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Carbon tax and revenue recycling: Impacts on households in British Columbia☆

Marisa Beck[a], Nicholas Rivers[b,c], Randall Wigle[a,d], Hidemichi Yonezawa[e,*]

[a] Balsillie School of International Affairs, 67 Erb Street West, Waterloo, ON N2L 6C2, Canada
[b] Graduate School of Public and International Affairs, University of Ottawa, 120 University, Ottawa, ON K1N 6N5, Canada
[c] Institute of the Environment, University of Ottawa, 555 King Edward Avenue, Ottawa, ON K1N 6N5, Canada
[d] School of Business and Economics, Wilfrid Laurier University, 75 University Avenue West, Waterloo, ON N2L 3C5, Canada
[e] Center for Economic Research at ETH (CER-ETH), Department of Management, Technology and Economics, ETH Zurich, Zürichbergstrasse 18, 8032 Zürich, Switzerland

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ABSTRACT

This study investigates the distributional implications of the revenue-neutral carbon tax policy in British Columbia. We use a computable general equilibrium (CGE) model of the Canadian economy and disaggregate households into deciles by annual income using data from a large household expenditure survey. Using the model, we find that the existing BC carbon tax is highly progressive even prior to consideration of the revenue recycling scheme, such that the negative impact of the carbon tax on households with below-median income is smaller than that on households with above-median income. We show that our finding is a result of welfare effects of a carbon tax being determined primarily by the source of a households' income rather than by the destination of its expenditures. Finally, we show that the existing revenue recycling scheme is also progressive. Overall, the tax appears to be highly progressive.

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* Corresponding author. Tel.: +41 446320648.
E-mail addresses: mbeck@balsillieschool.ca (M. Beck), nrivers@uottawa.ca (N. Rivers), rwigle@wlu.ca (R. Wigle), hyonezaw@ethz.ch (H. Yonezawa).

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1. Introduction

In 2008, British Columbia became the first jurisdiction in North America to introduce a meaningful carbon tax. The tax is now \$30/t CO_2, and applies to almost all fossil fuel combustion in the province. To date, there is little empirical research into the policy's environmental or economic impacts. In this paper, we use a computable general equilibrium model to study the impact of the tax on the distribution of household income, a persistent concern accompanying carbon taxes. We find that incidence of the carbon tax in BC falls most heavily on wealthy households, such that the carbon tax appears highly progressive. This finding has important implications for the social acceptability of carbon taxes as greenhouse gas mitigation policies.

A handful of studies have assessed the performance of the tax regime in its first five years. Empirical studies to date focus on questions related to the political process related to the passing of the regulation (Harrison, 2012) or the policy's environmental effectiveness (Elgie, 2012; Rivers and Schaufele, 2012; British Columbia, 2012b) and its economic effects (Rivers and Schaufele, 2014). These studies suggest that the tax has had a modest impact on the level of greenhouse gas emissions in the province, and do not report negative economic impacts.

There is little formal research on the effect of the policy on the distribution of household income in the province. Lee (2011) and Lee and Sanger (2008) use micro-simulation analysis to estimate the impact of the carbon tax on household energy expenditures by income level, and find that a substantial portion of carbon tax revenue should be dedicated to providing low-income household grants to ensure fairness. A number of studies, including Callan et al. (2009) and Grainger and Kolstad (2010) also diagnose strong regressivity of carbon taxes in other jurisdictions using similar micro-simulation models.

Recent research in other contexts, however, has found that the incidence of energy and carbon taxes is dictated by general equilibrium responses and not well approximated by partial equilibrium studies such as Lee (2011) and Lee and Sanger (2008), which only consider the distributional effects resulting from households' consumption of the taxed fuels and other carbon-intensive products. In particular, the incidence of a carbon tax in other jurisdictions is found to be determined by differences in household sources of income as well as by household expenditure patterns. Rausch et al. (2010) determine the distributional impacts of different carbon allowance allocation schemes in the U.S. Their results imply that pure carbon pricing effects independent of allowance allocation schemes is proportional or even mildly progressive due to heterogeneity in income sources among households rather than in consumption. Rausch et al. (2010) explain the progressivity by suggesting that lower income households receive a greater share of their total income from transfers, which remain unchanged by the carbon tax in real terms because they are usually indexed to inflation. Dissou and Siddiqui (2014) use a general equilibrium model to assess the incidence of federal carbon taxes in Canada accounting for changes in both commodity and factor prices. The results imply that tax-induced changes in household expenditures have regressive welfare effects while tax-induced changes in household income have the opposite impact. The study implies that the overall relationship between carbon taxes and inequality is U-shaped: at low tax levels, carbon taxation can reduce inequality but at high tax levels, this effect is reversed. The authors caution that the direction of the impact is highly context specific. Using an analytical general equilibrium model, Fullerton and Heutel (2010) find effects on household income can be progressive, regressive, or U-shaped, depending on parameter values, in particular assumed factor intensities and factor substitution rates. For example, if carbon intensive industries are also capital intensive and capital is easily substituted by labour, returns on capital will decline more than real wages and as such households with greater income shares derived from capital will suffer most from a carbon tax.

We use a static CGE model of the Canadian economy to simulate the effects of the carbon tax and its revenue recycling scheme on the welfare of households with different income levels. We 'backcast' outcomes for the year 2012 to evaluate the distributional impacts of the carbon tax in the first five years of its existence. To this end, we disaggregate households into deciles by annual income and simulate a carbon tax of \$30/t on all combustion GHGs as well as the revenue recycling measures implemented by the BC government including personal income tax cuts and low-income tax credits.

