_t k_t + p_t . \qquad (2)$$

Taking prices, public policies, and the state of the environment as fixed at each point in time, a rational household would manage its decisions concerning consumption, labor effort, and net capital investment to maximize the objective function subject to equation (2). This problem yields the first-order conditions:

$$-\frac{\partial u_t / \partial l_t}{\partial u_t / \partial c_t} = (1 - t_{lt}) w_t \qquad (3)$$

$$\frac{N_t \partial u_t / \partial c_t}{dN_{t+1} \partial u_{t+1} / \partial c_{t+1}} = 1 + (1 - t_{kt+1}) r_{t+1} . \qquad (4)$$

Under equation (3), households equate the marginal rate of substitution between consumption and labor with the after-tax wage rate. Equation (4), in contrast, implies that the marginal rate of intertemporal substitution is set equal to the after-tax return on capital investment. These conditions are standard results in the optimal taxation literature and are analogous to those described by Coleman.

Based on data from the United Nations (2001), we assume that population growth is governed by the recurrence relation:

$$N_{t+1} = N_t + 0.31 N_t (1 - N_t / 10.9) \tag{4}$$

with an initial value of N_0 = 6.1 billion persons. This equation provides a good fit to observed population trends in the late 20th century, and implies that global population achieves a long-run value of N_∞ = 10.9 billion, a figure that is consistent with the results of detailed demographic models.

As Coleman notes, the assumption that the utility function is logarithmic in consumption and leisure is consistent with empirical observations regarding households' response to changes in wages and interest rates. Since l_t is a measure of labor effort, the expression $1 - l_t$ represents the fraction of time that a typical person devotes to leisure. With this in mind, we work with the specification:

$$u_t = \ln(c_t) + 1.37 \ln(1 - l_t) + \ln\left(1 - 0.031(S_t - 590)/590)\right) \tag{5}$$

while assuming that the time preference parameter takes on the value d = 0.838. The parameter values in equation (5) were chosen to account for a number of stylized facts that pertain to the world economy under a "business-as-usual" scenario in which current tax policies are maintained into the future. Specifically, we assume that:

- Labor effort accounts for 34% of waking hours in the initial period of the model (UNDP, 1993).
- A doubling of carbon dioxide levels from the pre-industrial value of 590 billion tons would impose social costs equivalent to 1.75% of world income given the structure of the economy in the year 2000 (IPCC, 1996, ch. 6).

- The economy grows at an initial rate of 3.2% per year (International Monetary Fund, 2002).

In the context of the model, this last assumption implies that households discount future utility at a rate of 19% per decade, or 1.8% per year.

The way that this model represents the impacts of climate change deserves special attention. In this specification, the accumulation of excess carbon dioxide in the atmosphere imposes direct social costs through an amenity externality. Under equation (5), the term $1 - 0.031(S_t - 590)/590$ may be understood as an index of environmental quality that declines linearly as carbon dioxide levels increase. The parameterization of this function implies that a doubling of carbon dioxide concentrations relative to the pre-industrial norm would impose a welfare loss that is proportional to 3.1% of private consumption, or 1.75% of economic output in the first period of the analysis. The specific damage coefficient is chosen based on the IPCC's (1996, ch. 6) comprehensive literature review.

For the sake of simplicity, we abstract away from the impacts of greenhouse gases other than carbon dioxide while limiting attention to the case of a linear impact function. Since there are essentially no data concerning the costs of proceeding beyond a doubling of greenhouse gas concentrations, the validity of the linearity assumption is certainly open to debate. The assumption is generally consistent, however, with the approach taken by Nordhaus (1994), who assumes that: (a) environmental impacts are proportional to the squared deviation of mean global temperature from the pre-industrial norm; and (b) mean global temperature is a logarithmic function of greenhouse gas concentrations. Woodward and Bishop (1997; see also Howarth, 2001) provide an analysis that allows for the possibility of nonlinear, catastrophic costs at high greenhouse gas concentrations. A key point is that the specification adopted in this paper implies that the marginal benefits of carbon dioxide emissions abatement are similar in magnitude to those calculated by other authors (Manne *et al.*, 1995; Nordhaus and Boyer, 2000).

Producer Behavior

Production in this economy is carried out by a set of competitive firms that have common access to a technology that may be described by the net production function $f_t(K_t, L_t, E_t)$ that is concave and linearly homogeneous with respect to inputs of capital (K_t) and labor (L_t) and the release of carbon dioxide to the atmosphere (E_t). In this specification, $K_t = N_t k_t$ is the aggregate capital stock, or the summed capital wealth held by all N_t members of society, measured in billions of dollars. In a similar fashion, $L_t = N_t l_t$ is the aggregate labor supply, measured in billions of workers. Carbon dioxide emissions are denominated in billion metric tons of carbon.

