DRAFT – Comments Invited

Impacts of a Carbon Tax across U.S. Household Income Groups: What Are the Equity-Efficiency Trade-Offs?

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ABSTRACT

This paper assesses the impacts across U.S. household income groups of carbon taxes of various designs. We consider both the source-side impacts (reflecting how policies affect nominal wage, capital, and transfer incomes) as well as the use-side impacts (reflecting how policies alter the real prices of goods and services purchased by households). In contrast with most previous studies, this analysis applies a single consistent general equilibrium framework to assess both types of impact. The work is unique in applying extended measures of the source- and use-side impacts – measures that capture the full impact of policies on household utility. Exploiting the multi-period aspect of our modeling framework, we assess how the relative and absolute impacts of the carbon tax change over time.

We consider a range of carbon tax policies that differ according to how the carbon tax revenues are recycled to the private sector. In particular, we consider policies with and without compensation targeted to particular household income groups. By comparing the economic costs of the two types of policies, we are able to assess the economic sacrifices associated with achieving certain distributional objectives.

We find that under a range of recycling methods, the source-side impacts are generally progressive, while the use-side impacts are consistently regressive. The progressive source-side impacts tend to fully offset the regressive use-side impacts. Both the source- and use-side impacts are considerably larger once one takes account of the more comprehensive welfare measures introduced in this study. Inflation-indexed transfers avoid what otherwise would be significantly regressive overall impacts of climate policy.

The efficiency costs of achieving distributional objectives depend critically on the recycling method and compensation target. These costs are an order of magnitude higher when the revenues that remain after compensation are used for corporate income tax cuts, compared with the other ways of using the remaining revenues. Efficiency costs also rise dramatically when targeted compensation extends beyond the lowest income quintile.

1. Introduction

Economists tend to consider a carbon tax as the most cost-effective approach to reducing CO_2 emissions.[1] However, cost-effectiveness is not the only feature relevant to assessing this policy option. The distribution of the policy's impacts, and the associated implications for fairness, are also important considerations. The distribution of a carbon tax's impacts across household income groups, in particular, is a central consideration.[2]

The impacts on households can be decomposed into what economists have termed *use-side* and *source-side* effects. The use-side impact is the effect on purchasing power or well-being that stems from changes in the prices of goods and services that households purchase. A carbon tax alters the relative prices of the goods and services that households purchase. The goods and services that are more carbon-intensive in their production will generally rise relative to pries of other goods and services. This has distributional consequences: households that rely relatively more on those goods will experience a greater reduction in real income than households less reliant on those goods.

The source-side impact is the change in purchasing power or well-being attributable to policy-induced changes in a household's nominal labor, capital, and transfer income. A carbon

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[1] Several attributes of a carbon tax contribute to its greater cost-effectiveness. One is flexibility: rather than require a particular way to reduce emissions, a carbon tax gives firms flexibility to find the lowest-cost way to achieve the reductions. A second is the ability of a carbon tax (if broad-based) to promote equality of marginal abatement costs across firms that directly or indirectly use carbon-based fuels. Such equality is a condition for minimizing the aggregate costs of emissions abatement. On this, see, for example, Fischer, Kerr, and Toman (2001). Third, a carbon tax tends to encourage more demand-side conservation than conventional regulations that impose the same effective marginal cost of abatement. This is because, in contrast with conventional regulations, a carbon tax not only promotes emissions reductions but also charges for remaining emissions; this helps assure a more efficient output price and a more efficient level of demand-side conservation. See Goulder and Parry (2008) for a discussion of this point. Finally, because it brings in revenues, a carbon tax creates opportunities for revenue-recycling in the form of cuts in the rates of pre-existing distortionary taxes. As discussed by Oates (1993), Fullerton and Metcalf (2001), and others, this can reduce policy costs.

[2] The impacts across producers or industries is also relevant to fairness (and to political feasibility). A large number of studies have investigated the potential impacts of a carbon tax across industries. See, for example, Jorgenson *et al.* (2013). Since industry impacts are ultimately felt by workers, managers, and owners of firms, in some ways the question of fairness ultimately must involve relative impacts across individuals rather than firms.

tax generally will affect (positively or negatively) after-tax wages, returns to capital, and transfers. This differently affects different households to the extent that their reliance on these different forms of income differ.

This paper assesses the distribution of the impacts across U.S. household income groups of carbon taxes of various designs, taking into account both the use- and source-side impacts. We explore both the absolute impacts on various household income groups as well as the relative impacts such as the extent to which the impacts are regressive or progressive. In addition, we examine the potential aggregate costs of reducing or avoiding regressivity, or of avoiding absolute losses of welfare to households in the lowest income groups.

Our paper builds on an earlier literature that has considered the source- and use-side impacts of carbon taxes. Some studies focus exclusively on the use side, and these studies tend to obtain regressive impacts. Fremstad and Paul (2017) and Grainger and Kolstad (2010) employ input-output models to assess the use-side impacts.[3] Mathur and Morris (2014) consider these impacts using a general equilibrium model. In contrast, Rausch *et al.* (2011), Fullerton *et al.* (2011) and Williams *et al.* (2014) examine both the use- and source-side effects. These analyses tend to find progressive source-side impacts that fully offset the use-side impacts, causing the overall impacts carbon taxes to be progressive.[4]

The present paper builds on this work in four ways. First, it offers an especially consistent theoretical framework and numerical approach. The theoretical framework fully integrates the source- and use-side impacts on utility while revealing their separate contributions to welfare. In addition, rather than employ separate empirical models to measure the two types of impacts, this study applies a single general equilibrium modeling framework to assess the impacts on the source and use side as well as to quantify the efficiency costs of achieving various distributional goals.

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[3] Grainger and Kolstad (2010) show that the regressivity of the use-side impact varies with different recycling methods.

[4] Rausch *et al.* (2011) find that the source-side impact is progressive and sufficient to overcome the regressive use-side impact when the carbon tax policy involves lump-sum recycling. Fullerton *et al.* (2011) find that progressivity in U.S. transfer program indexing significantly offsets regressivity on the use side. Williams *et al.* (2014) show that the source-side impact is highly progressive when revenues are recycled as lump-sum payments to households, making the overall impact progressive. Cronin *et al.* (2017) focus mainly on the use-side impact; however, they consider transfers and argue that the impact of a carbon tax is progressive once one accounts for the indexing of transfers.

Second, in contrast with earlier work, the analysis develops and applies more complete measures of the household welfare impacts. The measures of source-side impacts account for the effects of policies on the value of households' time (labor and leisure), rather than just on the value of the labor income. And the measures of use-side impacts account for policy effects on the price of leisure (another "good" that households consume) in addition to the prices of other goods and services. To reveal the significance of these broader measures, we compare the welfare impacts that they yield with the impacts that result when the often-used narrower measures are applied.

Third, while previous studies have tended to focus on the distributional impacts at a single point in time (usually the present), we exploit the multi-period property of our numerical model to examine changes in the distributional impacts over time.

Fourth, we compare policies with and without targeted compensation, in order to assess the efficiency costs of avoiding certain distributional outcomes.

We find that under a range of recycling methods, the source-side impacts are generally progressive, while the use-side impacts are consistently regressive. The progressive source-side impacts tend to fully offset the regressive use-side impacts, so that the overall impacts are either slightly progressive or close to proportional. Under central case assumptions, the lowest income quintile enjoys a positive source-side impact sufficient to enable the household to experience a positive overall welfare impact from the climate change policy.[5] We also find that both the source- and use-side impacts are considerably larger once one takes account of the more comprehensive measures that we employ in this study. Inflation-indexed transfers avoid what otherwise would be significantly regressive overall impacts of climate policy by providing additional nominal transfers to compensate for higher overall consumer prices from climate change policy.

The efficiency sacrifices required to avoid adverse welfare impacts depend critically on the method of recycling and the particular households targeted. Efficiency costs are about an order of magnitude higher when remaining revenues are to be used for corporate income tax cuts, compared with the other ways of using the remaining revenues. These costs are also an order of

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[5] This is not to suggest that all households in the lowest quintile would experience a welfare gain. Given the heterogeneity of household expenditure patterns and income sources within a quintile, the welfare impacts within a quintile will vary.

magnitude higher under the more ambitious hybrid policy of avoiding an adverse impact on the lowest three quintiles, a reflection of the much higher level of rebates required under this policy.

The rest of the paper is organized as follows. Section 2 presents an analytical model of household behavior and utility, one that shows the channels through which a carbon tax yields the source- and use-side utility impacts. The next five sections focus on the numerical work. Section 3 indicates the structure of the numerical general equilibrium model, and section 4 describes the data and parameters employed in that model. Section 5 presents the economic outcomes in our reference (no-policy-change) case and the main features of the carbon tax policy we consider. Section 6 displays the carbon tax's aggregate impacts on emissions, prices and output. Section 7 then examines and interprets the distribution of impacts across household groups. Sections 8 evaluates the efficiency costs of achieving certain distributional objectives, while Section 9 focuses on the importance of government transfers to the distributional results. Section 10 offers conclusions.

2. Identifying and Measuring the Welfare Impacts

Here we derive analytical expressions for the source- and use-side impacts of a carbon tax (or other policy change) on a household that maximizes utility over an infinite horizon. We show that these two impacts combine to produce the total impact on utility.

a. The Utility-Maximization Problem

Consider the following dynamic (infinite-horizon) utility-maximization problem. A household receives an initial non-human wealth endowment W_0 and an annual labor endowment $\overline{l}_t$, and chooses "full consumption" C_t to maximize its lifetime utility, taking the price of consumption and the returns to non-human and human wealth as given. Utility is given by

$$U = \sum_{t=0}^{\infty} \beta^t U(C_t) \tag{1}$$

Nonhuman wealth evolves according to:

$$W_{t+1} - W_t = \bar{w}_t \bar{l}_t + \bar{r}_t W_t - P_t C_t \ . \qquad (2)$$

The left-hand side is the change in nonhuman wealth over two successive periods. This change is equal to after-tax wage income plus capital income minus the value of full consumption. In the above expression, P_t is the price of full consumption, $\bar{w}_t$ is the (after-tax) wage, and $\bar{r}_t$ is the (after-tax) return on capital.

The intertemporal budget constraint is

$$\sum_{t=0}^{\infty} \left[P_t C_t \right] d_t = W_0 + \sum_{t=0}^{\infty} \left[\bar{w}_t \bar{l}_t \right] d_t \qquad (3)$$

where

$$d_t = \prod_{u=0}^{t} \left[1 + \bar{r}_u \right]^{-1} \ . \qquad (4)$$

The transversality condition,

$$\lim_{t \to \infty} W_{t+1} d_t = 0 \, , \qquad (5)$$

is imposed to rule out eternal speculative bubbles. Equation (3) states that the present value of full consumption must not exceed the sum of financial and human wealth, where the latter is the present value of the time endowment.[6]

Full consumption at any point in time is a nested composite of current consumption of goods and services, $\bar{C}_t$, and current consumption of leisure, ℓ_t:

$$C_t = C(\bar{C}_t, \ell_t) \ . \qquad (6)$$

Total expenditure is the value of full consumption and is equal to expenditure on consumer goods and services plus the value of leisure: $P_t C_t = \bar{p}_t \bar{C}_t + \bar{w}_t \ell_t$, where $\bar{p}_t$ is the price of a unit of

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[6] We assume the intertemporal budget constraint is binding.

consumption of goods and services, and leisure is valued at the opportunity cost of time not spent working.[7]

Let $U_C = \frac{\partial U}{\partial C}\frac{\partial C}{\partial \overline{C}}$ and $U_\ell = \frac{\partial U}{\partial C}\frac{\partial C}{\partial \ell}$. The first-order conditions for the utility-maximization problem are

$$\frac{\partial L}{\partial \overline{C}_t} : U_C(\overline{C}_t, \ell_t) = \lambda_t \overline{p}_t \tag{7}$$

$$\frac{\partial L}{\partial \ell_t} : U_\ell(\overline{C}_t, \ell_t) = \lambda_t \overline{w}_t \tag{8}$$

$$\frac{\partial L}{\partial W_{t+1}} : \lambda_t = \beta(1 + \overline{r}_{t+1})\lambda_{t+1} \tag{9}$$

where λ_t is the Lagrange multiplier on the budget constraint. Equation (8) represents the intertemporal Euler condition. The expenditure functions that satisfy the first-order conditions can be written as

$$\overline{C}_t = c(\overline{p}_t, \overline{w}_t, \lambda_t) \tag{10}$$

$$\ell_t = \ell(\overline{p}_t, \overline{w}_t, \lambda_t) \ . \tag{11}$$

b. Measuring the Welfare Impacts

As indicated above, a carbon tax affects utility by changing returns to factors and the prices of goods and services purchased. We measure the welfare impact of these changes in prices using the *equivalent variation,* the change in wealth under reference-case (status quo) conditions that would have the same impact on utility as that of the policy change (Mas-Colell, Whinston, and Green 1995). In our intertemporal context, the equivalent variation can be expressed as the difference in expenditure across across two intertemporal scenarios. The first, the "reference case" scenario, is defined by the vectors $(\overline{p}_t(\text{ref}), \overline{w}_t(\text{ref}), \overline{r}_t(\text{ref}))$, which represent

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[7] In the numerical model, the consumption good $\overline{C}_t$ is a composite of 24 consumer goods and the price $\overline{p}_t$ represents the aggregate of the 24 different after-tax (or subsidy) consumer good prices. Here we do not specify the prices of individual consumption goods, as the price index $\overline{p}_t$ is sufficient to determine the welfare impacts.

the time-profiles of the prices of consumption, wages, and returns to capital, respectively, in the absence of a change in policy. The second, the "policy case" scenario, is defined by the vectors $(\bar{p}_t(\text{pol}), \bar{w}_t(\text{pol}), \bar{r}_t(\text{pol}))$, which are the time-profiles of the prices of consumption, wages and returns to capital under the policy change.

Let $U_S(\text{pol})$ denote intertemporal utility over the interval from period 0 to S in the policy case. $U_S(\text{pol})$is given by

$$U_S(\text{pol}) = \sum_{t=0}^{S} \beta^t U\left(\bar{C}_t(\text{pol}), \ell_t(\text{pol})\right). \tag{12}$$

As indicated in equations (10) and (11) above, the optimal values of $\bar{C}_t$ and ℓ_t can be expressed as a function of $\bar{p}_t$, $\bar{w}_t$, and λ_t, where λ_t follows the optimal trajectory given by the Euler condition (9): $\bar{C}_t(\text{pol}) \equiv c(\bar{p}_t(\text{pol}), \bar{w}_t(\text{pol}), \lambda_t(\text{pol}))$ and $\ell_t(\text{pol}) \equiv \ell(\bar{p}_t(\text{pol}), \bar{w}_t(\text{pol}), \lambda_t(\text{pol}))$.

To calculate the equivalent variation for any given household, we generate new paths for $\bar{C}_t$ and ℓ_t using reference case prices and an altered time-profile for λ_t, subject to the condition that intertemporal utility to that household (reflecting the adjustment to its wealth) match its utility under the carbon tax policy. Let λ_t^{ev} represent the value of λ_t along the path that yields, with reference case prices, the policy-case utility. Consumption and leisure along this altered path are given by $\bar{C}_t(\lambda_t^{ev}) \equiv c(\bar{p}_t(\text{ref}), \bar{w}_t(\text{ref}), \lambda_t^{ev})$ and $\ell_t(\lambda_t^{ev}) \equiv \ell(\bar{p}_t(\text{ref}), \bar{w}_t(\text{ref}), \lambda_t^{ev})$. Finally, define the reference case levels of consumption and leisure as $\bar{C}_t(\text{ref}) \equiv c(\bar{p}_t(\text{ref}), \bar{w}_t(\text{ref}), \lambda_t(\text{ref}))$ and $\ell_t(\text{ref}) \equiv \ell(\bar{p}_t(\text{ref}), \bar{w}_t(\text{ref}), \lambda_t(\text{ref}))$.