We find the following. First, the BC carbon tax as a stand-alone policy without accompanying programs for revenue recycling is highly progressive (i.e., the *absolute* incidence of the tax falls more heavily on wealthy households than poor households).[1] This result is primarily caused by general equilibrium changes in factor prices that accompany introduction of the carbon tax, rather than by changes in energy prices. Real wages drop, which affects higher-income households more as these are more dependent on labour as an income source. Second, a revenue recycling scheme as implemented in BC can impact the incidence of the tax. In the case of the revenue-recycling measures adopted to accompany the carbon tax in BC the revenue recycling scheme enhances the carbon tax's progressive incidence (i.e., the *differential* incidence of the tax also falls more heavily on wealthy households).[2]

By estimating the distribution of costs and benefits among different income groups this analysis provides important input to the political debate around the carbon tax in BC and potentially other jurisdictions. Insights on distributional effects are of great policy relevance considering that perceived equity and fairness of a carbon tax policy are key to achieving political acceptance. In fact, Harrison and Peet (2012) explain the large variety in local responses to the introduction of the BC carbon tax in 2008 was dictated by the public perception of winners and losers from the regulation rather than evidence of the actual distribution of costs. For example, the regions with the lowest anticipated costs were the ones where opposition was strongest: rural communities in Northern BC perceived the tax as unfair and considered their interests ignored by politicians, while suburban communities in Southern BC remained largely quiet. Similarly, Rabe and Borick (2012) look at de facto carbon tax policies in multiple US states and Canadian provinces and show that the labeling and framing of carbon pricing instruments in the public debate and the use of tax revenues crucially shape public perception of tax proposals.

The organization of the remainder of this paper is as follows. Section 2 describes key design features of the BC carbon tax regime. Section 3 presents the CGE model and data that we use for the analysis of distributive impacts. Section 4 outlines the simulation experiments. Section 5 reports the results, and Section 6 provides sensitivity analysis. Section 7 concludes and suggests policy implications.

2. Overview of the BC carbon tax

The carbon tax is the key policy measure to meet BC's 2020 emission reduction target of reducing GHG emissions by 33% below 2007 levels.[3] The tax covers all greenhouse gas emissions from fossil fuel combustion as well as emissions from combustion of other materials such as tires and peat for energy and heat generation, which together account for an estimated 77% of the Province's total emissions.[4] In 2008, the initial tax rate was set at $10/t$CO_2$e and it has since increased annually by $5/t$CO_2$e per year to reach its final, now constant level of $30/t$CO_2$e in July 2012. The carbon tax applies to fuels purchased or used in BC according to emission factors based on the specific carbon content of the different fuels (greenhouse gases other than carbon dioxide are included and weighted according to 100-year global warming potentials). All sectors and activities are treated the same.[5]

A key design feature of the BC carbon tax policy is revenue neutrality, i.e. the recycling of carbon tax income to BC residents by means of other tax reductions and lump-sum payments (British Columbia, 2012a). In fact to date, the BC government has not only ensured revenue neutrality, but implemented rebates and tax cuts slightly larger than the carbon tax. Each year from 2008 to 2012, the granted tax cuts and transfer payments exceeded carbon tax payments by roughly 10%. For example, in fiscal year 2011/12 total carbon revenue equalled $959 M but recycling measures amounted to $1,141 M. Table 1

[1] Fullerton and Metcalf (2002) divide tax incidence analysis into three variants: absolute, differential and balanced budget.

[2] Since revenue recycling is greater than revenue, combined with the lower tax revenue of non-carbon tax, government deficit is increased in the simulation. Thus, we have to be careful of how to interpret the level of the welfare change. As a sensitivity analysis, we run the scenario with the constant government deficit by using a lump-sum payment from households.

[3] Interim mitigation targets have been set at 6% in 2012 and 18% in 2016. There are a number of other policies implemented in the province to help meet these goals, which we do not consider in the current paper.

[4] The remaining emissions are non-combustion emissions from agriculture, land-use change, and industrial processes.

[5] This changed in BC's 2012 and 2013 budgets, in which the greenhouse sector and the rest of the agriculture sector, respectively, were granted partial exemptions to the carbon tax (Rivers and Schaufele, 2014). We do not model these exemptions in the current paper.

Table 1
Revenue recycling strategy in 2012 ($ M) (%).

Revenue recycling measures	2011/2012
Carbon tax revenue	959
Personal tax measures (total)	470 (41%)
BC Low income climate action tax credit	184
Reduction of 5% in the first two personal income tax rates	220
Northern and Rural Homeowner Benefit of up to $200	66
Business tax measures (total)	671 (59%)
General corporate income tax rate reduction	381
Small business corporate income tax rate reduction	220
Industrial property tax credit	68
School property tax reduction	2
Total revenue measures	1141

provides an overview of recycling measures implemented in the fiscal year 2011/12 and forecast for 2015/16 (British Columbia Ministry of Finance, 2013).

Carbon tax revenue in BC has been disposed through two channels: (a) personal tax reductions and transfers to households and (b) business tax rate reductions and corporate tax credits. In fiscal year 2011/2012, nearly 60% of revenue measures targeted businesses and 40% went to households. Revenue recycling to households combines personal income tax rate reductions and lump-sum transfers, both primarily targeted at protecting low income households. In 2008/09 the government cut the income tax rates for the two bottom brackets by 5% (i.e. for annual taxable income up to $70,000) using carbon tax revenues. In fiscal year 2011/12, $220 M or 23% of total carbon tax revenues were used to fund this personal income tax cut. In terms of direct transfers, the central program implemented to date is the BC Low Income Climate Action Tax Credit program, which received $184 M in support in 2011/12. The maximum Climate Action Tax Credit amounts to $115.50 per adult and $34.50 per child. Eligibility is tied to net household income. In 2011, the full credit could be claimed if net household income was below $31,711 for singles and $36,997 for married couples or single parents.[6] The third recycling measure to support households is the Northern and Rural Area Homeowner Benefit program, which has only received a small share of carbon revenue in 2011/12 ($66 M or 7%). Support of up to $200 is granted to homeowners outside the Capital, Greater Vancouver, and Fraser Valley districts. Eligibility for the homeowner benefit depends on property value and additional criteria related to age and income.

