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

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Abstract

This paper assesses the impacts across US 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) and the use-side impacts (reflecting how policies alter the real prices of goods and services purchased by households). We apply an integrated general equilibrium framework with extended measures of the source- and use-side impacts that add up to the overall welfare impact. Our results indicate that the distributional impacts depend importantly on the nature of revenue recycling and the treatment of transfer income. In the absence of targeted compensation to achieve distributional objectives, the use-side impacts tend to be regressive, while the source-side impacts are progressive. 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 into account the more comprehensive welfare measures introduced in this study. The efficiency costs of targeted compensation to achieve 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 than when the remaining revenues are used in other ways. Efficiency costs also rise dramatically when targeted compensation extends beyond the lowest income quintiles.

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1. Introduction

Economists tend to consider a carbon tax as the most cost-effective approach to reducing CO_2 emissions.[2] 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.[3]

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 prices 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 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 differs.

This paper assesses the distribution of the impacts across US 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 and the relative impacts, such as the extent to which

[2] 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 et al. (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 ensure 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 preexisting distortionary taxes. As discussed by Oates (1993), Fullerton and Metcalf (2001), and others, this can reduce policy costs.

[3] The impacts across producers or industries are 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.

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 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.[4] 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. (2015) examine both 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 of carbon taxes to be progressive.[5]

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 sides as well as to quantify the efficiency costs of achieving various distributional goals.

Second, in contrast with earlier work, our 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, whereas previous studies have tended to focus on the distributional impacts at a single point in time (usually the present), we exploit the multiperiod property of our numerical model to examine changes in the distributional impacts over time.

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

[5] 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 US transfer program indexing significantly offsets regressivity on the use side. Williams et al. (2015) 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.

Fourth, we compare policies with and without targeted compensation 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 offset fully the regressive use-side impacts, so 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.[6] We also find that both the source- and use-side impacts are considerably larger once one takes into account 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 than when the remaining revenues are used in other ways. These costs are also an order of 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 that shows the channels through which a carbon tax yields the source- and use-side utility impacts. The next two sections focus on the numerical model's structure (Section 3) and data and parameters (Section 4). Sections 5–9 present and evaluate the numerical model's results for the carbon tax's impacts. Section 5 provides the economic outcomes in our reference (no-policy-change) case. Section 6 describes 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.

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

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.

2.1. The Utility-Maximization Problem

Consider the following dynamic (infinite-horizon) utility-maximization problem. A household receives an initial nonhuman 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 nonhuman 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

$$W_{t+1} - W_t = \overline{w}_t \overline{l}_t + \overline{r}_t W_t - P_t C_t. \tag{2}$$

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, $\overline{w}_t$ is the (after-tax) wage, and $\overline{r}_t$ is the (after-tax) return on capital.

The intertemporal budget constraint is

$$\sum_{t=0}^{\infty} \left[P_t C_t \right] d_t = W_0 + \sum_{t=0}^{\infty} \left[\overline{w}_t \overline{l}_t \right] d_t \tag{3}$$

where

$$d_t = \prod_{u=0}^{t} \left[1 + \overline{r}_u \right]^{-1}. \tag{4}$$

The transversality condition,

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

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.[7]

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

$$C_t = C(\overline{C}_t, \ell_t). \tag{6}$$

Total expenditure is the value of full consumption and is equal to expenditure on consumer goods and services plus the value of leisure: $P_t C_t = \overline{p}_t \overline{C}_t + \overline{w}_t \ell_t$, where $\overline{p}_t$ is the price of a unit of consumption of goods and services, and leisure is valued at the opportunity cost of time not spent working.[8]

Let $U_C \equiv \frac{\partial U}{\partial C}\frac{\partial C}{\partial \overline{C}}$ and $U_\ell \equiv \frac{\partial U}{\partial C}\frac{\partial C}{\partial \ell}$. 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 (9) represents the intertemporal Euler condition. The expenditure functions that satisfy the first-order conditions can be written as

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

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

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

[8] In the numerical model, the consumption good $\overline{C}_t$ is a composite of 24 consumer goods, and the price $\overline{p}_t$ is the ideal price index based on the prices of the 24 different after-tax (or subsidy) consumer good prices.

2.2. 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 et al. 1995). In our intertemporal context, the equivalent variation can be expressed as the difference in expenditure across two intertemporal scenarios. The first, the reference case scenario, is defined by the vectors $\overline{p}_t(\text{ref})$, $\overline{w}_t(\text{ref})$, and $\overline{r}_t(\text{ref})$, which represent 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 $\overline{p}_t(\text{pol})$, $\overline{w}_t(\text{pol})$, and $\overline{r}_t(\text{pol})$, which are the time profiles of the prices of consumption, wages, and returns to capital under the policy change.

As indicated in equations (10) and (11), the optimal values of $\overline{C}_t$ and ℓ_t in the reference and policy cases are functions of $\overline{p}_t$, $\overline{w}_t$, and λ_t, where λ_t follows the optimal trajectory given by the Euler condition (9). Thus $\overline{C}_t(\text{ref}) \equiv c(\overline{p}_t(\text{ref}), \overline{w}_t(\text{ref}), \lambda_t(\text{ref}))$, $\ell_t(\text{ref}) \equiv \ell(\overline{p}_t(\text{ref}), \overline{w}_t(\text{ref}), \lambda_t(\text{ref}))$, $\overline{C}_t(\text{pol}) \equiv c(\overline{p}_t(\text{pol}), \overline{w}_t(\text{pol}), \lambda_t(\text{pol}))$, and $\ell_t(\text{pol}) \equiv \ell(\overline{p}_t(\text{pol}), \overline{w}_t(\text{pol}), \lambda_t(\text{pol}))$.

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

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

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. To calculate the equivalent variation for a given household, we generate new paths for $\overline{C}_t$ 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 $\overline{C}_t(\lambda_t^{ev}) \equiv c(\overline{p}_t(\text{ref}), \overline{w}_t(\text{ref}), \lambda_t^{ev})$ and $\ell_t(\lambda_t^{ev}) \equiv \ell(\overline{p}_t(\text{ref}), \overline{w}_t(\text{ref}), \lambda_t^{ev})$.

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. The equivalent variation EV_S is

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

where

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

and

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

respectively, and where

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

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

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

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

where $\overline{p}_t$ and $\overline{w}_t$ are policy case prices.[9] Applying the definition of the equivalent variation, we can rewrite expression (13) as

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

Presently, we will show that the first and second terms on the right-hand side of (18) are the source- and use-side impacts, respectively. We denote these as SS_S and US_S.

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

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

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

This is the change in the present value of expenditures multiplied by the fraction $EX_{S,\text{ev}} / EX_{S,\text{pol}}$.[10] From the household's intertemporal budget constraint (equation 3), the present value of expenditures is also equal to the present value of the returns to labor and capital:

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

This implies that the change in the present value of expenditures in expression (19) is equal to the changes in returns to labor and capital, respectively. Therefore, we can write the source-side impact as

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

where the labor and capital source-side components are

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

and

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

respectively. 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.[11]

[10] Scaling the source-side impact by the change in the price of full consumption ensures that the source and use-side impacts add up to the full welfare impact.

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

$$\begin{aligned} SS_S^K &= \sum_{t=0}^{S}\left[\left[(1+\overline{r}_t(\text{pol}))W_t(\text{pol}) - W_{t+1}(\text{pol})\right] - \left[(1+\overline{r}_t(\text{ref}))W_t(\text{ref}) - W_{t+1}(\text{ref})\right]\right]\overline{d}_t \\ &= \sum_{t=0}^{S}\left[\left(\overline{r}_t(\text{pol}) - \overline{r}_t(\text{ref})\right)W_t(\text{pol})\right]\overline{d}_t + \left[W_{S+1}(\text{pol}) - W_{S+1}(\text{ref})\right]\overline{d}_S \end{aligned}$$

The use-side impact is the change in welfare stemming from changes in the prices of consumption and 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

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

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 ($C_t(\text{pol})$),respectively.[12]

As the utility-maximization problem presented in Section 2.1 is for an infinitely lived household, the full measure of welfare applies when $S = \infty$.[13] 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 considers only time 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 revenues from a carbon tax. These additional endowments would enter the above analysis in the same way that the expression for the source-side impact accounts for the time and capital endowments.

[12] In a static model, the utility-equivalent and policy-change levels of consumption would be equal (to ensure equivalent utility), and the expression would reduce to $\frac{P_t(\text{ref})}{P_t(\text{pol})} EX_{S,\text{ref}} - EX_{S,\text{ref}}$. In the intertemporal model, price levels are more important to the use-side impact in periods in which households consume relatively more of the full consumption good.

[13] Because of 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 captures only changes in the return to capital.

3. The Numerical Approach

We employ a numerical model to solve, for a representative household in each of five household income groups, the utility-maximization problem introduced in Section 2. The 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, employing a framework with a single representative household. These general equilibrium prices are inputs into our disaggregated household (DH) model. Below, we offer brief descriptions of the E3 and DH models. Section 4 describes the data inputs for the models and the procedures employed to achieve a consistent linkage of the models.

3.1. The E3 Model

The E3 model, briefly described here,[14] comprises 35 distinct industries, a single representative household, and a single representative government for the US economy. It captures the interactions among 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. Adjustment costs affect the distribution of policy impacts in two ways. They imply windfall gains to quasi-immobile capital, yielding impacts on capital incomes that differ across households according to differences in capital ownership. They also influence the rate at which capital stocks will adjust through time. This affects the speed at which the distributional impacts change with time.

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

3.1.1. Producers and Carbon Dioxide Emissions

The 35 industry categories identify the industries that supply carbon-based fuels and 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, and 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 production 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 percentage 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 of the ultimate CO_2 emissions associated with fossil fuel demand,[15] even though some emissions occur when refined fuels are combusted downstream.

[15] Carbon content of fossil fuels accounts for ultimate CO_2 emissions, except for noncombustible uses of these fuels. In the United States, noncombustible uses currently account for less than 6 percent of fossil fuel use.

3.1.2. 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 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.

3.1.3. Representative Government

The government represents a combination of federal, state, and local governments in the United States. 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. In most simulations,[16] we assume that government transfers are indexed so that they are maintained at reference case levels in real terms. Under a carbon tax policy involving lump-sum rebates, the rebates represent another government outlay.

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

[16] In the E3 model, we set nominal transfers at levels that imply reference case real transfers, where the translation from nominal to real values is based on the consumer price index. To assess the distributional implications of transfer indexing, we compare our central case involving fixed real transfers with a counterfactual case in the DH model in which transfers to each quintile are fixed in nominal terms.

returned to the private sector either through cuts in the marginal rates of existing taxes or through lump-sum rebates.[17]

3.2. 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 match the values for 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

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

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

[17] 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.