The overall welfare impact of a policy change, as measured by the equivalent variation, is the difference in expenditure between the reference-case and policy-case optimal paths. Let $EX_{S,\text{ref}}$ and $EX_{S,\text{ev}}$ represent the levels of expenditure over time in the reference case and in the case generated by the altered time path for λ_t that yields policy-case utility, respectively. Then the equivalent variation EV_S is

$$EV_S = EX_{S,\text{ev}} - EX_{S,\text{ref}} \tag{13}$$

where

$$EX_{S,\,\text{ref}} = \sum_{t=0}^{S}\left[\,\bar{p}_t(\text{ref})\bar{C}_t(\text{ref}) + \bar{w}_t(\text{ref})\ell_t(\text{ref})\right]\bar{d}_t \tag{14}$$

and

$$EX_{S,\,\text{ev}} = \sum_{t=0}^{S}\left[\,\bar{p}_t(\text{ref})\bar{C}_t(\lambda_t^{ev}) + \bar{w}_t(\text{ref})\ell_t(\lambda_t^{ev})\right]\bar{d}_t\ , \tag{15}$$

respectively, and where

$$\bar{d}_t = (1+\bar{r}_0(\text{ref}))d_t(\text{ref}) = (1+\bar{r}_0(\text{ref}))\prod_{u=0}^{t}\left[1+\bar{r}_u(\text{ref})\right]^{-1}\ . \tag{16}$$

c. Decomposing the Welfare Impact into Source- and Use-Side Effects

We can decompose the overall welfare impact into the use- and source-side components as follows. Let $EX_{S,\,\text{pol}}$ denote total expenditures by the household in the policy case. $EX_{S,\,\text{pol}}$ is expressed by

$$EX_{S,\,\text{pol}} = \sum_{t=0}^{S}\left[\,\bar{p}_t(\text{pol})\bar{C}_t(\text{pol}) + \bar{w}_t(\text{pol})\ell_t(\text{pol})\right]\bar{d}_t\ . \tag{17}$$

where $\bar{p}_t$ and $\bar{w}_t$ are policy case prices.[8] Applying the definition of the equivalent variation, we can rewrite expression (13) as

$$EV_S = \frac{EX_{S,\,\text{ev}}}{EX_{S,\,\text{pol}}}\left[EX_{S,\,\text{pol}} - EX_{S,\,\text{ref}}\right] + \left[\frac{EX_{S,\,\text{ev}}}{EX_{S,\,\text{pol}}}EX_{S,\,\text{ref}} - EX_{S,\,\text{ref}}\right] \tag{18}$$

We will show that the first term on the right-hand side of (18) is the source-side impact (which we denote as SS_S) and that the second term is the use-side impact (which we denote as US_S).

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[8] The reference case discount factor is used to avoid confounding differences in expenditures by period with changes in the interest rate.

The source-side impact is the change in welfare that results from changes in the value of the endowments of time and capital. In equation (18), the source-side impact is equal to the change in the present value of expenditures,

$$SS_S = \frac{EX_{S,\,\mathrm{ev}}}{EX_{S,\,\mathrm{pol}}}\left[EX_{S,\,\mathrm{pol}} - EX_{S,\,\mathrm{ref}}\right] \tag{19}$$

Applying the household budget constraint (equation 2), the present value of expenditures is also equal to the present value of the returns to labor and capital:

$$EX_S = \sum_{t=0}^{S}\left[\bar{w}_t\bar{l}_t + (1+\bar{r}_t)W_t - W_{t+1}\right]\bar{d}_t \tag{20}$$

Hence, the above expression for source-side impacts can further be decomposed into the changes in returns to labor and capital, respectively:

$$SS_S = \frac{EX_{S,\,\mathrm{ev}}}{EX_{S,\,\mathrm{pol}}}\left[SS_S^L + SS_S^K\right] \tag{21}$$

where the labor source-side impacts are

$$SS_S^L = \sum_{t=0}^{S}\left[\left(\bar{w}_t(\mathrm{pol}) - \bar{w}_t(\mathrm{ref})\right)\bar{l}_t\right]\bar{d}_t \tag{22}$$

and the capital source-side impacts are

$$SS_S^K = \sum_{t=0}^{S}\left[\left(\bar{r}_t(\mathrm{pol}) - \bar{r}_t(\mathrm{ref})\right)W_t(\mathrm{pol})\right]\bar{d}_t + \left[W_{S+1}(\mathrm{pol}) - W_{S+1}(\mathrm{ref})\right]\bar{d}_S\,. \tag{23}$$

The labor source-side impact captures changes in the value of the time endowment (human wealth) caused by changes in the after-tax wage. The capital source-side impact captures changes in the return to financial wealth and the change in wealth in the terminal period.[9] The fraction $EX_{S,\,\mathrm{ev}} / EX_{S,\,\mathrm{pol}}$ scales the source-side impact by the change in the price of full consumption.

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[9] It follows from manipulation of the budget constraint that

$$SS_S^K = \sum_{t=0}^{S}\left[\left[(1+\bar{r}_t(\mathrm{pol}))W_t(\mathrm{pol}) - W_{t+1}(\mathrm{pol})\right] - \left[(1+\bar{r}_t(\mathrm{ref}))W_t(\mathrm{ref}) - W_{t+1}(\mathrm{ref})\right]\right]\bar{d}_t$$

$$= \sum_{t=0}^{S}\left[\left(\bar{r}_t(\mathrm{pol}) - \bar{r}_t(\mathrm{ref})\right)W_t(\mathrm{pol})\right]\bar{d}_t + \left[W_{S+1}(\mathrm{pol}) - W_{S+1}(\mathrm{ref})\right]\bar{d}_S$$

The use-side impact is the change in welfare stemming from changes in the prices of consumption and of leisure, holding total nominal expenditures fixed. Using the definition of full consumption, $P_t C_t = \overline{p}_t \overline{C}_t + \overline{w}_t \ell_t$, we can express the use-side impact as:

$$US_S = \left[\frac{EX_{S,\text{ ev}}}{EX_{S,\text{ pol}}} EX_{S,\text{ ref}} - EX_{S,\text{ ref}}\right] = \left[\frac{\sum_{t=0}^{S} C_t\left(\lambda_t^{ev}\right) P_t\left(\text{ref}\right)\overline{d}_t}{\sum_{t=0}^{S} C_t\left(\text{pol}\right) P_t\left(\text{pol}\right)\overline{d}_t}\right] EX_{S,\text{ ref}} - EX_{S,\text{ ref}} \ . \quad (24)$$

The expression to the right of the second equal sign indicates that the use-side effect reflects the ratio of the discounted weighted sum of reference case prices to the discounted weighted sum of policy case prices, where the weights are the utility-equivalent path of full consumption ($C_t(\lambda_t^{ev})$) and the policy-change path of full consumption (C_t (pol)), respectively.

As the utility-maximization problem presented in Section 2a is for an infinitely-lived household, the full measure of welfare applies when $S = \infty$.[10] However, it is also useful to consider the welfare impacts measured over finite intervals. In the numerical analysis below, we assess the source- and use-side impacts over various finite horizons as well as over the infinite horizon.

The analysis above only considers labor and capital endowments. In the numerical analysis below, the endowments also include government transfers and (in some cases) lump-sum rebates of some or all of the reveues from a carb on tax. These additional endowments would enter the above analysis in the same way that the time and capital endowments have been accounted for above.

3. The Numerical Approach

We employ a numerical model to solve, for a respressentative household in each of five household income groups, the utility-maximization problem introduced in Section 2. The

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[10] Due to the transversality condition, $SS_\infty^K = \sum_{t=0}^{\infty}\left[\left(\overline{r}_t(\text{pol}) - \overline{r}_t(\text{ref})\right)W_t(\text{pol})\right]\overline{d}_t$ and the infinite-horizon capital source-side impact only captures changes in the return to capital.

carbon tax alters consumer prices and the returns to factor endowments. Because households have different expenditure patterns and factor endowments, the use- and source-side impacts from changes in prices and factor returns will vary across households. To generate the paths of consumer prices and factor returns over time in the reference case and under various carbon tax policies, we use the Goulder-Hafstead Environment-Energy-Economy (E3) model, a detailed general equilibrium model of the US economy. This model solves for market-clearing prices of goods and factors in each period, using a framework with a single representative household. These general equilibrium prices are used as inputs into our disaggregated household (DH) model. Below, we offer brief descriptions of the E3 and DH models. Section 4 will describe the data inputs for the models and the procedures employed to achieve a consistent linkage of the models.

a. The E3 Model

The E3 model – briefly described here[11] -- comprises 35 distinct industries, a single representative household, a single representative government for the US economy. It captures the interactions between these agents and solves for market-clearing prices in each period. Each agent has perfect foresight. The model is solved at annual intervals, beginning in the benchmark year, 2013.

Two features of the E3 model are especially relevant for this study's evaluation of the impacts across households. First, it contains a detailed treatment of the US tax system. This allows us to measure how price and factor returns vary with how carbon tax revenue is recycled to households, and this in turn enables us to measure, with the DH model, how the welfare impacts across households vary with the form of revenue recycling. Second, the E3 model recognizes the adjustment costs associated with installing (or removing) physical capital. Adjusment costs affect the distribution of policy impacts in two ways. Adjustment costs imply windfall gains to quasi-immoble capital, yielding impacts on capital incomes that differ across households according to differences in capital ownership. These costs also influence the rate at which capital stocks will adjust through time. This affects the speed at which the distributional impacts change with time.

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[11] A complete description is in Goulder and Hafstead (2017).

Producers and Carbon Dioxide Emissions

The 35 industry categories identify the industries that supply carbon-based fuels and the those that use these fuels intensively. The carbon-based primary fuels in the model are crude oil, natural gas, and coal. Producers sell these fuels to secondary energy producers, which in the model include electricity generators, natural gas distributors, and petroleum refiners. Electricity, natural gas, and petroleum products are then sold to other industries, the representative household, or the representative government. The production functions have the constant-elasticity-of-substitution (CES) functional form. Table 1 displays the E3 industries, their benchmark output levels, the value share of energy as an input into each industry's production and the carbon intensity of each good.

In each industry, a representative firm combines variable inputs – labor, energy, and material inputs – and capital to produce its distinct output. Firms choose variable inputs to minimize unit costs and determine investment levels (subject to capital adjustment costs) to maximize the value of the firm.

The outputs from the 35 industries are used as intermediate inputs in the producton of consumer goods. The input intensities of the producer goods used to create any given consumer good are fixed. Table 2 displays for each consumer good, the benchmark expenditures on that good, the expenditure as a percent of total consumption, and the carbon intensity. The carbon tax's impact on a consumer good's price depends significantly on the direct and indirect carbon intensity of the good. As indicated in the table, electricity, natural gas, motor vehicle fuels, and heating oil are the most carbon intensive goods.

Technological progress takes the form of labor-augmenting Harrod-neutral technological change. Thus, effective hours worked are actual hours worked adjusted for annual productivity gains. We assume that all industries enjoy the same rate of labor productivity growth.

In the E3 model, the carbon tax is imposed as a tax on coal, crude oil, and natural gas inputs into production, where the tax is in proportion to the carbon content of each fuel. The representative household does not directly pay the carbon tax, but generally faces higher prices on carbon-intensive goods as a result of the tax. The model calculates emissions by applying carbon dioxide coefficients to the quantities of the fossil fuels purchased. This yields a close estimate[12] of the ultimate CO_2 emissions associated with fossil fuel demand, even though some emissions might actually take place when refined fuels are combusted downstream.

Representative Household

In both the E3 and DH models, the structure of the household utility-maximization matches the structure described in Section 2. This structure allows climate policy to affect behavior along several important dimensions: labor-leisure choice, the choice between current consumption and future consumption, and the allocation of expenditures across various goods and services at each point in time.

The two models also employ the same functional forms for all components of the nest. Figure 1 displays the nested consumption structure that applies to both models. At the lowest nest, the representative household uses a CES function to aggregate domestically and foreign supplied goods from producers. At the next level of the nest, a Leontief aggregation function is used to add transportation and trade costs (provided by domestic transportation and trade industries) to the final cost of the consumption good. At the top level of the nest, an aggregation function combines the consumption of each good into the composite consumption good

Representative Government

The government represents a combination of federal, state, and local governments in the US. Government purchases of goods and services (including fixed investment expenditures), labor, and household transfers are financed through tax revenue and new debt issue. The government uses labor, capital, and intermediate goods to produce government services. In each policy experiment, real government spending in any given period is maintained at the same level as in the reference case. Government transfers are also maintained at real reference-case levels; nominal transfers are equal to real government transfers adjusted for inflation (as measured by the consumer price index). Under a carbon tax policy involving lump-sum rebates, the rebates represent another government outlay.

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[12] Carbon content of fossil fuels accounts for ultimate CO_2 emissions, except for non-combustible uses of these fuels. In the U.S., non-combustible uses currently account for less than six percent of fossil fuel use.

Tax revenues are collected from households (personal income taxes and sales taxes) and firms (corporate income taxes, payroll taxes, and carbon taxes). All policies considered are revenue-neutral in the sense that the present value of revenues (net of tax-base impacts) must equal the present value of revenues returned to the private sector either through cuts in the marginal rates of existing taxes or through lump-sum rebates.[13]

b. The Disaggregated Household Model

The general structure of the household problem for both the E3 and DH models was described in Section 2. Here we indicate the functional forms and associated first-order conditions. We assume constant elasticity of substitution form to represent substitutability of consumption across time. With this functional form, equation (1) translates to

$$U_0 = \sum_{t=0}^{\infty} \beta^t \frac{1}{1-\sigma} (C_t^q)^{1-\sigma} \tag{25}$$

where q indicates the household (or quintile), β is the discount factor, and $1/\sigma$ is the intertemporal elasticity of substitution. These parameters are assumed to be equal across households and equivalent to the E3 household. Using a CES functional form, full consumption is

$$C_t^q = \left[(\bar{C}_t^q)^{\frac{\eta^q - 1}{\eta^q}} + (\alpha_\ell^q)^{\frac{1}{\eta^q}} (\ell_t^q)^{\frac{\eta^q - 1}{\eta^q}} \right]^{\frac{\eta^q}{\eta^q - 1}} \tag{26}$$

where η^q is the elasticity of substitution between goods and leisure and α_ℓ^q is the leisure intensity parameter. These parameters are calibrated to match data on consumption and leisure across households and generally vary across households. (In general, they also differ from the values for the representative household in E3. See Section 4 for further discussion.)

The first-order conditions for each household are

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[13] In individual years, the net revenues might slightly exceed or fall short of the revenues returned; such discrepancies are offset through lump-sum adjustments to taxes. In present value, these adjustments sum to zero.

$$\frac{\partial L^q}{\partial \bar{C}_t^q} : \left[(\bar{C}_t^q)^{\frac{\eta^q-1}{\eta^q}} + (\alpha_\ell^q)^{\frac{1}{\eta^q}} (\ell_t^q)^{\frac{\eta^q-1}{\eta^q}} \right]^{\frac{1-\sigma\eta^q}{(\eta^q-1)}} (\bar{C}_t^q)^{\frac{-1}{\eta^q}} = \lambda_t^q \bar{p}_t^q \tag{27}$$

$$\frac{\partial L^q}{\partial \ell_t^q} : \left[(\bar{C}_t^q)^{\frac{\eta^q-1}{\eta^q}} + (\alpha_\ell^q)^{\frac{1}{\eta^q}} (\ell_t^q)^{\frac{\eta^q-1}{\eta^q}} \right]^{\frac{1-\sigma\eta^q}{(\eta^q-1)}} (\alpha_\ell^q)^{\frac{1}{\eta^q}} (\ell_t^q)^{\frac{-1}{\eta^q}} = \lambda_t^q \bar{w}_t \tag{28}$$

$$\frac{\partial L^q}{\partial W_{t+1}^q} : \lambda_t^q = \beta(1+\bar{r}_{t+1})\lambda_{t+1}^q \tag{29}$$

These first-order conditions determine each household's allocation of expenditure between the consumption composite and leisure, given $\bar{w}$ and the composite price $\bar{p}$. The price $\bar{p}$, in turn, depends on the composition of the bundle of consumer goods that make it up. Because consumption bundles differ, the unit price for the consumption of goods and services generally differs across households.

In the numerical models, households have Cobb-Douglas preferences over consumption goods and services with constant expenditure share parameters $\alpha_j^{C,q}$. The price of the aggregate consumption good for each household is given by

$$\bar{p}_t^q = \prod_{j=1}^{N_c} \tilde{p}_{j,t}^{\alpha_j^{C,q}} \ . \tag{30}$$

where $\tilde{p}_{j,t}$ denote the price of consumer good or service j at time *t*, as determined by the E3 model, inclusive of any commodity taxes and net of any subsidies. All households face the same after-tax or subsidy prices. However, the five representative households in the DH model have different expenditure shares $\alpha_j^{C,q}$ and therefore the composite price $\bar{p}_t^q$ in the first-order equations differs across households.

In the numerical models, the budget constraint expands on the simple budget constraint presented in the analytical model of Section 2. There, households only received endowments of time and capital. In the DH and E3 models, we also include endowments of transfer income (held fixed in real terms across policies), a lump-sum component of taxes, and (in some policy cases) lump-sum rebates. The augmented equation of motion for household wealth is

$$W_{t+1}^{q} - W_{t}^{q} = \bar{w}_{t}\bar{l}_{t}^{q} + \bar{r}_{t}W_{t}^{q} + G_{t}^{q} + LS_{t}^{q} - T_{t}^{q} - \bar{p}_{t}^{q}\bar{C}_{t}^{q} - \bar{w}_{t}\ell_{t}^{q} \ . \tag{31}$$

where G, LS, and T refer to nominal levels of government transfer income, lump-sum rebates (if any), and lump-sum taxes, respectively.