In terms of business measures, the government has cut the provincial corporate income tax rate for both small and general businesses. The general rate was lowered from 12% in 2008 to 10% in 2011. The small business corporate income tax rate declined from 4.5% to 2.5% in 2008. In addition, the small business tax rate threshold was increased from $400,000 in 2009 to $500,000 from January 2010. An Industrial Property Tax Credit of 50% of school property taxes for light and major industrial properties was introduced in 2009 and increased to 60% in 2011. Finally, carbon tax revenues funded a cut in school property taxes for land classified as ‘farm’ starting in 2011.

3. The model

To investigate the distributional impacts of the carbon tax on BC households, we use a static, multi-sector, multi-region, multi-household CGE model of the Canadian economy. This section includes a brief, non-technical overview of the model. A more detailed and formal model description is provided

[6] Households with net income above the threshold are still eligible but not for the maximum credit value. The credit they can claim is reduced by 2% of the amount by which their income exceeds the threshold value. For example, a household with two adults and two children with an annual income below $36,997 would receive the full credit of $300 (i.e. 2*$115.50 plus 2*$34.50). The same family with an annual income of $51,997 (=$36,997 + $15,000) would receive nothing since the reduction is equal to the credit (2% of $15,000).

Table 2
Sectors included in the model.

Mnemonic	Sector
GAS	Natural gas
CRU	Crude oil
COL	Coal mining
OIL	Petroleum and coal products manufacturing
ELE	Electric power generation, transmission and distribution
AGR	Agriculture and forestry
MIN	Other mining
CON	Construction
PPP	Pulp and paper mills
PRM	Primary metal manufacturing
CHM	Chemical manufacturing
CEM	Cement
MFR	Other manufacturing
TRD	Wholesale trade (WHL) and retail trade (RTL)
TRN	Public transport and warehousing
SER	Services
GOV	Government sector

in the Appendix. The model is based on the principles of general equilibrium theory. It combines microeconomic detail to project agents' behaviour with the requirement of market clearing.

The model is calibrated to a dataset that captures characteristics of provincial production and consumption patterns through detailed input–output tables. The data include bilateral trade flows between provinces as well as between each province and the rest of the world. The model also incorporates a detailed tracking of energy flows and greenhouse gas emissions. Furthermore, in order to assess the distributional impacts of the carbon tax, the model includes characteristics of energy spending and income source for different household income classes. There are 10 representative households in each province differentiated by income levels (deciles). Each household is endowed with three primary factors: labour, capital and natural resources. Other than primary factors, each household collects income from government transfers. Households whose current period expenditures exceed current period income finance the difference by borrowing.[7]

The model treats each province as a region with the exception of Prince Edward Island and the Territories which are combined into one region. Canadian regions interact with the rest of the world through exports and imports and in these trades Canada is assumed to be a price taker. The economy is represented by 17 sectors shown in Table 2, including five energy sectors (coal, natural gas, crude oil, refined oil products, and electricity). With the available data, choices on sector disaggregation in the model were made in order to separate carbon-intensive sectors, which allows for differentiated assumptions on carbon intensity and substitutability.

3.1. Factor markets

Markets for all factors are assumed to clear perfectly (i.e., there is no friction in any of the factor markets). Labour is treated as mobile between sectors in each region but immobile between regions, as is conventional. We adopt a putty-clay formulation for the capital stock. In particular, we specify that half of the total capital stock is specific to each sector in each region (clay), while the other half of capital is mobile between both sectors and provinces (putty). This reflects a medium-run model closure, which is appropriate of the context we study. In a sensitivity analysis later in the paper, we examine the impact of changing the capital market closure to allow for capital mobility between sectors, but not between regions, as is common in single-country CGE analysis. The fossil fuel resource factor is specific to three fossil fuel extracting sectors in each region, i.e. coal, crude oil, and gas (i.e., immobile between both regions and sectors).

[7] Full income and expenditure includes leisure. Our treatment of leisure is detailed below.