As noted above, firms rent labor and capital from households at the wage rate w_t and the interest rate r_t. In addition, they pay a tax t_{Et} on each unit of greenhouse gas emissions. Under these assumptions, a typical firm's profits are $f_t(\cdot) - r_t K_t - w_t L_t - t_{Et} E_t$. Given profit maximization, firms equate the price of each factor input with its marginal productivity so that:

$$r_t = \partial f_t / \partial K_t \tag{6}$$

$$w_t = \partial f_t / \partial L_t \tag{7}$$

$$t_{Et} = \partial f_t / \partial E_t \,. \tag{8}$$

Since the production function is linearly homogeneous, expenditures on inputs are equal to the value of output, and firms' profits are zero at each point in time.

For the purposes of this study, the key problem is to choose a realistic functional form and parameter values for the production function. Towards this end, we adapt Coleman's Cobb-

Douglas technology to account for the costs of greenhouse gas emissions abatement. In particular, we work with the specification:

$$f_t(\cdot) = A_t K_t^{0.4} L_t^{0.6} - 0.389 K_t - 486 E_{0t} \left(\frac{E_{0t} - E_t}{E_{0t}} \right)^{4.32} \tag{9}$$

where A_t is the level of total factor productivity and where:

$$E_{0t} = B_t A_t K_t^{0.4} L_t^{0.6} \tag{10}$$

is the level of carbon dioxide emissions that would occur in the absence of emissions control policies – i.e., in the case where the emissions tax was set equal to zero. In this setting, E_{0t} is linearly proportional to the term $A_t K_t^{0.4} L_t^{0.6}$ that defines the level of gross economic output, while B_t is a time varying parameter that determines the emissions intensity of the economy.

The first two terms of equations (9) are based on stylized facts that are drawn directly from Coleman:

- Under business-as-usual, payments to capital account for 40% of the value of gross output while labor accounts for the remaining 60%.
- The capital stock depreciates at the rate of 4.8% per year.

The third term in equation (9), however, is original to this study, representing firms' expenditures on carbon dioxide emissions abatement. When emissions are uncontrolled, then $E_t = E_{0t}$, and abatement costs are zero. Costs rise rapidly, however, with the stringency of abatement effort. The parameters of this equation are chosen so that the marginal cost of emissions abatement is:

- $10 per ton when emissions are reduced by 20% relative to uncontrolled levels.
- $100 per ton when emissions are reduced by 40%.

The first assumption is supported by the IPCC's (1996, ch. 9) finding that a 20% emissions reduction could be achieved at little or no economic cost. The second assumption is grounded in the Energy Modeling Forum's review of the costs of compliance with the Kyoto Protocol, which would require abatement levels of roughly 40% in industrialized countries in the year 2010 (Weyant, 1999). While these specific numbers are open to debate, they are consistent with the center of opinion in the underlying literature.

Finally, it is necessary to estimate the initial capital stock and to describe the time path followed by the total factor productivity and carbon dioxide emissions parameters. Following the IPCC (1996, ch. 4), we assume that the marginal productivity of capital is 6% per year in the first period of the analysis. Given the structure of the model, this implies that the initial capital stock is K_0 = 151,000 billion dollars.

In our model, total factor productivity grows according to the recurrence relation:

$$A_{t+1} = A_t (1 + g_t) \tag{11}$$

from an initial value of A_0 = 2473. The growth parameter g_t falls linearly from 0.106 per decade at date t = 0 to zero three centuries from the present. These values were calibrated based on production statistics from the International Monetary Fund (2002), which suggest that:

- The economy achieves an initial output level of $44.6 trillion per year.
- Technological change augments productivity at an initial rate of 1.0% per year.

Based on data from the IPCC (2000), we assume that carbon dioxide emissions would start out at 7.97 billion tons per year in the absence of control policies, which implies that the emissions-output coefficient assumes an initial value of B_0 = 0.000179. Since future technological progress will lead to declines in emissions intensity, we assume that B_t decreases at the rate of productivity growth so that:

$$B_{t+1} = B_t (1 - g_t)\,. \tag{12}$$

Although more detailed models represent emissions as an explicit function of land-use changes and the combustion of fossil fuels, the approach taken here provides a realistic time path for emissions when judged in comparison with the IPCC's (2000) comprehensive review.