The returns on labor and capital, $\bar{w}_t$ and $\bar{r}_t$, are from the E3 model. We specify them as the same across households, in both the reference case and in policy cases.[14] Total transfers from the E3 model are allocated across the five representative households according to their shares in data described below from the Survey of Consumer Finances. This applies in both the reference case and policy cases. Consequently, under a carbon tax policy the percentage change in household transfer income is the same across households. In most policy scenarios, we specify equal allocations of lump-sum transfers across households, but in Section 8 we consider policies involving unequal allocations designed to achieve certain distributional objectives.

The cuts in marginal tax rates or the total lump-sum rebates needed for revenue-neutrality are determined in the E3 model. We apply the same marginal tax cuts in percentage terms to each of the separate household groups in the DH model. To the extent that lump-sum rebates apply, each household receives an equal share of the the overall rebate from E3 in each period.

Because households in the DH model respond to policy changes, their tax payments are endogenous. To check on the consistency between the DH and E3 models, we aggregate these tax payments and compare them with the payments from E3. We find that these payments nearly perfectly aggregate to the levels from E3, never differing by more than 0.9 percent. This close correspondence reflects the consistent aggregation in the initial allocation of endowments, income sources, and expenditures in the DH model. The next section describes the relevant procedures.

4. Data and Parameters

a. Data Sources

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[14] We assume that Harrod-neutral (labor-augmenting) technological progress applies uniformly across all household groups. Hence the relative returns to labor across households do not change over time.

Here we briefly describe the data sources and the ways we organize the data to obtain the complete dataset. We also describe the steps we make to achieve consistency between the E3 and DH models. Details are provided in the appendix.

For the DH model, we obtain data on before-tax income from the 2013 Survey of Consumer Finances (SCF). The SCF data indicate before-tax household income by source (labor, capital, and transfer income) for a representative sample of 6015 households. The appendix offers detail on the elements of each source of income.

We obtain household after-tax incomes by applying tax information from the NBER's TAXSIM model (Feenberg and Coutts, 1993) to the SCF before-tax idata. The TAXSIM data do not break down tax liabilities by income source. To provide this breakdown, we calculate the share of before-tax income from each source for each household and multiply by total tax liability.

We obtain household expenditures on each consumer good using the 2013 Consumer Expenditure Survey (CEX) microdata collected by the U.S. Department of Labor's Bureau of Labor Statistics (BLS). The CEX provides data on expenditures, income, and demographic characteristics of representative consumers in the United States.

These data are collected through two surveys, the Interview Survey and Diary Survey. The Interview Survey focuses on large consumer goods, such as spending on housing, vehicles, and health care. The Diary Survey collects data on weekly expenditures of different households who are followed for only two weeks. In order to account for a complete listing of expenditures for each household, we combine data from both surveys. The appendix describes in detail the procedure we adopt to combine the survey data.

We combine the survey data two ways in order to rank households both by expenditure and by income. In this study we focus on results by expenditure quintiles, but we also display (in Section 7 some results when quintiles are defined in terms of income.

We combine the SCF income data and CEX expenditure data in a way that assures that, for each quintile, household expenditure is consistent with income and saving. As described in the appendix, this involves matching expenditure data from the CEX to each SCF household and using CEX data to calculate household saving for each household quintile.

Table 3 shows the average after-tax income by source by quintile, and Table 4 shows the average expenditures shares by good by quintile.

b. Achieving Consistency in Aggregation

We adjust the data so that the benchmark outcome of the DH model, when aggregated across households, match the outcome of the more aggregated E3 model, which includes only one representative household. Specifically, we impose the requirement that aggregate after-tax income (by source), consumption (by good), and savings match across models in the benchmark dataset. Using the merged SCF-CEX dataset, we calculate quintile shares of income source, consumption good, and savings. For each quintile in the DH model, the level of after-tax income, consumption, and savings is equal to the quintile share times the E3 level of after-tax income, consumption, and savings.[15]

c. Parameters

Here we briefly describe the household utility parameters for the E3 and DH models.[16] In the E3 model, the discount factor β is calibrated to be consistent with a long-run interest rate of 4 percent. We use a value of 2 for σ, which implies an intertemporal elasticity of substitution in consumption ($1/\sigma$) of 0.5, a value between time-series estimates (Hall 1988) and cross-sectional studies (Lawrence 1991). We apply the same values to the DH households.

In the E3 model, the compensated elasticity of labor supply and the nonlabor income elasticity are functions of the consumption-leisure ratio, the price of consumption-after tax wage ratio, the elasticity of substitution between consumption and leisure, η, and the fraction of time spent working. Conditional on our data for prices, consumption and labor supply, we set the values of the elasticity of substitution and between consumption and leisure and the fraction of time spent working to 0.773 and 0.66, respectively, so that the compensated elasticity of labor supply is 0.3 and the nonlabor income elasticity is 0.25.[17] In the DH model, we assume each

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[15] The SCF-CEX and E3 datasets differ in aggregate share of income by source and share of consumption by good. In applying this procedureto assure that the aggregated shares of various income sources match the E3 shares, we cause the shares to depart from those implied by merged SCF-CEX data.

[16] For more information on production parameters and elasticities, please refer to Goulder and Hafstead (2017).

[17] The compensated elasticity if labor supply is at the high end of estimates for married men and single women (0.1-0.3) and in the middle range of estimates for married women (0.2-0.4). McClelland and Mok (2012) provide a general review of recent labor supply estimates.

household spends the same fraction of time working. Given the differences in consumption-leisure ratios, we re-calibrate the elasticity of substitution between consumption and leisure for each quintile, η^q, so that each household has the same compensated elasticity of labor supply and the nonlabor income elasticity as in the E3 model. Expenditure shares $\alpha_j^{C,q}$ are derived from our SCF-CEX household data set.

5. The Reference Case Path and Carbon Tax

a. The Reference Case

With the data described in the previous section, the E3 model would generate a balanced growth path. In particular, the ratio of CO_2 emissions to GDP would be constant along that path. Such an outcome would not be consistent with the business-as-usual projections from a range of leading private and government studies. To generate a more plasible reference (business-as-usual) time-profile of emissions, we introduce some changes to the model structure and key parameters. This causes the model to generate a reference case path that approximates the business-as-usual forecast offered by the Energy Information Administration's (EIA) Annual Energy Outlook (AEO) 2016. We focus on matching AEO 2016 forecasts for economic growth, fossil fuel prices, electric generation shares and total emissions.[18]

b. Carbon Tax Design

We consider a tax with the following features:[19]

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[18] See Goulder and Hafstead (2017) for a complete description of the reference case calibration procedure. Chen, Goulder, and Hafstead (2018) describe the sensitivity of future emissions to alternative baseline forecasts .

[19] The price path we apply has some similarities to the one in the proposed Whitehouse-Schatz American Opportunity Carbon Fee Act, which calls for a price starting at $49 (in $2018) in 2018 and rises at 2 percent above inflation.

Time Profile: The tax starts at $40 per metric ton in 2013 dollars in 2020 after a three-year phase-in. In 2018 and 2019, the tax is $13.33 and $26.67, respectively. After 2020, the tax increases in real terms at rate of 2 percent annually. The tax is held constant in real terms after 2050. Figure 2 displays the time-profile of the carbon tax.

Coverage: The tax covers all direct purchases of primary fossil fuels and imports of refined products such as gasoline, diesel, and heating oil. This specification covers 99.9 percent of all domestic emissions from the combustion of fossil fuels.[20]

Point of Regulation: The tax is imposed midstream; that is, at the industrial user's gate and the port of entry for imports of refined products. It is based on the carbon content of the fuel purchased and it covers both emissions from industrial combustion of the product and the combustion of any downstream products. Relative to the case where the points of regulation are upstream (at the wellhead or minemouth), midstream implementation allows for alternative specifications of the sectoral coverage of the policy.

Revenue recycling: We consider four revenue-neutral uses of carbon revenue: (1) lump-sum rebates, (2) payroll tax cuts, (3) personal income tax cuts, and (4) corporate income tax cuts. The revenue returned to the private sector is equal to the net revenue yield of the carbon tax, where the latter is the gross carbon tax revenue adjusted for any revenue impacts of policy-induced changes in the tax base of other taxes.[21] Such recycling leaves unchanged the revenue available to finance government expenditures.

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[20] The model does not rebate taxes paid on crude oil that is ultimately exported in the form of refined products.

[21] By affecting incomes, the carbon tax influences the tax base of income and payroll taxes. It can also indirectly alter revenues from sales and other commodity taxes to the extent it affects patterns of consumer spending.

6. Aggregate Impacts of the Carbon Tax

Here we focus on aggregate (economy-wide) impacts, displaying and interpreting the carbon tax's impacts on on emissions, prices, factor returns, GDP, and (according to the equivalent variation) welfare. We consider the impacts across several recycling options.

Figure 3 displays the CO_2 emissions in the reference case and under the carbon tax when revenues are recycled through lump-sum tax cuts.[22] The carbon tax reduces emissions by 17 and 30 percent, in 2020 and 2035, respectively. Over the interval 2017-2050, 64-68 percent of annual reductions are due to reductions in emissions from the power sector, which substitutes away from coal-fired generation toward natural gas generation and nonfossil based generation.

The carbon tax achieves the emissions reductions by changing the relative prices of intermediate goods and consumer goods and services. Tables 5 and 6 display the price impacts across the model's producer (intermediate) good and consumer good categories. Table 5 shows the percent change in nominal producer good prices relative to the reference case, for years 2020, 2035, and 2050. As expected, the price impacts are largest in the industries with the greatest carbon intensities. The reduction in the prices of coal and natural gas reflect the backward shifting of the burden of the carbon tax, which is imposed on the purchasers of these fuels (e.g., coal-fired electricity generators and natural gas distributors). This reduces the demands for coal and natural gas, which results in a decrease in the producer prices of coal and natural gas in those two extractive industries.

The use-side impact of the carbon tax mainly reflects the changes in consumer good prices and households' consumption shares of each good. Table 6 displays the change in consumer prices by good under the carbon tax, when revenue-recycling involves lump-sum rebates. The price of motor vehicle fuels, fuel oils, electricity, and natural gas increase the most, in keeping with the high carbon intensities of those goods and services shown in Table 2 above. The welfare impact of these prices on different households in the DH model will depend on their relative consumption shares of each good. Households with larger consumption shares of these goods will experience the largest adverse use-side impacts.

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[22] Emissions reductions are similar with other forms of recycling.

The carbon tax's source-side impact reflects impacts on factor prices – the after-tax nominal returns to labor, capital, and transfer endowments.[23] Table 7 displays the change in these returns across the four recycling options, for years 2020, 2035, and 2050.

In the E3 model, the before-tax wage is the numeraire. Therefore the nominal after-tax wage changes only under recycling that alters the labor tax; namely, recycling via cuts in the payroll tax or individual income tax. With these forms of recycling, the after-tax wage increases in proportion to the reduction in the tax rate.

The after-tax return to capital falls under all recycling options, except in the case of corporate income tax recycling.[24] The negative impact on the return to capital is largest under lump-sum recycling. These negative impacts stem from reductions in the equity value of firms in the carbon-intensive industries.

As previous studies have pointed out,[25] changes in nominal transfers can significantly influence the source-side impacts of a carbon tax. Our simulations assume that transfers are inflation-indexed. Accordingly, the carbon tax causes nominal transfers to change in proportion to the policy-induced change in the consumer price index.[26] Generally, the carbon tax raises this index. Hence nominal nominal transfers rise, which yields positive source-side impact that offsets the adverse use-side impact from the policy-induced increase in consumer prices. As we will see in the next section, this positive source-side impact is especially important for low-income households, for whom transfers represent an especially large share of income.

Table 8 shows the GDP and welfare impacts of the carbon tax under the four forms of recycling. In the model, the corporate income tax is more distortionary than the individual income tax and the payroll tax: it has the highest marginal excess burden. Accordingly, recycling through cuts in corporate income tax rates offers the lagest benefit and thus both the GDP costs and welfare costs are lowest in this case. The GDP and welfare costs are highest

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[23] The nominal returns apply here because the use-side effects capture the impacts associated with the loss of purchasing power from the changed prices of goods purchased.

[24] Capital goods are relatively carbon intensive in their production. As a result, much of the burden of a carbon tax falls on capital. However, revenue-recycling in the form of cuts in the corporate ncome tax overcomes the carbon tax's potential adverse impact of a carbon tax on the return to capital.

[25] See, for example, Fullerton *et al.* (2011), and Cronin *et al.* (2017).

[26] In our policy simulations, we assume that the government maintains the real value of transfers. Transfers are indexed to the consumer price index in the E3 model. Indexing to the price of consumption (the ideal price index) allows for shifts in the composition of goods and would lead to smaller increases in nominal transfers.

under lump-sum recycling. This form of recycling does not involve any cuts in marginal rates and thus does not reap the potential efficiency gains from rate reductions.

7. Distributional Impacts in the Absence of Targeted Compensation

Here we examine the impacts across the five representative household groups. As mentioned in Section 4, the household groups reflect expenditure rankings.[27] When aggregated, the results from the DH model conform to the more aggregated outcomes of the E3 model.[28]

a. Use- and Source-Side Impacts

Use-Side Impacts

We gauge the use-side welfare impacts two ways, either at specified moments (periods) of time, or over given intervals of time. In every case, the use-side impact is in terms of the welfare change is measured via the equivalent variation.

Figure 4 displays single-period use-side impacts by quintile and under the four recycling options. In the recycling cases involving tax cuts, we assume that the rate cuts are the same for all quintiles. Impacts are shown for the years 2020, 2030, and 2050 and are expressed as a percentage of reference case wealth.

The two columns calculate the impacts in two ways. In the left-hand column, the use-side impact accounts for the policy-induced changes in the prices of goods and services, excluding the impact on the price of leisure (another "good" that a household can "purchase" by working less and sacrificing income). The right-hand column offers results from our broader measure of the use-side impact, one that accounts for policy-induced changes in the price of leisure.

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[27] Expenditure more closely correlates with lifetime income than income from a single year. We are in the process of examining results when households are ranked by income.

[28] The reference case and policy case outcomes from the DH model do not perfectly aggregate to those in the single-household E3 model, but the differences are very small, in keeping with the perfect aggregation that we impose on the benchmark data. Under all recycling options, the difference between the sum of the equivalent variation welfare impacts summed across quintiles and the equivalent variation for the E3 model's representative consumer is never above 3 percent.

Figure 4 gives rise to four key findings. First, under each of the four recycling options, the use-side impact is regressive: the welfare impact is more negative, the lower the expenditure rank of the quintile. This reflects the fact that lower-quintile households spend a larger share of their incomes on carbon-intensive goods and services than do higher-quintile households. The outcome is regressive regardless of whether changes in the price of leisure are ignored (left-hand column) or considered (right-hand column).[29]

Second, for all quintiles, the magnitude of the use-side impact increases with time, paralleling the increasing size of the carbon tax and the associated increases in the scale of the price impacts.

Third, the size of the use-side welfare impact in any given year depends on the type of recycling. The impacts are smallest when recycling is via cuts in the corporate income tax. This is in keeping with the fact that the corporate tax induces households to save more and consume less, which implies smaller increases in consumer good prices.[30]

Fourth, when recycling takes the form of payroll tax cuts or individual income tax cuts, the use-side impacts are larger when changes in the price of leisure are accounted for: effects in the right-hand column are larger than those in the left-hand column. Each of these two forms of recycling involves cuts in the tax on wages. This raises the after-tax wage, which is also the price of leisure. Thus, the use-side impacts are larger when leisure's price is considered.

Figure 5 shows the use-side impacts when measured over time intervals rather than points in time, indicating the effects over the intervals 2018–2020 and 2018–2040, as well as over the over the interval of infinite length that begins in the year 2018. As with our first measure, it provides the dollar equivalent to the change in utility. And as before, the two columns compare results without and with consideration of impacts on the price of leisure.[31]

Figure 5's results parallel those in Figure 4. Again, the results are regressive and increase with the amount of attention to the longer term. And accounting for the impact on the price of

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[29] Earlier studies also have tended to obtain regressive use-side impacts, although the earlier studies did not include attention to the influence of changes in the price of leisure. Nor did they consider how the impacts change over time.

[30] In the model, the corporate income tax is the most distortionary: it has the highest marginal excess burden. Recycling via cuts in the corporate income tax helps reduce the overall costs of the carbon tax. The welfare gains from these cost-reductions are mainly captured as benefits on the source (income) side.

[31] In all present value calculations, we use the reference case nominal interest rate to discount future values back to the initial period of the policy.

leisure again expands the adverse welfare impact in the cases of recycling via cuts in the payroll tax or individual income tax.

Source-Side Impacts

Now we consider the source side, again examining the impacts at given points in time (Figure 6) and over specified intervals of time (Figure 7) and under the four forms of revenue recycling considered previously. Source-side impacts depend on specifics features of revenue-recycling. In figures 6 and 7, the results for the case of lump-sum rebates are from policies in which each quintile receives one-fifth of the total rebate provided in each period. Later we will consider alternative rebate schemes aimed at achieving certain objectives in terms of the distribution of impacts across households. The results for the cases with recycling via cuts in marginal tax rates, it is assumed that the tax rate cuts are in the same proportion for all households.