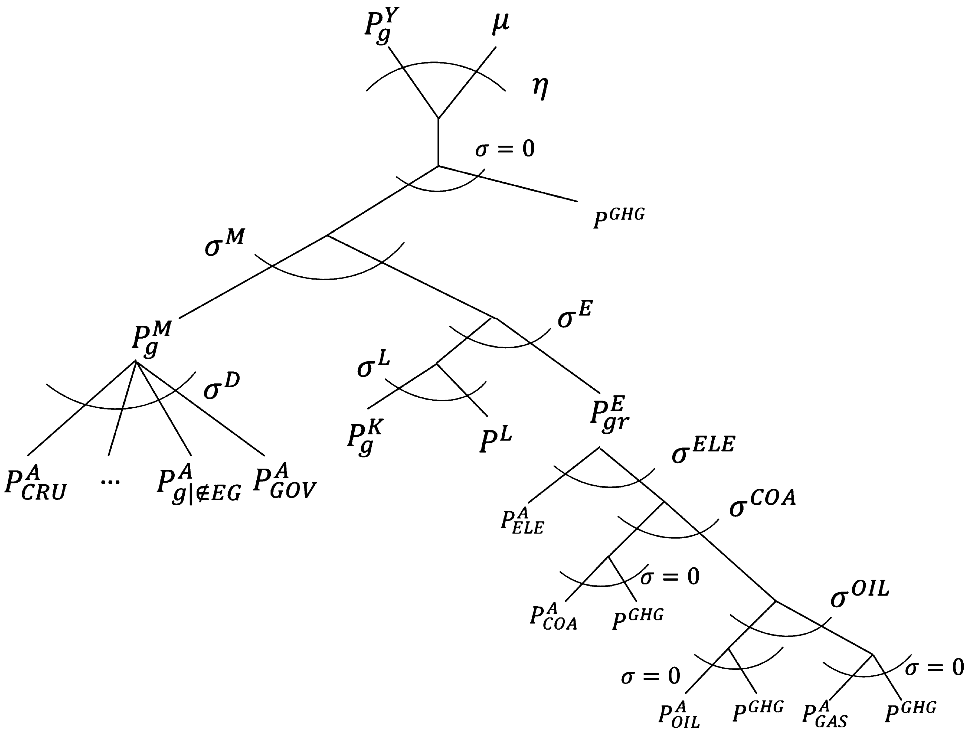

Fig. 1. Production function for non-extractive sector g. Elasticities of substitution are given by σ and elasticities of transformation are given by η. Prices are given by p and μ (the latter is the price of foreign goods). Notation corresponds to algebraic production functions given in the Appendix, and a description of the production function is presented in the text.

3.2. Production

For each region and each sector, nested constant elasticity of substitution (CES) cost functions describe the price-dependent use of capital, labour, energy and materials for the production of commodities other than primary fossil fuels (Fig. 1).[8] Producers choose to substitute between different inputs (labour, capital, different types of energy and materials) to maximize profits. Combustion-related greenhouse gas emissions are generated in fixed proportions to the use of fossil fuels (with emission coefficients that vary by fuel type). Process-related emissions are generated in fixed proportions to sector output (i.e., we do not consider abatement for fixed process emissions, which is appropriate in this context as the BC carbon tax targets only combustion-related emissions).

The production function in Fig. 1 can be described intuitively as follows. At the top level, with a fixed proportion to the output level, non-combustion greenhouse gas emissions are generated. Non-combustion greenhouse gas emissions include emissions from limestone calcination for cement production and emissions associated with the anode consumption in aluminum production, for instance. Because the policy we consider does not cover this type of emission, we do not model abatement opportunities for non-combustion emissions, but do track those emissions. At the second level, a CES composite of non-energy intermediate material demands trades off with an aggregate of energy, capital, and labour subject to a constant elasticity of substitution. At the third level, a CES function describes the substitution possibilities between intermediate demand for the energy aggregate and

[8] The elasticities are summarized in an Appendix.

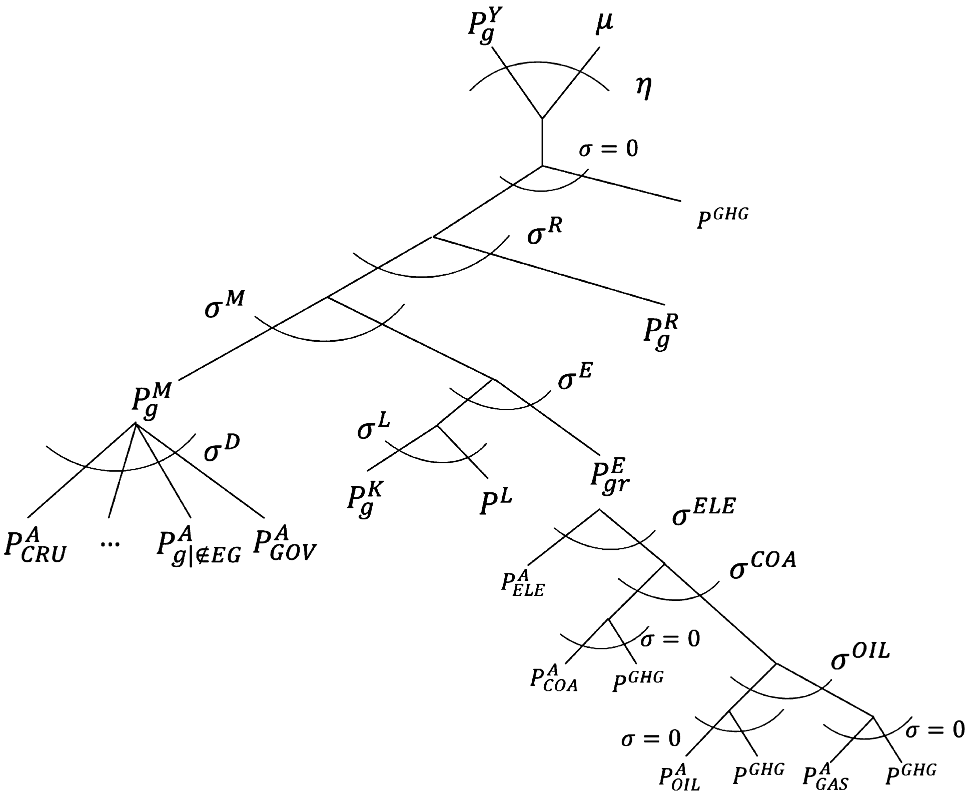

Fig. 2. Production function for extractive sector g. Elasticities of substitution are given by σ and elasticities of transformation are given by η. Prices are given by p and μ (the latter is the price of foreign goods). Notation corresponds to algebraic production functions given in the Appendix, and a description of the production function is presented in the text.