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

These first-order conditions determine each household's allocation of expenditure between the consumption composite and leisure, given the wage $\overline{w}$ and the composite price $\overline{p}$. The price $\overline{p}$, 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

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

where $\tilde{p}_{j,t}$ denotes 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 $\alpha_j^{C,q}$; hence the composite price $\overline{p}_t^q$ 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 received endowments only 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

$$W_{t+1}^q - W_t^q = \overline{w}_t \overline{l}_t^{\,q} + \overline{r}_t W_t^q + G_t^q + LS_t^q - T_t^q - \overline{p}_t^q \overline{C}_t^q - \overline{w}_t \ell_t^q \tag{31}$$

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, $\overline{w}_t$ and $\overline{r}_t$, are from the E3 model. We specify them as the same across households in both the reference and policy cases.[18] Total transfers from the E3 model are allocated across the five representative households according to their shares in data described below from the Survey

[18] 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.

of Consumer Finances. This applies in both the reference 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 differing 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 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

4.1. Data Sources

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 6,015 households. The appendix offers details on the elements of each source of income.

We obtain household after-tax incomes by applying tax information from the National Bureau of Economic Research's TAXSIM model (Feenberg and Coutts 1993) to the SCF before-tax data.[19] The TAXSIM data do not break down tax liabilities by income source. To provide this breakdown, we calculate for each household the share of before-tax income from each source and multiply each share by the total tax liability.

We obtain household expenditures on each consumer good using the 2013 Consumer Expenditure Survey (CEX) microdata collected by the US 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 that are followed for only two weeks. To account for a complete listing of expenditures for each household, we combine data from the two surveys. The appendix describes our procedure in detail.

We combine the SCF income data and CEX expenditure data in a way that ensures 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.

[19] The SCF does not provide state of residence. We randomly assign each household to a state based on population weights to determine state tax liabilities.

When defining quintiles, we 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.

Table 3 shows the average after-tax income by source by quintile, and Table 4 shows the average expenditure shares by good by quintile, when quintiles are defined in terms of their total expenditure.

4.2. Achieving Consistency in Aggregation

We adjust the data so that the benchmark outcome of the DH model, when aggregated across households, matches the outcome of the more aggregated E3 model. 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.

4.3. Parameters

Here we briefly describe the household utility parameters for the E3 and DH models.[20] 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 the compensated elasticity of labor supply is 0.3 and the nonlabor income elasticity is 0.25.[21] In the DH model, we

[20] Details are provided in Goulder and Hafstead (2017).

[21] 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 review of recent labor supply estimates.

assume each household spends the same fraction of time working. Given the differences in consumption-leisure ratios, we recalibrate 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 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

5.1. 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. However, 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 plausible 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 *Annual Energy Outlook 2016* (AEO; EIA 2016). We focus on matching AEO 2016 forecasts for economic growth, fossil fuel prices, electric generation shares, and total emissions.[22]

5.2. Carbon Tax Design

We consider a tax with the following features:[23]

Time Profile: The tax starts at $40 per metric ton in 2013$ 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 a 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.[24]

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 emissions from both industrial combustion of the product and combustion of any downstream products.

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

[23] 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 rising at 2 percent above inflation.

[24] The model does not rebate taxes paid on crude oil that is ultimately exported in the form of refined 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.[25] Such recycling leaves unchanged the revenue available to finance government expenditures.

[25] 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 that 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 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.[26] The carbon tax reduces emissions by 17 and 30 percent in 2020 and 2035, respectively. Over the interval 2017–50, 64–68 percent of annual reductions are due to reductions in emissions from the power sector, reflecting electric utilities' substitution away from coal-fired generation and toward natural gas generation and non-fossil-based generation.

Tables 5–7 indicate the carbon tax's impacts on prices of inputs, consumer goods, and returns to factors. Table 5 shows the percentage change in 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 (coal-fired and other fossil electricity generation, petroleum refining, and electricity transmission and distribution). 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 higher relative prices of carbon-intensive inputs motivate producers to substitute away from these inputs, and such substitution represents a channel through which emissions reductions are achieved.

Tables 6 and 7 show the percentage changes in consumer good prices and in returns to factors that result from the carbon tax. A household that relies disproportionately on consumer goods with relatively large percentage increases in prices will experience a larger adverse use-side impact than other households. Similarly, a household that relies disproportionately on a source of income with a relatively large increase in that factor's return will experience a larger positive source-side impact.

The differing percentage changes in these tables underlie differences across households in their use- and source-side impacts. To the extent that households differ in their reliance on the goods and services or sources of income whose prices have changed by different amounts, the household impacts will differ. It should be noted that the choice of numeraire good, by affecting the absolute changes in prices, also affects

[26] Emissions reductions are similar under the other forms of recycling.

the calculated percentage changes. However, the choice of numeraire does not affect the rankings of the percentage changes across goods or across factor returns. Thus, while the percentage changes shown in Tables 6 and 7 stem from a particular numeraire choice,[27] the tables convey which goods and factor returns have the largest relative price changes irrespective of this choice. Hence they indicate the distributional implications of differences across households in expenditure shares or in sources of income.

As indicated in Table 6, the carbon tax causes the largest relative price increases for motor vehicle fuels, fuel oils, electricity, and natural gas. This is in keeping with the high carbon intensities of those goods and services shown in Table 2. Thus the adverse use-side impacts will be disproportionately large for households with higher expenditure shares for these goods. We address the expenditure-share differences in our assessment of distributional impacts in the next section.

Table 7 shows the carbon tax's impact on the after-tax returns to labor, capital, and transfer endowments—the impacts that underlie the source-side effects.[28] The table displays the change in these returns across the four recycling options, for years 2020, 2035, and 2050. Three key results emerge from the table. First, in the shorter term (up to 2020), the return to capital falls relative to the return to labor under every form of recycling except corporate tax recycling. Capital goods are relatively carbon-intensive in their production. As a result, much of the burden of a carbon tax falls on capital. The decline in capital's return relative to labor's is greatest when recycling is via lump-sum rebates. In that case, recycling does not involve any reduction in rates on individual or corporate capital income. In contrast, the return to capital rises relative to the return to labor under corporate tax recycling, reflecting the focused reduction in corporate income tax rates in this case.

Second, over the longer term, the adverse impact on the return to capital tends to diminish. This is in keeping with the adverse impact of the carbon tax on investment. In the longer term, the lower capital intensity of the economy implies higher returns to capital.

Third, in all cases, the carbon tax implies higher nominal transfers. Our simulations assume that transfers are indexed to the consumer price index (CPI). Hence the carbon tax prompts changes in nominal transfers in proportion to the policy-induced change in the CPI. Generally, the carbon tax raises the CPI, and thus the carbon tax implies an increase in nominal transfers. As we will see in the next section, this positive

[27] We employ the consumer good "financial services and insurance" as the numeraire good. We offer our rationale for this choice in Section 7.1.

[28] All figures in the table are in nominal terms. 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.

source-side impact is especially important for low-income households, for whom transfers represent an especially large share of income. Previous studies have pointed out that changes in nominal transfers can significantly influence the source-side impacts of a carbon tax.[29] In the next section, we consider the implications of transfer indexing by comparing our central case outcomes with the results from a counterfactual simulation in which transfers are fixed in nominal terms.

Table 8 shows the GDP and aggregate welfare impacts of the carbon tax in the E3 model under the four forms of recycling. In the model, the corporate income tax is more distortionary than the individual income tax and payroll tax; that is, it has the highest marginal excess burden. Accordingly, recycling through cuts in corporate income tax rates offers the largest benefit, and thus both the GDP costs and the aggregate welfare costs are lowest in this case. The GDP and welfare costs are highest 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.

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

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 households are grouped and ranked by total expenditure.[30] When aggregated, the results from the DH model conform to the more aggregated outcomes of the E3 model.[31]

7.1. Use- and Source-Side Impacts

As indicated in Section 2, in this analysis the overall welfare impacts applying to each household group are expressed as the equivalent variation relative to the household's reference case wealth. This measure of the welfare impact is a ratio whose value is independent of the choice of numeraire. However, the division of the overall welfare impact between the source- and use-side components does depend on the particular numeraire employed.[32] We selected a numeraire under which the carbon tax increases the price of a consumer good according to the increase in cost associated with the direct and indirect carbon intensity of that good. Consistent with this goal, we sought as numeraire a good with an exceptionally low direct and indirect carbon intensity—thus a good whose price is likely to be relatively unaffected by the carbon tax. With such a good as numeraire, the changes in prices of other goods can be attributed to their higher direct and indirect carbon intensities, and hence to the carbon tax itself. Based on these considerations, we chose the

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[30] Expenditure more closely correlates with lifetime income than with income from a single year.

[31] 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.

[32] We are grateful to Gib Metcalf, Don Fullerton, and Rob Williams for pointing this out to us. To see this, imagine that a very carbon-intensive good were chosen as numeraire. In that case, most goods' prices would decline when expressed in terms of that numeraire, suggesting that the carbon tax produced a negative use-side effect. Obtaining a division between use- and source-side impacts consistent with researchers' conceptions of these impacts requires careful choice of numeraire. Williams et al. (2015) provide an insightful discussion of related issues. Rausch et al. (2011) offer an alternative method for examining the distributional implications of the use- and source-side price changes, an approach in which numeraire choice takes on less significance because the focus is mainly on the distributional rather than absolute welfare impact of each effect. Below, we briefly present and evaluate results from the application of this alternative approach.

good in the category "financial services and insurance" as the numeraire good. Table 2 indicates that this good has the lowest carbon intensity of all the consumer goods distinguished in the E3 and DH models.[33]

7.1.1. 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.

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, one that accounts for policy-induced changes in the price of leisure.

Figure 4 gives rise to four key findings. First, under each of the 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).[34]

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 magnitude 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

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[33] Instead of choosing a single good, one could consider employing a broad price index as numeraire. But this poses difficulties because such an index would already incorporate the prices of carbon-intensive goods and thus would be affected by the carbon tax's impact on prices. One wants to be able to evaluate price changes relative to the numeraire, and this is not possible if the numeraire itself already incorporates the price impacts. Using the CPI, for example, would imply that a carbon tax induced no change in average consumer good prices, which in turn would imply that the use-side impact is zero and that all the impact is on the source side. Analogous difficulties arise with the use of producer-good-related indices. A further difficulty is that calculating the index itself requires prior choice of numeraire: one cannot calculate any price index without already having chosen a numeraire to obtain the values of the prices on which the index is built.

[34] 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.

with the fact that the corporate tax induces households to save more and consume less, which implies smaller increases in consumer good prices.

