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A suite of economic models of the U.S. economy - two macroeconometric and two computable general equilibrium models - are used to examine the consequences of mitigating carbon dioxide (CO_2) emissions by imposing carbon taxes while recycling the revenues in various ways. The results indicate that in addition to their efficacy as Pigouvian taxes that reduce a negative externality, carbon taxes can be used to reduce distortions created by other taxes. The costs of a carbon tax may be largely and perhaps even fully offset by taking advantage of its efficiency value and using the revenues to cut existing taxes that discourage capital formation or labor supply. The results depend in part on whether costs are measured in terms of changes in GNP, consumption, or welfare. As with all studies of the economics of climate change mitigation, the results are sensitive to assumptions about future rates of technological change and the ease of substitutability between fossil fuels and other factors of production.

INTRODUCTION

Over the past two centuries, economic activity has increased atmospheric concentrations of the "greenhouse" gases, such as carbon dioxide (CO_2), methane (CH4) and nitrous oxides. By raising concentrations above the levels that would otherwise occur, industrial activity and deforestation enhance the naturally occurring greenhouse effect. These activities will therefore initiate a change in the global climate, with uncertain but potentially far-reaching environmental and economic effects.

Greenhouse gases vary in their respective capacities to trap radiation, their atmospheric lifetimes and decay profiles, and their indirect and interactive effects.[1] However, it is clear that CO_2 accounts for at least 50% and perhaps as much as 80% of the warming potential resulting from global anthropogenic greenhouse gas emissions. Therefore, any attempt to mitigate the potential for global climate change will likely involve measures to reduce CO_2 emissions. This is especially likely because, unlike the other greenhouse gases, CO_2 emissions result mainly from the combustion of fossil fuels, which is relatively easily identified and subject to government control. Although perfect economic efficiency might require curbs on emissions of all greenhouse gases, the relative ease of administering controls on fossil fuels use may weigh heavily in the choice of climate change mitigation measures.

In 1988, U.S. CO_2 emissions were approximately 22% of worldwide CO_2 emissions, or about 12% of worldwide anthropogenic greenhouse gas emissions. Because the physical consequences and economic impacts of increased greenhouse gas concentrations are highly uncertain, the U.S. government has embraced a "no regrets" strategy. This strategy encourages those mitigation actions that have broad-ranging benefits and can be justified on merits other than climate change mitigation. Until more information on the consequences of climate change becomes available, the U.S. government is likely to give serious consideration only to policies that have minimal adverse consequences for economic growth or welfare.

CARBON TAXES AS A POLICY TOOL FOR CONTROLLING GREENHOUSE GAS EMISSIONS

As discussed above, an effective mitigation policy would have to provide incentives to reduce CO_2 emissions. One such policy that has attracted considerable interest is a broad-based tax on the use of fossil fuels in proportion to their carbon content - i.e. a carbon tax. A carbon tax would fall most heavily on coal, which has the highest CO_2 content per unit of energy released; it would fall less heavily on oil and least heavily on natural gas.[2] (Other energy sources, such as nuclear, hydroelectric, wind and solar, do not involve the release of carbon and therefore would not be subject to tax.) This tax is attractive from an economic point of view because it taxes carbon equally across fossil fuel emission sources[3] and, in addition, would be relatively easy to administer.

A carbon tax forces fossil fuel users to internalize the external costs imposed on society by their emissions. This gives them an incentive to cut these emissions so that the marginal costs of abatement are equated across sources. By raising the prices of these fuels, a carbon tax in isolation would affect economic behavior by 1) depressing real income and thus reducing consumption of all goods; 2) inducing consumers and producers to substitute carbon-free or less carbon-intensive energy sources for carbon-intensive ones, and to substitute energy-saving goods and processes for energy-intensive ones; and 3) stimulating research, development and adoption of less expensive substitute technologies.

In this study, each policy scenario analyzes the impact of a carbon tax of $15 per ton imposed in 1990, growing 5% annually to $39.80 per ton in 2010, and remaining at that level thereafter. By fuel, this tax amounts to $8.69 per ton of coal, $1.89 per barrel of oil (about five cents per gallon of gasoline), and 24 cents per thousand cubic feet of natural gas in 1990; rising to $23.06 per ton of coal, $5.01 per barrel of oil (about 12 cents per gallon of gasoline), and 64 cents per thousand cubic feet of natural gas by 2010. These taxes would have raised the 1990 prices of coal, oil and natural gas by 32%, 11%, and 14%, respectively, and would raise their prices by 84%, 28% and 37%, respectively, in 2010, assuming constant supply prices. Gasoline prices would have been 4% higher in 1990 and would be 10% higher in 2010. Total revenues from the tax would have been about $20 billion in 1990 (compared with total 1990 federal tax revenues of $1.1 trillion) and, according to the models used in this study, would be between $50 billion and $85 billion in 2010.

These levels of tax are of a magnitude that would induce a discernible economy-wide reduction in fossil fuel use, particularly coal use; and given the great uncertainty of the ultimate costs of climate change, they are not inconsistent with crude estimates of the benefits to the U.S. economy of global climate change mitigation.[4]

THE EFFICIENCY VALUE OF CARBON REVENUES

Although the principal aim of a carbon tax is to reduce greenhouse gas emissions as efficiently as possible, carbon taxes (and pollution taxes in general) are attractive because the revenues could also be used to offset some of the more distortionary existing taxes, with short-term stabilizing effects and growth-enhancing effects in the longer run. A properly designed carbon tax could improve economic efficiency and remove an existing distortion by charging users the true cost of fossil fuel consumption. In contrast, a substantial portion of government revenue is collected from distortionary taxes that impose significant deadweight losses. Taxes on labor income, for instance, create distortions by driving a wedge between the cost of labor to firms and the net wage. These taxes induce workers to substitute leisure for work, reducing aggregate labor supply and output. Likewise, taxes on capital drive a wedge between the marginal product of capital and its after-tax return, affecting individuals' and firms' decisions to save and invest.

Substituting carbon taxes for other distorting taxes could potentially improve economic efficiency beyond the gains from reducing CO_2 emissions, and could have beneficial macroeconomic as well as long-run growth impacts. This implies that such taxes have an "efficiency value" over and above their desirable environmental effects. Although a carbon tax-induced price rise would tend to reduce economic activity below what it would have been in the absence of the tax, the beneficial effects of lower tax distortions can in principle compensate for the shock and perhaps even lead to higher output (especially in the longer term) than in the non-tax case. For instance, if the carbon revenues were used to reduce taxes on savings or investment, and this resulted in a higher rate of capital formation, the recycling of revenues would tend to mitigate the tax-induced decline in economic growth rates. In other words, a carbon tax would supply the government with sufficient revenues to pursue a supply-side tax policy that could, in principle, offset the tax-induced supply shock.

The standard economics literature treats Pigouvian taxes and emissions permit trading systems as being equally efficient because the two options equate the marginal cost of controlling emissions across sources. In principle, this would be true if all agents had perfect information about the externality costs of emissions and the substitution effects induced by a tax; and if the emissions permits were auctioned off. In this case taxes and permit prices would each be set so as to yield equal amounts of revenue, and the revenues could be recycled so as to yield efficiency gains. In practice, however, there is a trade-off between ease of administration and certainty of hitting a particular emissions target. Permit trading systems offer greater certainty of hitting an environmental target than a tax, but they also involve a greater administrative burden. Furthermore, permit trading systems typically are grandfathered (distributed to agents according to their historical emissions levels) and yield no revenues, and thus offer no potential for efficiency gains through revenue recycling. Given the great uncertainty about the optimal level of greenhouse gas emissions, both the ease of administration and the efficiency value of carbon tax revenues can increase the relative attractiveness of a taxation approach to greenhouse gas mitigation relative to other options.

To date, most studies of carbon taxes rely on detailed representations of the substitution possibilities in the energy sector, but do not capture the economy-wide repercussions of tax revenue recycling.[5] Energy sector models implicitly rebate the energy tax revenues in a lump-sum fashion. There are two problems with this: first, lump-sum rebates are not the only or even most likely choice of revenue recycling options; second, the potential benefits of revenue recycling are ignored. The most important conclusion of this paper is that the choice of revenue recycling options has a critical effect on the economic impact of carbon taxes. Economic models that fail to account for these options are inadequate for capturing the general equilibrium effects of a carbon tax, even when they effectively characterize the substitution possibilities in the energy sector.

REVENUE RECYCLING OPTIONS

Carbon taxes could raise tens of billions of dollars annually: under the tax regimes considered in this paper, total revenues would have amounted to about $20 billion in 1990, and could reach as much as $85 billion in 2010 (in real 1990 dollars). Given these magnitudes, the means by which the carbon taxes are recycled could well have as great an influence on overall resource allocation and economic growth as the tax itself. With the above considerations in mind, this study examines a carbon tax in six alternative fiscal policy environments, in which the revenues are:

recycled through a lump sum tax rebate;

used to reduce the federal budget deficit;

recycled through reductions in marginal personal income tax rates;

recycled through reductions in corporate income tax rates;

recycled through reductions in payroll tax rates; or

recycled through increases in the investment tax credit.

The policy options are examined in four models of the U.S. economy: the DRI/McGraw-Hill (DRI) and LINK-TGAS (LINK) macroeconometric models, and the Jorgenson/Wilcoxen (JW) and Goulder computable general equilibrium models (or CGE models). We use both macro and CGE models because they tend to complement each other: macro models are generally superior in capturing short- and medium-term adjustments to exogenous shocks, while the CGE models best capture medium- and long-run responses to changes in relative prices. Use of more than one type of model allows us to assess the impact of carbon taxes on the economy while distinguishing the effects of model-specific assumptions on the outcomes. (The models are described in the Appendix to this paper, as are their respective baseline forecasts.)

Each policy scenario assumes no change in real federal purchases of goods and services. Total federal expenditures and receipts, however, vary with changes in inflation, interest rates, and unemployment. In all of the models, recycled revenues are scaled to equal gross carbon taxes collected, less the required increase in net federal payments so as to hold the full-employment deficit to baseline levels.[6] The models for which money is a relevant variable assume constant nominal money supply growth rates across scenarios. All scenarios assume the elimination of the alternative minimum tax (AMT).[7]

THE RECYCLING SCENARIOS

The tax scenarios yield five important results. First, despite the wide variation of the predicted outcomes across models, a general hierarchy of revenue recycling options emerges fairly clearly from the results. In three of the four models, revenue recycling options that encourage capital formation tend to offset the effect of the carbon tax on output (as measured by gross national product, or GNP) and consumption (as measured by personal consumption expenditures) better than do options that encourage final consumption, private or public.[8] All of the models find that the investment tax credit goes a long way toward offsetting the negative economic effects of the carbon tax; indeed, growth is even enhanced in the macro model simulations. Similarly, cuts in other taxes that reduce capital and labor costs, such as the corporate income tax or the employer portion of the payroll tax, substantially offset the effects of the carbon tax. In contrast, in all but the Jorgenson-Wilcoxen model, if the carbon revenues are used to cut either the federal deficit or taxes that fall primarily on labor income, such as the personal income tax or the employee portion of the payroll tax, the effects of the carbon tax are barely offset relative to the lump sum case.[9]

Second, one can use several different ways to measure the economic costs of reducing carbon emissions, including changes in GNP, changes in consumption expenditures, and alternative measures of changes in utility or economic welfare. In addition, one must choose an appropriate discount rate and period of time over which to measure costs and benefits. The costs of reducing emissions depend greatly on the choice of measure, discount rate and period of measurement. We therefore present several alternative measures of costs in a later section of the paper.

Third, the models' technology and labor force growth rate assumptions greatly overshadow tax regimes in the determination of GNP growth. The carbon tax and revenue recycling methods have only a marginal impact on the economy; the average annual GNP growth rate over the next two decades is cut by eight hundredths of one percent at most. (At best - in DRI's investment tax credit scenario - the GNP growth rate is two-tenths of a percent higher than in the baseline forecast.) Nevertheless, these tax effects are quite noticeable when expressed in terms of levels of GNP - if baseline GNP growth is 2% per year, a 0.08 percentage point decrease in the growth rate leaves GNP more than 1.5% below the baseline after twenty years.

Fourth, the effect of the carbon taxes on GNP, consumption and welfare varies widely, both between models for a given recycling scenario and for a given model between different scenarios. In the DRI model, a recycled carbon tax of the magnitude examined in this study could reduce the discounted stream of GNP relative to the baseline by 0.6% or raise it by 1.6% over the next twenty years, depending on the use to which the revenues are put. In terms of consumption, the tax could reduce the discounted stream of consumption by 0.8% or raise it by 0.4% relative to the baseline. In the LINK model, GNP could be cut by 1.0% or raised by nearly 1.7%; while consumption could be cut by 0.9% or raised by 1.4%. In the Jorgenson/Wilcoxen model GNP could be cut by over 0.6% or raised by nearly as much relative to baseline; while consumption could be 0.3% lower or 0.3% higher. Finally, in the Goulder model GNP could fall by as much as 0.2% or virtually not at all relative to baseline, while discounted consumption could fall by 0.2% to 0.1%, depending on the way the revenues are recycled.