a value-added composite of labour and capital.[9] At the fourth level, capital and labour substitution possibilities within the value-added composite are captured by a CES function. The aggregate energy input is defined as a CES function of electricity and the composite of coal, oil and gas. At the fifth level, the composite coal, oil and gas is a CES function of coal and a CES aggregate of oil and gas. Production output responds to demands from each of the domestic regions and from the rest of the world. The ratio of regional and international prices feeds into a constant elasticity of transformation (CET) function which in turn determines the price-responsive quantities supplied to each province and to the international market. The production of fossil fuels (coal, crude oil and natural gas) is the same structure except that resource factor is combined with the composite of labour, capital, energy and materials (Fig. 2). The corresponding elasticity of substitution is calibrated to match empirical estimates of fossil fuel supply elasticities.

3.3. *Welfare, final consumption, leisure and investment*

Each province includes 10 households differentiated by income levels. Each representative household maximizes welfare subject to a budget constraint. Households receive income from primary

[9] We use the production elasticities in Okagawa and Ban (2008) as our central case. We confirm that our results are insensitive to using the elasticities in Dissou et al. (2012) and alternative nesting structure (capital-energy composite instead of capital-labour composite).

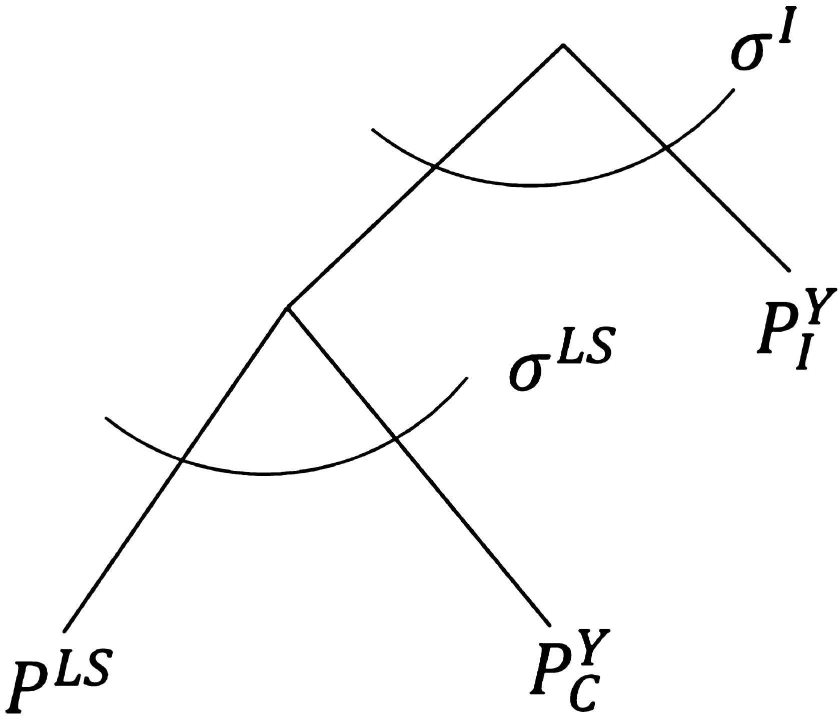

Fig. 3. Welfare function. Elasticities of substitution are given by σ and prices are given by p. Notation corresponds to algebraic functions given in the Appendix, and a description of the function is presented in the text.

factors of production (labour, capital, and natural resources) as well as from government transfers. Households can also borrow to finance current period consumption. The welfare of each household is a function of final consumption, leisure and investment. The nesting structure is shown in Fig. 3. At the top level, a composite of leisure and final consumption trades off with investment. At the second level, a CES function describes the substitution between leisure and final consumption. Final consumption follows the same structure as the production function for non-extractive sectors except that capital and labour input are zero (Fig. 1). The elasticity of substitution between leisure and final consumption is calibrated to the empirical estimates of the labour supply elasticities. Specifically, following the process described in Ballard (2000), we calculate the leisure share and elasticity of substitution between leisure and consumption. We use values of 0.05 and 0.3 for the uncompensated and compensated labour supply elasticities, respectively. These values are consistent with empirical evidence (Cahuc and Zylberberg, 2004).

3.4. Government

The model includes regional governments for each region and one federal government. Government demand is fixed in real terms within each region. To fund public expenditures, governments raise taxes on output, consumption, investment, intermediate goods, and the primary production factors: labour, capital, and natural resources. These rates are calculated from provincial input–output tables and provincial economic accounts. The provincial budget balance in all provinces except BC is unchanged from the benchmark year. The budget balance of the provincial government in BC is adjusted in the counterfactual simulations as explained in the scenario section. The federal budget for each province remains fixed compared to the benchmark year, i.e. the difference between the province's federal tax payments and its federal spending is fixed. Specifically, the assumption of fixed federal budgets for