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. Accounting for the increased price of leisure enlarges the use-side effect.

Figure 5 shows the use-side impacts when measured over time intervals rather than at points in time, indicating the effects over the intervals 2018–20 and 2018–40, as well as over the interval of infinite length that begins in 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.[35]

The results in Figure 5 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 leisure again expands the adverse welfare impact in the cases of recycling via cuts in the payroll tax or individual income tax.

7.1.2. Source-Side Impacts

Now we consider the source-side impacts. These reflect the changes in the values of sources of income or leisure, measured in nominal terms. Nominal values are appropriate since the use-side impacts already account for how changes in goods prices affect the real purchasing power associated with given levels of nominal income or endowment value. Again, we examine 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. The impacts depend on the nature 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 consider alternative rebate schemes aimed at achieving certain distributional objectives.) In the cases involving recycling via cuts in marginal tax rates, the tax rate cuts are in the same proportion for all households.

In each figure, the left-hand column shows results based on the narrower, typical "income-only" measure of the source-side impact, one that considers only the policy's effects on after-tax labor income,

[35] 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.

after-tax capital income, and transfer income. The right-hand column offers a measure that is broader in that it considers the impact of policy on each household's overall endowment of labor—the sum of the value of labor supplied and the value of the household's nonlabor (leisure) time. The broader measure can offer a more accurate assessment of the welfare consequences of changes in labor supply. When a household decides to work less, its labor income is reduced. A welfare measure that considers only this loss of income would overstate the welfare loss associated with this change, since the value of the increase in nonwork (leisure) time compensates to an extent for the reduction in income. Our broader measure accounts for this offset.[36]

The key messages from Figures 6 and 7 are similar. First, in almost every case, 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 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 generally progressive—although there are some exceptions in some years under corporate income tax recycling.[37] 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 returns to labor, as 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

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[36] 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 can 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 perfectly match the overall welfare impact, as measured by the equivalent variation for the period or interval in question.

[37] In the short term under the income-only measure, the results are close to proportional under payroll tax and individual income tax recycling.

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.

Rausch et al. (2011) offer an alternative approach for identifying the distributional impacts on the use and source sides. Their approach employs two counterfactual simulations. In one, all households are specified as having equal expenditure shares across goods. This simulation helps focus on the source-side distributional impact by indicating what the overall (use- plus source-side) welfare impact would be if the use-side impact were distributionally neutral—that is, if all households experienced the same (average) use-side impact. The authors find that in this case, the overall impact is significantly progressive. We have performed the same counterfactual with our models and data and also obtain progressive overall impacts under all forms of recycling.[38] In the other counterfactual simulation, Rausch et al. specify all households as having identical income shares. This helps isolate the distribution of the impacts from the use side. The welfare impact is negative and regressive in this case. We obtain similar results under all forms of recycling when we implement this approach in our model. An attraction of this approach is that the choice of numeraire has little bearing on the results. It is worth noting that in contrast with the main approach used in this paper, the Rausch et al. approach does not separate the use- and source-side impacts. Rather, it shows what the combined use- and source-side impact would be if one of the effects had homogeneous impacts across households.

7.2. 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 illustrate 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 absolute size of the impacts is 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

[38] This squares with our earlier finding that the source-side impact, when separated from the use-side effect, is progressive. The progressivity is strongest under lump-sum rebates and weakest under corporate income tax cuts.

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, which, as mentioned earlier, is often 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 by income puts more retirees in the lowest quintile than 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 often smaller when households are ranked by income. The overall shapes of the impacts are fairly similar.39

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 scale of the impacts for a given quintile does not change much over time, a reflection of the higher rates of investment and higher incomes associated with the corporate tax cuts. This growing beneficial impact offsets the potentially increasing adverse impact of rising carbon tax rates.

[39] Other studies have observed larger differences between the results under expenditure- and income-ranked household groups. For example, Fullerton and Heutel (2010) find that ranking by expenditure implies significantly greater regressivity on the use side. Metcalf et al. (2012) obtain significantly less regressivity in this case.

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

Many commentators 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 source side. As a percentage 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 indicates, over the longer term, quintiles 2 and 3 experience welfare losses under recycling involving marginal rate cuts. (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 two sets of "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 prevent a welfare loss to quintile 2 (upper figure) or quintiles 2 and 3 (lower figure). Under the former hybrid policies, quintiles 1 and 2 are better off relative to the corresponding pure recycling policies, 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).[40]

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 these cost increases 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.[41] This opportunity cost is highest when compensation takes away revenues that otherwise would have been used to cut corporate income taxes. As mentioned earlier, 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 quintiles 3 and 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.

[40] More complex policies could involve levels of compensation that were differentiated across the targeted quintiles in such a way as to prevent an increase in welfare to the representative household in any of the targeted quintiles.

[41] Under the hybrid policies that prevent a welfare loss to the representative household in the second quintile, the targeted lump-sum 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 quintiles, compensation reduces gross revenues for cuts in payroll, individual, and corporate taxes by 16.9, 15.6, and 10.8 percent, respectively.

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 US policy, government transfers are indexed to inflation. Accordingly, in our central analysis, we assume in both the E3 and DH models that the time profile of transfers is maintained in real terms for every representative household. By raising the prices of consumer goods, a carbon tax leads to an increase in the price level, which necessitates an increase in nominal transfers. Higher transfers contribute to a positive source-side impact.

To gauge the contribution of transfer indexing to the overall impact on the source side, we consider a counterfactual case where households in the DH model receive fixed nominal transfers. Figure 12 offers a comparison of results in the indexed transfers (left side) and fixed nominal transfers (right side) cases. 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 slightly regressive under tax recycling options. Thus 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 display the overall welfare impacts across households for three time intervals in cases of indexed and fixed (nonindexed) nominal transfers. Over the longer term, the welfare impact is negative for all households under all recycling options when transfers are fixed in nominal terms, except for quintile 1 under recycling via lump-sum rebates. As in the earlier cases involving indexed transfers, the outcome is strongly progressive under lump-sum recycling. But in contrast with the indexed transfers 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 the indexing of transfers contributes significantly to progressive outcomes. In fact, in the DH model, 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 US households, considering both source- and use-side impacts under a variety 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 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.[42] We also find larger source- and use-side impacts than what the 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 of compensation are about an order of magnitude higher when remaining revenues are to be used for corporate income tax cuts than when the remaining

[42] 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.

revenues are used in other ways. 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 caveats are in order. First, our analysis has not considered the extent of heterogeneity of impacts within quintiles.[43] Second, we have considered the distributional impacts across only 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 an 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.

[43] 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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Tables and Figures

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

Industry	Output[a]	Pct. of total output	Energy input[b]	Energy value share	Carbon intensity[c]
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
Non-fossil 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	1,365.6	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	1,376.8	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	1,010.5	3.9%	68.2	6.7%	0.00016
Trade	2,465.6	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	1,186.1	4.5%	5.3	0.4%	0.00009
Services	9,935.6	38.0%	125.8	1.3%	0.00014
Real estate and owner-occupied housing	2,606.8	10.0%	90.9	3.5%	0.00016
Total	**26,148.1**	**100%**	**1,549.6**	**5.9%**	

[a] In billions of 2013$.
[b] In billions of 2013$. Energy inputs include the values of purchases of fossil fuels, wholesale electricity, distributed natural gas, and refined petroleum products.
[c] Metric tons of catbon dioxide emissons per dollar.

Table 2. Consumption Good Benchmark Expenditures and Carbon Intensities

Consumption category	Consumption[a]	Pct. of total consumption	Carbon intensity[b]
Motor vehicles	549.0	4.8%	0.00026
Furnishings and household equipment	394.5	3.4%	0.00035
Recreation	1,022.1	8.9%	0.00020
Clothing	425.8	3.7%	0.00025
Health care	2,372.1	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	1,780.9	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 accommodations	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	**11,478.9**	**100.0%**	

[a] In billions of 2013$.

[b] Metric tons of carbon dioxide emissions per dollar.

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 Good 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	0.7	1.9	2.4
Natural gas extraction	–13.6	–0.1	0.1
Coal mining	–16.8	–2.5	0.4
Electric transmission and distribution	10.1	14.9	16.1
Coal-fired electricity generation	40.2	75.4	106.6
Other fossil electricity generation	21.6	31.8	41.0
Non-fossil electricity generation	17.7	6.6	3.0
Natural gas distribution	5.9	15.2	20.3
Petroleum refining	13.0	16.5	19.7
Pipeline transportation	0.3	3.6	4.6
Mining support activities	0.4	1.8	2.1
Other mining	–0.8	0.4	0.5
Farms, forestry, fishing	0.4	1.3	1.5
Water utilities	0.3	0.4	0.6
Construction	0.4	0.7	0.8
Wood products	0.2	0.8	0.9
Nonmetallic mineral products	0.2	1.1	1.3
Primary metals	1.1	2.3	2.5
Fabricated metal products	0.1	0.7	0.8
Machinery and misc. manufacturing	–0.4	0.3	0.3
Motor vehicles	–0.1	0.5	0.5
Food and beverage	0.3	0.9	1.0
Textile, apparel, leather	0.1	0.4	0.5
Paper and printing	0.3	1.0	1.1
Chemicals, plastics, and rubber	1.1	2.6	2.9
Trade	–0.1	0.1	0.1
Air transportation	2.0	3.1	3.6
Railroad transportation	–1.5	0.4	0.9
Water transportation	1.8	2.7	3.1
Truck transportation	1.9	2.6	2.8
Transit and ground passenger transportation	1.1	1.3	1.4
Other transportation and warehousing	0.4	0.8	0.8
Communication and information	–0.2	–0.1	0.0
Services	0.0	0.0	0.0
Real estate and owner-occupied housing	0.3	0.4	0.6
All industries (Producer Price Index)	**0.8**	**1.6**	**2.0**

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

Consumption category	2020	2035	2050
Motor vehicles	0.0	0.2	0.2
Furnishings and household equipment	0.0	0.4	0.4
Recreation	−0.1	0.1	0.1
Clothing	−0.1	0.2	0.1
Health care	0.0	0.1	0.2
Education	0.0	−0.1	−0.1
Communication	−0.2	−0.1	0.0
Food	0.2	0.6	0.7
Alcohol	0.2	0.5	0.6
Motor vehicle fuels (and lubricants and fluids)	7.5	10.2	12.8
Fuel oil and other fuels	7.4	10.0	12.5
Personal care	0.1	0.3	0.4
Tobacco	0.3	0.6	0.8
Housing	0.3	0.4	0.6
Water and waste	0.2	0.3	0.5
Electricity	9.7	14.3	15.4
Natural gas	5.6	14.5	19.3
Public ground	0.9	1.2	1.3
Air transportation	1.2	2.0	2.2
Water transportation	1.3	2.0	2.3
Food services and accommodations	0.0	0.0	0.0
Financial services and insurance	0.0	0.0	0.0
Other services	0.0	0.0	0.0
Net foreign travel	1.5	2.4	2.7
All consumer goods (Consumer Price Index)	**0.6**	**1.0**	**1.2**

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

	After-tax wage	After-tax interest rate	Transfers
Lump-sum rebates			
2020	–0.2	–2.2	0.6
2035	–0.5	–1.0	1.0
2050	–0.7	–0.4	1.2
Payroll tax cuts			
2020	0.7	–1.8	0.6
2035	0.4	–0.9	1.0
2050	0.2	–0.4	1.2
Individual income tax cuts			
2020	0.4	–1.2	0.5
2035	0.3	–0.5	0.9
2050	0.1	–0.2	1.1
Corporate income tax cuts			
2020	–0.1	0.4	0.5
2035	0.1	0.1	0.7
2050	0.1	0.0	0.8

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, 2016–50, 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 billion 2013$.