Fifth, the effect of the carbon taxes on emissions depends on both the GNP impact and the degree of substitutability between fossil fuels and other inputs in the model. On the one hand, the macro models yield larger responses to investment incentives than do the CGE models. On the other hand, the macro models incorporate lower estimates of substitutability away from energy use, and as a consequence the carbon tax has less effect on the rates of change of either the carbon intensity of the economy (i.e. the carbon/output ratio) or aggregate carbon emissions than it does in the CGE models.[10] The degree of substitution differs considerably in the DRI and LINK models but is relatively modest compared with the CGE models; by 2010 emissions are cut by at most 12% from baseline in the DRI model, and 7% in the LINK model. In contrast, the CGE models allow for a greater degree of substitution, particularly away from electricity. As a result, the carbon/output ratio falls twice as quickly in the carbon tax scenarios as in the baseline forecast, and emissions are cut by 22% to 32% from baseline, substantially below current levels. Thus emissions are not stabilized in the macro models, but are more than stabilized in the CGE models. The GNP and emissions results of the scenarios by model are shown in Figures 7 through 18 in the Appendix.

"Lump Sum" Recycling

In the CGE models, lump-sum recycling is implemented as a decrease in the intercept of the income tax function faced by the household or households; in the macroeconometric models, this recycling scenario is accomplished through an increase in the personal exemption. In all four models, consumers face higher fuel prices because of the carbon tax, but are compensated by lower average tax rates at any given level of income. In all four models, lump-sum recycling keeps real GNP well below baseline levels throughout the forecast (Figure 1).

This policy scenario is useful in that lump-sum taxes have the least impact on economic behavior, and are thus considered the most neutral form of taxation. Recycling the carbon revenues through a lump-sum tax rebate, therefore, should have no further effect on the aggregate distortionary impact of the U.S. tax system. In contrast, all other existing taxes generate distortions relative to the lump sum tax. Therefore, recycling the carbon revenues by reducing some other existing tax should reduce the aggregate distortionary effects of the tax system relative to the lump-sum case. As a consequence, this lump-sum tax scenario can be thought of as the neutral carbon tax recycling policy against which the efficiency value of different revenue recycling policies can be measured.

Revenue Raising (Deficit Reduction)

Using carbon tax revenues to reduce the deficit yields significantly different economic effects across the models (Figure 2). Deficit reduction produces no change relative to the lump-sum case in the Goulder model[11] and a significant efficiency loss in the LINK model. In both models, real GNP stands 1% below the baseline by 2010. In the DRI model, on the other hand, real GNP falls a maximum of 0.5% below the baseline during the 1990's, but returns to baseline by 2010. The scenario was not performed with the Jorgenson/Wilcoxen model. In the longer term, a benefit

Figure 1: Lump-Sum Rebate

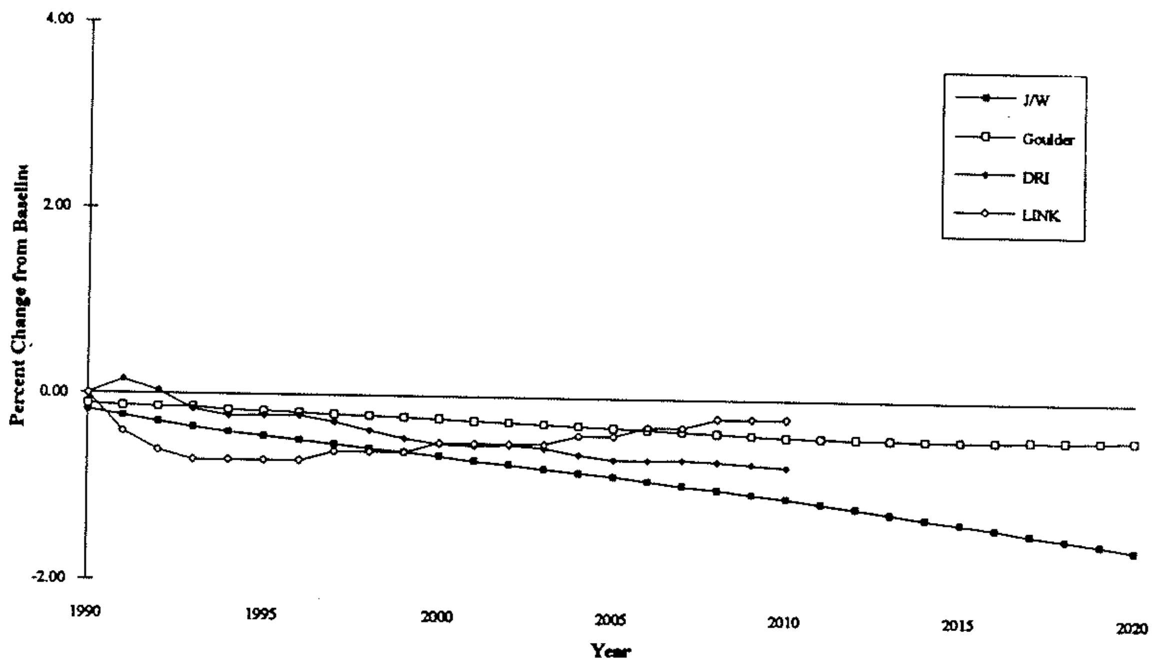
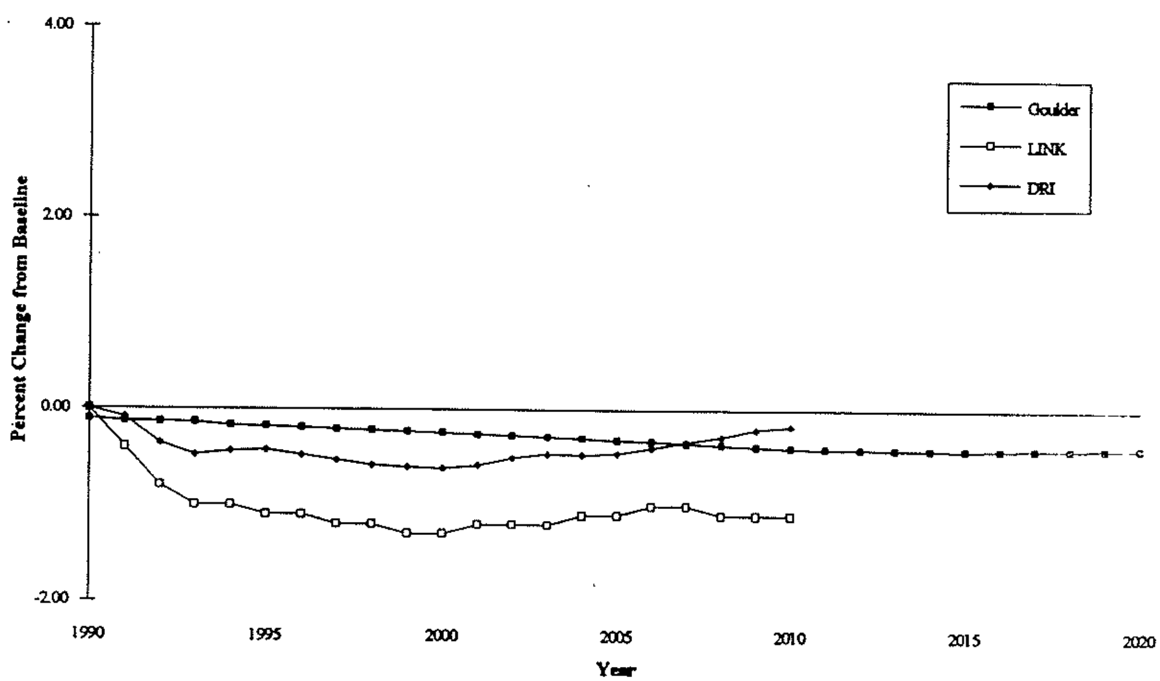


Figure 2: Revenue Raising



accrues from lower government borrowing in the DRI model: lower real interest rates stimulate private investment and enhance the supply potential of the economy.

PERSONAL INCOME TAX REDUCTION

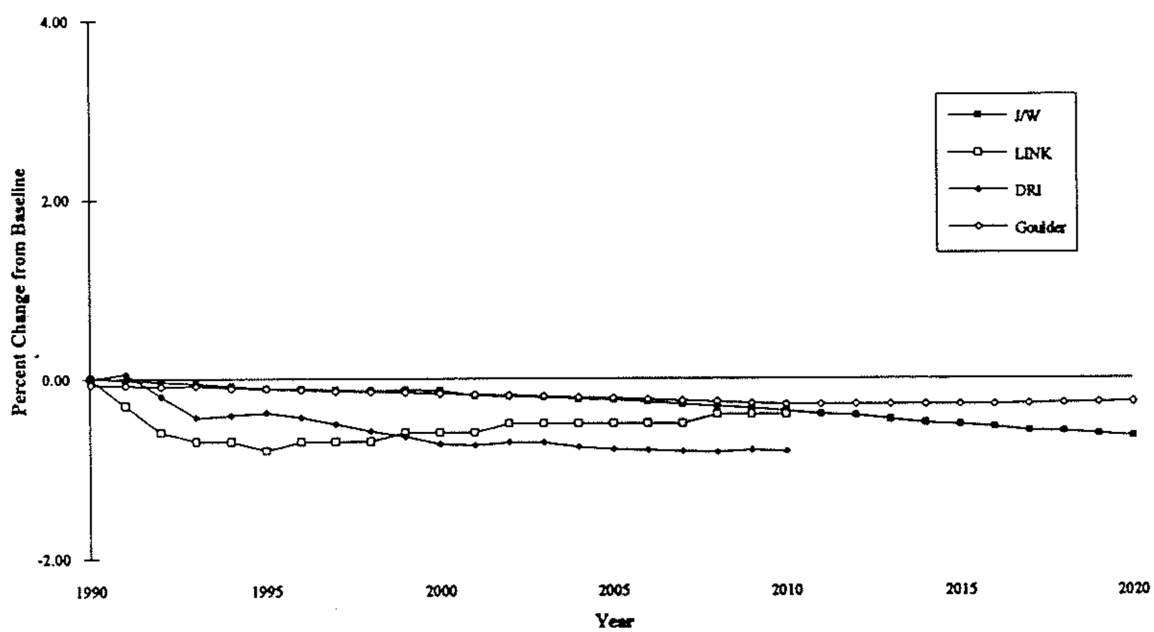
Recycling revenues through cuts in marginal personal income taxes is less detrimental to output than lump-sum rebates in all but the LINK model (Figure 3). This option improves real GNP relative to the deficit reduction case in the Goulder and LINK models, but depresses it further in the DRI model. The latter result occurs in the DRI model because the restoration of income through the personal income tax cut increases the short-term inflationary aspects of the policy. In reaction, interest rates rise and investment suffers. Consumption is supported at the expense of investment. Lower investment, in turn, translates into a smaller productive capital stock and lower output potential. The LINK model obtains a similar result, though with a smaller interest rate effect.

The CGE model results are quite similar, even though the Jorgenson/Wilcoxen model examines a generic labor tax, while the Goulder model considers the personal income tax explicitly. (This result is reasonable since about 85% of the revenue from the personal income tax is labor income.) In these simulations, both CGE models produce a decline in real GNP relative to the baseline and an increase relative to the lump-sum tax scenario. Furthermore, both yield more optimistic results than the macro models.