The Global Atmosphere

Completing the model requires us to specify the accumulation of carbon dioxide in the atmosphere as a function of past emissions. To accomplish this task, we employ the functional form and parameter values adopted by Nordhaus (1994), according to which the atmospheric stock of carbon dioxide follows the recurrence relation:

$$S_{t+1} = 49.0 + 0.917 S_t + 0.64 E_t \,. \tag{13}$$

This equation is based on the assumptions that:

- The carbon dioxide stock would converge to a long-term level of 590 billion tons in the absence of emissions.
- Carbon dioxide levels in excess of this amount are removed from the atmosphere at a rate of 0.86% per year.

As Schultz and Kasting (1997) note, this simplified model abstracts away from aspects of global biogeochemical cycles that may have significant policy implications. In particular, feedback mechanisms may reduce the rate at which carbon dioxide is removed from the atmosphere in the face of climate change. Addressing this concern, however, would require a more detailed model than the stylized specification considered here.

POLICY SCENARIOS

The preceding section describes the essential features of a competitive economy and the response of households and firms to policy decisions concerning tax rates on labor, returns to capital, and carbon dioxide emissions. Given this representation, we are ready to examine the impacts of alternative policy regimes on the economy's behavior over time. We assume that governments maintain balanced budgets in each period, setting the value of public expenditure (G_t) and transfer payments equal to the total revenues obtained through taxation:

$$G_t + N_t p_t = t_{lt} w_t L_t + t_{kt} r_t K_t + t_{Et} E_t \, . \tag{14}$$

While we do not explicitly model the social benefits provided by public expenditures – instead we assume that governments aim to finance fixed levels of expenditure at each point in time – it is natural to suppose that government spending provides amenity benefits and/or augments private-sector productivity.

Given a set of feasible public policies – i.e. a choice of the variables G_t, p_t, t_{lt}, t_{kt}, and t_{Et} for all dates $t \in [0,\infty)$ – equations (2)-(14) define a time path for the world economy and its relationship to the global environment. Along this path, the value of output is divided between consumption, net capital investment, and government expenditure so that:

$$N_t c_t + K_{t+1} - K_t + G_t = f_t(K_t, L_t, E_t) \, . \tag{15}$$

Against this backdrop, we consider the welfare implication of four distinct policy regimes. Each model run was solved numerically using the Solver routine in Microsoft Excel. In each case, the model converges to a long-run steady state with the passage of roughly four hundred years. Using this fact, we were able to find solution values for the model along its full (infinite) horizon. The details of each scenario may be described as follows.

Business-as-Usual

Under *business-as-usual* (BAU), governments tax labor income and returns to capital at the common rate $t_{lt} = t_{kt} = 1/3$. Half of the resulting revenues are used to finance public expenditures, while the remainder is returned to households in the form of transfer payments. Hence $G_t = N_t p_t = (t_{lt} w_t L_t + t_{kt} r_t K_t)/2$. While this setup does not correspond precisely to the tax policies of any one nation, data from the Organization for Economic Cooperation and Development (1998) suggest that the assumptions of this case are broadly representative of conditions in the world's advanced industrial nations, which dominate both global economic output and greenhouse gas emissions. In addition, these assumptions are numerically similar to those used by Lucas (1990) and Coleman (2000) in their analyses of U.S. fiscal policies.

In the business-as-usual scenario there are no efforts to control greenhouse gas emissions. Hence $t_{Et} = 0$ for all values of t.

"First-Best" Decision Rule

Under the *first-best decision rule*, governments maintain public expenditures and the tax rates on labor and capital at the levels that hold under business-as-usual. They recognize, however, that carbon dioxide emissions generate negative externalities that impair economic efficiency. To address this market failure, policy-makers implement an emissions tax that is set equal to the discounted marginal cost that current emissions impose on future society:

$$t_{Et} = \sum_{i=1}^{\infty} \left(MC_{t+i} \frac{\partial S_{t+i}}{\partial E_t} \prod_{j=1}^{i} \frac{1}{1 + r_{t+j}} \right). \qquad (16)$$

In this equation, the expression:

$$MC_{t+i} = -N_{t+i} \frac{\partial u_{t+i} / \partial S_{t+i}}{\partial u_{t+i} / c_{t+i}} \qquad (17)$$

represents the marginal cost that carbon dioxide imposes at date $t+i$, which depends on the prevailing population size (N_{t+i}) and individuals' marginal willingness to pay to reduce carbon dioxide concentrations $(-(\partial u_{t+i}/\partial S_{t+i})/(\partial u_{t+i}/\partial c_{t+i}))$. This expression is multiplied by the term $\partial S_{t+i}/\partial E_t$, which captures the impacts of current emissions on future environmental quality.