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 billion 2013$.

[b] Numbers in parentheses express percentage changes in welfare costs relative to the "no targeted compensation" case.

Figure 1. Nested Consumption Structure

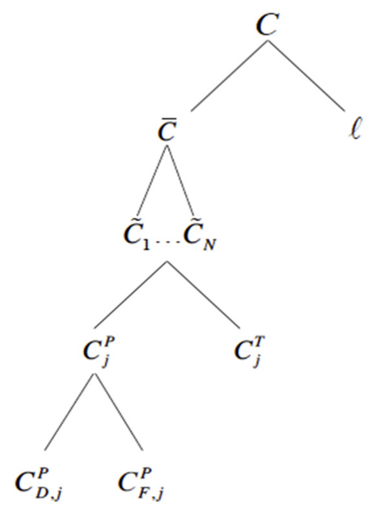


Figure 2. Time Profile of Carbon Tax, 2017–50

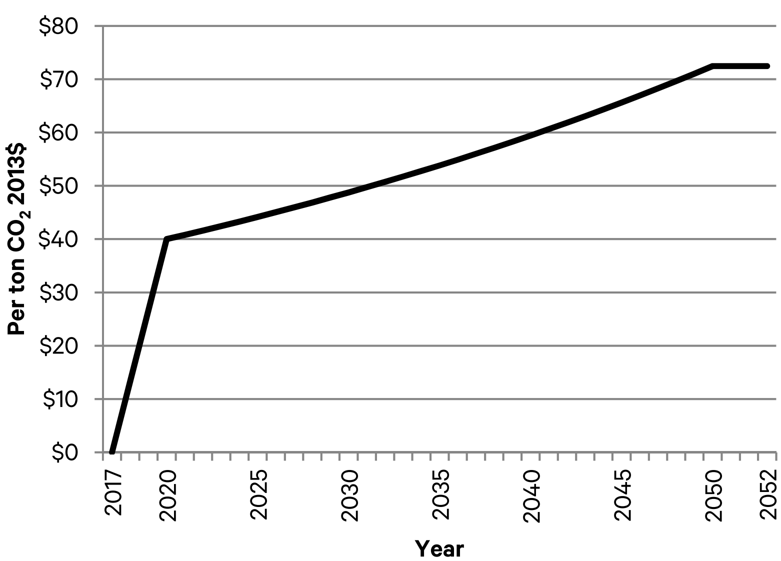


Figure 3. Economy-Wide Carbon Dioxide Emissions, 2017–50

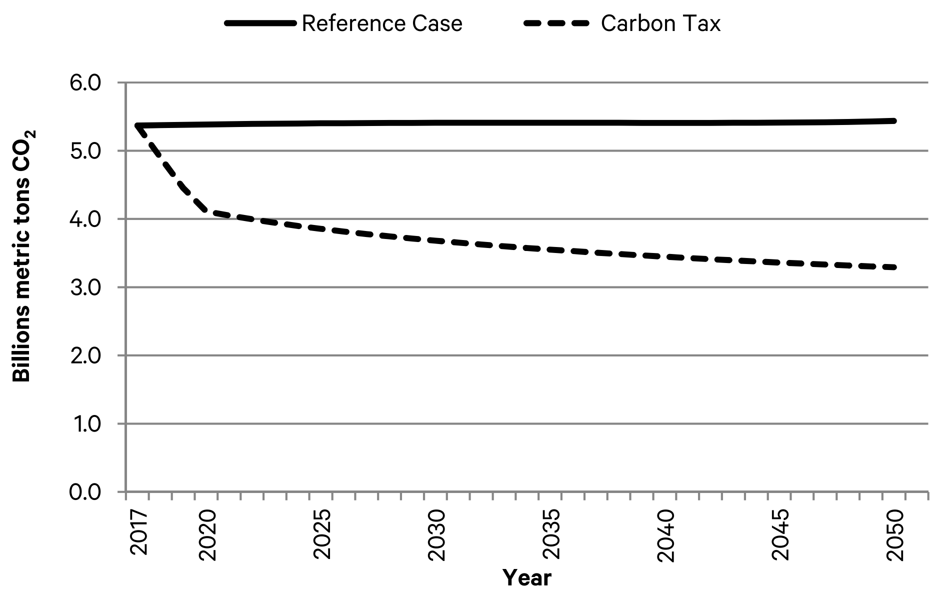
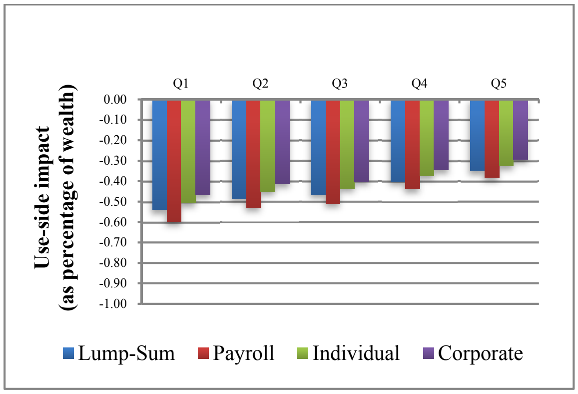
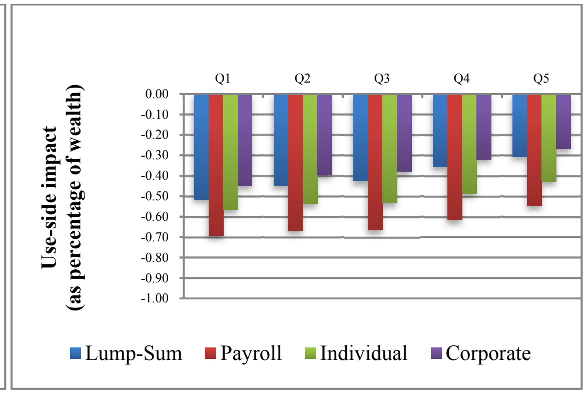


Figure 4. Use-Side Impacts by Year by Quintile

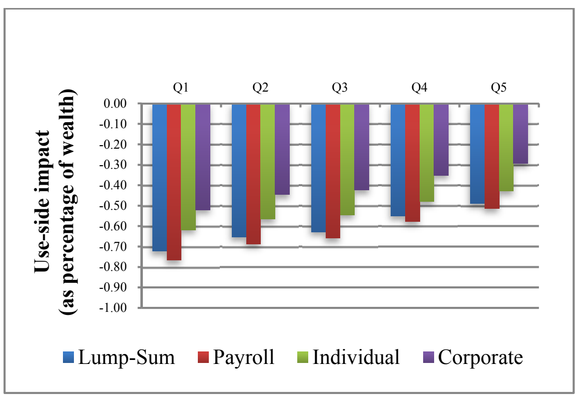
Goods-Only Measure | **Goods and Leisure Measure**

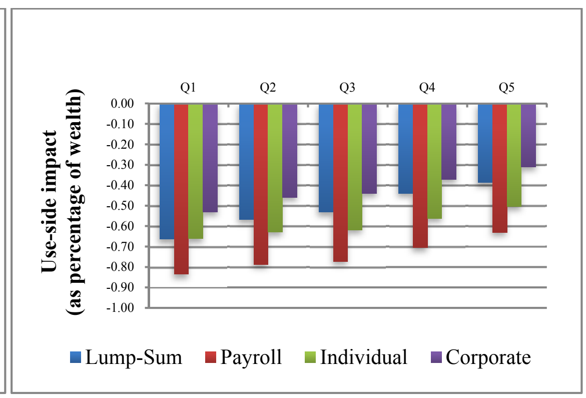
(a) 2020



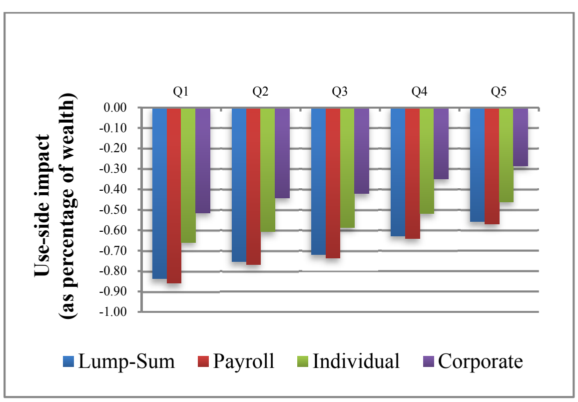


(b) 2030





(c) 2050



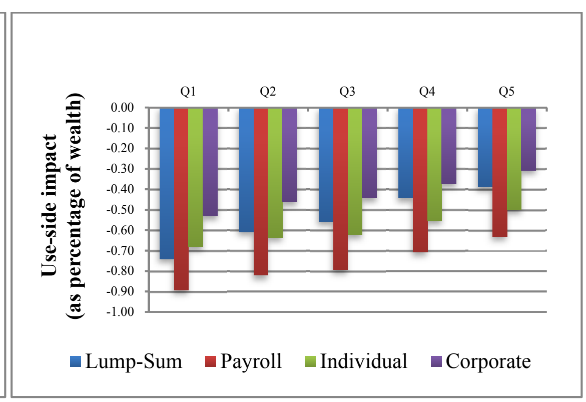
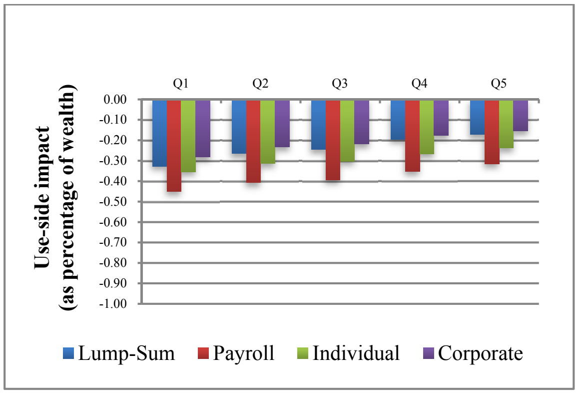
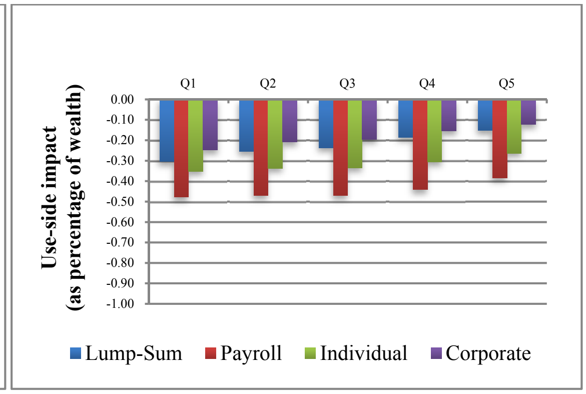