The two columns in each figure show the results under the two measures of the source-side impact. The left-hand column employs the narrower, typical "income-only" measure of the source-side impact, one that considers only the policy's effects on after-tax labor income, after-tax capital income, and transfer income. The right-hand column offers a measure that is broader in two ways. First, in connection with labor, it considers the impact of policy on each household's overall endowment of labor—which is the sum of the value of labor supplied and the value of the household's nonlabor (leisure) time. When a household decides to work less, this reduces the labor income that the household receives. Measuring the welfare impact would overstate the welfare loss associated with this change, since the reduction in income is compensated for by the value of the increase in nonwork (leisure) time. Our broader measure accounts for this offset.[32]

It is important to keep in mind that the source-side impacts reflect changes in *nominal*

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[32] The broader measure also accounts for the impact of policy on each household's savings in a given period or during the time interval of focus. Any increase (decrease) in saving implies greater (lower) potential for future consumption and utility. Although some of this change in future consumption may occur beyond the period or time interval of focus, the source of this change is in the period or during the interval of focus; hence it can be attributed to those points in time. Accounting for the savings impact also has the virtue of enabling the sum of the source- and use-side impacts to match perfectly the overall welfare impact, as measured by the equivalent variation for the period or interval in question.

income or the *nominal* value of endowments. The use-side impacts account for how changes in prices alter the real purchasing power associated with the nominal changes in income or endowment value.

The key messages from figures 6 and 7 are similar. First, the source-side impacts are positive, in contrast with the impacts on the use side. One factor behind the positive welfare impacts is revenue recycling. Each form of recycling contributes to nominal income: the lump-sum rebates do so directly, while the cuts in the marginal rates of payroll, individual income, or corporate income taxes do so by increasing the after-tax returns to factors. Changes in nominal transfers are another key factor behind the positive source-side impacts. As mentioned, our simulations assume that government transfers are kept constant in real terms. Because the carbon tax raises overall prices to consumers, nominal transfers must be higher under the carbon tax than in the reference case in order to maintain their real value. This is especially important for low-income households, for which transfers constitute a large share of overall income.

Second, the impacts are progressive in almost every case – although there are some exceptions in some years under corporate income tax recycling. The progressive outcome is strongest in the case of recycling through lump-sum rebates, in keeping with the fact that the rebates (of equal value for every household) are larger relative to the household's benchmark expenditure, the lower the quintile (or benchmark expenditure) of the household. Also contributing to the progressivity is the fact that the carbon tax tends to reduce after-tax returns to capital more than to labor, as was indicated in Table 7. Because higher quintiles rely more on capital income than do lower quintiles, this exerts a progressive impact.

Third, the source-side impacts are considerably larger when the broader measure is employed. Recycling through cuts in the payroll tax or the individual income tax reduces labor taxes and thereby raises the after-tax wage. This not only increases labor income but also raises the value of leisure. The broader measure captures this latter effect by considering the impact on the labor time endowment.

Overall Welfare Impacts

As indicated in Section 2, the full welfare impact, as measured by the equivalent variation (EV), is exactly equal to the sum of our broader use- and source-side impacts. Figures 8 and 9 display the overall welfare impacts based on these comprehensive measures. Figure 8 shows the impacts for selected years; Figure 9 shows them over selected intervals of time.

The figures show that the overall impacts are progressive under recycling via lump-sum rebates: the very progressive source-side impacts outweigh the regressive impacts on the use side. The overall impact is most progressive under lump-sum recycling, reflecting the strong progressive source-side impact of this form of recycling. Under corporate income tax recycling, the impacts are smaller than under the other recycling methods, and the results are close to proportional. Recycling via a corporate income tax cut is especially beneficial to higher income households on the source side, and as a result the source-side effect is only mildly progressive. This accounts for the fact that the overall (source- plus use-side) impact is the least progressive.

We have offered results across households sorted into quintiles by expenditure. As mentioned, expenditure can be viewed as a rough proxy for lifetime income. An alternative is to rank households by income. Figure 10 compares the results under the two sorting methods. Changing the ordering of households mainly alters impacts on the source side, especially for the lowest quintile. Ranking households by income puts more retirees in the lowest quintile than is the case when households are ranked by expenditure. Retirees tend to have greater wealth than the average individual in quintile 1 under expenditure ordering. As a result, quintile 1 has more wealth under income ordering than under expenditure ordering. Since the welfare effects are expressed as a percentage of wealth, these percentages are smaller when households are ranked by income.

The general picture emerging from this section is that the source-side impacts tend to be progressive, offsetting the regressivity of the use-side effect. Our results also show that both the scale and the regressivity or progressivity of the overall (use- plus source-side) impacts depend importantly on the method of recycling, which exerts a strong influence on the source-side. The extent of progressivity is greatest under lump-sum recycling, although it is significant under payroll tax and individual income tax recycling as well. The overall impact is close to proportional under corporate income tax recycling. The scale of the overall impact is much smaller under corporate income tax recycling than under the other recycling approaches.

Impacts change over time. In the cases involving recycling through cuts in payroll or individual income tax rates, the household groups tend to experience larger welfare losses over time, in keeping with the steady rise in the carbon tax rate. However, in the case of recycling through cuts in the corporate income tax, the impacts for a given quintile are relatively steady over time, a reflection of the higher rates of investment and associated higher incomes associated with the corporate tax cuts.

8. Policies with Targeted Compensation: Impacts and Trade-Offs

Many commenators have expressed concern about the potential regressive impact of a carbon tax. However, our results suggest that the outcome is not regressive once one accounts for the impact on the soruce side. As a percent of baseline expenditure, the adverse impacts on the lowest two quintiles tend to be no larger than the impacts on the higher quintiles.

This could suggest that the outcome under these forms of recycling is fair, and that no additional compensation elements are needed to bring about a desirable outcome. Fairness can also depend on absolute (as opposed to relative) impacts, however. As Figure 9 indicated, over the longer term quintiles 2 and 3 experience welfare losses under individual income tax or corporate income tax recycling. (The lowest quintile enjoys gains under all forms of recycling.) To the extent that considerations of fairness call for reducing the impacts on these groups of households, it is worth considering the potential trade-off in avoiding adverse impacts.

Here we apply the numerical model to quantify this potential trade-off. We examine the impacts of three "hybrid" policies that involve a combination of recycling through lump-sum rebates and recycling through cuts in payroll, individual or corporate income tax rates. Some of the net revenue from the carbon tax is devoted to lump-sum rebates, while the rest is devoted to one of the three tax cuts. In the rebate and tax cut combination, the rebates are targeted either (a) to lowest two income quintiles at a level just sufficient to prevent a welfare loss to the second quintile, or (b) to the lowest three income quintiles at a level just sufficient to prevent a welfare loss to the third quintile. The total rebate is split evenly across the two (in case (a)) or three (in case (b)) quintiles that receive the targeted compensation.

Figure 11 shows the distribution of welfare impacts from the hybrid policies and the previously discussed "pure" policies involving recycling through lump-sum rebates alone or tax cuts alone under the full infinite-horizon welfare measure. The top and bottom panels display outcomes for the hybrid policies designed to hold harmless the second quintile and the third quintile, respectively. Under the former hybrid policies, quintiles 1 and 2 are better off relative to the corresponding pure recycling policy, while quintiles 3-5 are slightly worse off. Under the latter hybrid policies, the differences between the hybrid and pure policies are more stark, as quintile 3 requires very large rebates as targeted compensation to avoid adverse welfare impacts (and, by design, quintiles 1 and 2 also receive these significant rebates).[33]

Table 9 compares the economy-wide welfare costs in the hybrid cases with those in the pure recycling cases. Targeted compensation raises overall costs by reducing the amount of remaining revenue for financing cuts in distortionary taxes. The table shows that the costs of are very sensitive to both the way that remaining revenues are to be recycled and the span of the groups targeted for compensation. Lump-sum compensation has an opportunity cost: it reduces the amount of revenue available to finance cuts in distortionary taxes.[34] This opportunity cost is highest when compensation takes away revenues that otherwise would have been used to cut corporate income taxes. The corporate tax is the most distortionary among the taxes compared in Table 9; hence the lowered ability to reduce the corporate tax rate is especially costly. For any given recycling method, the cost of compensation is an order of magnitude higher under the more ambitious hybrid policy that prevents a welfare loss to both quintile 3 and quintile 2, a reflection of the much higher level of lump-sum rebates required under this policy. We leave it to the reader to assess the importance of the distributional objectives served by these policies and decide whether achieving these objectives is worth the sacrifice of efficiency.

9. The Role of Transfer Income

As discussed in Section 7, increases in nominal transfer income are a key factor behind the positive and progressive source-side impacts under most recycling options. Under current U.S. policy, government transfers are indexed to inflation. Accordingly, in our central analysis, we assume in both the E3 and DH models that real transfers are maintained for every

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[33] Policymakers could consider an alternative hybrid policy that awards rebates relative to income (up to a threshold) to avoid overcompensating quintiles 1 and 2.

[34] Under the hybrid policies that prevent a welfare loss to the representative household in the second quintile, the targeted lump-compensation reduces gross revenues available for payroll, individual, and corporate tax cuts by 1.7, 1.1, and 1.1 percent, respectively. Under the more extensive hybrid policy that prevents a welfare loss to the representative household in both the second and third quintile, compensation reduces gross revenues for cuts in payroll, individual, and corporate taxes by 16.9, 15.6 and 10.8 percent, respectively.

representative household. By raising the prices of consumer goods, a carbon tax leads to an increase int the price level that necessitates an increase in nominal transfers. Higher transfers contribute to a positive source-side impact. To gauge the contribution of this source-side impact to the overall impact on the source side, we consider the case where nominal transfers are not changed by climate policy; that is, where transfers are not indexed. The difference in the results between this case and the case with indexed transfers highlights the significance of indexed transfers for the source-side impact.

The comparison is offered in Figure 12. The left and right columns of the figure display the source-side impacts across three time intervals in the cases in which transfers are or are not indexed, respectively. In the figure, the results involve the full source-side measure that includes changes in the value of leisure and changes in savings rates. When transfers are not indexed, the potential beneficial source-side impact from indexing is absent, and the overall source-side impacts are regressive. This shows that the progressive source-side impacts in our main analysis under tax recycling options are strongly driven by policy-induced increases in nominal transfer income. Further, while the source-side impacts are positive in the case involving indexed transfers, in the case of recycling via cuts in the corporate income tax these impacts tend to be negative.

The left and right columns of Figure 13 displays the overall welfare impacts across households for three time intervals in the presence and absence of transfer income, respectively. Over the longer term, the welfare impact is negative for all households under all recycling options in the absence of transfer income. As in the earlier cases involving transfer income, in the absence of transfer income the outcome is strongly progressive under lump-sum recycling. But in contrast with the transfer income case, the impact under other forms of recycling is regressive, reflecting both the regressive use- and source-side impacts in the absence of transfer income. These results reinforce the arguments in Fullerton *et al.* (2011) and Cronin *et al*. (2017) that transfer income indexing tends to lead to progressive outcomes. In fact, in the DH model, transfer income indexing completely mitigates the adverse impacts of a carbon tax on the average household in the lowest expenditure quintile.

10. Conclusions

We have examined the distribution of the impacts of a carbon tax across U.S. households, considering both source- and use-side impacts under a range of revenue-recycling scenarios.

We find that under a range of recycling methods, the use-side impacts are consistently regressive, while the source-side impacts are usually progressive. The source-side impacts tend to more than fully offset the use-side impacts, so that the overall impact is either progressive or close to proportional.

Our approach differs methodologically from earlier studies in several ways. We offer an analytical approach that employs broader measures of the source- and use-side effects; in contrast with more conventional measures, our measures together yield the full welfare impact. In addition, we consider a range of recycling methods, an approach that reveals that the distributional impacts are sensitive to the nature of recycling – particularly the distribution of impacts on the source side.

Ours is not the first study to find that the overall impact of a carbon tax can be progressive. Some recent studies that consider both the source- and use-side impacts have reached a similar conclusion. However, in contrast with earlier studies we find that, under plausible assumptions, the lowest household income quintile does not suffer an absolute reduction in welfare under the carbon tax.[35] We also find larger source- and use-side impacts than what the narrower narrower welfare measures used in previous studies would predict.

Inflation-indexed government transfers very significantly influence the distributional impacts of climate policy. They avoid what otherwise would be significantly regressive overall impacts providing additional nominal transfers to compensate for higher overall consumer prices from climate change policy. Since transfers represent an especially large share of income for low income households, the increase in nominal transfers exerts a significant progressive impact.

We apply our general equilibrium model to assess the costs of including targeted compensation as part of a carbon tax policy. The costs of avoiding adverse impacts depend critically on the method of recycling and the particular target involved. The costs associated

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[35] In contrast, Goulder and Hafstead (2017) show that in the absence of compensation, firms in some industries would suffer significant profit losses, with significant impacts on the wealth of owners of these firms. This suggests that providing compensation to certain industries might be critical to the political feasibility of a carbon tax.

with compensation are about an order of magnitude higher when remaining revenues are to be used for corporate income tax cuts, compared with the other ways of using the remaining revenues. These efficiency costs also are an order of magnitude higher under the more ambitious hybrid policy of avoiding an adverse impact on the middle quintile, a reflection of the much higher level of rebates required under this policy.

Two important caveats are in order. First, our analysis has not considered the extent of heterogeneity of impacts within quintiles.[36] Second, we have only considered the distributional impacts across one household dimension – income. Fairness (and political feasibility) of climate policy can depend on the distribution along other demographic dimensions.

These results underscore the importance of integrated approach to distributional analysis, one that considers closely the use of policy-generated revenues and the nature of existing government transfer programs. In addition, they reveal that one's conclusions as to the distributional consequences of policies depend on the welfare measure employed. We find that the results under the more comprehensive measures we have introduced differ significantly from those under the narrower, more conventional measures.

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[36] Cronin *et al.* (2017) analyze policies involving redistribution of carbon tax revenues, accounting for heterogeneity within income groups. Fischer and Pizer (2017) examine how to account for household heterogeneity in the evaluation of carbon taxes and tradable performance standards.

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Table 1. Benchmark Output, Energy Inputs, and Carbon Intensities by Industry

Industry	Output[a]	Pct of Total Output	Energy Input[b]	Energy Value Share	Carbon Intensity
Oil Extraction	277.3	1.1%	7.6	2.8%	0.00553
Natural Gas Extraction	118.2	0.5%	2.9	2.5%	0.02254
Coal Mining	41.1	0.2%	2.4	5.8%	0.02439
Electric Transmission and Distribution	389.2	1.5%	214.2	55.0%	0.00347
Coal-Fired Electricity Generation	74.5	0.3%	21.5	28.9%	0.00724
Other Fossil Electricity Generation	67.9	0.3%	36.7	54.0%	0.01118
Nonfossil Electricity Generation	59.2	0.2%	0.1	0.1%	0.00003
Natural Gas Distribution	136.2	0.5%	50.5	37.1%	0.00798
Petroleum Refining	719.2	2.8%	576.1	80.1%	0.00437
Pipeline Transportation	42.4	0.2%	3.2	7.5%	0.00027
Mining Support Activities	47.5	0.2%	5.9	12.4%	0.00075
Other Mining	196.2	0.8%	5.9	3.0%	0.00057
Farms, Forestry, Fishing	435.9	1.7%	26.4	6.1%	0.00023
Water Utilities	84.2	0.3%	2.0	2.4%	0.00039
Construction	1365.6	5.2%	53.9	3.9%	0.00044
Wood Products	92.4	0.4%	3.0	3.3%	0.00063
Nonmetallic Mineral Products	105.2	0.4%	6.4	6.1%	0.00122
Primary Metals	288.9	1.1%	19.8	6.8%	0.00052
Fabricated Metal Products	337.3	1.3%	7.5	2.2%	0.00029
Machinery and Misc. Manufacturing	1376.8	5.3%	13.5	1.0%	0.00039
Motor Vehicles	593.1	2.3%	4.8	0.8%	0.00050
Food and Beverage	817.7	3.1%	15.1	1.8%	0.00036
Textile, Apparel, Leather	86.7	0.3%	1.7	1.9%	0.00055
Paper and Printing	231.1	0.9%	12.8	5.5%	0.00102
Chemicals, Plastics, and Rubber	1010.5	3.9%	68.2	6.7%	0.00016
Trade	2465.6	9.4%	38.7	1.6%	0.00104
Air Transportation	163.5	0.6%	36.8	22.5%	0.00033
Railroad Transportation	106.0	0.4%	6.2	5.8%	0.00094
Water Transportation	51.9	0.2%	9.8	18.8%	0.00087
Truck Transportation	288.1	1.1%	51.5	17.9%	0.00051
Transit and Ground Passenger Transportation	58.5	0.2%	5.9	10.1%	0.00143
Other Transportation and Warehousing	291.5	1.1%	16.9	5.8%	0.00037
Communiction and Information	1186.1	4.5%	5.3	0.4%	0.00009
Services	9935.6	38.0%	125.8	1.3%	0.00014
Real Estate and Owner-Occupied Housing	2606.8	10.0%	90.9	3.5%	0.00016
Total	**26148.1**	**100%**	**1549.6**	**5.9%**	

[a] In billions of 2013 dollars.