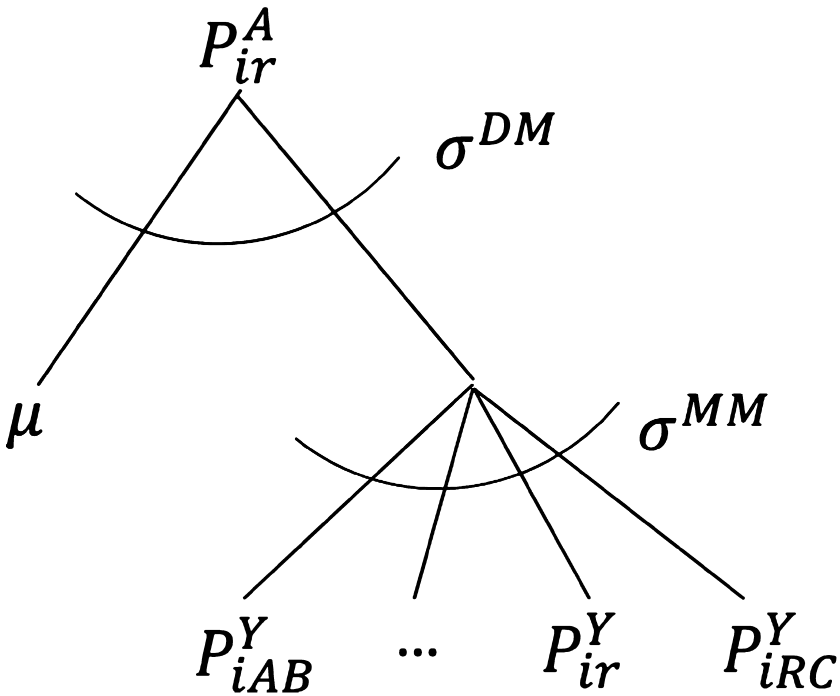

Fig. 4. Production of Armington good i in region r. Elasticities of substitution are given by σ and prices are given by p and μ. Notation corresponds to algebraic functions given in the Appendix, and a description of the function is presented in the text.

each province implies that if BC's federal tax payments decline due to carbon regulation, the federal government will not collect more money from all other provinces to balance the reduced contribution from BC. This eliminates the possibility of a vertical fiscal externality, as described in Böhringer et al. (2014).

3.5. Trade

Sector output in each province is converted through a constant elasticity of transformation function into goods destined for the domestic market (own region or other regions in Canada) and goods destined for international export (Figs. 1 and 2). Imports from other provinces as well as from the rest of the world are modelled using the Armington (1969) approach, which distinguishes goods according to their origin. The nesting structure is shown in Fig. 4. At the top level, a composite of Canadian domestic production trades off with international imports. At the second level, a CES function aggregates goods from all regions in Canada. Canada is modelled as a small open economy; all provinces are assumed to be price takers in the world market. For the country as a whole, the flexible foreign exchange rate makes the Canadian current account fixed at the benchmark.

3.6. Emissions

The model keeps track of all six types of greenhouse gas emissions: CO_2, CH_4, N_2O, HFCs, PFCs and SF_6.[10] Non-CO_2 greenhouse gas emissions are converted to CO_2 equivalent by using a 100-year global warming potential. There are two types of emissions: combustion-related and process-related.

[10] Since HFCs, PFCs and SF_6 are not combustion-related emissions, these emissions are not the target of BC carbon tax. However, they are tracked by the model and reported in the results section.

The first type of emissions is associated with the use of fossil fuels with fixed emission coefficients varying by carbon content of the different fossil fuels. The second type of emissions is associated with the output level of production (e.g., SF_6 is released in aluminum production). The BC carbon tax is imposed only the first type or fossil fuel related combustion emissions. Reduction of combustion-related emissions can be achieved either by switching to fuels with lower carbon content, replacing energy with non-energy factor inputs or reducing output.

3.7. Parameterization

The model is calibrated to the economic transactions in the benchmark year, 2006, as compiled in Statistics Canada's System of National Accounts (Statistics Canada, 2006a,b). Since provincial tables are not as detailed as the national table in terms of sectors, the national table is used to disaggregate some sectors in the provincial tables. Also, data on public expenditures and revenues by provincial and federal governments is retrieved from the public accounts available from Statistics Canada. We adopt the standard calibration procedure in applied general equilibrium analysis, in which free parameters of functional forms (i.e., cost and expenditure functions) are determined so that the economic flows represented in the data are consistent with the optimizing behavior of the economic agents. The elasticities determining agents' responses to price changes are determined exogenously, and they are summarized in an Appendix. To investigate the distributional impacts of BC's carbon tax, we construct a counterfactual benchmark where no carbon tax applies. The benchmark scenario is created through forward-calibration of the 2006 base year data set using Environment Canada projections of sector output by province and energy demand.[11] Our model focuses on evaluation of the BC carbon tax in 2012, when it has reached its full level of \$30/t CO_2.

3.8. Household disaggregation

In order to analyze distributional effects, we disaggregate households into deciles based on income, using data from the Survey of Household Spending (SHS) 2006 produced by Statistics Canada (Statistics Canada, 2012).[12] The SHS collects information on household expenditures and it also contains data on household income and demographics. The SHS is produced annually for the 10 provinces and bi-annually for the territories. In 2006, the sample included more than 21,000 private households across all provinces. Participants were interviewed in person about their spending patterns, dwelling characteristics, and household equipment. Based on this data, for our analysis, we organize households into ten groups, or deciles, of equal number. The ten household groups differ in their composition of income sources and their consumption patterns and are therefore differently affected by the carbon tax.

It is important to acknowledge that the Survey of Household Spending has some potential flaws as a source of comprehensive income and expenditure data. On the expenditure side, data comes primarily from respondent survey responses, and is subject to recall errors. This is potentially a particular problem for durable goods, which are purchased infrequently. On the income side, income from survey data are known to deviate from administrative data as a result of both recall issues as well as differences in accounting that we describe below. However, the Survey of Household Spending is the only source of micro-data available to record both household expenditures and incomes, and this type of data is used in a number of other studies of the type we conduct here.

The main data set underlying our model is the System of National Accounts, which consists of industry input and output tables, as well as final demand tables (including bilateral trade matrices). In order to use the more detailed household data from the SHS in the CGE model, we need to ensure consistency between these two data sets. Specifically, aggregate consumption by commodity in the

[11] We use the forward calibration technique explained in Böhringer et al. (2009).