Figure 5. Use-Side Impacts over Time Intervals, by Quintile

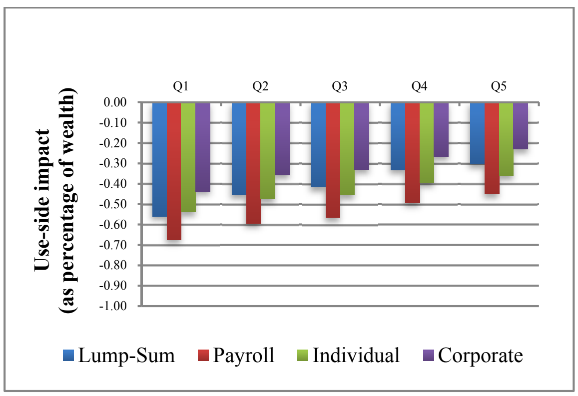
Goods-Only Measure | **Goods and Leisure Measure**

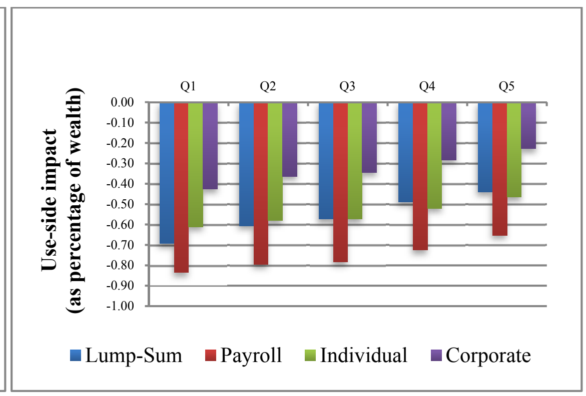
(a) 2018–20



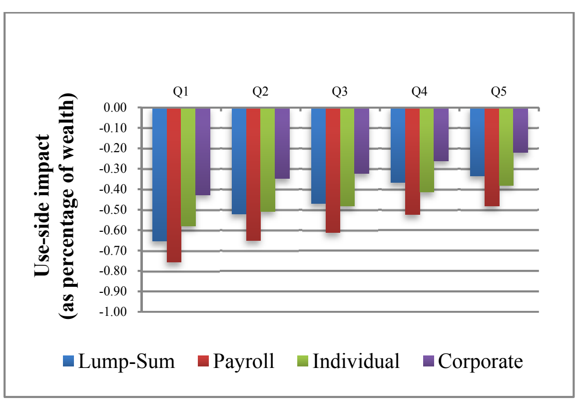


(b) 2018–40





(c) 2018–∞



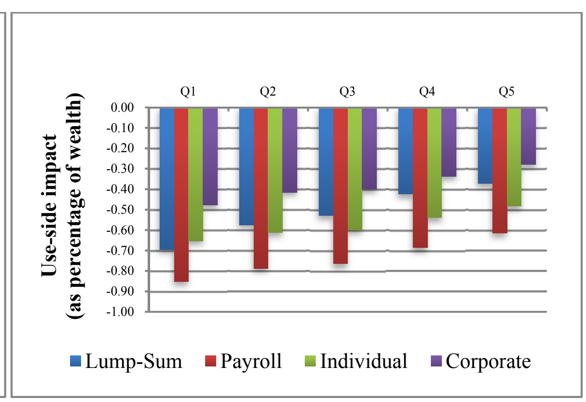
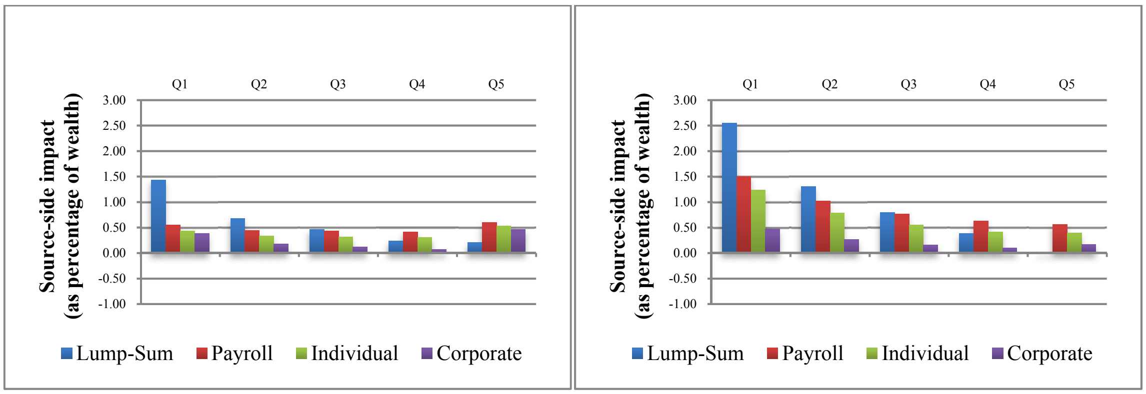


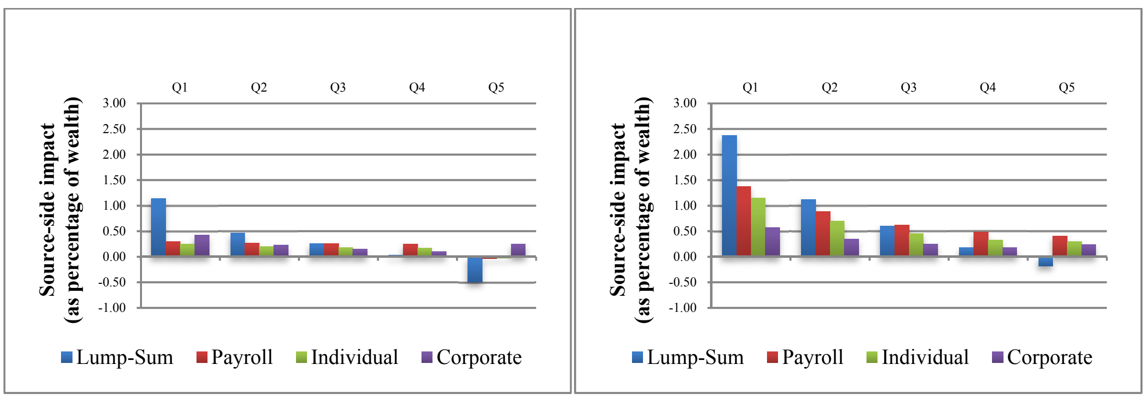
Figure 6. Source-Side Impacts by Year by Quintile

Income-Only Measure | **Full Measure**

(a) 2020



(b) 2030



(c) 2050

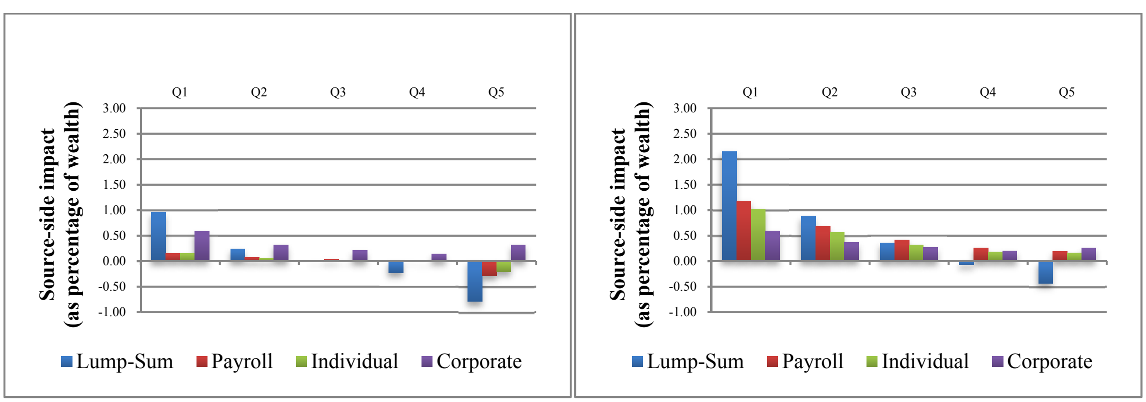
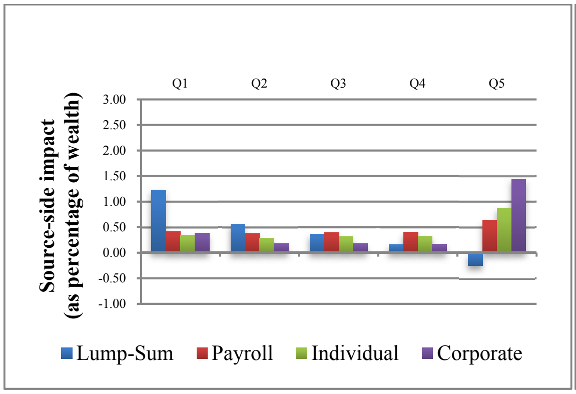
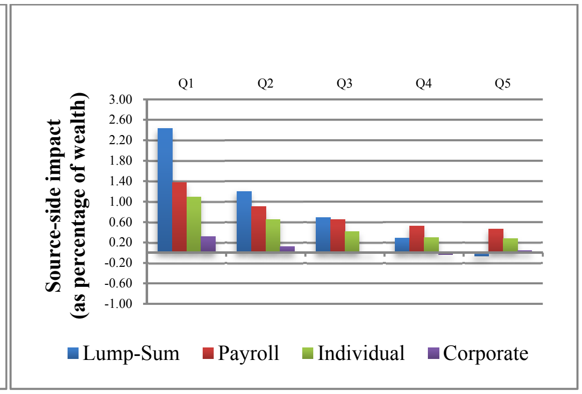