[b] In billions of 2013 dollars. Energy inputs include the values of purchases of fossil fuels, wholesale electricity, distributed natural gas, and refined petroleum products.

Table 2. Consumption Good Benchmark Expenditures and Carbon Intensities

Consumption Category	Consumption[a]	Pct of Total Consumption	Carbon Intensity
Motor Vehicles	549.0	4.8%	0.00026
Furnishings and Household Equipment	394.5	3.4%	0.00035
Recreation	1022.1	8.9%	0.00020
Clothing	425.8	3.7%	0.00025
Health Care	2372.1	20.7%	0.00022
Education	277.1	2.4%	0.00014
Communication	283.1	2.5%	0.00010
Food	750.3	6.5%	0.00038
Alcohol	124.7	1.1%	0.00034
Motor Vehicle Fuels (and Lubricants and Fluids)	381.8	3.3%	0.00298
Fuel Oil and Other Fuels	26.6	0.2%	0.00255
Personal Care	245.3	2.1%	0.00032
Tobacco	108.0	0.9%	0.00037
Housing	1780.9	15.5%	0.00016
Water and Waste	136.4	1.2%	0.00020
Electricity	169.1	1.5%	0.00347
Natural Gas	51.2	0.4%	0.00796
Public Ground	42.3	0.4%	0.00047
Air Transportation	49.5	0.4%	0.00104
Water Transportation	3.2	0.0%	0.00073
Food Services and Accomodations	714.7	6.2%	0.00014
Financial Services and Insurance	826.7	7.2%	0.00014
Other Services	700.5	6.1%	0.00015
Net Foreign Travel	44.2	0.4%	0.00101
Total	**11478.9**	**100.0%**	

[a] In billions of 2013 dollars

Table 3. Average After-tax Income Shares by Source by Quintile

	Quintile 1	Quintile 2	Quintile 3	Quintile 4	Quintile 5
Labor	53%	71%	76%	80%	50%
Capital	9%	8%	12%	13%	47%
Transfer	38%	21%	12%	6%	3%
Total	100%	100%	100%	100%	100%

Table 4. Average Expenditure Shares by Source by Quintile

	Quintile 1	Quintile 2	Quintile 3	Quintile 4	Quintile 5
Motor Vehicles	2.2%	3.5%	5.5%	5.6%	5.2%
Furnishings and household equipment	2.2%	2.5%	3.0%	3.2%	4.0%
Recreation	7.3%	7.9%	7.9%	8.4%	9.7%
Clothing	4.1%	3.7%	3.5%	3.8%	3.9%
Health Care	23.3%	22.8%	20.0%	21.5%	19.5%
Education	0.6%	0.8%	1.8%	2.3%	2.7%
Communication	2.4%	2.7%	3.0%	2.9%	2.3%
Food	8.7%	8.6%	7.9%	7.1%	5.8%
Alcohol	0.9%	1.5%	1.3%	1.2%	1.2%
Motor Vehicle Fuels (and lubricants and fluids)	3.9%	4.5%	4.7%	4.4%	3.4%
Fuel Oil and Other Fuels	0.3%	0.2%	0.2%	0.2%	0.3%
Personal Care	2.0%	2.1%	2.2%	2.2%	2.2%
Tobacco	3.1%	2.8%	1.9%	1.2%	0.7%
Housing	26.4%	20.8%	19.0%	14.8%	12.5%
Water and Waste	1.6%	1.6%	1.6%	1.5%	1.3%
Electricity	2.4%	2.0%	1.9%	1.6%	1.3%
Natural Gas	0.5%	0.5%	0.5%	0.5%	0.5%
Public Ground	0.4%	0.4%	0.3%	0.3%	0.4%
Air Transportation	0.1%	0.2%	0.4%	0.5%	0.8%
Water Transportation	0.0%	0.0%	0.0%	0.0%	0.0%
Food Services and Accommodations	1.7%	3.0%	4.2%	6.0%	8.1%
Financial Services and Insurance	3.5%	5.1%	5.8%	6.8%	8.0%
Other Services	2.3%	2.6%	3.2%	3.9%	5.7%
Net Foreign Travel	0.1%	0.2%	0.3%	0.3%	0.5%
Total	100.0%	100.0%	100.0%	100.0%	100.0%

Table 5. Impacts on Producer Prices

(Percentage Changes from Reference Case Values)

Industry	**2020**	**2035**	**2050**
Oil Extraction	0.9	2.5	3.2
Natural Gas Extraction	-13.4	0.5	0.8
Coal Mining	-16.7	-2.0	1.1
Electric Transmission and Distribution	10.3	15.5	16.9
Coal-Fired Electricity Generation	40.4	76.3	108.0
Other Fossil Electricity Generation	21.8	32.5	42.0
Nonfossil Electricity Generation	17.9	7.2	3.8
Natural Gas Distribution	6.1	15.8	21.2
Petroleum Refining	13.2	17.1	20.6
Pipeline Transportation	0.5	4.1	5.3
Mining Support Activities	0.6	2.4	2.8
Other Mining	-0.6	0.9	1.2
Farms, Forestry, Fishing	0.5	1.8	2.2
Water Utilities	0.5	0.9	1.3
Construction	0.6	1.3	1.5
Wood Products	0.4	1.3	1.6
Nonmetallic Mineral Products	0.4	1.7	2.0
Primary Metals	1.2	2.9	3.2
Fabricated Metal Products	0.3	1.3	1.5
Machinery and Misc. Manufacturing	-0.2	0.8	1.0
Motor Vehicles	0.1	1.0	1.2
Food and Beverage	0.5	1.4	1.8
Textile, Apparel, Leather	0.2	1.0	1.2
Paper and Printing	0.5	1.5	1.8
Chemicals, Plastics, and Rubber	1.3	3.1	3.6
Trade	0.1	0.6	0.8
Air Transportation	2.2	3.7	4.3
Railroad Transportation	-1.3	1.0	1.7
Water Transportation	2.0	3.3	3.8
Truck Transportation	2.1	3.2	3.6
Transit and Ground Passenger Transportation	1.2	1.8	2.2
Other Transportation and Warehousing	0.6	1.3	1.6
Communiction and Information	-0.1	0.5	0.7
Services	0.2	0.5	0.7
Real Estate and Owner-Occupied Housing	0.4	0.9	1.4
All Industries (Producer Price Index)	1.0	2.1	2.7

Table 6. Impacts on Consumer Good Prices
(Percentage Changes from Reference Case Values)

Consumption Category	2020	2035	2050
Motor Vehicles	0.2	0.7	0.9
Furnishings and Household Equipment	0.2	0.9	1.1
Recreation	0.1	0.6	0.8
Clothing	0.1	0.7	0.8
Health Care	0.2	0.7	0.9
Education	0.1	0.5	0.6
Communication	0.0	0.5	0.7
Food	0.4	1.1	1.4
Alcohol	0.4	1.1	1.4
Motor Vehicle Fuels (and Lubricants and Fluids)	7.7	10.8	13.6
Fuel Oil and Other Fuels	7.6	10.6	13.3
Personal Care	0.3	0.9	1.1
Tobacco	0.4	1.2	1.5
Housing	0.4	0.9	1.4
Water and Waste	0.4	0.9	1.2
Electricity	9.9	14.9	16.2
Natural Gas	5.8	15.1	20.2
Public Ground	1.1	1.7	2.0
Air Transportation	1.4	2.5	3.0
Water Transportation	1.5	2.6	3.0
Food Services and Accomodations	0.2	0.5	0.7
Financial Services and Insurance	0.2	0.5	0.7
Other Services	0.2	0.6	0.7
Net Foreign Travel	1.7	2.9	3.4
All Consumer Goods (Consumer Price Index)	0.7	1.5	1.9

Table 7. Impacts on Nominal Factor Prices and Transfers
(Percentage Changes from Reference Case Values)

	2020	2035	2050
After-Tax Wage			
Lump-Sum Rebates	0.0	0.0	0.0
Payroll Tax Cuts	1.0	1.0	1.0
Personal Income Tax Cuts	0.8	0.8	0.8
Corporate Income Tax Cuts	0.0	0.0	0.0
After-Tax Interest Rate			
Lump-Sum Rebates	-2.2	-1.0	-0.4
Payroll Tax Cuts	-1.8	-0.9	-0.4
Personal Income Tax Cuts	-1.2	-0.5	-0.2
Corporate Income Tax Cuts	0.4	0.1	0.0
Nominal Transfers			
Lump-Sum Rebates	0.7	1.5	1.9
Payroll Tax Cuts	0.9	1.6	2.0
Personal Income Tax Cuts	1.0	1.5	1.8
Corporate Income Tax Cuts	0.6	0.6	0.7

Table 8. GDP and Welfare Costs of a Carbon Tax Under Alternative Recycling Options

	Recycling Method			
	Lump-Sum Rebates	Cuts in Employee Payroll Taxes	Cuts in Individual Income Taxes	Cuts in Corporate Income Taxes
GDP Costs[a]				
- as Pct of Reference GDP	0.28%	0.13%	0.16%	0.19%
- per Ton of CO_2 Reduced[b]	\$54.67	\$26.41	\$31.25	\$38.38
Welfare Costs[c]	\$2,563.44	\$2,046.83	\$1,684.82	\$380.99
- as Pct of Wealth	0.43%	0.34%	0.28%	0.06%
- per Dollar of Gross Revenue	\$0.39	\$0.31	\$0.26	\$0.06
- per Ton of CO_2 Reduced	\$46.97	\$37.63	\$31.08	\$7.25

[a] GDP costs measured as present value of real GDP loss, 2016-2050, using 3 percent real interest rate

[b] Present value of cumulative tons reduced, using 3 percent real interest rate

[c] Welfare costs are the negative of the equivalent variation, expressed in $2013 billions

Table 9. Aggregate Welfare Costs of a Carbon Tax
With and without Targeted Compensation

	Tax Rate Recycling Method		
	Payroll Tax Cuts	Individual Income Tax Cuts	Corporate Tax Cuts
No Targeted Compensation			
Welfare Costs[a]	$2,046.83	$1,684.82	$380.99
- per Ton of CO_2 Reduced	$37.63	$31.08	$7.25
Targeted Compensation to Prevent Adverse Impact on Quintile 2[b]			
Welfare Costs[a]	$2,075.97 (1.4%)	$1,716.51 (1.9%)	$468.40 (22.9%)
- per Ton of CO_2 Reduced	$38.16 (1.4%)	$31.66 (1.9%)	$8.90 (22.7%)
Targeted Compensation to Prevent Adverse Impact on Quintiles 2 and 3[b]			
Welfare Costs[a]	$2,345.02 (14.6%)	$2,155.90 (28.0%)	$1,222.72 (220.9%)
- per Ton of CO_2 Reduced	$43.03 (14.3%)	$39.63 (27.5%)	$22.93 (216.2%)

[a] Welfare costs are the negative of the equivalent variation, expressed in $2013 billions.

[b] Numbers in parentheses reflect percentage change in welfare costs relative to "No Targeted Compensation"

Figure 1. Nested Consumption Structure

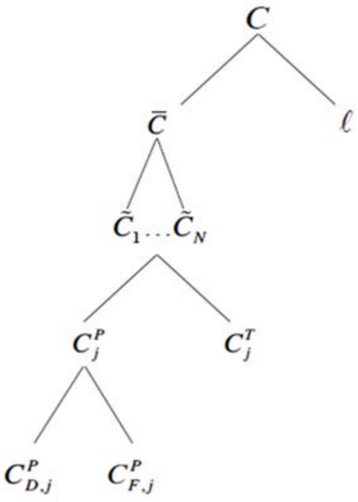


Figure 2. Time Profile of Carbon Tax, 2017-2050

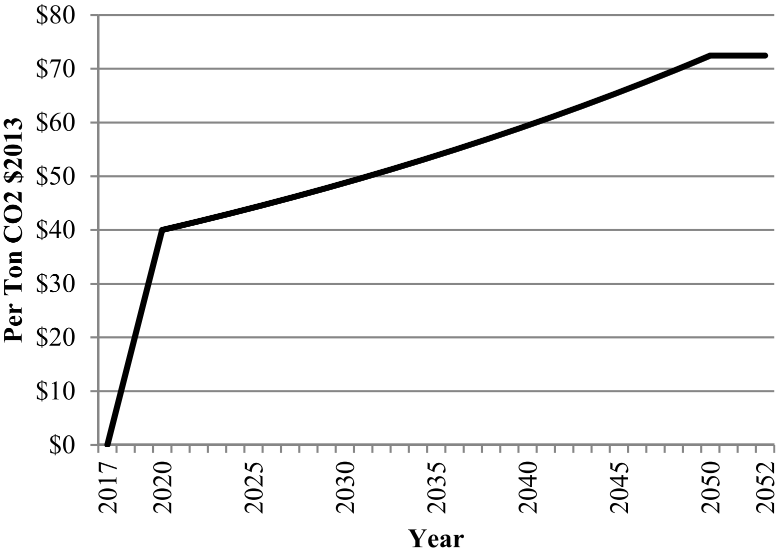


Figure 3. Economy-Wide Carbon Dioxide Emissions, 2017-2050

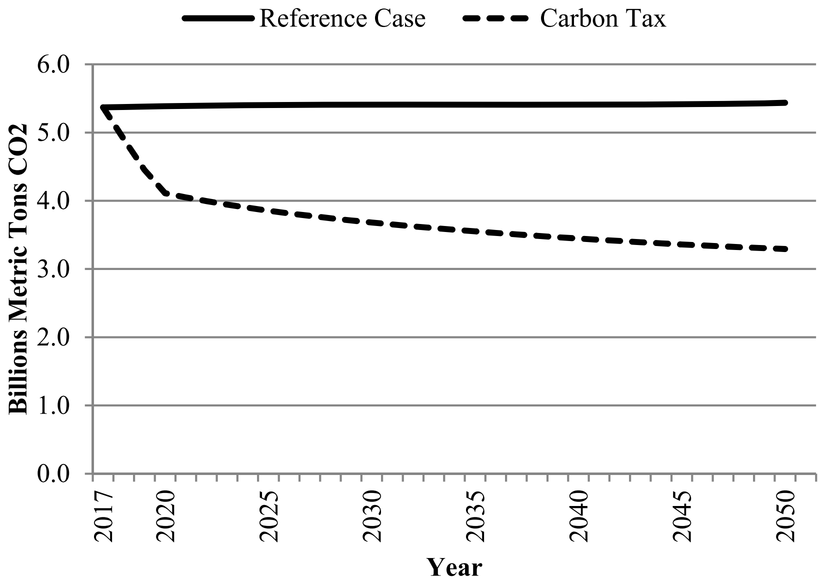
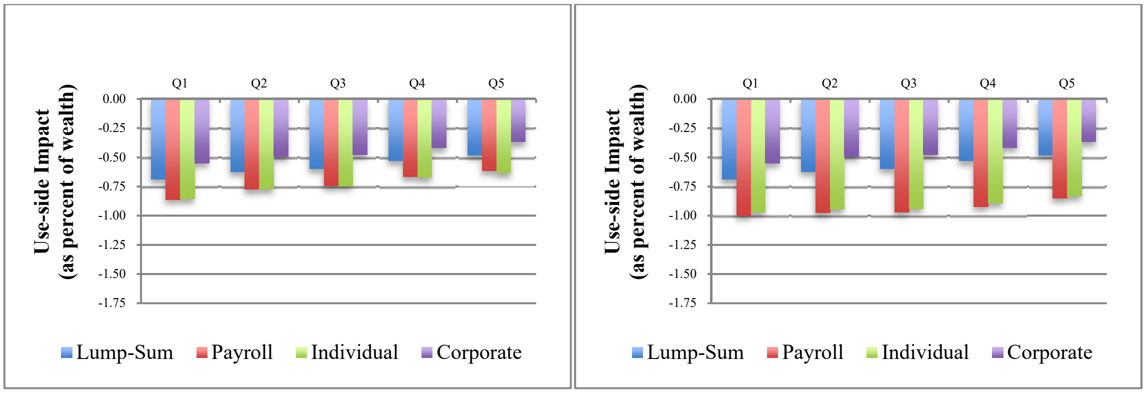