[12] Current-year expenditure is often considered a better measure of lifetime income than current-year income (Poterba, 1989). We replicated our analysis by grouping households by expenditure rather than income, and the main qualitative conclusions remain identical. Results are available from the authors.

Table 3
Income and expenditure categories for reconciliation of the two data sets: System of National Accounts (SNA) and Survey of Household Spending (SHS).

SNA concept	SHS concept
Income sources	
Wages and salaries	Earnings
Supplementary labour income	
Investment income	Investment income
Transfer income	Transfer income
Expenditure categories	
Petroleum and coal products	Gasoline
	Other fuel
Natural gas	Natural gas
Electricity	Electricity
Public transport and warehousing	Public transport
Other current consumption	Other current consumption
Federal personal income tax	Federal personal income tax
Provincial personal income tax	Provincial personal income tax
Saving	Income–expenditure

Survey of Household Spending must match aggregate household consumption by commodity in the System of National Accounts, and aggregate income by source in the Survey of Household Spending must match aggregate household income by source in the System of National Accounts. In each case, we use the SNA as the reference data set (and leave it unchanged), and reconcile the two data sets by adjusting SHS data to achieve consistency. We describe this process here.

We begin by categorizing each household in the SHS data into income deciles based on pre-tax household income, using household weights provided by Statistics Canada based on Census demographic characteristics. We aggregate all sampled households (after weighting) from the SHS into a representative household for each income decile. Based on SHS data, we retain information on aggregate household income by source as well as aggregate expenditure by category for each representative household.

There are two steps in reconciling household income and expenditure from the constructed SHS representative households with the SNA. First, because accounting and reporting conventions differ somewhat between the SNA and SHS, we need to develop a concordance between different concepts used in the two data sets. Second, because total income and expenditure differ in the two data sets, we need to scale the representative households based on SHS data so that they match the SNA income and expenditure totals.

Table 3 captures how we reconcile income and expenditure by source in the two data sets. Generally, the overall concordance is relatively clear; however, there are some differences to point out. We are able to directly match expenditure categories for energy goods and public transport, which is an energy-intensive sector and likely to be significantly affected by carbon tax. However, we are not able to directly match other expenditure categories at a disaggregate level, so instead we group all other household expenditures as “other.” We accommodate this by assuming all households consume an identical bundle of “other” goods that makes up the reminder of consumption (after accounting for expenditures on energy goods and public transport). After establishing concordance between the two data sets, there remain some differences in concepts. For example, the imputed value of household rent for owner-occupied dwellings is included as income and expenditure in the SNA, but not the SHS. Likewise, the imputed value of financial services is included as expenditure in the SNA but not the SHS. There are also differences in treatment of retirement savings income and in treatment of the non-profit sector. In this paper, we do not attempt to address these differences in concepts, as there is insufficient information available to perfectly match the two data sets.

After establishing concordance between the two data sets, we scale the SHS such that the aggregate value in each category is identical to the SNA total. We conduct the scaling by maintaining the share of earnings or expenditure by household decile constant. Formally, indexing household groups as h, $hh = 1, \ldots, H$, and income and expenditure categories as $m = 1, \ldots, M$, and using the notation $SHS_{h,m}$

Table 4
Benchmark household income source, tax and net saving shares. Calculated by reconciling data from System of National Accounts with data from Survey of Household Spending as described in text.

Household decile	Income (upper)	Labour income share	Investment income share	Transfer income share	Tax share of income	Net saving share of income
hh1	17,000	0.224	0.025	0.751	0.048	−0.894
hh2	26,000	0.392	0.026	0.581	0.063	−0.504
hh3	35,000	0.511	0.030	0.458	0.104	−0.434
hh4	45,000	0.643	0.050	0.306	0.132	−0.389
hh5	55,000	0.758	0.021	0.221	0.141	−0.338
hh6	68,000	0.831	0.025	0.144	0.167	−0.167
hh7	82,000	0.837	0.031	0.132	0.169	−0.069
hh8	100,000	0.884	0.023	0.093	0.169	−0.022
hh9	130,000	0.921	0.025	0.054	0.206	0.074
hh10	+	0.933	0.046	0.021	0.239	0.243

Table 5
Benchmark household consumption shares. Calculated by reconciling data from System of National Accounts with data from Survey of Household Spending as described in text.

Household decile	Natural gas share	Refined petroleum products share	Electricity share	Transportation share	Other consumption share
hh1	0.007	0.024	0.012	0.033	0.925
hh2	0.010	0.033	0.010	0.026	0.921
hh3	0.008	0.034	0.008	0.025	0.926
hh4	0.009	0.034	0.008	0.022	0.927
hh5	0.008	0.034	0.007	0.021	0.930
hh6	0.008	0.032	0.007	0.028	0.925
hh7	0.008	0.037	0.006	0.022	0.927
hh8	0.008	0.033	0.006	0.023	0.930
hh9	0.007	0.034	0.006	0.021	0.933
hh10	0.008	0.026	0.005	0.025	0.936

to refer to household aggregate income or expenditure in category m by group h as determined from the SHS, and SNA_m to refer to aggregate income or expenditure in category m as determined from the SNA, we impute $\widetilde{SNA}_{h,m}$, which is the disaggregate household income and expenditure data reconciled with the SNA data using:

$$\widetilde{SNA}_{h,m} = SNA_m \frac{SHS_{h,m}}{\sum_{hh} SHS_{hh,m}}$$

Tables 4 and 5 show the results of our calculations. Sources of income differ significantly between households. Households in the first income decile earn just 22% of total income from labour, and receive more than 75% from government transfers. The share of labour in earnings increases with income, while the share of income from transfers decreases with income, such that the households in the highest income decile receive income mostly from labour, and the households in the lowest income decile receive income mainly from government transfers. Investment income is least important for all the households except the highest income households.[13] While households at the upper end of the income distribution are net savers, all other households are net borrowers. Income taxes also represent a much larger share of income for the wealthiest households as compared to the poorest households.