Figure 7. Source-Side Impacts over Time Intervals, by Quintile

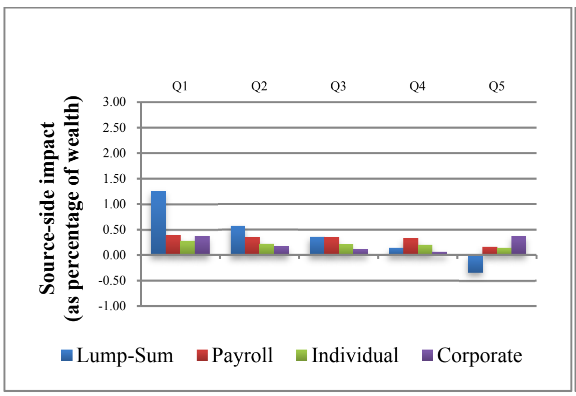
Income-Only Measure | **Full Measure**

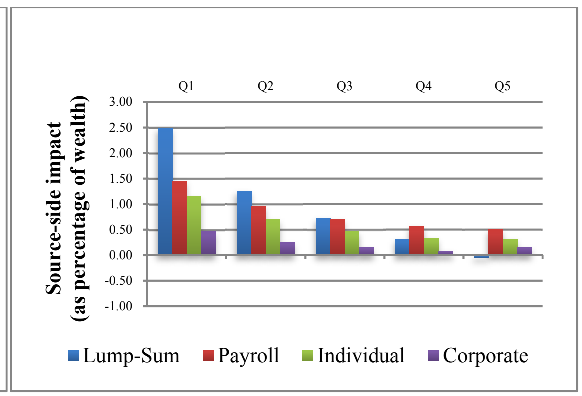
(a) 2018–20



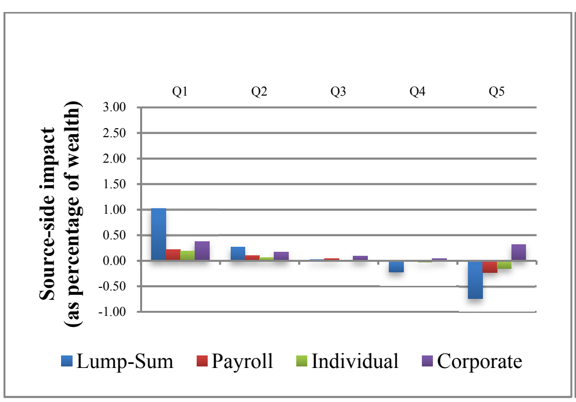


(b) 2018–40





(c) 2018–∞



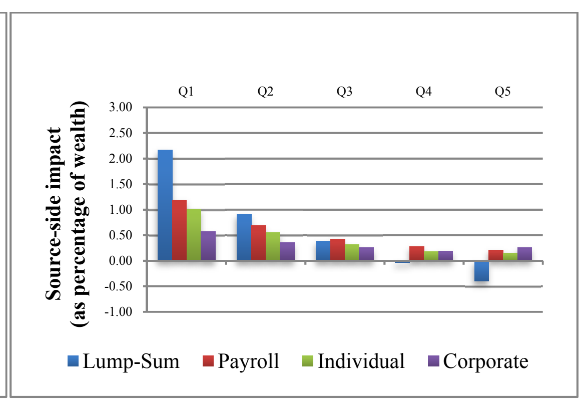
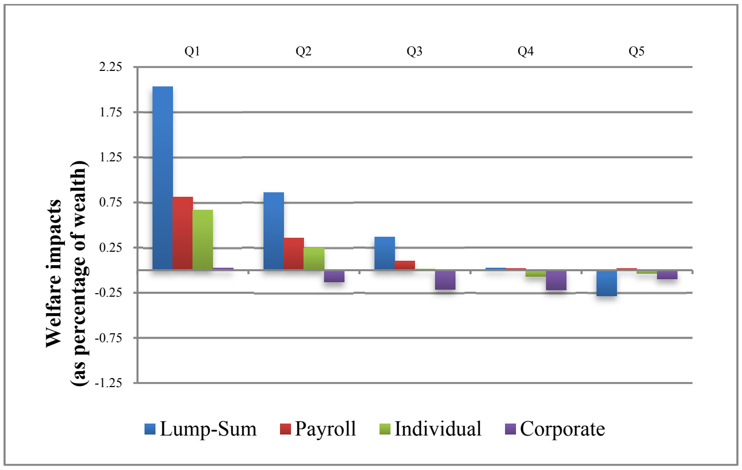
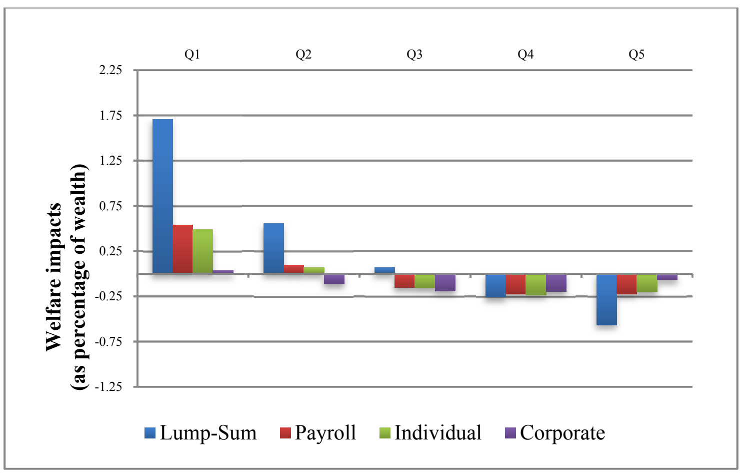


Figure 8. Overall Welfare Impacts by Year, by Quintile

(a) 2020



(b) 2030



(c) 2050

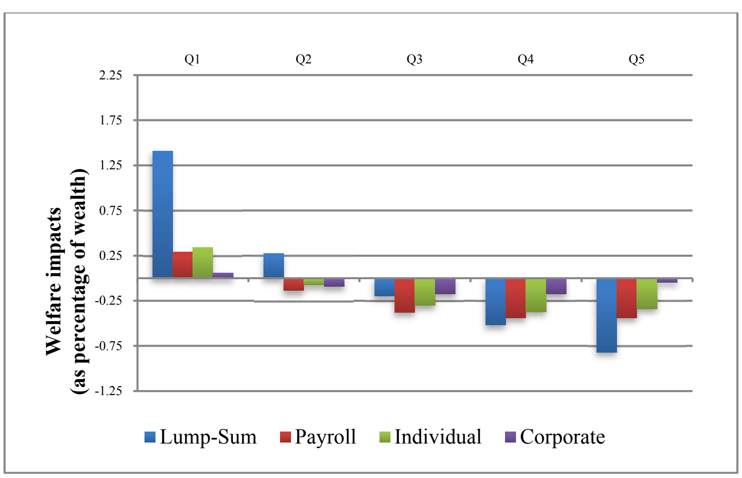
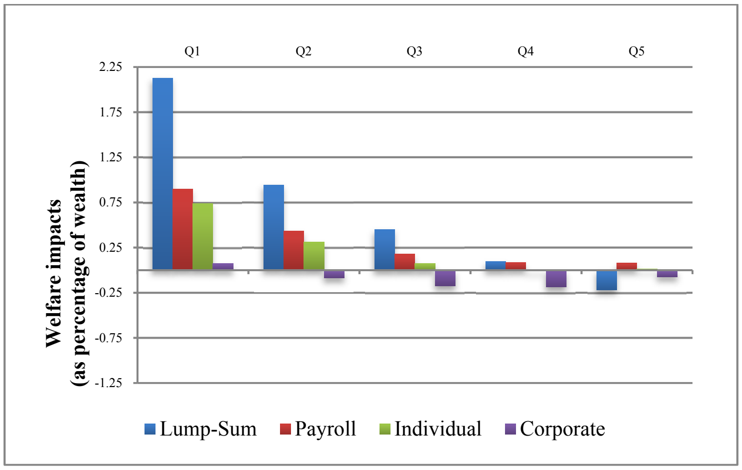
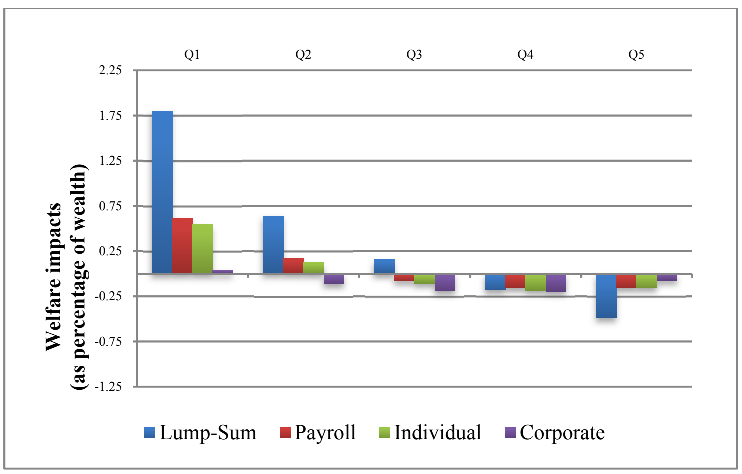