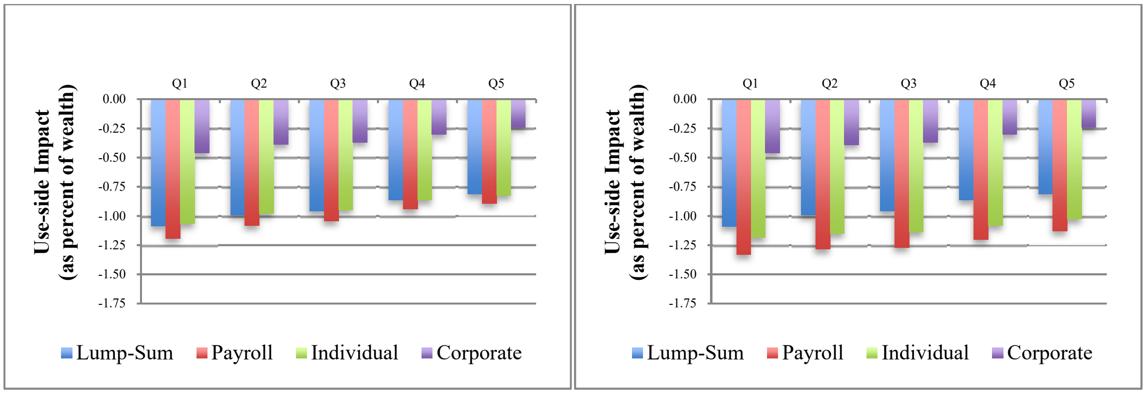
Figure 4. Use-side Impacts by Year by Quintile

Goods-Only Measure **Goods and Leisure Measure**

(a) 2020



(b) 2030



(c) 2050

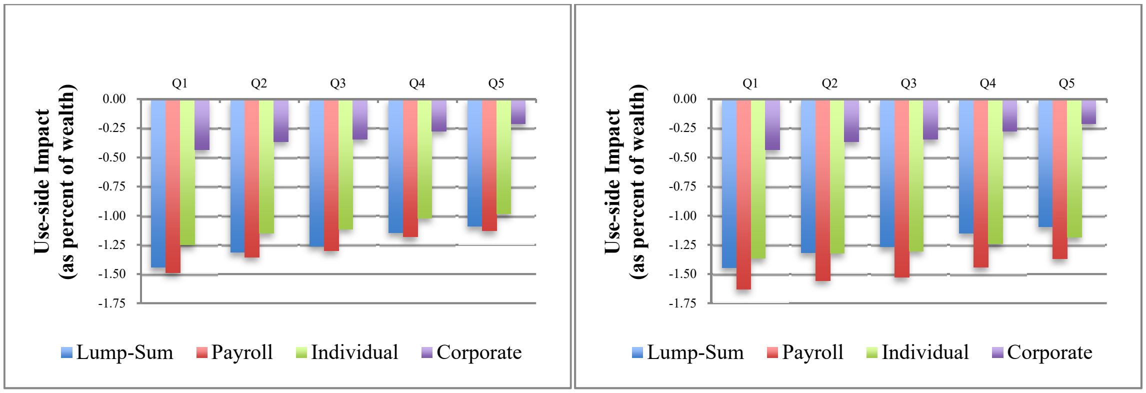
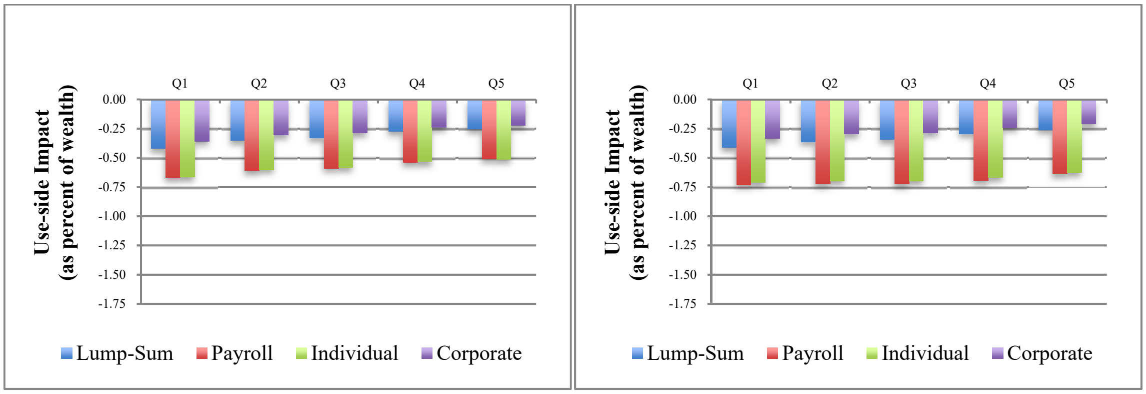


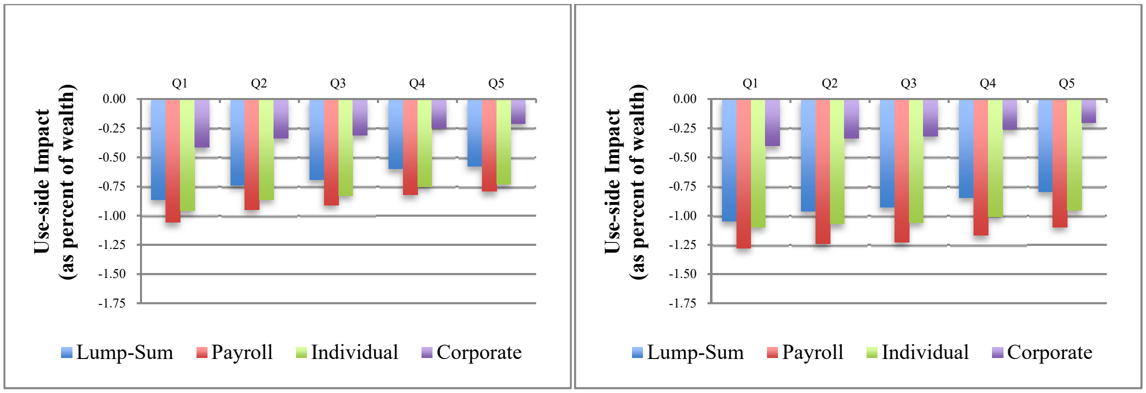
Figure 5. Use-side Impacts Over Time-Intervals, by Quintile

Goods-Only Measure **Goods and Leisure Measure**

(a) 2018-2020



(b) 2018-2040



(c) 2018-∞

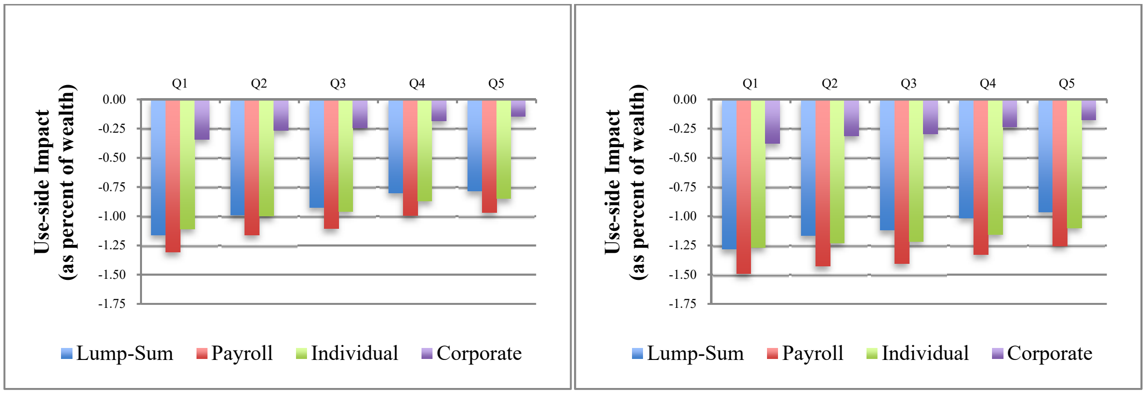
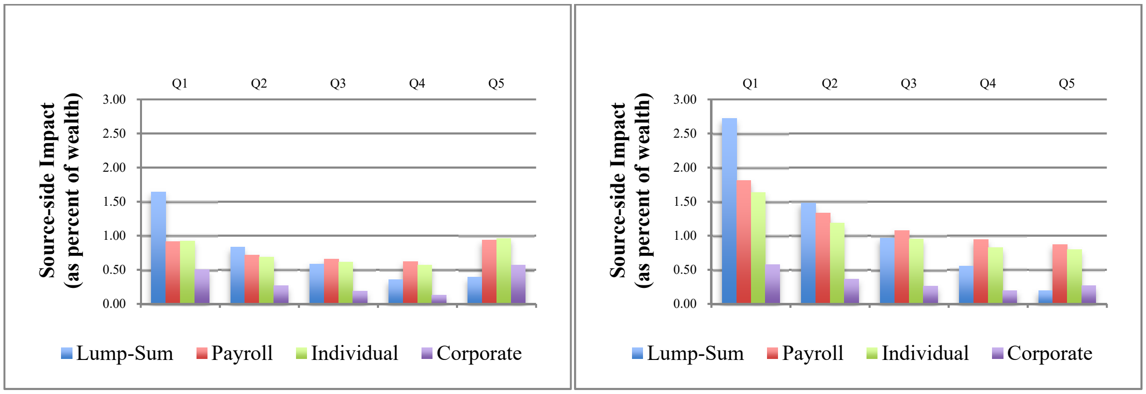


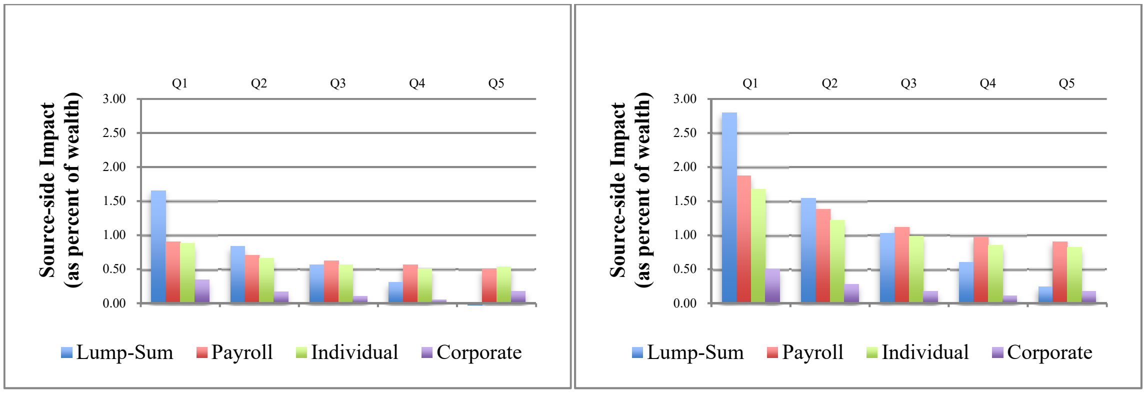
Figure 6. Source-side Impacts by Year by Quintile

Income-Only Measure **Full Measure**

(a) 2020



(b) 2030



(c) 2050

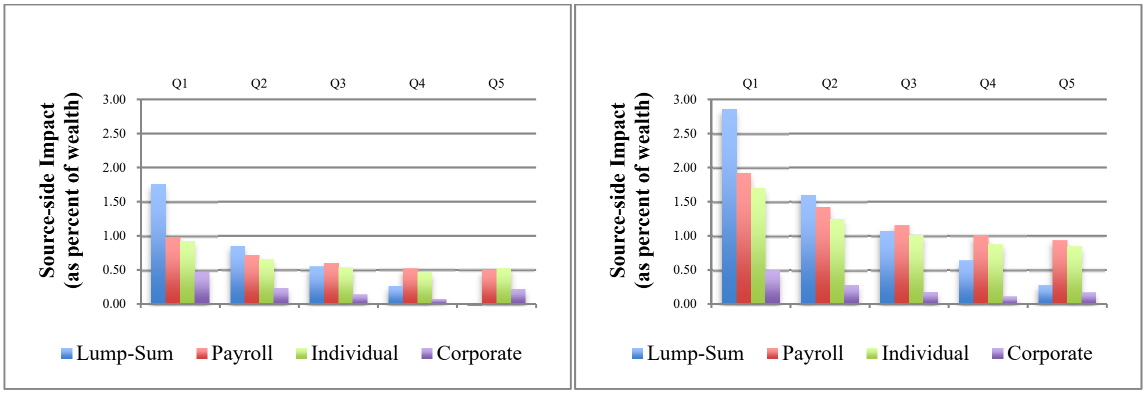
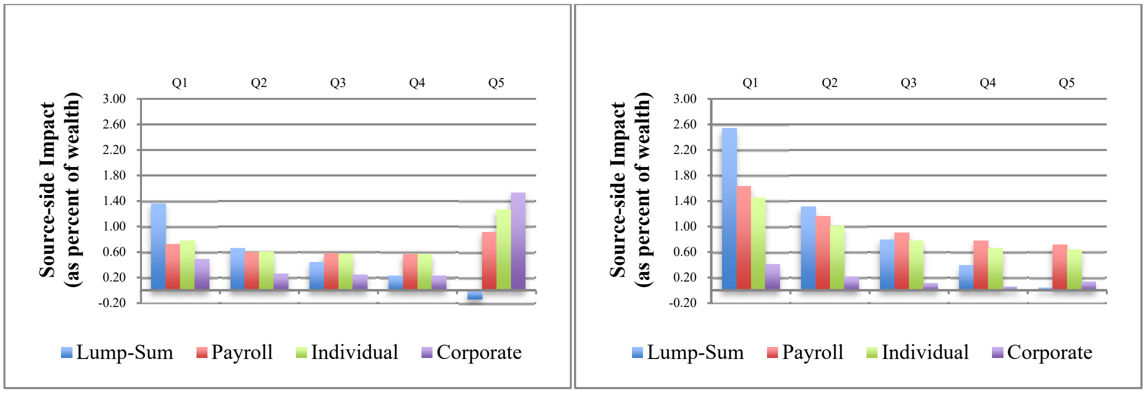


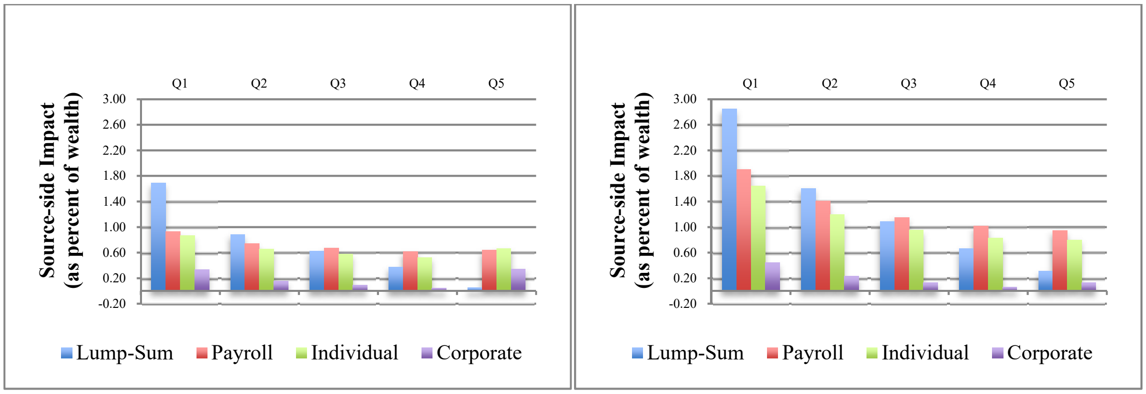
Figure 7. Source-side Impacts Over Time-Intervals, by Quintile