In the first-best tax formula, r_{t+j} is the discount rate at date $t+j$, which is set equal to the pre-tax return to capital investment so that $r_{t+j} = r_{t+j}$. In the special case where the discount rate is constant over time at the rate $r_{t+j} = r$, the discount factor $\prod_{j=1}^{i} 1/(1+r_{t+j})$ reduces to the more familiar $1/(1+r)^i$. As we noted in the introduction, this decision rule is favored by analysts who worry that the use of lower discount rates would lead to the displacement of private capital formation by public investments that generated substandard rates of return.

In the absence of distortionary taxes on labor and capital, this decision rule would be sufficient to achieve a first-best outcome that maximized the welfare of a representative household (V) subject to the model's technical constraints (equations (13) and (15)) (Brekke and Howarth, 2002, ch. 7). In a first-best world, the government would use lump-sum taxes to finance required levels of public expenditure, setting the tax rates on labor and capital equal to zero. In the present scenario, however, policy-makers leave labor and capital taxes in place while releasing emissions tax revenues through increases in the level of transfer payments (p_t). Of course, this approach abstracts away from the interactions that exist between environmental taxes and pre-existing tax distortions, leaving room for further welfare improvements through the fine-tuning of tax policies.

Second-Best Policies

In the remaining scenarios, policy-makers equate the carbon dioxide emissions tax with the discounted value of the marginal costs that present emissions impose on future society according to the standard formula embodied in equation (16). They recognize, however, that setting the discount rate equal to the pre-tax return on capital investment can be inappropriate in the presence of distortionary taxes on capital and labor. Accordingly, they choose the discount rate at each date (r_t) endogenously to maximize the perceived welfare of a representative household (V) subject to the full set of technical constraints and equilibrium conditions that characterize the economy's evolution over time (equations (2)-(17)).

In these scenarios, the level of public expenditure is fixed according to the time path that prevails under business-as-usual. Since carbon dioxide emissions taxes raise revenues and since governments (by assumption) maintain balanced budgets, it is necessary to describe how governments release emissions tax revenues to the private sector. For the sake of analysis we focus on two alternatives:

1. *Lump-sum recycling.* Emissions tax revenues are used to finance increased transfer payments (p_t) while holding labor and capital tax rates fixed.

2. *Targeted recycling.* Emissions tax revenues are used to cut labor tax rates (t_{lt}) in the first two periods ($t \in [0,1]$) and capital tax rates (t_{kt}) at all subsequent dates ($t > 1$), holding transfer payments fixed throughout the analysis.

Why focus on the "targeted recycling" scenario rather than a case in which emissions tax revenues were used to cut either labor or capital tax rates at each point in time? In short, this policy regime is fine-tuned in an effort to obtain the largest possible welfare gains. This scenario is inspired by the work of Chamley (1986), who noted that the supply of capital is fixed in the short run but highly elastic in the long run. Accordingly, cutting short-run capital tax rates is relatively inefficient because it shifts the tax burden towards other factor inputs. In the long run, however, cutting capital taxes leads to large welfare gains by stimulating private investment (Lucas, 1990; Coleman, 2000). In the present model, using carbon dioxide emissions taxes to cut labor taxes in the early stages of the analysis while cutting capital tax rates in the more distant future leads to larger welfare gains than those obtained given a revenue recycling scheme that focused on reducing taxes on just one factor of production.

RESULTS

The main questions addressed in this paper concern how: (a) the presence of distortionary taxes affects the choice of the discount rate that should be used in the analysis of climate change response strategies; and (b) the choice of discount rates affects the time path followed by carbon dioxide emissions taxes. In the absence of taxation, social welfare would be maximized if the future benefits of carbon dioxide emissions abatement were discounted at a rate equal to the pre-tax return on capital investment. In the model under consideration, the pre-tax rate of return achieves an average value of 4.8% per year over the course of the next century (Figure 1). Given this rate of time preference, the "first-best" decision rule implies a carbon dioxide emissions tax that rises from $25 per ton in the present to $183 per ton in the year 2100 (Figure 2). This in turn supports an outcome in which carbon dioxide emissions rise from 5.9 to 12.8 billion tons per year – figures that are (respectively) 26% and 48% below the levels occurring under business-as-usual (Figure 3).