Figure 9. Overall Welfare Impacts over Time Intervals, by Quintile

(a) 2018–20



(b) 2018–40



(c) 2018–∞

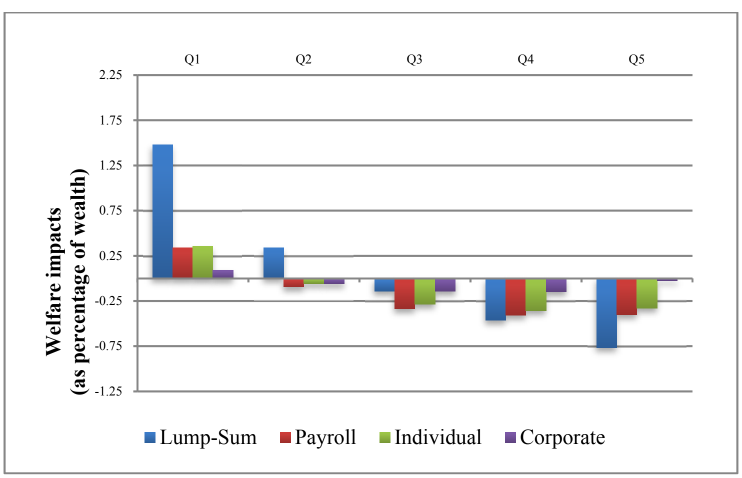
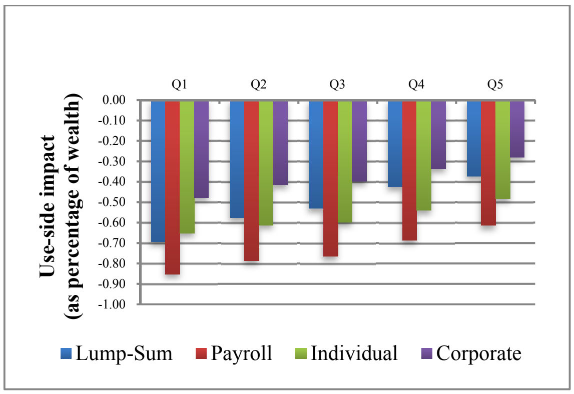
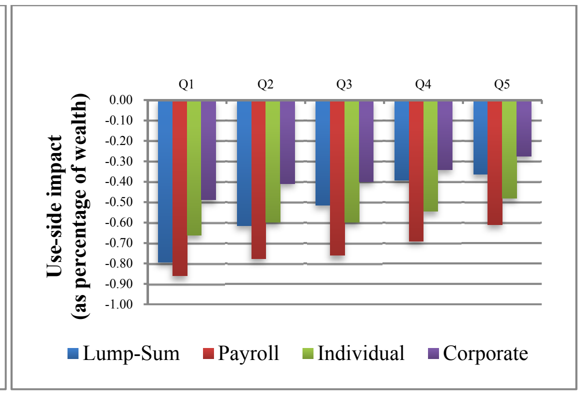


Figure 10. Distributional Impacts over the Infinite Horizon under Alternative Orderings of Households (using full welfare measure)

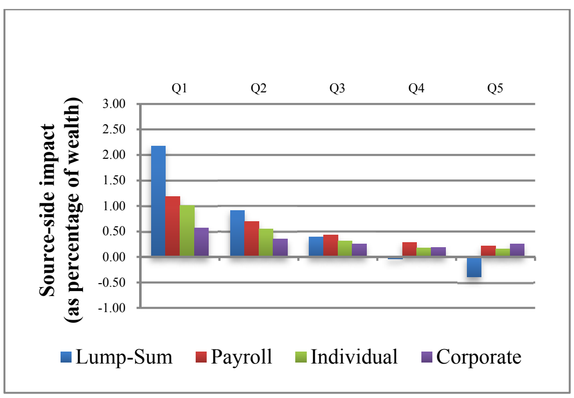
Households Ranked by Expenditure **Households Ranked by Income**

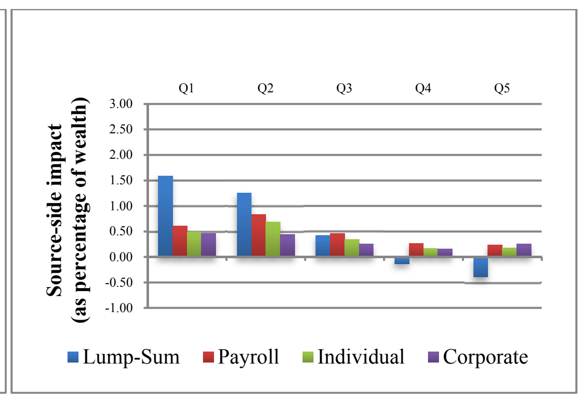
(a) Use-Side Impact



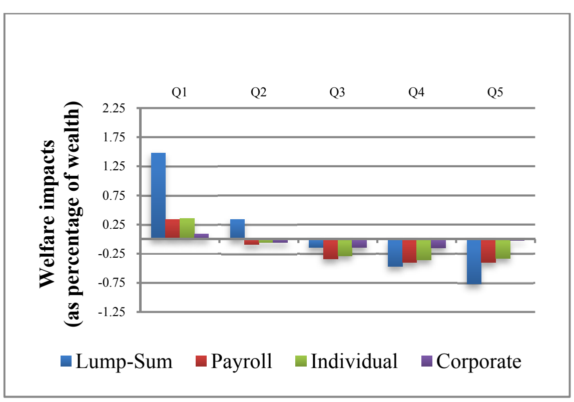


(b) Source-Side Impact





(c) Overall Impact



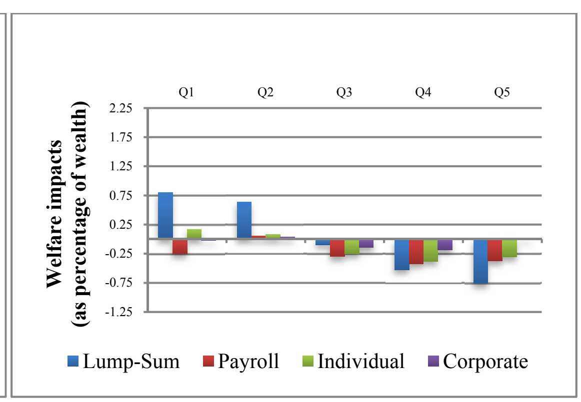
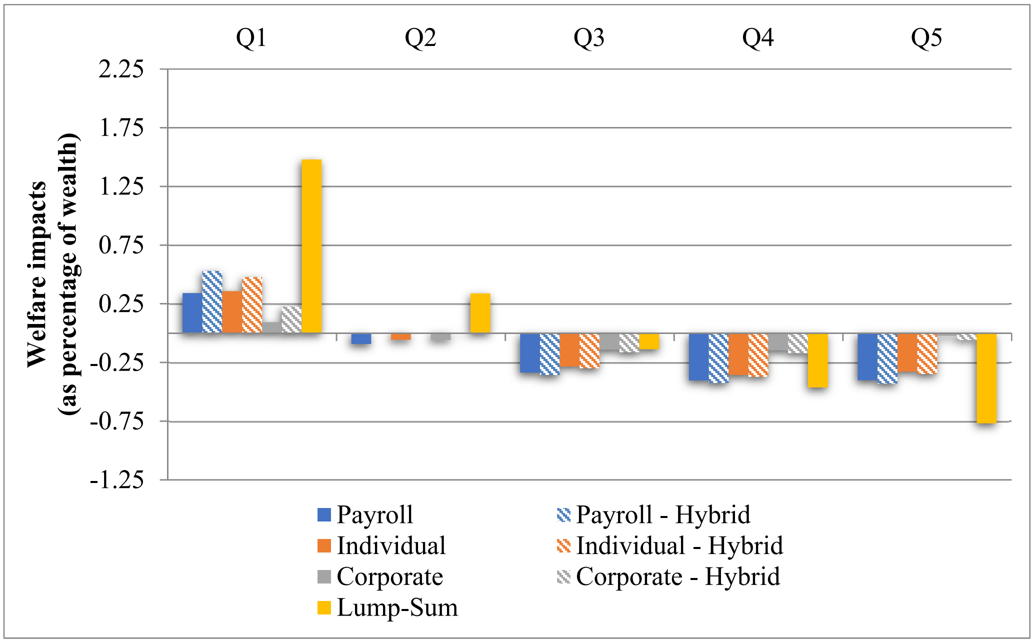


Figure 11. Results under "Pure" and "Hybrid" Revenue Recycling Impacts over the Infinite Horizon, by Quintile

(a) Targeted Compensation to Prevent Loss to Quintile 2



(b) Targeted Compensation to Prevent Loss to Quintiles 2 and 3

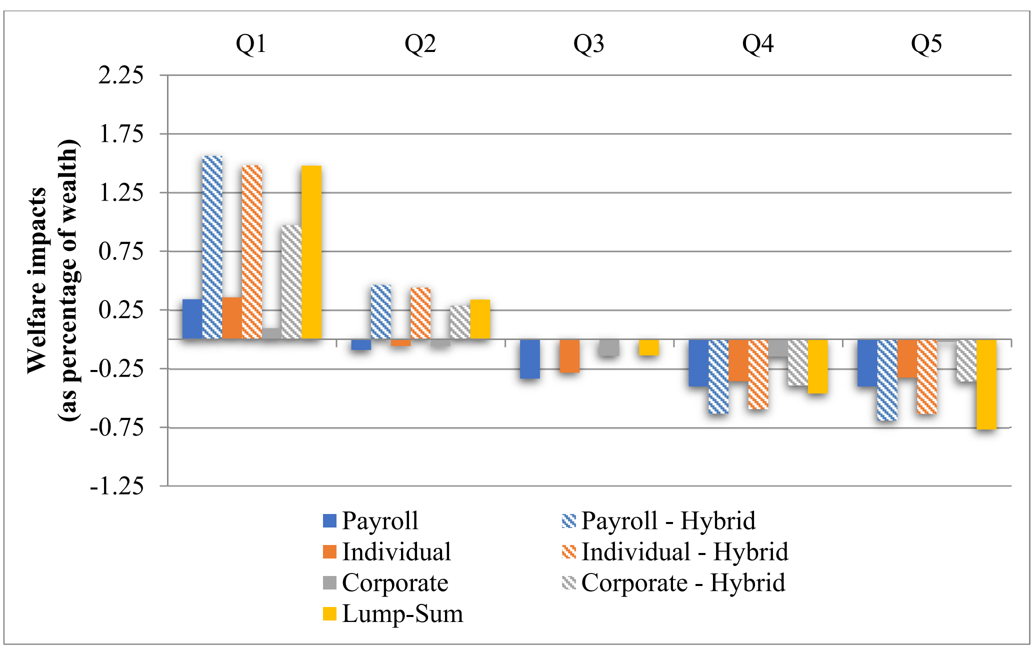
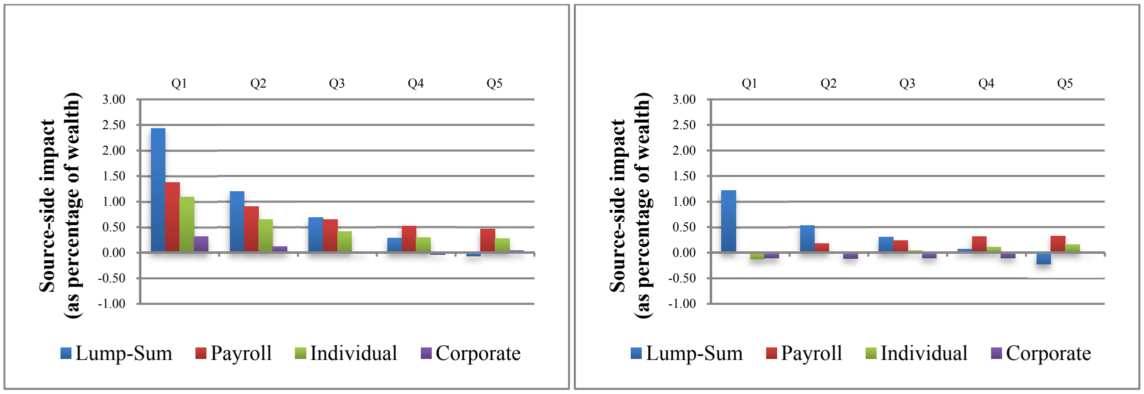