Income-Only Measure **Full Measure**

(a) 2018-2020



(b) 2018-2040



(c) 2018-∞

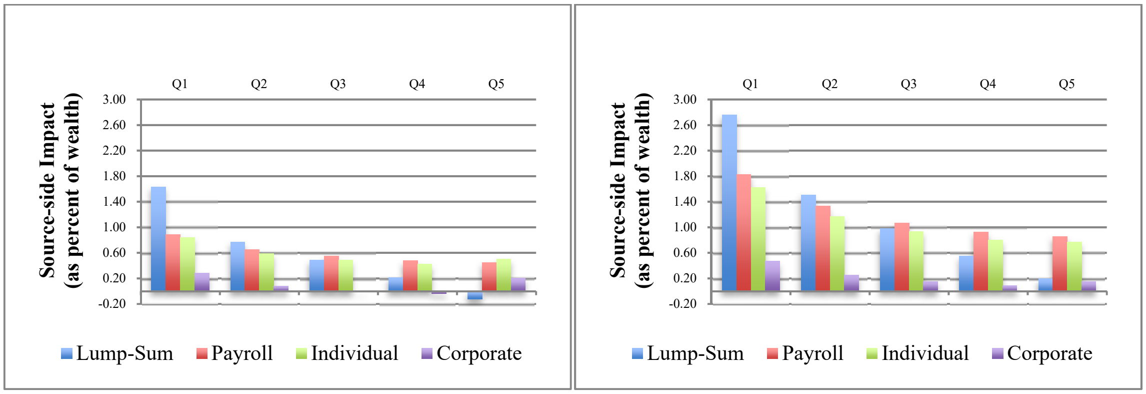
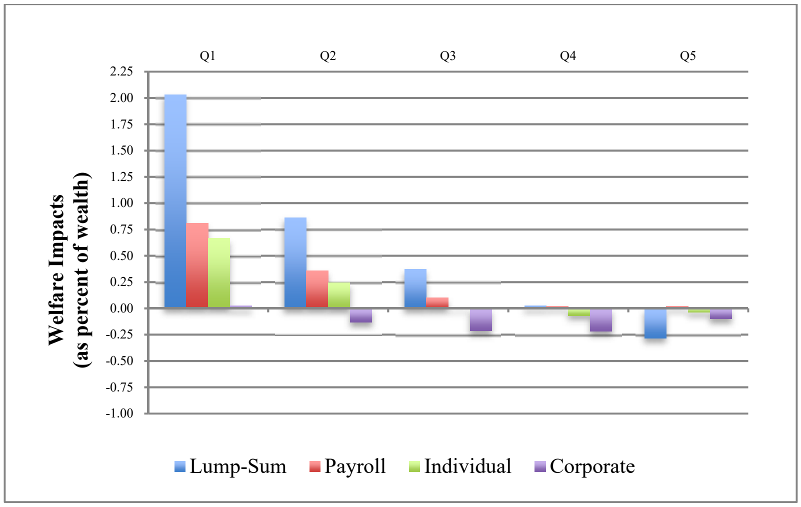
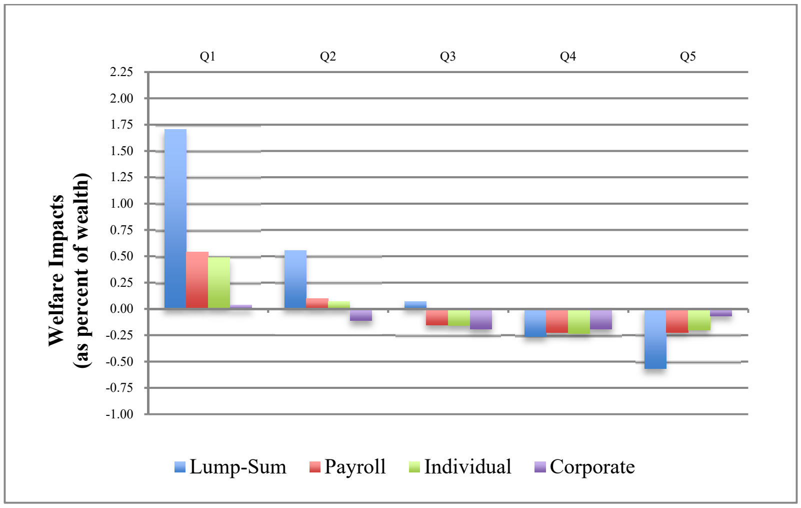


Figure 8. Overall Welfare Impacts by Year, by Quintile

(a) 2020



(b) 2030



(c) 2050

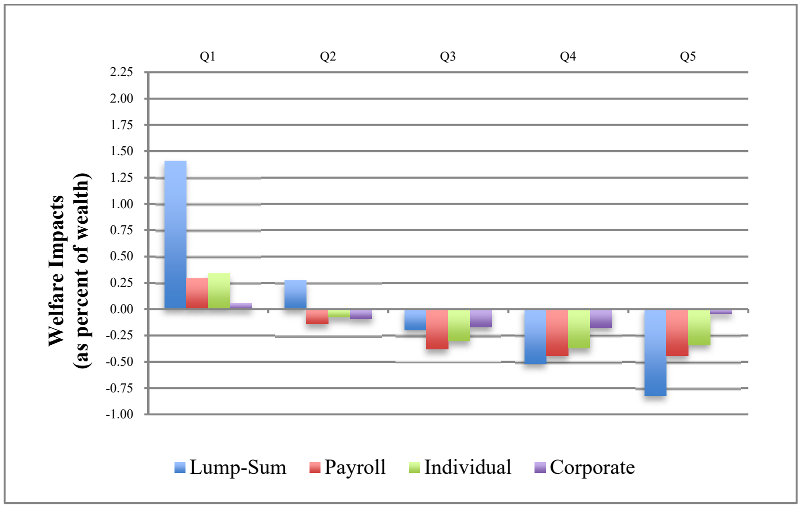
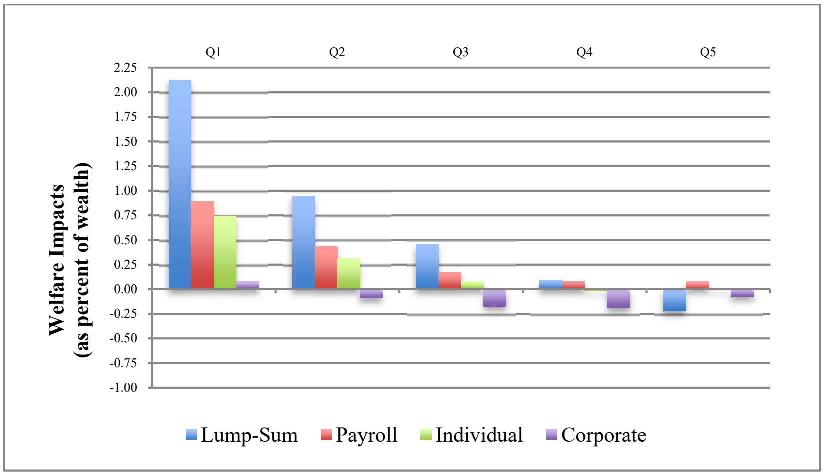
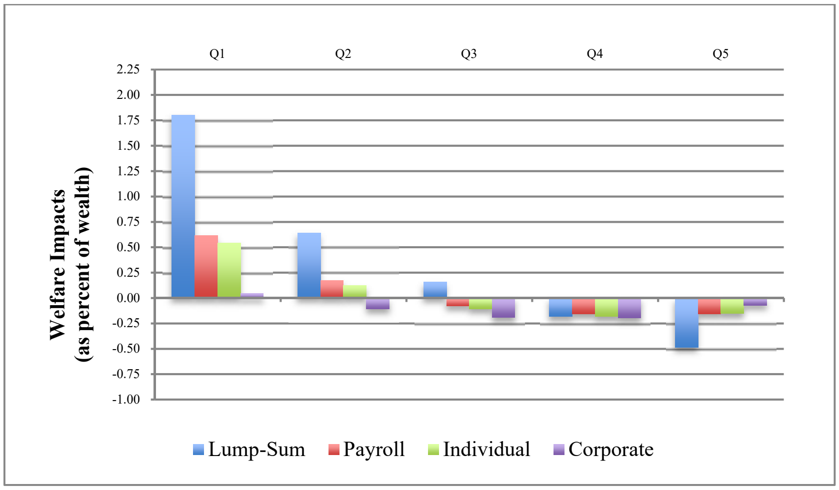


Figure 9. Overall Welfare Impacts Over Time-Intervals, by Quintile

(a) 2018-2020



(b) 2018-2040



(c) 2018-∞

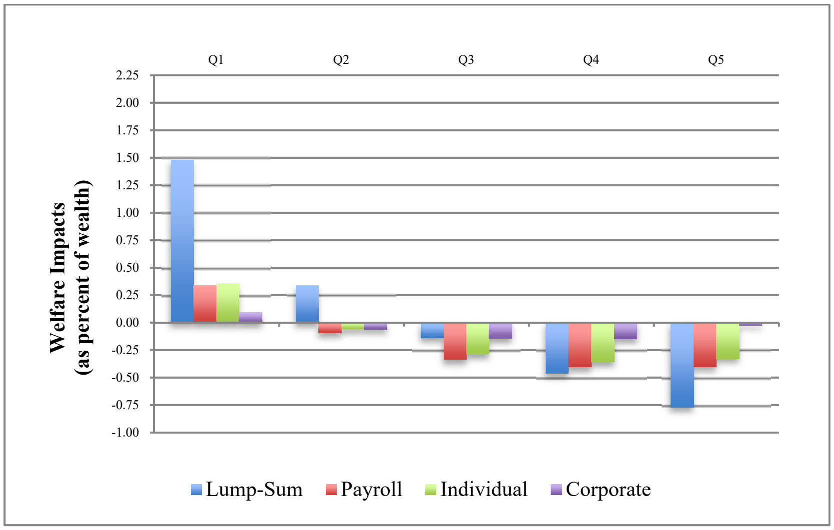
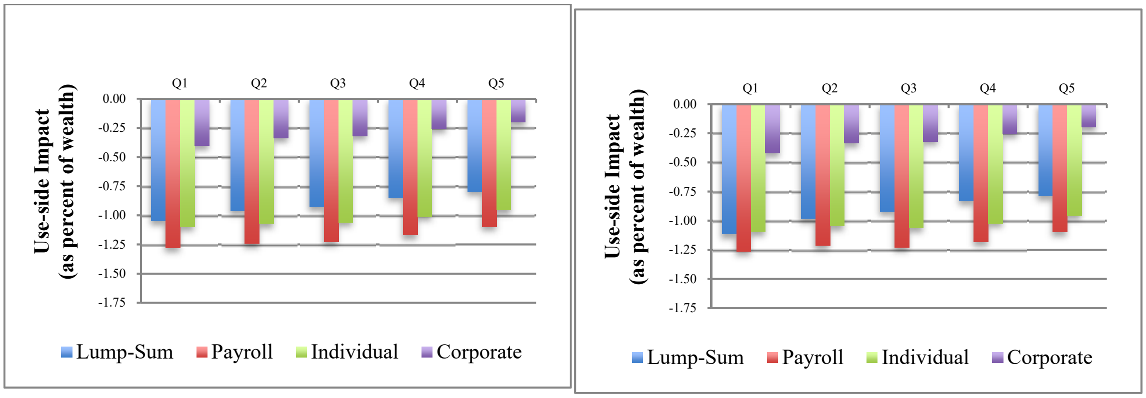


Figure 10. Distributional Impacts over the Interval 2018-2040 Under Alternative Orderings of Households

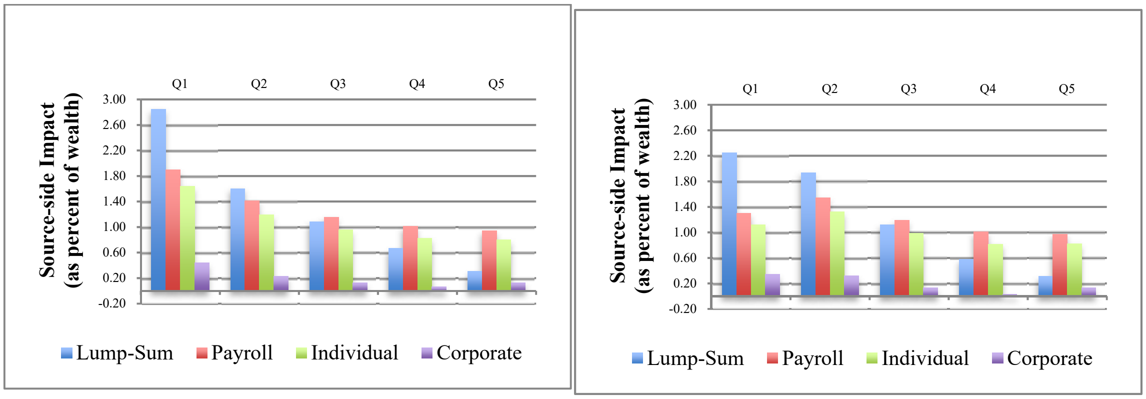
(using Full Welfare Measure)

Households Ranked by Expenditure **Households Ranked by Income**

(a) Use-Side Impact



(b) Source-Side Impact



(c) Overall Impact

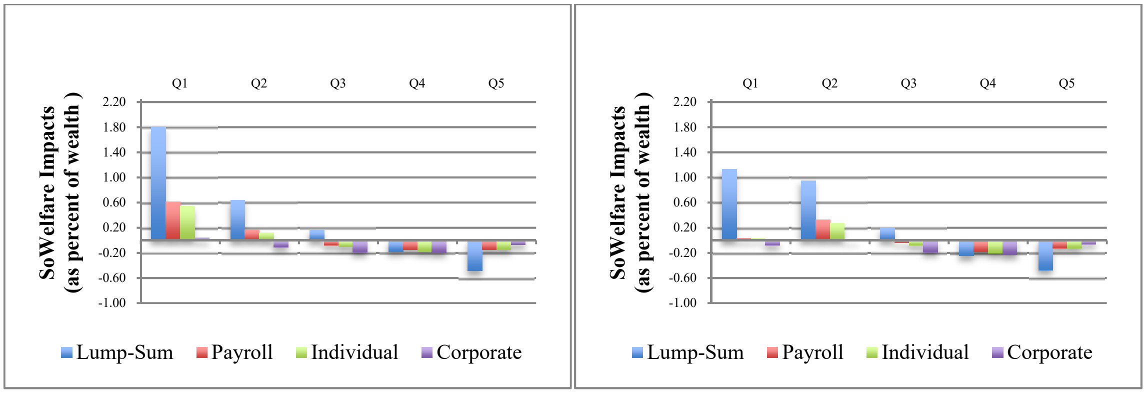
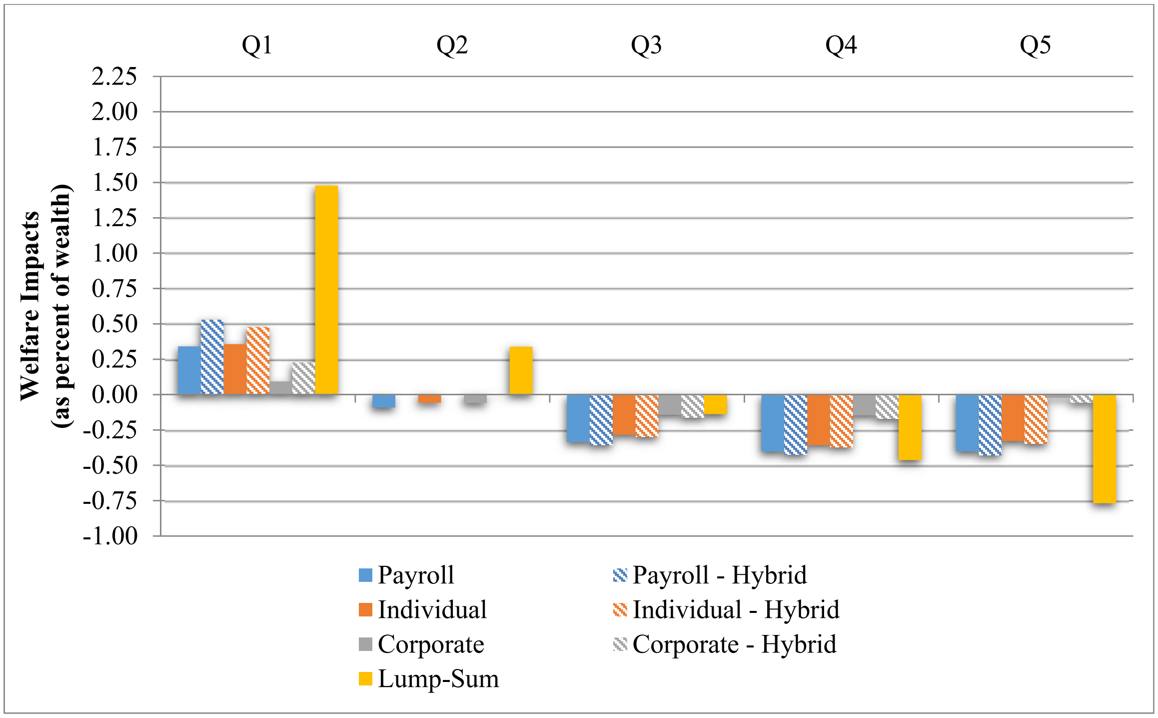