A rather different outcome arises under the lump-sum recycling scenario. When the revenues generated by taxing carbon dioxide emissions are returned to households in the form of lump-sum transfers, social welfare is optimized by a path in which the discount rate assumes an average value of 7.5% over the course of the next century – a figure that is significantly above the pre-tax return to capital investment. Since high discount rates imply that relatively little weight is attached to the future costs of climate change, this scenario leads to an outcome in which the carbon dioxide emissions tax is limited to $13 per ton in the present and $144 per ton in 2100. Accordingly, optimal emissions rise from 6.2 to 13.6 billion tons over the period of analysis.

What factors explain the differences between the "first-best" decision rule and the lump-sum recycling scenario? In short, the disparities in question provide a good illustration of the "tax interaction effect" described in the environmental tax literature (see Goulder, 2002). Taxing carbon dioxide emissions raises production costs and reduces the marginal productivity of labor and capital. As Table 1 shows, reliance on the "first-best" decision rule leads to slight decreases in the labor supply and capital investment in comparison with business-as-usual. In the presence of distortionary taxes, private decision-makers attach too little weight to the impacts of environmental policies on labor and savings. In effect, the carbon dioxide emissions tax exacerbates the distortions caused by existing taxes on capital and labor. Accounting for this cost provides a reason to employ relatively high discount rates or (equivalently) low emissions taxes.

It is important to note, however, that these results do not extend to the case where the revenues raised by taxing carbon dioxide emissions are used to provide targeted reductions in labor and capital taxes. Under the targeted recycling scenario, the discount rate applied to the future benefits of carbon dioxide emissions abatement attains an average value of just 2.6% per year, a figure that is significantly below the 3.5% after-tax return available on capital investment. Interestingly, the discount rate takes on a highly negative value in the initial period of the model, suggesting that short-run tax cuts may provide especially large welfare gains. In this period, workers increase labor effort while simultaneously accelerating the rate of capital accumulation. In this scenario, the optimal emissions tax drops from $84 per ton in the present to $41 dollars per ton in 2020. The emissions tax then grows monotonically to a value of $283 per ton in 2100.

On average, the optimal emissions tax exceeds the "first-best" tax by 83%, resulting in emissions levels that rise from just 5.0 billion tons in the present to 11.3 billion tons in 2100.

The results of the "targeted recycling" scenario suggest that the so-called "revenue recycling effect" described in the environmental tax literature (see Goulder, 2002) is particularly large in the context of the dynamic model considered in this analysis. Just as the "tax interaction effect" can exacerbate the distortions associated with pre-existing taxes, the use of environmental tax revenues to reduce labor and capital taxes can yield powerful improvements in the efficiency of resource allocation. In comparison with the outcome generated by the "first-best" decision rule, for example, the targeted recycling scenario leads to a small but significant increase in short-term labor effort and the long-run capital stock. Together, these changes support increased production and consumption at each point in time despite relatively stringent rates of carbon dioxide emissions abatement. These results support the intuition behind the so-called "double dividend" hypothesis advanced by Pearce (1991) and explored by Jaeger (2002) in the context of a static model that abstracts away from the dynamic considerations emphasized in this paper.

How important are the differences between these policy scenarios in terms of their overall impacts on social welfare? In comparison with business-as-usual, the "first-best" decision rule yields a net welfare gain of $14.8 trillion (Figure 4). This figure was calculated by dividing the net increase in household welfare (*V*) by the marginal utility of consumption in the initial period. Under the "lump-sum recycling" scenario, the fine-tuning of discount rates and carbon dioxide emissions taxes leads to a somewhat larger welfare gain of $15.5 trillion. The net welfare gain, however, increases to a full $25.4 trillion when the revenues raised by taxing carbon dioxide emissions are used to provide targeted cuts in labor and capital taxes.

As Table 1 suggests, these four policy scenarios differ only slightly in terms of their consequences on macroeconomic variables such as aggregate consumption, the labor supply, and capital accumulation. Nonetheless, these small changes are quite important in terms of their impacts on long-term economic welfare. Indeed, the analysis presented in this paper suggests that fine-tuning the links between environmental and fiscal policy can yield social benefits that are two-thirds as large as the benefits that would arise if climate change policies were defined through the use of a naïve decision rule that abstracted away from issues of taxation and public expenditure. In this sense, reliance on a simple "first-best" approach can lead policy-makers to misgauge the true welfare implications of environmental policies.