Corporate Income Tax Reduction

Recycling carbon tax revenues through a cut in corporate income taxes has quite different effects in the models. The tax cut eventually raises real GNP relative to the baseline in all but

Figure 3: Personal Income Tax Cut



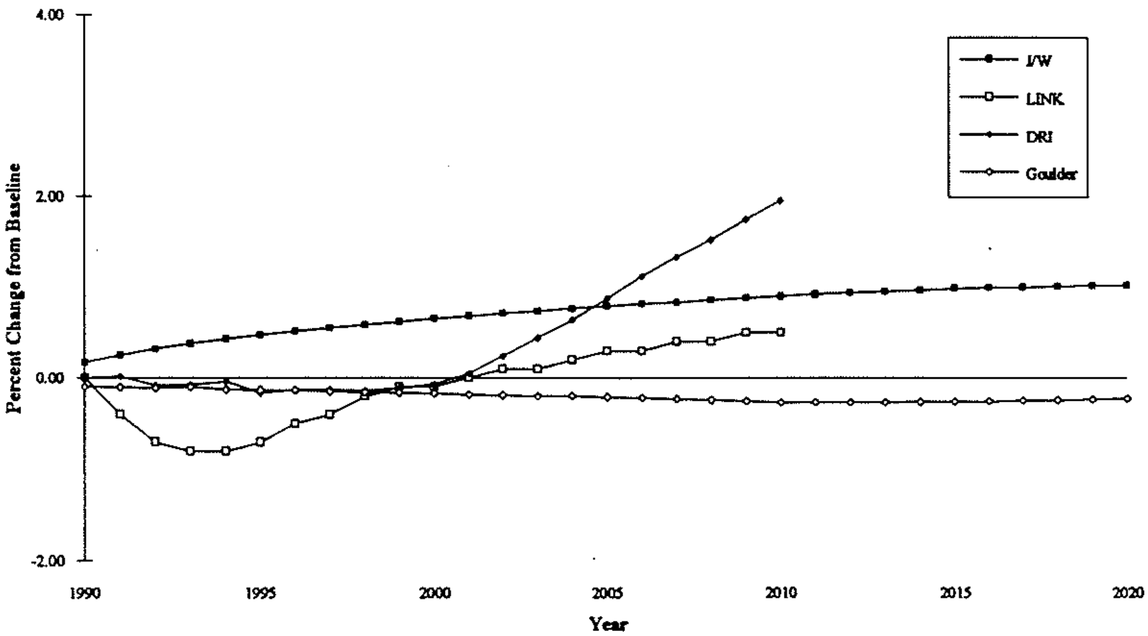
the Goulder model (Figure 4). Furthermore, all models agree that this recycling option is preferable to a lump-sum or personal income tax rebate or to deficit reduction.

The improvement in real GNP is largest in the DRI model: investment is stimulated by a decline in the real cost of capital services, brought about by a stronger stock market and consequent lower equity financing costs. This investment effect is strong enough to hold real GNP nearly to baseline levels through 2000. Higher investment expands the productive capital stock over baseline levels by 2010, leading to higher output. As in the DRI model, real GNP rises relative to the baseline in the LINK model after 2000. However, the GNP response in the early years of the tax is negative and little different from the other recycling options. By 2010, real GNP is only 0.5% above the baseline.

In the Jorgenson/Wilcoxen model, the capital tax cut increases the after-tax return to capital, and induces an increase in saving and hence in investment. The critical parameter is thus the interest elasticity of saving, which in this model is relatively large. The investment response is large enough to raise real GNP relative to the baseline throughout the simulation period and 0.8% by 2010.

In the Goulder model, the investment stimulus is too weak to offset the negative effects of the carbon tax; real GNP is 1% below the baseline by 2010. This is because the corporate tax cut increases the after-tax return to corporate income (rather than all capital income as in the Jorgenson/Wilcoxen model), and reduces the present discounted value of future depreciation deductions on current investment. This latter effect is also incorporated in the DRI and LINK models but not in the Jorgenson/Wilcoxen model.

Figure 4: Corporate Income Tax Cut



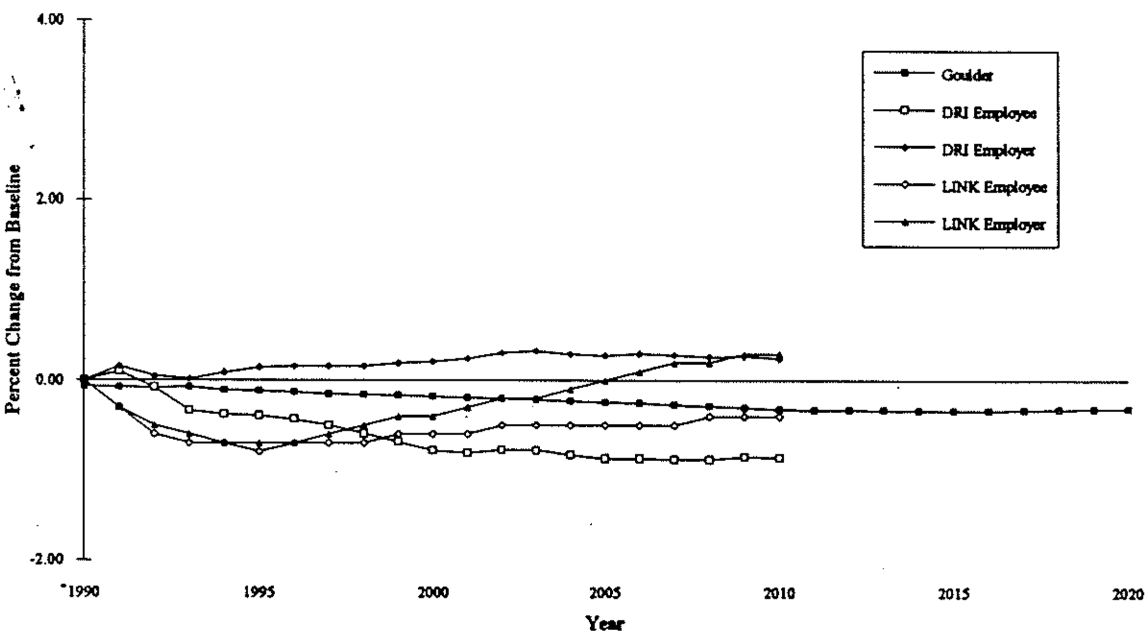
Payroll Tax Reduction

The incidence of the payroll tax - who actually bears the burden of the tax as opposed to who nominally is responsible for paying it - is a matter of controversy that has not been resolved in the economics community. Moreover, the effectiveness of a payroll tax cut depends critically on the incidence of the tax on workers and firms. The models in this study differ in their assumptions about the incidence of the payroll tax, and therefore yield quite different findings as to the effectiveness of recycling through payroll tax cuts (Figure 5).

Cuts in the employee- and employer-paid portions of the payroll tax are analyzed separately in the DRI and LINK models. A combined employee-employer tax cut is analyzed in the Goulder model. The payroll tax cut could not be simulated with the Jorgenson/Wilcoxen model. In both the DRI and LINK models, the employee-paid tax cut is virtually equivalent to a cut in the personal income tax rate. The same differences between the models' results cited in the section on the personal income tax cut thus apply here. In the Goulder model, both portions of the tax are treated as a tax on labor; a cut in either portion, therefore, is essentially equivalent to a personal income tax cut of similar size. In the Goulder models and in the employer-paid tax cuts in the macroeconometric models, this tax option improves long-term income growth by encouraging businesses to substitute lower-priced domestic labor for higher-priced energy.

Both the DRI and LINK models produce similar results over the longer term when carbon taxes are recycled through cuts in the employer-paid portion of the payroll tax; real GNP is eventually higher under this option than in the baseline. In terms of growth, this recycling option is preferable to lump-sum recycling, deficit reduction, or personal income tax recycling; it is not preferable to offsetting cuts in corporate income taxes or increases in the investment tax credit. The two models' short-term responses, however, differ significantly from one another. Furthermore, their long-term GNP gain contrasts with a GNP loss in the Goulder model.

Figure 5: Payroll Tax Cut



In the DRI model, recycling carbon tax revenues through cuts in the employers' portion of the payroll tax offsets the negative impact of the carbon tax in the first two or three years, and leads to real GNP gains thereafter. The tax cut lowers labor costs by the same amount that energy costs rise, keeping average production costs unchanged. It thus removes the tax's adverse effect immediately. In the LINK model, the employer-paid payroll tax cut is virtually equivalent to an employee-paid tax cut through 1996, with real GNP dropping significantly below the baseline. After 1996, real GNP strengthens, rising above the baseline after 2005.

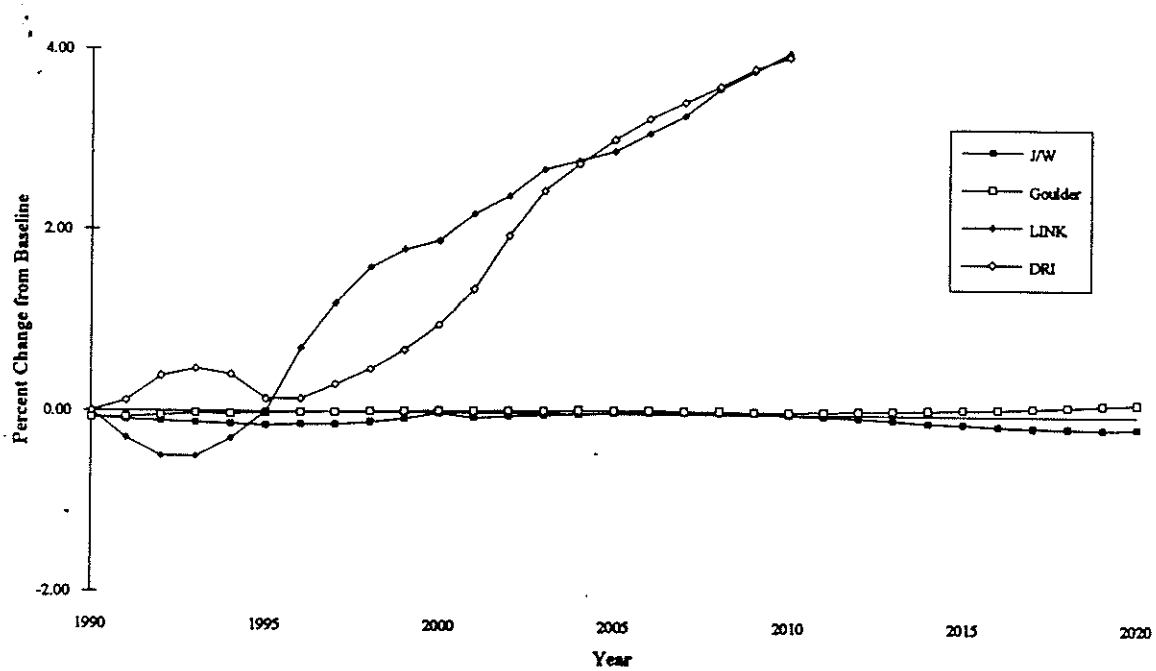
Investment Tax Credit

Recycling carbon tax revenues through an investment tax credit leads to a significantly stronger economy in both the DRI and LINK models. In the Jorgenson/Wilcoxen model, the credit returns economic activity essentially to the baseline, while in the Goulder model, the investment tax credit just offsets the GNP loss (Figure 6). All the models agree that it is the most effective recycling option for offsetting the negative long-run GNP effects of the carbon tax, with one exception: the Jorgenson/Wilcoxen model ranks the general capital tax cut as more effective.

The investment tax credit offsets higher energy costs with lower capital costs. As in the payroll tax cut case, it improves long-term income prospects by encouraging business to substitute lower-priced factors (in this case capital, in the payroll tax case labor) for higher-priced energy. In the longer term, cuts in capital costs stimulate more growth than cuts in labor costs. While the labor force will not expand significantly in response to higher after-tax wages, business can continue to add productive capital and thus increase the economy's potential to produce.

In the DRI model, the investment tax credit stimulates more capital accumulation and economic growth than a corporate tax cut because it greatly decreases the cost of new capital. Both tax policies increase after-tax corporate profits and dividends, and, thus, investment in the

Figure 6: Investment Tax Credit



stock market. These effects act to reduce equity financing costs. However, part of the benefit of the corporate rate cut is offset by an increase in the after-tax cost of debt, which occurs because interest deductions become less valuable. Moreover, because the tax credit is available only for new investment, the capital spending stimulus per dollar of federal revenue lost is maximized. The corporate tax rate cut, in contrast, applies to the returns on all capital, including that already in place. These windfall gains to owners of existing assets provide less stimulus to investment than the investment tax credit.[12] In the macro models, the substantial increase in the capital stock that occurs over two decades is made possible by strong foreign capital inflows ù nearly half a trillion constant 1990 dollars worth over a twenty-year period in the DRI model.

Comparison of the DRI and Goulder models yields several useful insights that highlight both the influence of model structures on the results and the importance of using a suite of models to analyze a given policy proposal. Despite their differences, the models yield responses of similar magnitude to a given investment tax credit. Moreover, in both models a portion of the increase in investment in financed through capital that flows into the U.S. from abroad in response to the higher return to capital. Nevertheless, the models differ substantially in their specification of the response of fossil fuel demand to price changes. As the carbon tax raises the price of fossil fuels, the fall in demand is smaller - and therefore the carbon tax revenues higher ù in the DRI model than in the Goulder model. There is therefore more money available to finance an investment tax credit in the DRI model, and therefore more investment. Over time, this effect seems to be enhanced as the DRI model's larger capital stock yields more income, more saving, and more investment.[13] Furthermore, while real interest rates remain relatively stable over the longer term in the Goulder model, they fall in the DRI model, further enhancing the investment response.