Figure 11. Results under “Pure” and “Hybrid” Revenue Recycling

Impacts over the Infinite Horizon, by Quintile

(a) Targeted Compensation to Hold Quintile 2 Harmless



(b) Targeted Compensation to Hold Quintile 3 Harmless

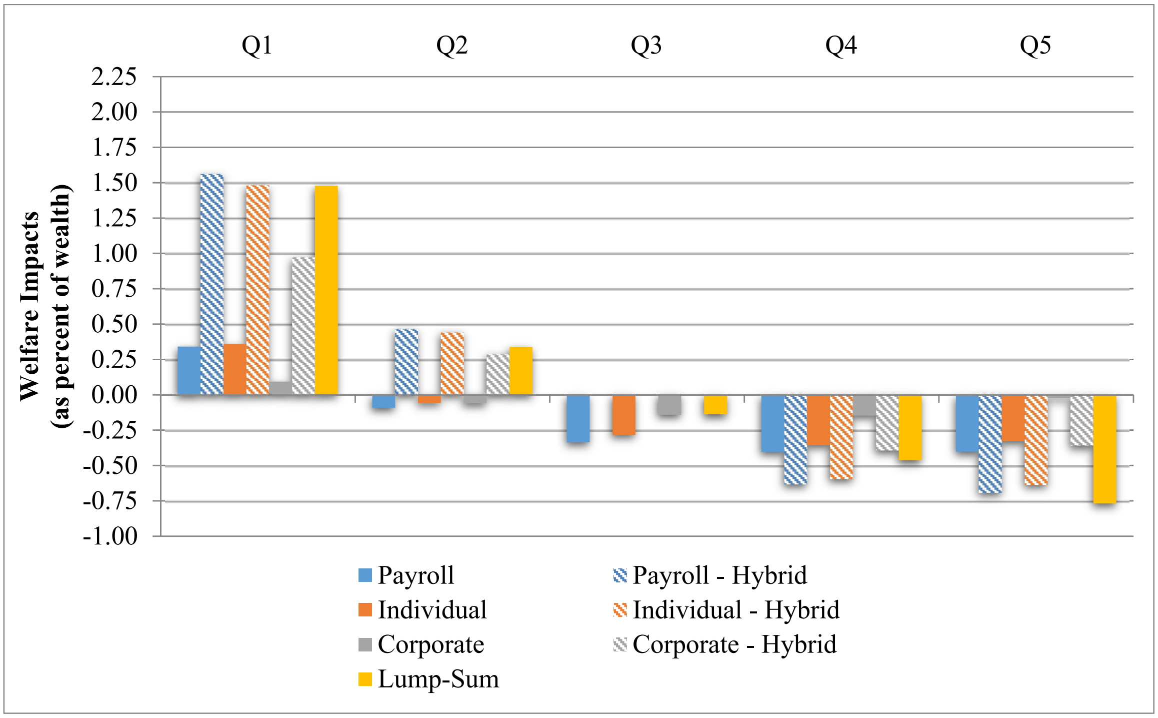
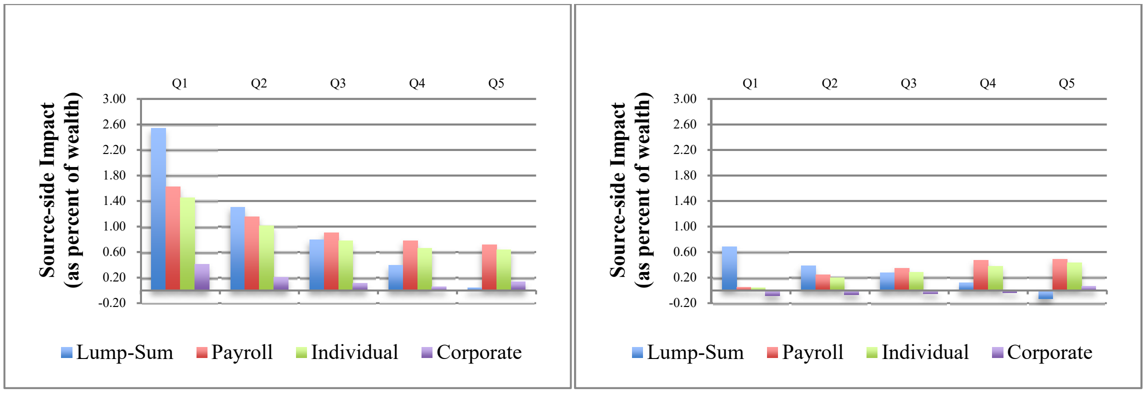


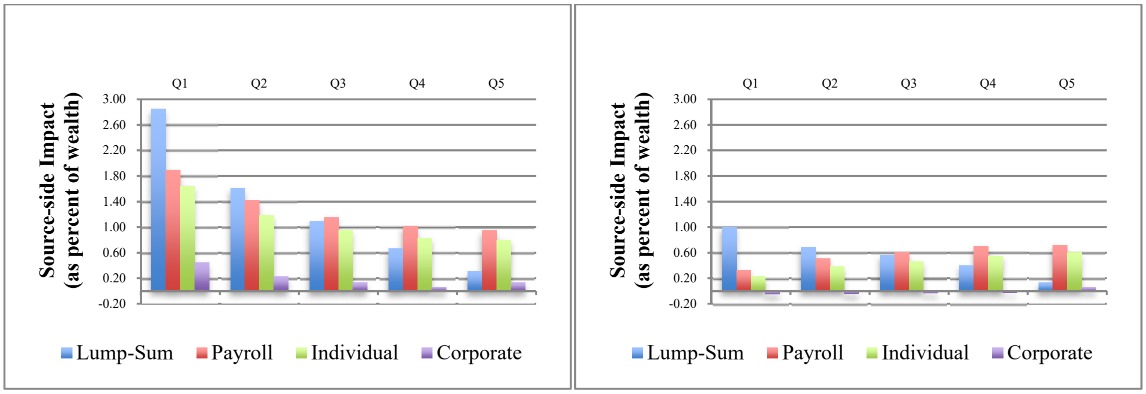
Figure 12. Source-Side Impacts over Time-Intervals, Full Measure, by Quintile

Indexed Transfer Income **Non-Indexed Transfer Income**

(a) 2018-2020



(b) 2018-2040



(c) 2018-∞

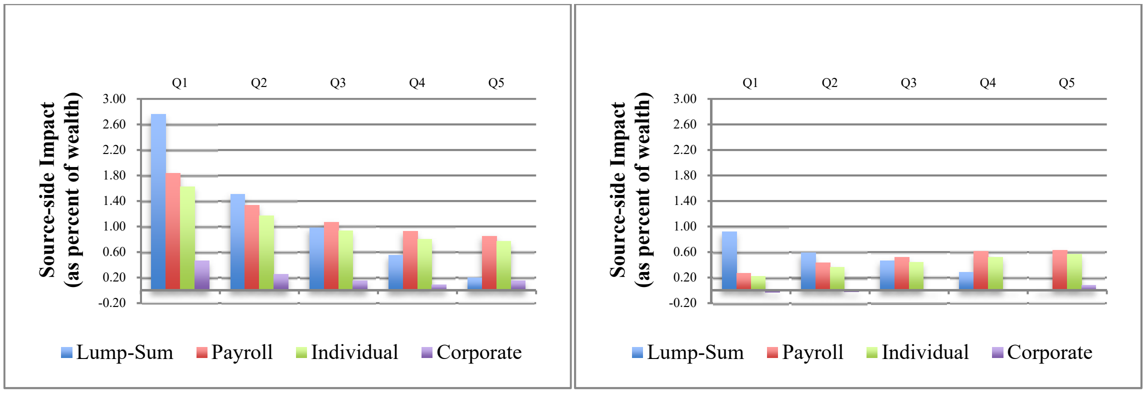
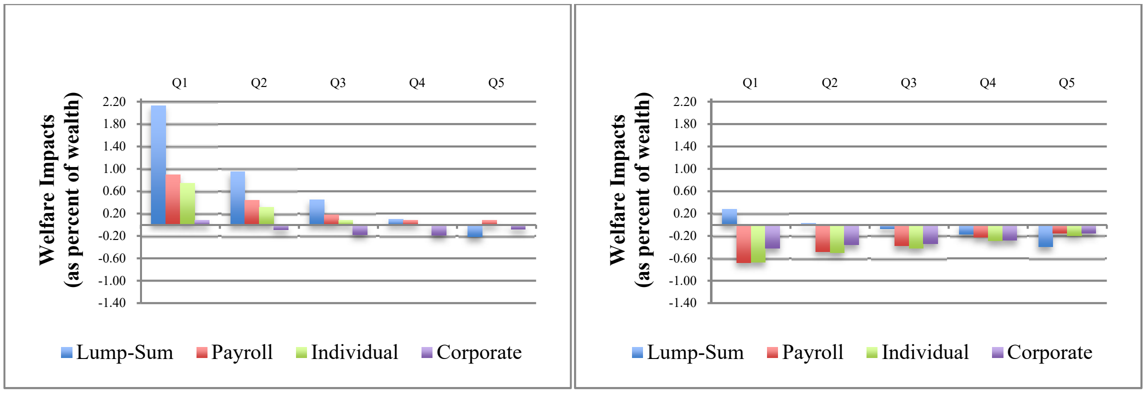


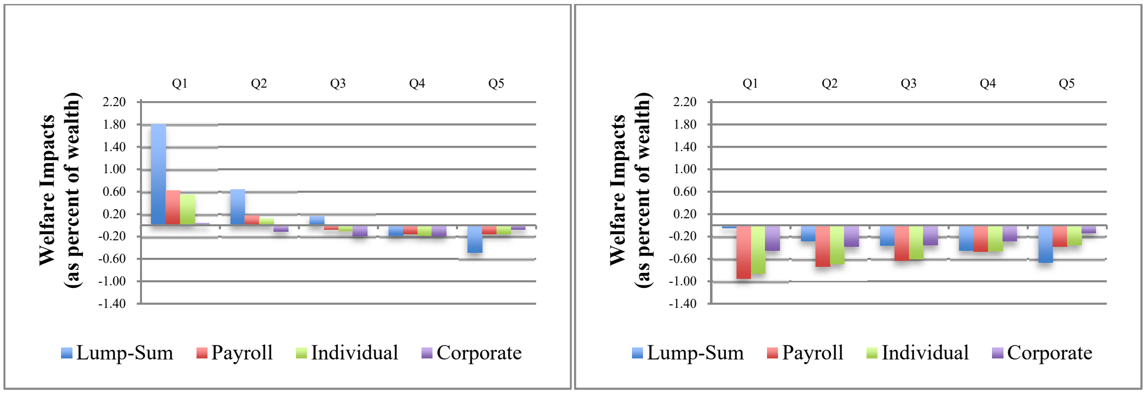
Figure 13. Overall Welfare Impacts over Time-Intervals, by Quintile

Indexed Transfer Income **Non-Indexed Transfer Income**

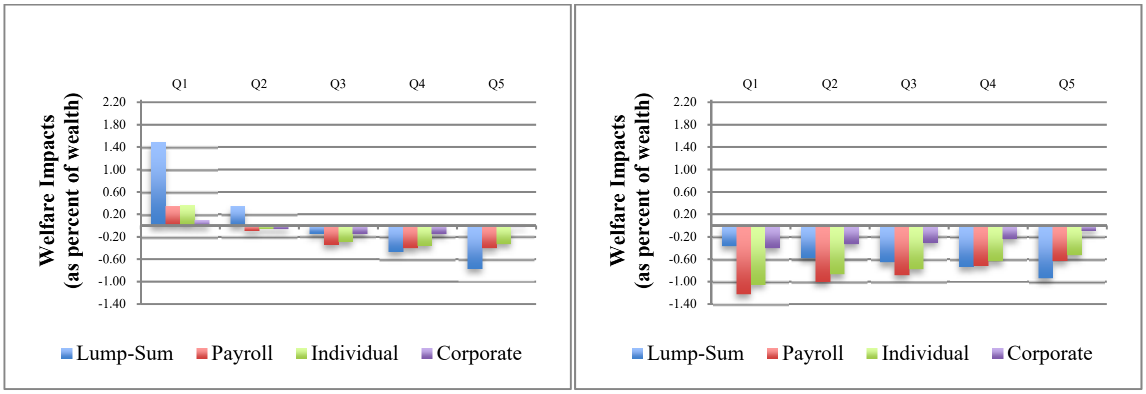
(a) 2018-2020



(b) 2018-2040



(c) 2018-∞



Appendix: Data Sources and Consistency Procedures

This appendix provides detail on the sources of data used in this study, as well as the procedures adopted to assure consistency between the income and expenditure data derived from sources.

A. Data

1.. Income

For the DH model, we obtain data on before-tax income for the DH model from the 2013 Survey of Consumer Finances (SCF). The SCF data include labor, capital and transfer income for a representative sample of 6015 households. Labor income is defined as the income from wages and salaries. Capital income is the sum of income from a sole proprietorship or a farm, income from dividends, income from gains or losses from mutual funds or from the sale of stocks, bonds, or real estate, income from other businesses or investments, net rent, trusts, or royalties, income from other interest, income from child support or alimony, and income from other sources including IRA, IRA/401(k) withdrawal, withdrawal from deferred-compensation and settlement of other employer-provided pension. Transfer income refers to the sum of social security benefits, unemployment or worker's compensation, income from TANF, SNAP (food stamps), or other welfare or assistance such as SSI, and income from non-taxable investments such as municipal bonds[37]. Pension income is excluded from transfer income for consistency with the E3 and DH models which do not include retirement income.

We derive after-tax income by applying information on tax liabilities from the NBER's TAXSIM model (Feenberg and Coutts, 1993) to the SCF before-tax data. The SCF microdata do not provide information on place of residence, but this information is needed to determine household state tax liabilities in the DH model. To obtain state tax liability for each household, we randomly assign each household in SCF microdata to a state such that the proportion of households in each state matches the real population share in 2013.

TAXSIM does not calculate tax liability by income source. To obtain this more disaggregated information, we assign tax liabilities to labor, capital and transfer incomes, we calculate the share of before-tax income from each source for each household and multiply by total tax liability. Specifically, we get total federal tax liability, total state tax liability and Federal Insurance Contributions Act (FICA) for each household using TAXSIM. In TAXSIM, FICA is the sum of employee and employer payroll

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[37] Non-taxable investments are defined as transfer income in TAXSIM. For consistency with TAXSIM, we include non-taxable investments in transfer income when calculating before-tax income.

taxes. In E3 model, we include employee payroll taxes as a tax on labor income. Therefore we allocate federal and state tax liabilities to labor, capital, and transfer incomes using before-tax income shares. We assume that payroll taxes divide evenly between the portion paid by employees and employers. Households with zero income and nonnegative tax liabilities are dropped. After-tax incomes by income source are then calculated as before-tax income minus the tax liability by source.

2, Expenditure

We obtain household expenditures on each consumer good using the 2013 Consumer Expenditure Survey (CEX) microdata collected by the U.S. Department of Labor's Bureau of Labor Statistics (BLS). The CEX provides data on expenditures, income, and demographic characteristics of representative consumers in the United States. These data are collected through two surveys, the Interview Survey and the Diary Survey.[38]

In order to obtain a complete listing of expenditures for each household, we combine data from the two surveys. The Interview Survey focuses on large consumer goods, such as spending on housing, vehicles, and health care. It collects data on monthly expenditures of households who are selected as samples for five consecutive quarters, after which they are dropped from the sample. The Diary Survey gives greater focus to small frequently purchased goods, such as expenditures on food, beverages and personal care products. This survey collects data on weekly expenditures of different households who are followed for only two weeks.

Before integrating data from the two surveys, we calculate a weighted expenditure cost of each consumer good for each household in both surveys.[39] Then we define sub-groups using five demographic characteristics: age, education level, marital status, family size, and income decile. Using these sub-groups, we combine weighted expenditures for each household in the Interview Survey with each sub-group's average weighted expenditures from the Diary Survey. In this way, we create a large dataset of representative households with combined expenditures from both surveys.

B. Achieving Income-Expenditure Consistency

To produce a complete dataset with both income and expenditure information for each SCF household, we match expenditure data from the CEX to each SCF household.[40] Specifically, we match expenditure patterns in the CEX to a similar SCF household. First, we define 720 "CEX cells" using

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[38] There are overlapping consumer good categories across the two surveys. In choosing which data to take from which survey, we followed Bureau of Labor Statistics guidelines.

[39] Each household in the microdata represents a given number of households in the U.S. population.

[40] Our method resembles the approach of Cronin et al. (2017).

demographic characteristics for each household: education (less than high school or high school degree; some college, no degree; college degree), marital status, age (<30, 31-40, 41-50, 51-60, 61-65, 66+), family size (with, without kids) and before-tax income deciles.

For each SCF record (there are five records for each household to help maintain anonymity), we assign the SCF record to its corresponding CEX cell. If there are more than one CEX record in the CEX cell, the averages of expenditure data of all CEX records in the cell are used as the expenditure information for the SCF record. If the CEX cell is empty, we do a nearest neighbor match based on before-tax income, assigning the SCF record to the CEX cell with the nearest before-tax income and (and identical non-income demographics). To find the nearest neighbor, we compare the "distances" between the SCF record's income decile and (1) nearest lower income neighbor, (2) nearest higher income neighbor, (3) "average" neighbor – the average decile of the nearest lower and nearest higher neighbor. We assign the SCF record to the cell with the shortest distance. SCF records with no close neighbor decile, defined as the nearest neighbor is at least 2 deciles away, are dropped from our data set.[41] SCF records that have no corresponding CEX cell with the same demographics are dropped from our data set as well.[42]

The SCF also does not include information on the level of savings for each household. From the CEX, we obtain the level of savings by subtracting total expenditures from after-tax income.[43] The implied savings rate is then matched to the SCF households using the same matching algorithm described above for expenditure shares. Total expenditures for each SCF record are equal to after-tax income less savings. Expenditure levels by good are equal to total expenditures times the matched CEX expenditure shares.

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[41] There are 174 SCF records (out of 30075) that do not have a nearest neighbor.

[42] There are only 10 records in the SCF that are dropped because CEX cells with identical non-income demographics do not contain any CEX households.

[43] The CEX tends to overstate savings rates by household as tax liabilities are generally under-reported in self-reported surveys such as the CEX (Metcalf *et al.*, 2012). Savings rates are scaled to match E3 savings rates in the calibration procedure.