Figure 1. Discount Rates

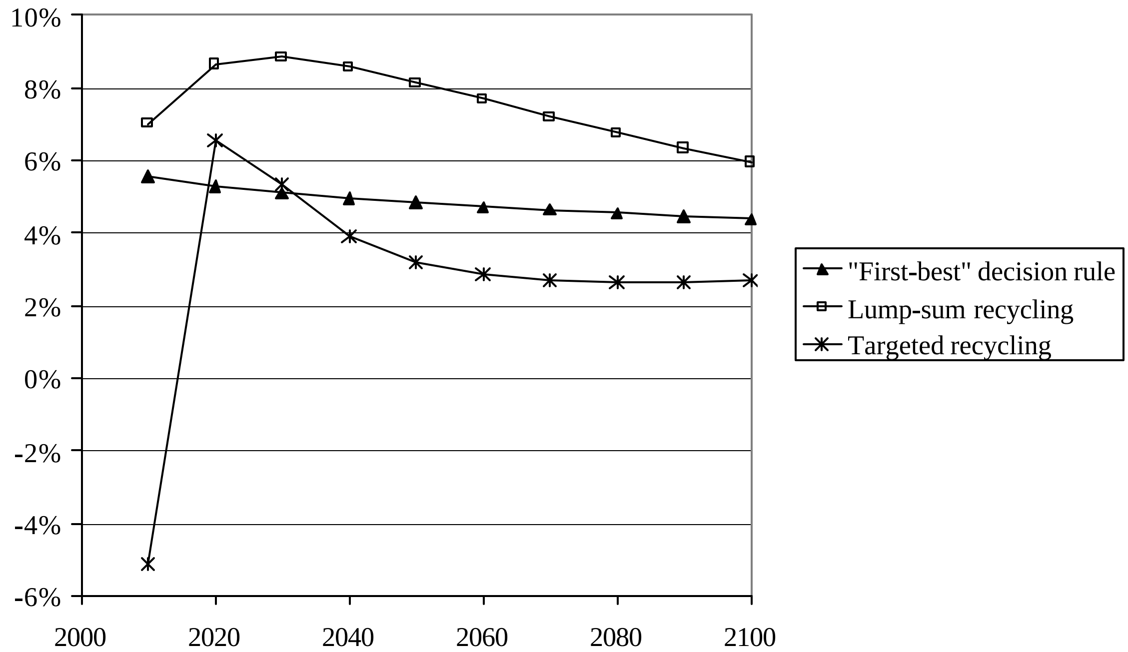

Figure 2: Carbon Dioxide Emissions Tax (U.S. dollars per ton, 2000 prices)

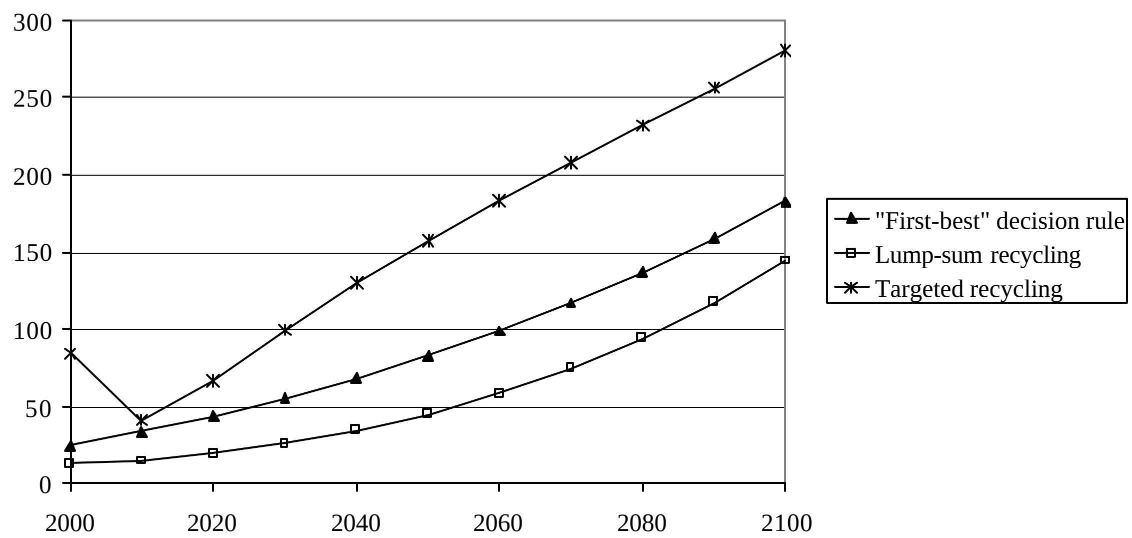

Figure 3. Carbon Dioxide Emissions (billion tons per year)