COSTS OF REDUCING CARBON EMISSIONS WHEN REVENUES ARE RECYCLED

To assess the economic costs of reducing carbon emissions, one can use several different measures, each with its own strengths and weaknesses. These measures include changes in GNP, changes in consumption expenditures, and alternative measures of changes in utility or economic welfare. In addition to choosing a measure, one must address the related problems of choosing the appropriate period of time over which to measure costs, and choosing an appropriate rate for discount rate, so as to compare costs and benefits that occur at different points in time. In view of these difficulties, it seems best to analyze costs by considering several alternative potential measures of welfare, each with its own attractions and limitations, rather than just one. This is the approach taken in this paper.

The GNP cost measure used in the preceding discussion has the virtue of being well-defined and widely recognized and understood in the policy community. It is also convenient for comparing results from different types of models because all economic models yield predictions of GNP. Nevertheless, from the point of view of economic theory, GNP is a measure of market expenditures on goods and services that at best only approximates the more intangible concept of economic well-being.[14] Furthermore, GNP includes investment expenditures that do not directly contribute to consumption, but instead lay the basis for future increases in consumption and, presumably, welfare.

To better approximate welfare, we may therefore wish to focus on personal consumption expenditures on goods and services (and, if possible, that portion of government final expenditure that can be appropriately thought of as consumption.) This is probably the best proxy for welfare in the macroeconometric models, though again, it is a measure of market expenditures rather than a measure of welfare, and we can measure changes in consumption only over the twenty years of the forecast. The general equilibrium models, in contrast, produce several measures of the change in long-term welfare that are more attractive gauges of welfare from a theoretical standpoint. The Goulder model produces a measure of the change in lifetime welfare in terms of the equivalent variation, which converts changes in utility into a money equivalent.[15] This measure of welfare includes the value of leisure time. The Jorgenson-Wilcoxen model produces a similar measure of changes in lifetime welfare; and Jorgenson-Wilcoxen also offer a measure of changes in total social welfare that includes the effects of changes in the distribution of wealth.[16]

Because of the limited quality or availability of welfare measures in the different models, in the tables below we present for comparison several different measures of changes in welfare for each model and each scenario in the tables below - GNP costs, consumption costs over the period 1990-2010, and various lifetime welfare changes as measured in the general equilibrium models. The GNP and consumption cost values assume a 3% discount rate, which is sometimes presented as reflecting the typical consumer's rate of time preference. For the welfare change measures, both general equilibrium models incorporate a real after-tax private return to savings of about 5%; the Jorgenson-Wilcoxen welfare measures incorporate a 3% consumer rate of time preference, while the Goulder welfare measure incorporates a 0.7% rate of time preference. Finally, we present measures of lost GNP and lost consumption per tonne of carbon emissions reduced, using a 3% discount rate for all four models.[17] (Again, the Jorgenson-Wilcoxen results presented are for labor and capital tax cuts, rather than for personal and corporate income tax cuts.)

The tables above show that in all models, revenue recycling mechanisms that reduce taxes on capital, especially those that encourage new capital formation, yield the greatest gains in GNP. Moreover, in the macro models, the same mechanisms yield the greatest gains in terms of consumption. In the general equilibrium models, however, the results are somewhat more ambiguous. In the Goulder model, the consumption loss over the period 1990-2010 is minimized through personal income and payroll tax cuts; while in the Jorgenson-Wilcoxen model, consumption rises more if carbon taxes are recycled through labor tax cuts.

GNP Loss, 1990-2010
(Percentage of discounted constant price GNP)

	DRI	LINK	J/W	Goulder
Lump Sum Tax Cuts	-0.58%	-0.46%	-0.62%	-0.24%
Revenue Raising	-0.40%	-1.02%		-0.24%
Personal Income Tax Cuts	-0.56%	-0.53%	-0.16%	-0.16%
Corporate Income Tax Cuts	0.40%	-0.11%	0.60%	-0.17%
Payroll Tax Cuts				-0.18%
(Employee Only)	-0.58%	-0.53%		
(Employer Only)	0.19%	-0.25%		
Investment Tax Credit	1.55%	1.67%		0.00%

Consumption Loss, 1990-2010
(Percentage of discounted constant price consumption)

	DRI	LINK	J/W	Goulder
Lump Sum Tax Cuts	-0.39%	-0.46%	-0.32%	-0.18%
Revenue Raising	-0.75%	-0.87%		-0.18%
Personal Income Tax Cuts	-0.39%	-0.51%	0.29%	-0.12%
Corporate Income Tax Cuts	-0.16%	-0.10%	0.17%	-0.17%
Payroll Tax Cuts				-0.10%
(Employee Only)	-0.39%	-0.51%		
(Employer Only)	0.17%	-0.25%		
Investment Tax Credit	0.40%	1.41%		-0.16%

Welfare Loss

	J/W Wealth Welfare	J/W Social Welfare[18]	Goulder Welfare
Lump Sum Tax Cuts	-0.83%	-0.94 to -0.70%	-0.44%
Revenue Raising			-0.44%
Personal Income Tax Cuts	1.01%	0.48 to 0.33%	-0.39%
Corporate Income Tax Cuts	0.19%	-0.06 to 0.08%	-0.36%
Payroll Tax Cuts			-0.39%
Investment Tax Credit			-0.27%

The welfare changes shown in the last table are more ambiguous. The results from the Goulder model are similar to those from the macro models: the welfare losses associated with a carbon tax clearly are minimized through an investment tax cut. However, the results from the Jorgenson-Wilcoxen model imply that the welfare loss is minimized (or rather, the welfare gain is maximized) through labor tax cuts. The results differ mainly because of the difference in consumer rates of time preference between the two models: because the Jorgenson-Wilcoxen model incorporates a considerably higher rate of time preference, the near-term consumption losses brought about by the combination of carbon tax increase and capital tax decrease outweigh the long-term gains in consumption flowing from the resulting increase in capital formation.

As the tables show, the cost of a carbon tax of the magnitude assumed in this study over the period 1900-2010 ranges considerably, even for a specific recycling option or a specific model. In terms of foregone GNP, the cost varies from about 1.0% of the discounted stream of GNP to -1.7% of GNP. That is, at worst the carbon tax lowers GNP by 1.0% percent, and in the best case GNP is raised by 1.6%. In terms of foregone consumption, the cost varies from about 0.9% of the discounted stream of GNP to -1.4% of GNP. With only two exceptions, the consumption cost of a particular option is lower than the GNP cost.

GNP Cost per Metric Tonne of Carbon, 1990-2010
(Constant 1990 dollars)

	DRI	LINK	J/W	Goulder
Lump Sum Tax Cuts	750.53	1,527.11	191.72	51.41
Revenue Raising	502.64	1,590.78		51.41
Personal Income Tax Cuts	730.64	1,622.97	50.30	35.05
Corporate Income Tax Cuts	-600.72	479.00	-191.75	35.99
Payroll Tax Cuts				38.30
(Employee Only)	762.78	1,622.97		
(Employer Only)	-326.11	1,138.22		
Investment Tax Credit	-3,395.61	-400,816.58		-0.75

Consumption Cost per Metric Tonne of Carbon, 1990-2010
(Constant 1990 dollars)

	DRI	LINK	J/W	Goulder
Lump Sum Tax Cuts	236.51	1,050.80	57.63	21.18
Revenue Raising	437.96	946.87		21.18
Personal Income Tax Cuts	236.73	1,089.59	-52.52	14.14
Corporate Income Tax Cuts	114.77	314.17	-32.25	19.97
Payroll Tax Cuts				11.47
(Employee Only)	237.68	1,089.59		
(Employer Only)	-137.06	788.57		
Investment Tax Credit	-415.71	-234,658.85		19.15

Furthermore, in three of the models some of the scenarios yield a gain in GNP over baseline along with a reduction in carbon emissions. This implies a negative cost to reducing emissions. In some cases, such as the investment tax credit scenario in the LINK model, the GNP and consumption gains are large relative to the cut in emissions, implying a very large negative cost for a small reduction in emissions.[19] Even where emissions are cut at the cost of a clear loss of GNP, the appropriate measure of costs is not clear cut because both GNP and emissions follow unique time paths, and the summary measure is sensitive to the discount rate used.

In the DRI scenarios, the cost estimates range from about $800 per ton for the employee portion of the payroll tax to -$3,400 for the investment tax credit. In the LINK runs, the estimates range from about $1,600 per ton for deficit reduction to a very large benefit for the investment tax credit (though with a very small cut in emissions over the period as a whole). The computable general equilibrium models produce much lower costs per ton because the reductions are so much larger than in the macroeconometric models. In the Jorgenson/Wilcoxen scenarios, the cost estimates range from about $190 per ton for the lump sum case to -$190 for the capital tax; while in the Goulder runs, the estimates range from $50 per ton for the lump sum rebate to essentially $0 for the investment tax credit.

CONCLUSIONS

The results described in this paper suggest that recycled carbon taxes confer two separate benefits. In addition to their effectiveness as a Pigouvian tax that reduces a negative externality, carbon taxes have a potentially large additional efficiency value in that the revenues from the tax can be used to reduce other taxes and thus offset some of the distortions in the existing tax system. Some of the models used in this analysis suggest that the cost of a carbon tax can be more than offset if the revenues are used to cut distortionary pre-existing taxes on new capital formation. In contrast, using the revenues to reduce the federal budget deficit or to finance cuts in taxes on labor tends to stimulate consumption but not investment; in these cases, therefore, the adverse economic impact of the carbon charge is offset only slightly. The differences between the model results suggest that further research needs to be undertaken to integrate the modeling of microeconomic activity approximated in the CGE models with the aggregate effects captured by the macro models. Despite this qualification, it seems reasonable to conclude that the economic effects of a carbon tax can be significantly offset through appropriate use of the revenues.

A number of important related issues will need to be addressed in future work. Most importantly, results from the macro models used in this study suggest that carbon emission reductions may be achieved with essentially on loss in GNP through hybrid revenue recycling options combining cuts in taxes on both consumption and capital formation. Hybrid options might prove to be more politically palatable than tax cuts solely favoring capital. Moreover, the international trade effects of carbon taxes need to be examined more thoroughly than they have been in this study. In addition, the distributional consequences - in terms impacts on income, expenditures and regions - of different recycling options are being examined.[20] Furthermore, research suggests that forestry options that encourage the planting of trees to sequester carbon may be quite cost-effective at the margin; it may therefore be useful to incorporate forestry tax incentives into the current analysis.[21] Finally, differences in the results of the investment tax credit simulations reveals that substantial work is still needed to narrow the range of estimates of, first, the degree of substitutability between fossil fuels and other factors of production, and second, the interest rate response changes in savings and investment.

APPENDIX: TYPES OF ECONOMIC MODELS

The models employed in this study differ in their representations of the U.S. economy's structure, dynamics and tax systems. Several distinct approaches to large-scale economic modeling are currently used in economic policy analysis; this study uses two of these approaches: aggregate macroeconometric (macro) and computable general equilibrium (CGE) models. In general, the outcomes vary across models because of differences in the degree to which agents in the models adjust to price changes, and in the degree to which carbon taxes reduce aggregate economic activity. The two types of models tend to complement each other in that macro models generally capture short- and medium-term adjustments to exogenous shocks, while the CGE models best capture medium- and long-run responses. Use of more than one type of model allows us to assess the impact of carbon taxes on the economy while distinguishing the effects of model-specific assumptions on the outcomes.

Aggregate macroeconometric (macro) models represent the economy through sets of simultaneously solved, econometrically estimated equations that forecast aggregate components of economic activity. The macro models simulate short- and medium-term aggregate demand and supply responses to policy and supply shocks, as well as the adjustment process. While the models generally incorporate detailed representations of the effects of taxes on demand, the economy's supply potential is modeled with an aggregate production function. The factor inputs in the production function respond to changes in the relative prices of aggregate factor inputs. However, the models do not simulate equilibrium responses in disaggregated asset, factor, and commodity markets.

In contrast, computable general equilibrium (CGE) models include product- and factor-specific supply and demand equations that embody neoclassical general equilibrium (GE) theoretical assumptions about individuals' preferences and constraints, and about producers' profit maximizing behavior. This approach allows one to capture unique characteristics of specific sectors of the economy. Given an exogenous shock, such as the imposition of a tax, this type of model produces a price-dependent general equilibrium response that reflects GE theoretical assumptions. CGE models can thus be used to measure the magnitude of comparative statics (i.e. the "before" and "after") of exogenous shocks such as relative price changes, and can be extended to simulate a dynamic equilibrium path, given assumptions about individuals' preferences between current and future consumption. The CGE approach generally assumes very mobile inputs and instantaneous market clearing adjustments to shocks, and typically does not fully account for adjustment processes. Thus, the CGE approach generally fails to capture important short- to medium-term business cycle phenomena, such as inventory adjustments, investment accelerator effects, "sticky" prices and extensive unemployment of factors.