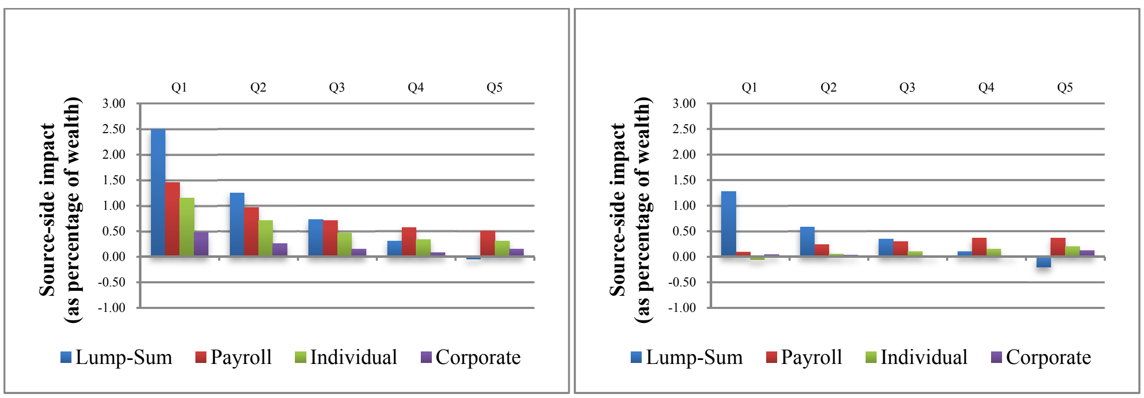
Figure 12. Source-Side Impacts over Time Intervals, Full Measure, by Quintile

Indexed Transfer Income **Fixed Nominal Transfer Income**

(a) 2018–20



(b) 2018–40



(c) 2018–∞

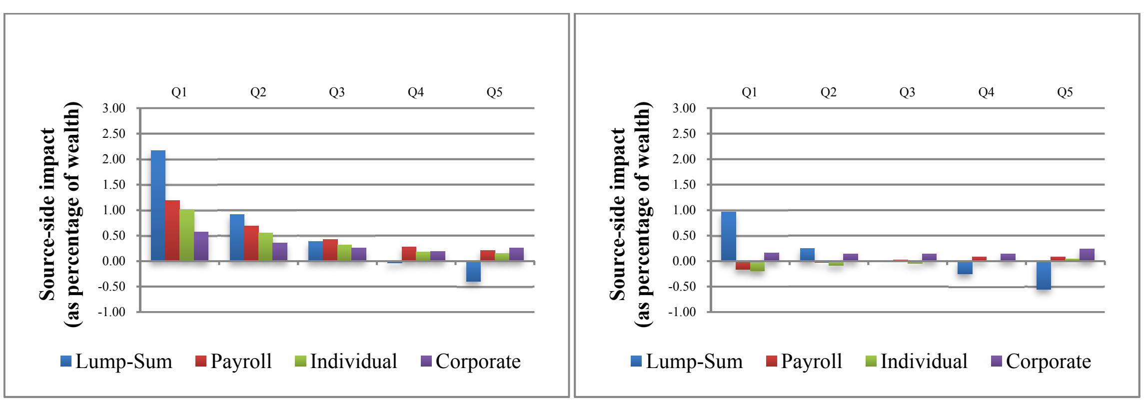
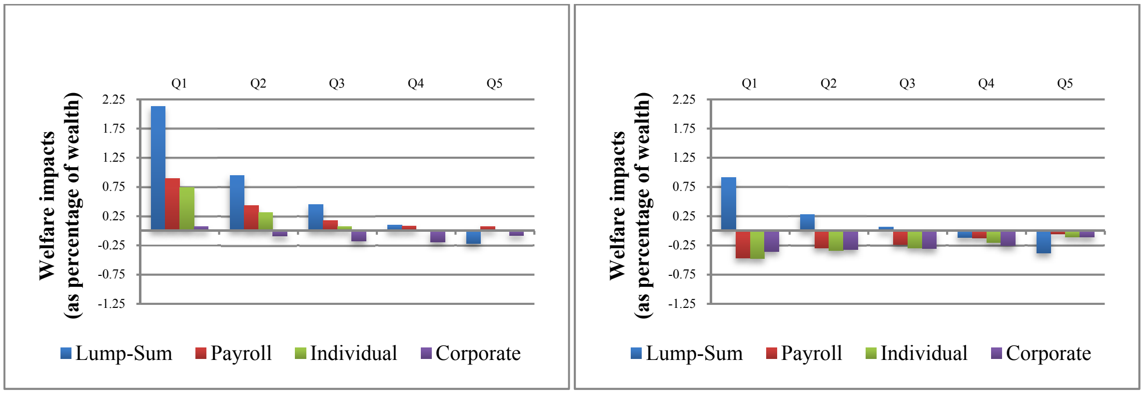


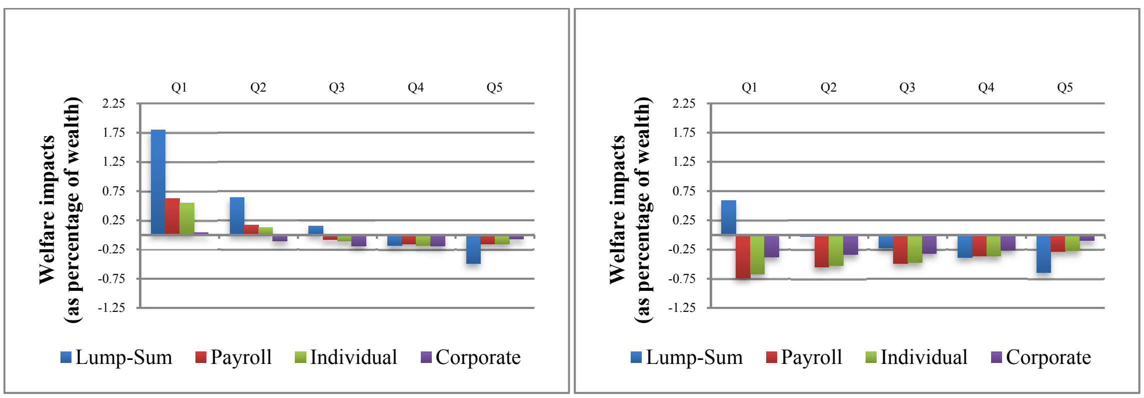
Figure 13. Overall Welfare Impacts over Time Intervals, by Quintile

Indexed Transfer Income | **Fixed Nominal Transfer Income**

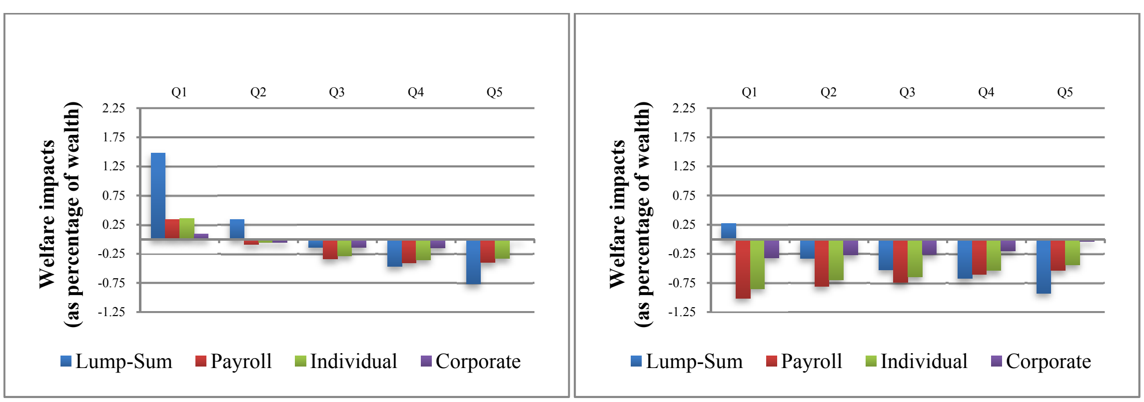
(a) 2018–20



(b) 2018–40



(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 ensure consistency between the income and expenditure data derived from sources.

A. Data

A.1. Income

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 workers' compensation; income from Temporary Assistance for Needy Families (TANF), Supplemental Nutrition Assistance Program (SNAP; food stamps), or other welfare or assistance such as Supplemental Security Income (SSI); and income from nontaxable investments such as municipal bonds.[44] 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 National Bureau of Economic Research'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.

[44] Nontaxable investments are defined as transfer income in TAXSIM. For consistency with TAXSIM, we include nontaxable investments in transfer income when calculating before-tax income.

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 and calculate the share of before-tax income from each source for each household. Then we multiply these shares by the total tax liability. Specifically, we get total federal tax liability, total state tax liability, and Federal Insurance Contributions Act (FICA) tax for each household using TAXSIM. In TAXSIM, FICA is the sum of employee and employer payroll taxes. In the 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 portions paid by employees and employers. Households with no income but positive tax liabilities are dropped. After-tax incomes by income source are then calculated as before-tax income minus the tax liability by source.

A.2. Expenditure

We obtain household expenditures on each consumer good using the 2013 Consumer Expenditure Survey (CEX) microdata collected by the US 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.[45]

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 that 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 that 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.[46] Then we define subgroups using five demographic characteristics: age, education level, marital status, family size, and income decile. Using these subgroups, we combine weighted expenditures for each household in the Interview Survey with each subgroup'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.

---

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

[46] Each household in the microdata represents a given number of households in the US population.

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.[47] Specifically, we match expenditure patterns in the CEX to a similar SCF household. First, we define 720 "CEX cells" using 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 children), 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 is 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 identical nonincome 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, and (3) "average" neighbor, the average decile of the nearest lower- and nearest higher-income neighbors. We assign the SCF record to the cell with the shortest distance. SCF records with no close-neighbor decile, defined as the nearest neighbor at least 2 deciles away, are dropped from our data set.[48] SCF records that have no corresponding CEX cell with the same demographics are dropped from our data set as well.[49]

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.[50] 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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[47] Our method resembles the approach of Cronin et al. (2017).

[48] There are 174 SCF records (out of 30,075) that do not have a nearest neighbor.

[49] Only 10 records in the SCF are dropped because CEX cells with identical nonincome demographics do not contain any CEX households.

[50] The CEX tends to overstate savings rates by household, as tax liabilities are generally underreported 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.