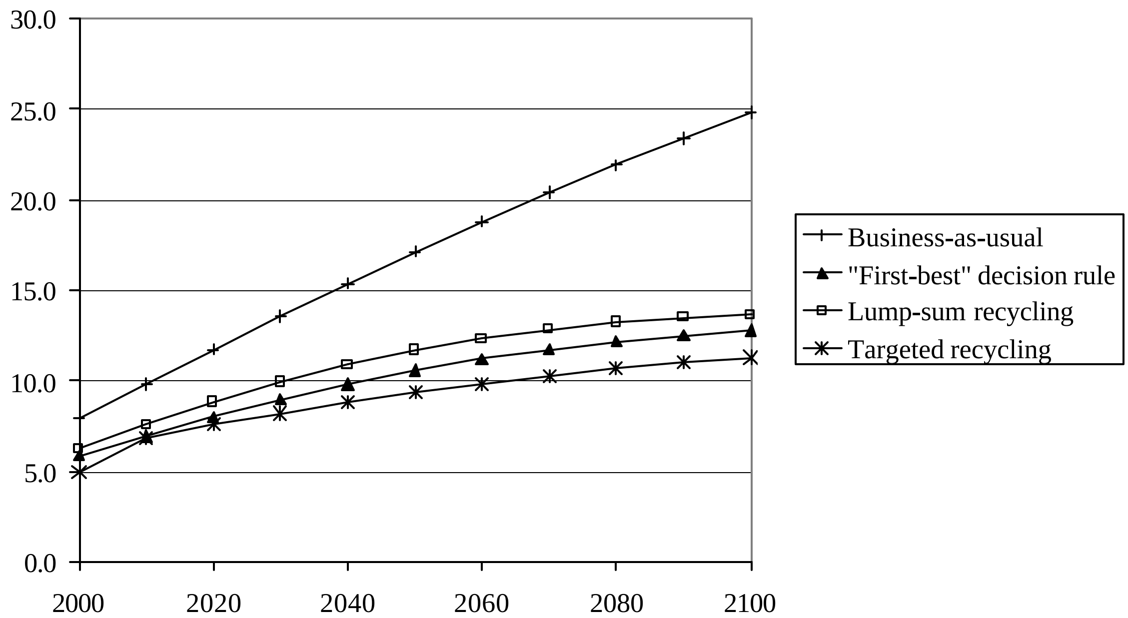

Figure 4. Welfare Gain Relative to BAU (trillion U.S. dollars, 2000 prices)