In this analysis, the two model types yield different projections of aggregate economic growth, CO_2 emissions and tax revenues through time. These differences are largely due to differences in model structure with respect to:

future technological change, which helps determine the rate of growth of output;

substitution between fossil fuels and other production inputs;

the economy's elasticity of demand for energy, particularly for electricity;

the elasticity of labor supply;

the elasticity of savings; and

the inclusion of international and financial influences.

THE DRI/MCGRAW-HILL (DRI) MODEL

The DRI/McGraw-Hill Model is a large (1215 variable) macroeconometric model designed primarily for policy analysis and private sector planning. The model merges aspects of Keynesian, neoclassical, monetarist, supply-side, and rational expectations analysis in its simulation of short-run, private sector behavior, and integrates this short-run behavior with a long-run growth model based on the work of James Tobin and Robert Solow. It also contains detailed representation of international and government policy responses to domestic economic phenomena.

Demand, production and price levels in specific goods markets are jointly determined. Real demand is driven by income, relative prices, wealth, expectations of growth and inflation, and financial conditions. Potential output is modeled as a Cobb-Douglas function of labor hours, capital stocks and energy inputs; while total factor productivity is determined by the state of technology embodied in the capital stock and the accumulated, depreciated stock of research and development expenditures. Prices and wages respond fully to one another and to gaps between sectoral demands and capacity. Many aspects of fiscal policy are endogenous in the model, including all state and local government variables, government purchase prices, many federal tax rates, and public interest and transfer payments.

Banking reserves are set exogenously by the Federal Reserve. Deposit demand are highly disaggregated and are driven by transactions and own-rate and competing yields on securities and physical assets. The monetarist emphasis on portfolio choice is respected, but significant interest elasticities and the endogeneity of the physical capital stock temper the naive monetarist link between inflation and money growth. The federal funds rate depends on the balance between the supply and demand of reserves to the banking system. Other interest rates are modeled as a term

Figure 7: DRI Gross National Product (1990$)

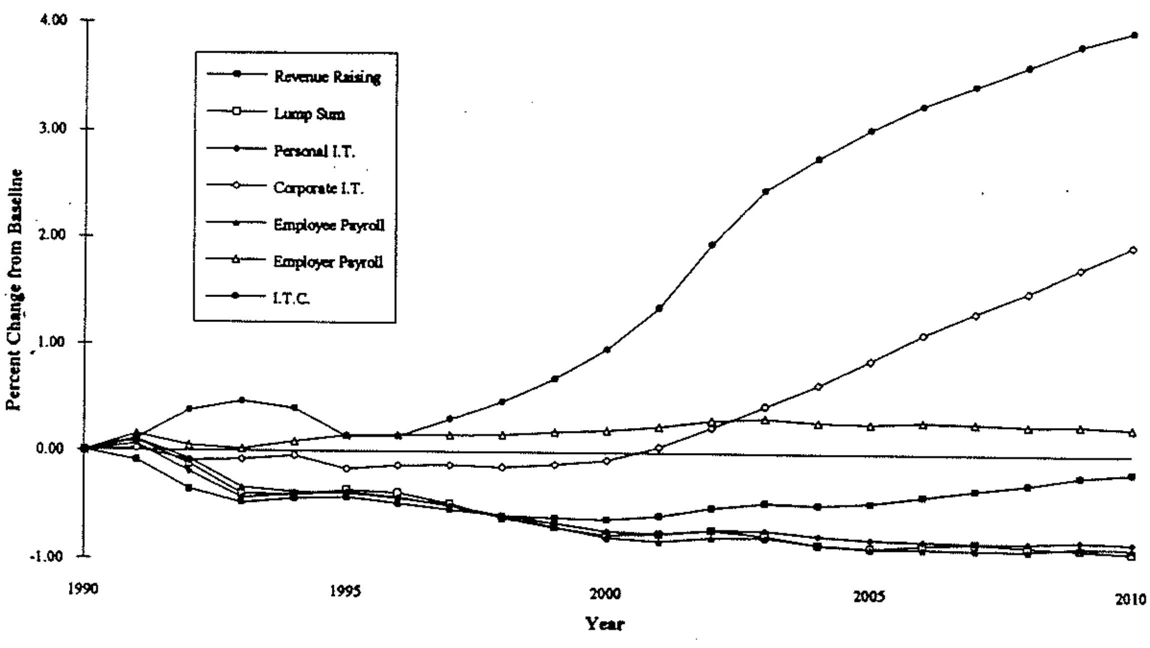


Figure 8: DRI Consumption (1990$)

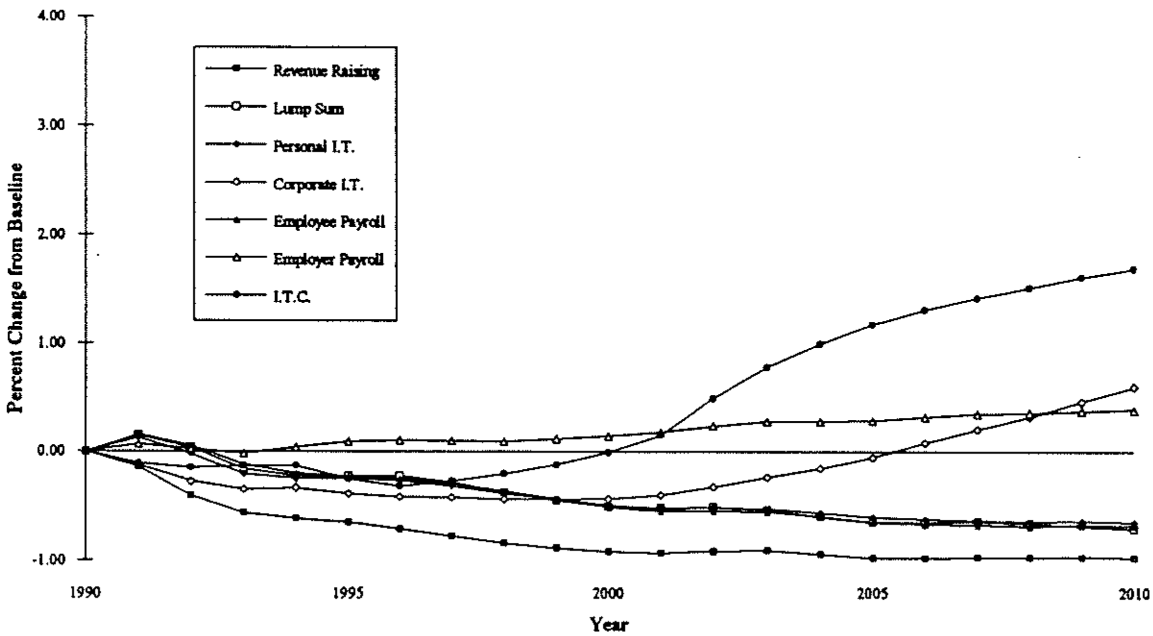
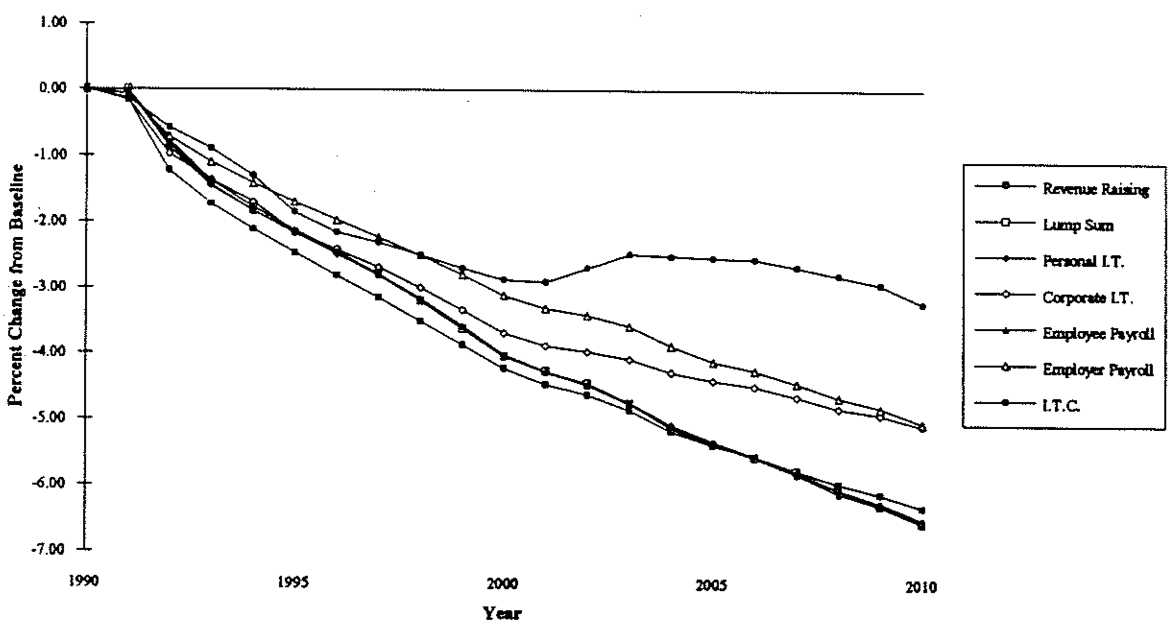


Figure 9: DRI Carbon Emissions



structure, pivoting off the federal funds rate. Yield spreads are driven by lagged adaptive inflation expectations and expectations of structural government deficits and monetary policy.

In the DRI model, the real exchange rate is modeled as a function of the current account deficit and U.S.-foreign real bond yield differentials. Foreign inflation and bond rates, in turn, adjust in response to domestic developments, as do foreign activity levels which appear in the export equations.

THE LINK-TGAS (LINK) MODEL

The LINK-TGAS system consists of two components which are connected for purposes of analyzing economic and environmental effects of carbon control policies; a description can be found in Kaufmann, Li, Pauly and Thompson (1991). The LINK-TGAS system is solved iteratively to provide a full range of energy-economy feedbacks.

The economic sub-module, which is provided by Project LINK, is, like the DRI model, a large macroeconometric model designed primarily for policy analysis. LINK is a large global econometric model based on about 80 national econometric models. For this carbon tax recycling project, the national model of the United States, which is being contributed by the WEFA Group, was run independently of the international system.

The Trace Gas Accounting System (TGAS) analyzes energy use and carbon emissions, based on a disaggregated analysis of primary energy demand, first-purchase prices, end-user prices and carbon emission levels; the system is described in detail in Kaufmann, Moore and Lynch (forthcoming).

Figure 10: LINK Gross National Product (1990$)

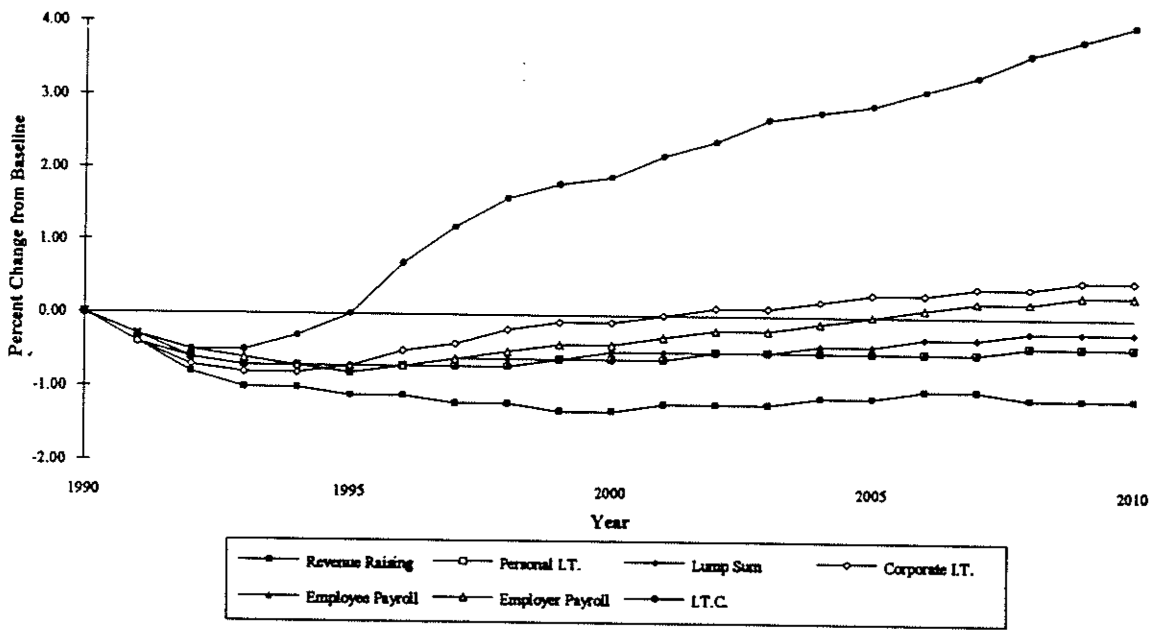


Figure 11: LINK Consumption (1990$)

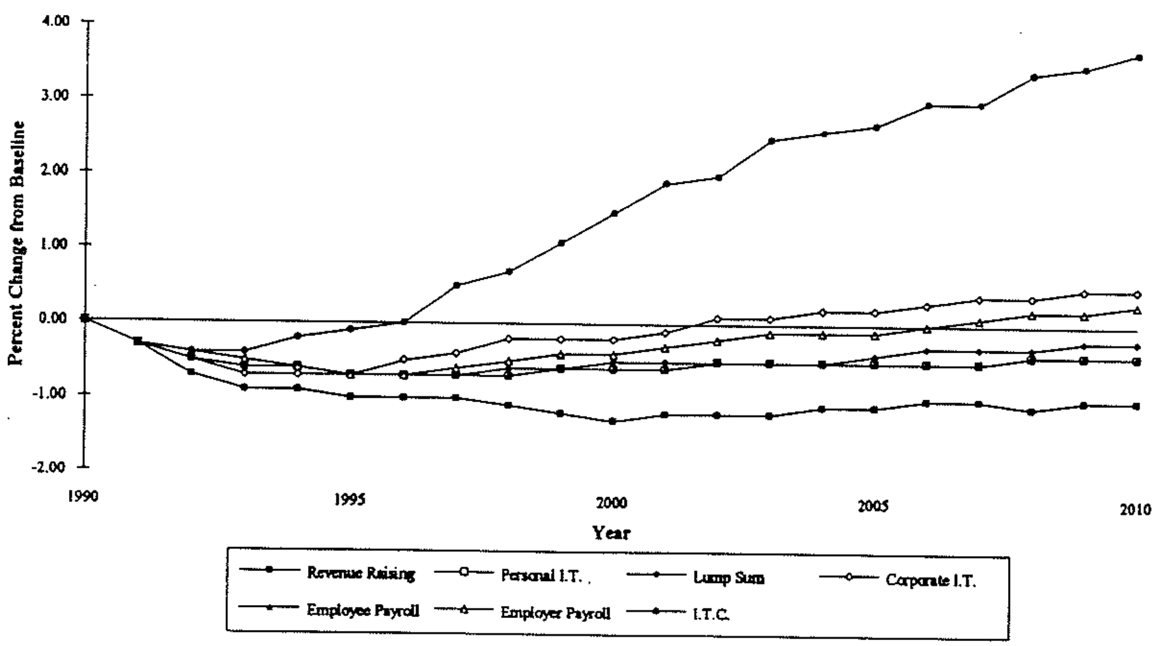
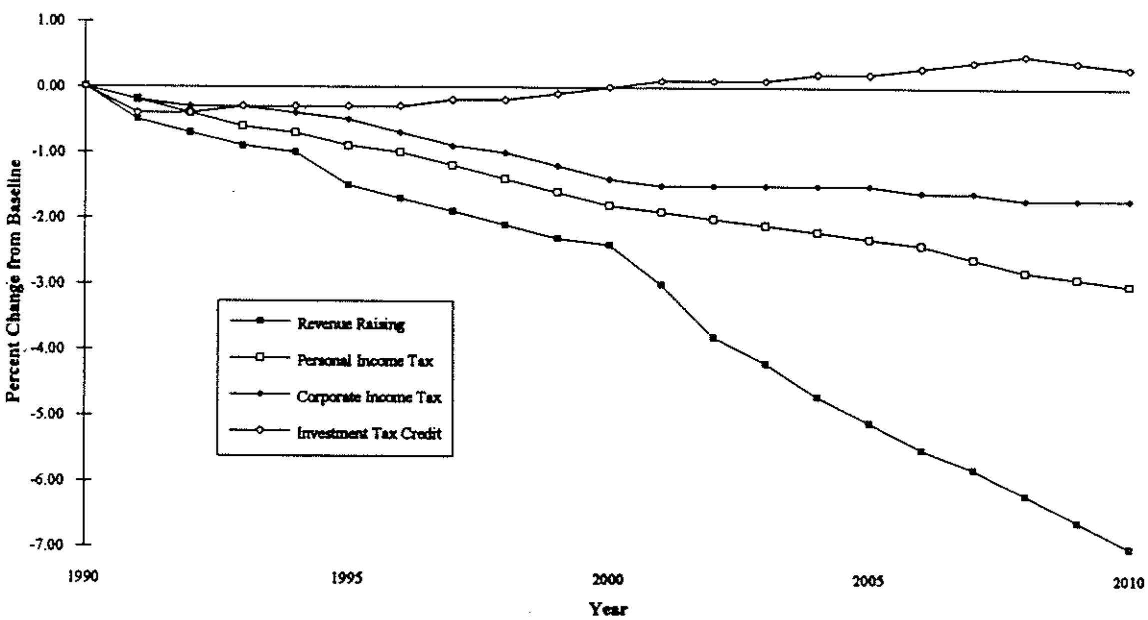


Figure 12: LINK Carbon Emissions



THE JORGENSON/WILCOXEN (J/W) MODEL

The Jorgenson/Wilcoxen model, developed specifically for intertemporal general equilibrium modeling of U.S. environmental regulation, incorporates a set of rigorously estimated econometric cost functions covering 35 separate industries and demand functions covering 35 products. These equations provide a detailed description of demand and supply elasticities and technical change, and allow for a great deal of substitution between intermediate, energy, and primary factors. Importantly, the equations allow technical change to be biased toward specific factors; so that, for instance, if the relative price of energy rises, technical change will tend toward increased energy efficiency rather than, say, labor saving.

The model also simulates the behavior of forward-looking consumers, whose preferences and expectations drive savings and asset accumulation decisions. As with most CGE models, the Jorgenson/Wilcoxen model assumes perfect factor mobility and ignores business cycles, disequilibrium adjustment processes, and long-term unemployment of factors.

THE GOULDER MODEL

The Goulder model was developed specifically for the analysis of inter-industry and intertemporal general equilibrium responses to changes in energy and environmental policy. The model has several unique features. First, it integrates elements of tax models and energy models by combining a detailed treatment of corporate and individual taxes within a disaggregated, general equilibrium representation of energy use in the U.S. economy. Second, the model incorporates within a disaggregated, general equilibrium framework an attention to nonrenewable supply dynamics (exhaustability) and backstop technologies; such resource dynamics are usually considered only in optimization models. Finally, the model incorporates capital adjustment

Figure 13: J/W Gross National Product (1990$)

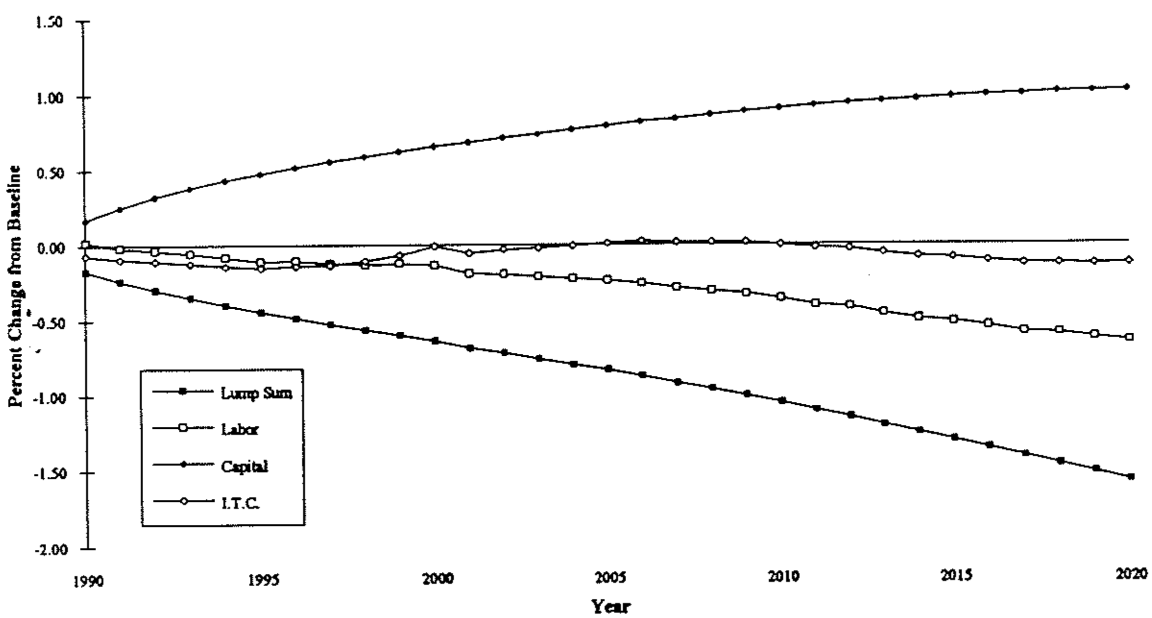


Figure 14: J/W Consumption (1990$)

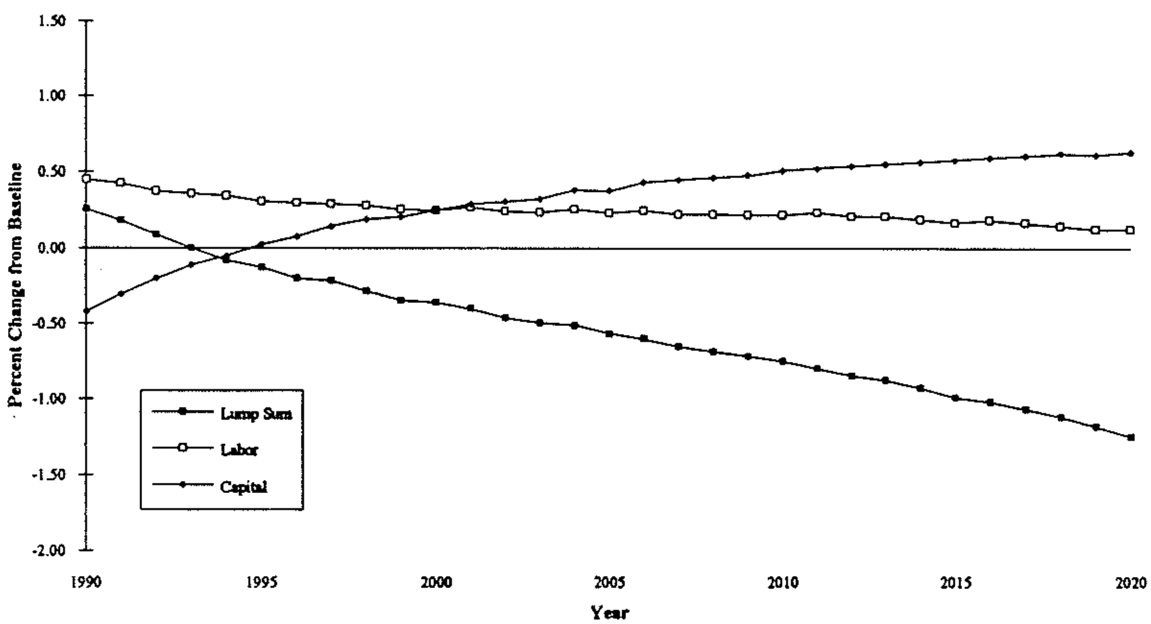


Figure 15: J/W Carbon Emissions

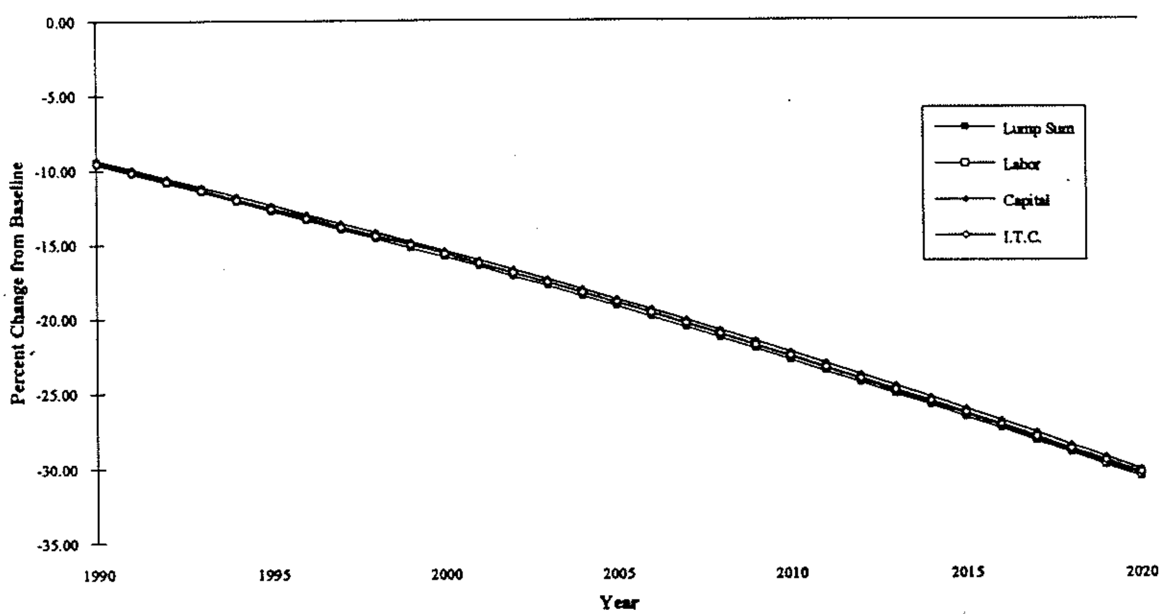


Figure 16: Goulder Gross National Product (1990$)