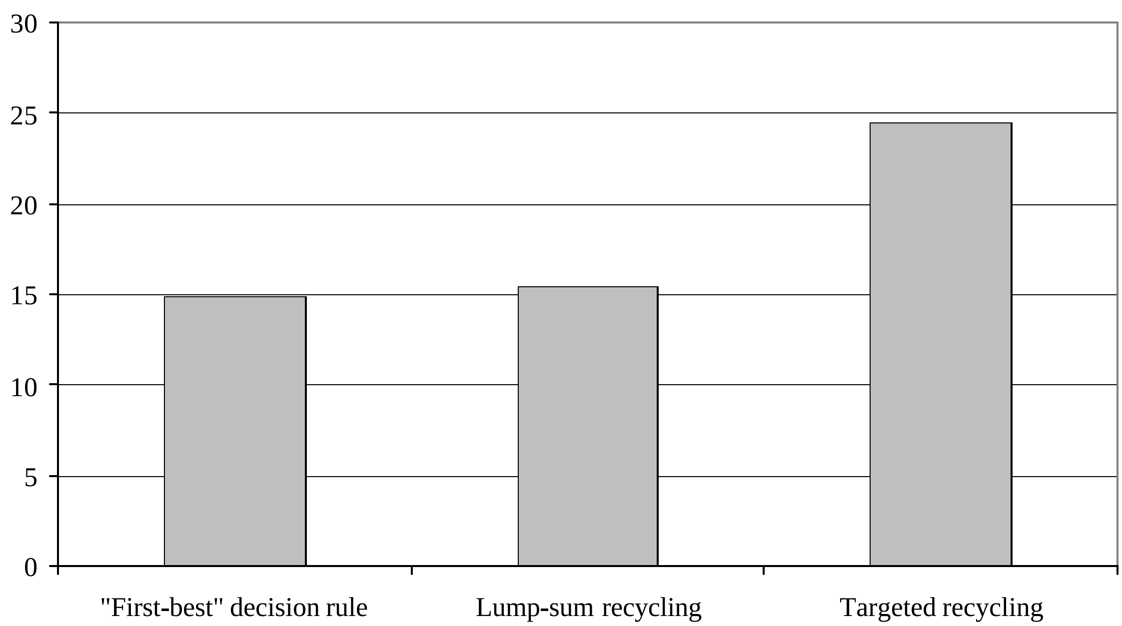

Table 1. Solution values for key endogenous variables

Decade	2000	2020	2040	2060	2080	2100
Consumption (U.S. dollars/capita, 2000 prices)						
Business-as-usual	4,133	6,233	8,860	12,147	16,192	21,057
"First best" decision rule	4,131	6,207	8,803	12,050	16,042	20,837
Lump-sum recycling	4,132	6,221	8,832	12,091	16,093	20,893
Targeted recycling	4,136	6,240	8,868	12,144	16,166	20,994
Labor Effort (fraction of waking hours)						
Business-as-usual	0.340	0.331	0.325	0.321	0.319	0.317
"First best" decision rule	0.339	0.330	0.323	0.320	0.317	0.316
Lump-sum recycling	0.340	0.330	0.324	0.320	0.318	0.316
Targeted recycling	0.343	0.331	0.324	0.320	0.317	0.316
Capital Stock (trillion U.S. dollars, 2000 prices)						
Business-as-usual	151	306	520	793	1,132	1,541
"First best" decision rule	151	304	514	784	1,115	1,516
Lump-sum recycling	151	305	517	788	1,121	1,522
Targeted recycling	151	312	531	809	1,150	1,560
Labor Tax Rate						
Targeted recycling	0.321	0.333	0.333	0.333	0.333	0.333
All other scenarios	0.333	0.333	0.333	0.333	0.333	0.333
Capital Tax Rate						
Targeted recycling	0.333	0.311	0.306	0.306	0.308	0.310
All other scenarios	0.333	0.333	0.333	0.333	0.333	0.333

CONCLUSION

This paper has examined the links between discounting techniques, greenhouse gas emissions taxes, and distortionary taxes on labor and capital in a numerically calibrated model of climate change and the world economy. Although the model is highly simplified, it is carefully grounded on a set of stylized facts that have been developed in the literatures on public finance and the economics of climate change. Indeed, the model's structure is closely patterned after Coleman's (2000) study of optimal taxation in the U.S. economy. It is also similar to Nordhaus' (1994; see also Nordhaus and Boyer, 2000) Dynamic Integrated model of Climate and the Economy (DICE), although DICE does not explicitly account for the role of taxation and public expenditure as they relate to the welfare effects of environmental policies.

The principal findings of the analysis may be summarized as follows. First, although the literature on discounting and climate change is multifaceted (see IPCC, 1996, ch. 4), one leading view holds that the future benefits of greenhouse gas emissions abatement should be discounted at a rate equal to the marginal productivity of capital as measured by the pre-tax return on private investment (Manne, 1995). In the presence of distortionary taxation, however, we find that significantly higher discount rates should be used when emissions tax revenues are returned to the economy using lump-sum transfers. Much lower discount rates, in contrast, become optimal when emissions tax revenues are used to finance targeted reductions in labor and capital taxes. In this latter case, the optimal discount rate is in fact lower than the post-tax return to private investment. In line with Stiglitz's (1982) theoretical discussion, our analysis therefore casts doubt on the view that optimal discount rates should be calculated as a weighted average of pre- and post-tax returns (Sandmo and Dreze, 1971).

Second, our analysis finds that reliance on a "first-best" decision rule in the presence of distortionary taxation may lead analysts to mischaracterize optimal environmental policies by a rather wide margin. Under the "first-best" decision rule, the carbon dioxide emissions tax is equated with the discounted marginal benefits provided by emissions abatement, with the discount rate set equal to the pre-tax return to private investment. In the context of our model, fine-turning emissions taxes with an eye towards interactions with labor and capital taxes yields additional benefits of $9.6 trillion.

Finally, our analysis confirms Pearce's (1991) conjecture that second-best greenhouse gas emissions taxes might be substantially higher than those identified using conventional "first-best" techniques. When emissions tax revenues are used to provide targeted cuts in labor and capital taxes, the optimal emissions tax is on average 83% higher than the level prescribed by the "first-best" decision rule. Following the insights of authors such as Bovenberg and de Mooij (1994), Bovenberg and Goulder (1996), and Parry *et al.* (1999), however, we also find that comparatively low emissions tax rates emerge as optimal when the resulting revenues are returned to the economy in the form of lump-sum transfers. In this case, tax interaction effects reduce the fiscal benefits provided by taxing greenhouse gas emissions, suggesting that this policy approach is relatively inefficient.

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