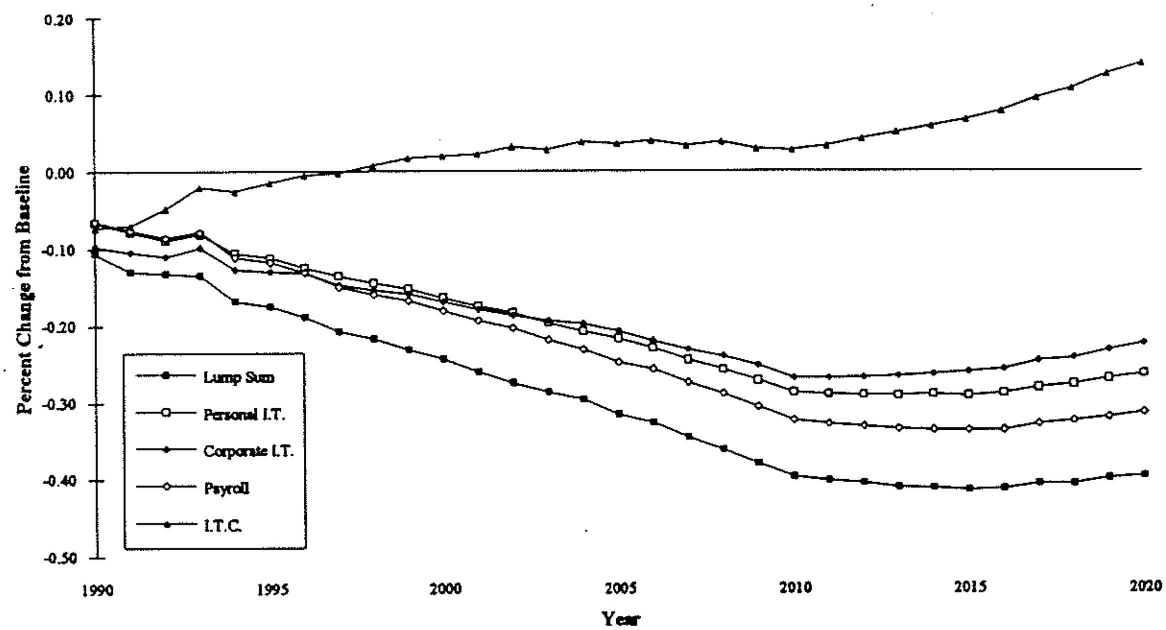


Figure 17: Goulder Consumption (1990$)

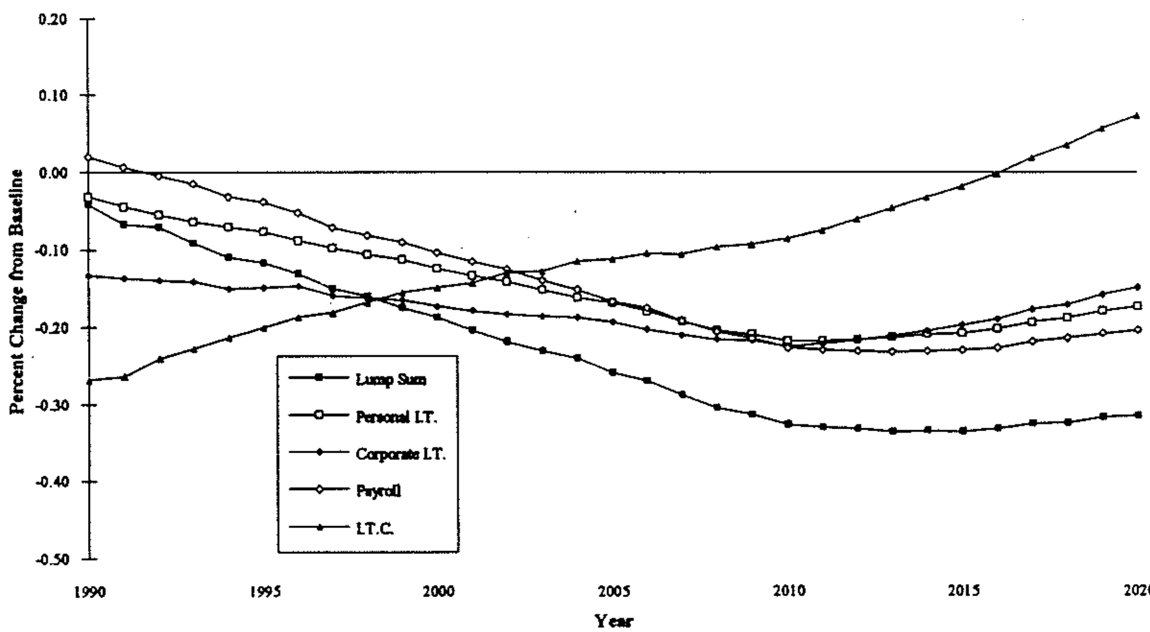
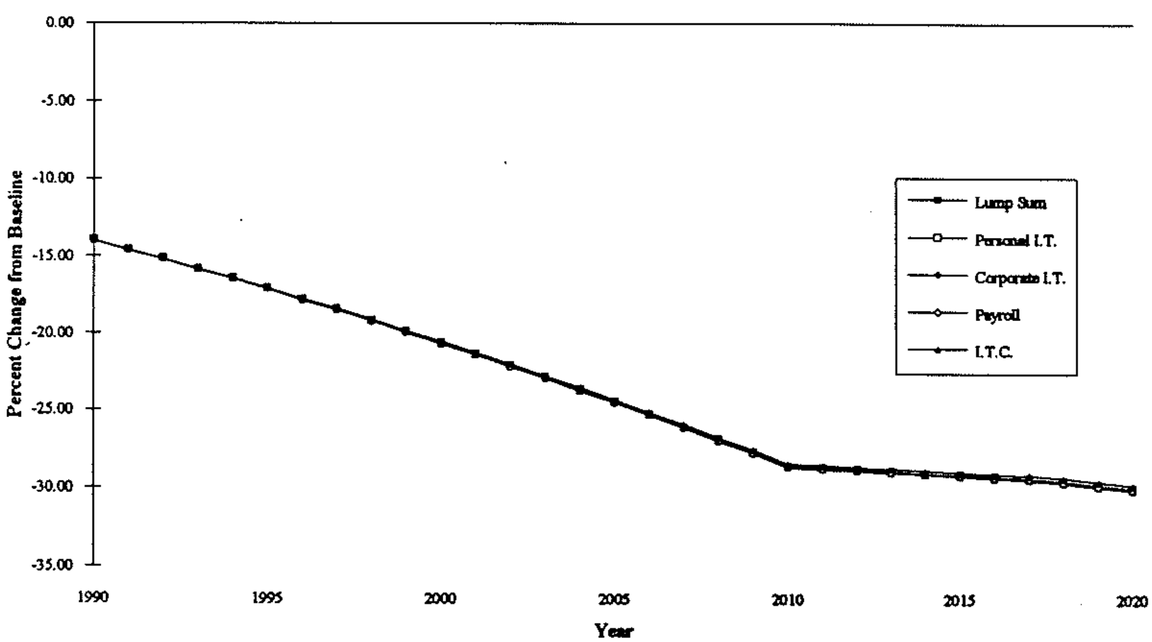


Figure 18: Goulder Carbon Emissions



dynamics; investment decisions in each industry consider future as well as current prices and take account of the adjustment costs inherent in the installation of new capital.

The model distinguishes thirteen industries, of which six are in the energy sector; the input demand and output supply parameters are derived from those of the Jorgenson/ Wilcoxen model. The model also distinguishes seventeen consumer products which are consumed in constant value proportions over time. This last property of the model constrains price elasticities for all consumer goods to be equal to -1.0 and consumer income elasticities to 1.0.

BASELINE FORECASTS

As mentioned above, the models differ in their embodied assumptions about central parameters over which there is great uncertainty, such as labor force growth and rates of technological change. These differences in assumptions yield different baseline forecasts and affect the tax scenario results. A crucial difference between the models lies in assumptions about rates of future technological change. Technological change allows the economy to produce more output with the same levels of inputs. (Assumptions about the rate of growth of the labor force are also important, but tend to be similar across models.) Largely because of the diverging assumptions about technological change, the models forecast baseline annual real GNP growth rates over the next twenty years that range from a low of 1.76% for the Jorgenson/Wilcoxen model to a high of 2.38% for LINK. Furthermore, the time path of economic growth varies between models, so that the Jorgenson/Wilcoxen model exhibits the highest growth rates during the 1990's, while the macro models continue to maintain high rates of growth into the twenty-first century. As a result of these differences, the models produce forecasts of real GNP growth from 1990 to 2010 that range from 42% to 60%, as shown in Figure 19.

Figure 19: Baseline Gross National Product (1990$)

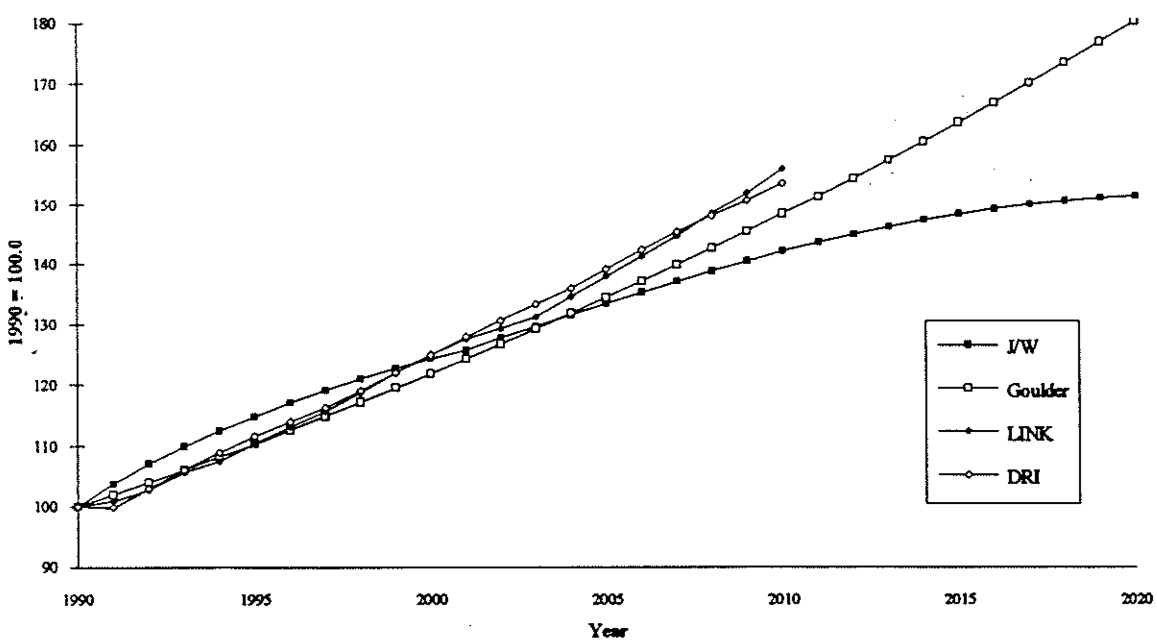


Figure 20: Baseline Carbon/GNP Ratio

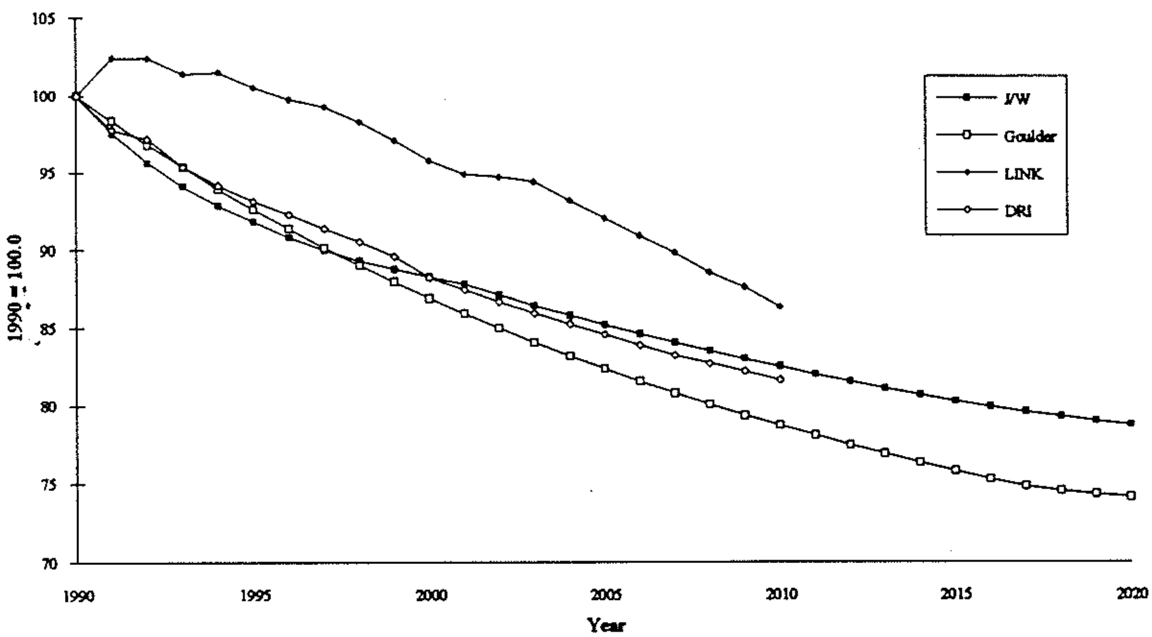
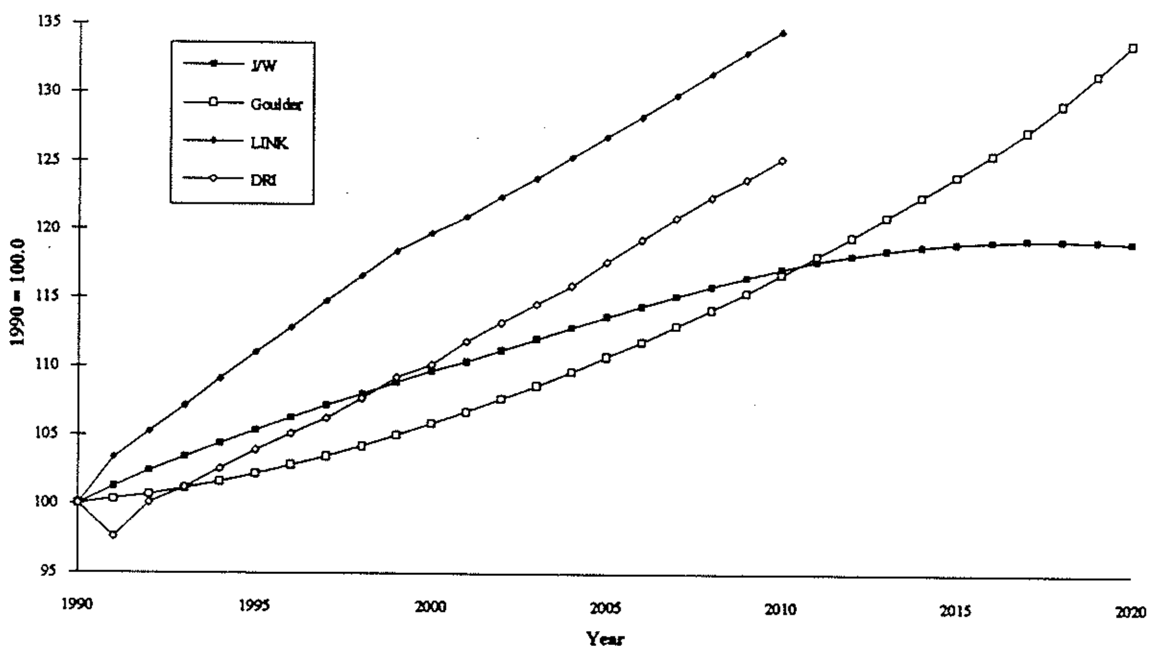


Figure 21: Baseline Carbon Emissions



A second crucial difference involves changes in the carbon intensity of the economy, or average carbon emissions per unit of output (Figure 20). The carbon/GNP ratio can be thought of as the product of two others, namely the energy/GNP ratio (whose growth rate is often referred to as the "autonomous energy efficiency increase" or AEEI)24 and the carbon/energy ratio. Three of the models assume that the economy's average carbon/GNP ratio will decline approximately 1.0% annually during the next two decades, even in the absence of carbon charges. Consequently, the discrepancies between the models' baseline forecasts of carbon emissions is due primarily to diverging forecasts of output growth. (The exception is the LINK model, in which the baseline carbon/GNP ratio rises slightly during the 1990's and declines slightly thereafter, returning close to its 1991 level in 2010.) The Jorgenson/Wilcoxen model forecast is on the low side, with baseline carbon emissions growing at an average annual rate of 0.79%, while the LINK model is at the other extreme, with emissions growing 2.5% annually. These baseline differences, shown in Figure 21, are important because the higher the model's growth forecast, ceteris paribus, the greater will be the model's prediction of the economic sacrifice necessary to limit or reduce carbon emissions.

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ENDNOTES

1. There is currently a significant degree of uncertainty in the scientific assessment of the greenhouse gases. The most recent assessment by the World Meteorological Organization suggests that nitrous oxides, chlorofluorocarbons and ozone have a number of complex interactive effects that tend to cancel out the direct ones, so that these gases have no net greenhouse effect. However, future advancements in scientific research may result in significant reassessments.

2. However, a carbon tax would raise the price of natural gas more than that of oil in percentage terms. The price increase depends on tons of carbon per dollar of fuel, which is the product of (a) energy units per dollar of fuel and (b) tons of carbon per energy unit. Oil is greater than natural gas in terms of (b), but natural gas is greater than oil in terms of (a) and the product is greater for natural gas because the natural gas price level is so much lower.

3. A carbon tax could also be extended to include tax credits to carbon sinks, such as forestry activities that result in carbon sequestration in trees.

4. William Nordhaus estimates that a doubling of CO_2 concentrations would result in damages on the order of 0.25% of U.S. gross national product. This translates into roughly $10 per ton of carbon at current levels of economic activity and carbon emissions. This estimate does not include non-market damages such as ecological effects. Given the great uncertainty in estimating the cost of such effects, a wide range of tax rates could be considered reasonable from the standpoint of economic efficiency, including the levels of tax analyzed in this paper. See Nordhaus in Dornbusch and Poterba (1991).

5. See the models reviewed in the 1990 Congressional Budget Office study and in Cline (June 1991); see also references to models used in EMF 12: AES Corporation (1990), Burniaux et al. (1991), Decision Focus, Inc. (1990), Edmonds and Barns (1991), ICF Incorporated (1988), Manne and Richels (1989), and Peck and Teisberg (1991).

6. The general equilibrium effects of a change in the tax system will include second-order cyclical effects on government receipts and expenditures. Although the full-employment budget deficit is an inherently imperfect concept, it is a better measure of the direction of fiscal policy than the actual budget deficit because it helps distinguish between long-run equilibrium effects and cyclical effects of an active change in fiscal policy.

7. The alternative minimum tax (AMT), introduced in the Tax Reform Act of 1986, is a corporate tax system separate from but parallel to the regular corporate income tax. Corporations are required to calculate their tax assessments under both systems and pay the greater of the two assessments. The AMT provides for considerably less favorable depreciation rates, discriminates against corporations with high capital intensity and/or high levels of investment, complicates the process of calculating tax payments, is generally considered a disincentive to capital formation; and is difficult to model since it requires a case-by-case analysis of its impacts on individual corporations. Unless eliminated, the AMT would reduce the effectiveness of corporate tax cuts, employer payroll tax cuts or the investment tax credit in offsetting the impact of a carbon tax.

8. Even in the Jorgenson-Wilcoxen model, the capital tax cut is preferable to the labor tax cut in terms of its effect on GNP. However, the labor tax cut is preferable in terms of its effect on consumption. Even in this case, however, only for the first four years is consumption higher in the labor tax simulation than in the capital tax simulation; within five years consumption is higher after a capital tax cut than after a labor tax cut (see Figure 14). The preferability of a labor tax cut results from the fact that it boosts consumption substantially in the short run at the expense of consumption in the long-run.

9. It is true that using the taxes to reduce the federal deficit can have beneficial growth effects because deficit reduction is likely to reduce interest rates, and lowers the level of future taxes needed to retire government debt. However, in the models used in this study, these effects are small relative to the effect of reducing taxes on capital formation.

10. Emission levels tend to follow GNP growth in the macro models; and in the LINK model, the investment tax credit actually raises carbon emissions above baseline levels after the turn of the century.

11. In Goulder's implementation, the present value of the tax reductions made possible by the carbon tax revenues is virtually the same in this revenue-raising case as in the lump-sum tax case. The difference between the simulations is mainly the timing of the tax reductions. In the revenue raising case, there are no lump-sum reductions in taxes in the near term. However, the model includes an intertemporal budget constraint for the government which requires that future taxes be lowered at some point. In the revenue-raising simulation, Goulder reduces taxes in a lump-sum fashion beginning in 2040. This simulation produces results nearly identical to the lump-sum case because households are forward-looking and face infinite horizons. In this model, households are largely indifferent to the timing of lump-sum tax cuts provided that the present value of the tax reductions is the same. Thus their behavior is the same in the lump-sum and revenue-raising simulations.

12. For a more skeptical analysis of investment tax credits, see Gravelle (1992). In practice, the investment tax credits that have found their way into law have favored short-lived assets over longer-lived ones and therefore have had distortionary impacts on the allocation of investment resources. This issue is not entirely adequately addressed in the models included in this study, and such distortions are likely to reduce the efficacy of the ITC in offsetting the impacts of a carbon tax. However, it is possible in principle to design an ITC that does not favor short-lived assets.

13. More recent versions of the DRI model estimated on updated data yield a somewhat smaller investment response to the tax credit, narrowing the differences between the models. These results were not yet available at the time of publication for all the scenarios discussed in this paper, and were therefore not included in this paper.

14. One very important omission is that GNP fails to account for any of the externalities due to carbon emissions, the welfare-reducing externalities that the carbon tax is intended to ameliorate. The simulations therefore begin with the "wrong sign" on the welfare measure. This is true, however, for any measure that we could use to gauge welfare effects in the models used here, because none of the models are designed to capture environmental externalities.

15. For a given change in prices, the equivalent variation measures the amount an individual would have to be paid before the price change to make him as well off as he would be after the price change; it is thus a money equivalent of the change in welfare due to the price change.

16. Jorgenson-Wilcoxen use a social welfare function in which society's welfare depends on the degree of equality of the distribution of wealth. They consider two polar cases; in one, society is indifferent to the distribution of wealth; in the other, society strongly prefers an equal distribution of wealth.

17. Although a ton of carbon emissions in any particular year yields a stream of global warming potential (GWP) that may extend over many decades, discounting the emissions in the year they take place is equivalent to discounting the stream of GWP at the same discount rate.

18. The first values for social welfare refer to the case in which society is indifferent as to the distribution of wealth; the second values refer to the case in which society strongly prefers an equal distribution of wealth.

19. In preliminary scenarios with one of the models, both GNP and emissions rose; this would imply a positive cost for reducing emissions, but the measure would be meaningless since emissions would not be reduced at all. For a complete description of the social welfare function used in this study, see Jorgenson, Slesnick and Wilcoxen (1992).

20. See Schillo et al. (1992) for a discussion of current analysis of the tax regimes discussed in this paper.

21. Preliminary analysis suggests that the costs of stabilizing U.S. carbon emissions through offsetting forestry programs over the period under consideration here may be an order of magnitude lower than the costs of reducing fossil fuel emissions through a carbon tax.