[13] One of the potential shortcomings of the SHS is in accounting for income from capital. Rather than reporting total capital income, the SHS reports household income from investments, interest, and dividends, which is a subset of total capital income (the remainder includes depreciation and fixed capital investments by corporations). Our model assumes other capital income is balanced by firm re-investments and depreciation, and focuses especially on household investment income. We also test the sensitivity of our results to changing the assumption about the distribution of investment income. In particular, we try allocating investment income such that the share of investment income across households is identical, such that investment income should not drive the incidence results. We do not find a change in the qualitative results that we present later in the paper. Results are available upon request.

On the consumption side, the share of natural gas, refined petroleum products and transportation in terms of consumption are not significantly different between the households. The electricity share of consumption decreases from the lowest income household to the highest income household although it is a small portion of total consumption.

Tables 4 and 5 provide some intuition into the results we find later in the paper. In particular, it appears from the tables that there is significantly more heterogeneity on the income sources side than on the consumption side. While consumption shares of each good fall within a fairly narrow range for all households, the share of income from labour, investment, and government transfers varies very significantly across households. To the extent that the incidence of the carbon tax is borne differently by different income sources, the impact on different households could be significantly different. In contrast, it would take a very substantial change in product prices for the small differences in consumption shares to impact significantly on relative household welfare.

4. Simulation experiments

We compare two scenarios with a carbon tax against a benchmark scenario where no carbon tax is present. The two scenarios differ in whether a revenue recycling scheme is implemented or not.

No Revenue Recycling: A carbon tax at $30/tCO$_2$e on GHG emissions from combustion is introduced, in line with current legislation. To reveal the 'pure' impact of carbon regulation without any kind of revenue recycling it is assumed that carbon tax revenues are held by the provincial government to reduce the government deficit instead of being redistributed to households and businesses.[14] This allows us to determine the *absolute* incidence of the carbon tax.[15] With this scenario, we also conduct a decomposition exercise. As explained in the previous section, when we split the household into deciles, we consider two types of heterogeneity for each household group: spending pattern and income source. As a decomposition exercise, which is also conducted by Rausch et al. (2010), we conduct two extra scenarios: 1. We run a scenario in which we suppress all heterogeneity between households on the income side, but retain heterogeneity on the expenditure side. This allows us to estimate the welfare effect of expenditure side heterogeneity. 2. We run a scenario in which we suppress all heterogeneity between households on the expenditure side, but retain heterogeneity on the income side. This allows us to estimate the welfare effect of income side heterogeneity.

With Revenue Recycling: In this scenario we model the same $30/tCO$_2$e carbon tax but we also represent the existing BC revenue recycling scheme as closely as possible (Table 6).[16] Table 7 shows which decile receives each type of revenue recycling. The bulk of revenue is recycled through tax reductions (labour and capital taxes), with some being directed to transfers. This allows us to determine the *differential* incidence of the carbon tax.

We model personal income tax cuts associated with the carbon tax as labour tax cuts. As discussed earlier, a significant share of carbon tax revenue has been used to cut the tax rate for the two lowest tax brackets by 5%.

[14] Even by keeping the revenue to reduce the deficit, there are some implications on the distributional impact. First, the government deficit is related to foreign balance and thus foreign exchange rate. However, considering the size of BC economy relative to Canadian economy, the impact on foreign exchange rate is minimal. Second, change in government deficit could have different impact on the households depending on the income level. However, this is beyond the scope of our paper.

[15] We also simulate the case where carbon tax revenues are used to increase the government spending (this determines the *balanced-budget* incidence), and the results are very similar to our case. Although we need to be careful of how to interpret the welfare impact when government deficit is not fixed, in the *absolute* incidence analysis, the way of revenue spending will not distort the distributional impact of the carbon tax because the revenue is not spent at all.

[16] The difference in carbon tax revenue is caused from the difference in the model and reality in terms of the emissions without the policy and the emissions reduction because of the policy.

Table 6
Revenue Recycling: Actual vs. Simulation ($ M).

Tax/Expenditure Measure	2011/12 Actual	Simulation
Carbon Tax Revenue	959	1291
Low Income Tax Credit	184	184
Northern and Rural Homeowner Benefit	66	66
Personal Income Tax Cut	220	220
Business Tax Measures	671	671
Total Revenue Recycling Measures	1141	1141

Table 7
Dollar Values of Revenue Recycled in the simulation ($ M). Personal income tax cut is conducted as marginal tax cut for deciles 1–6 and as lump-sum payment for deciles 7–10.

Household Decile	Low Income Tax Credit	Northern and Rural Homeowner Benefit	Personal income tax cut	Capital tax cut	Total
hh1	46.1	6.6	2.5		
hh2	46.1	6.6	5.6		
hh3	46.1	6.6	11.9		
hh4	46.1	6.6	17.5		
hh5		6.6	24.8		
hh6		6.6	31.5		
hh7		6.6	31.5		
hh8		6.6	31.5		
hh9		6.6	31.5		
hh10		6.6	31.5		
Total	184.5	66.2	219.7	670.7	1141.3

This measure lowers the marginal tax rate for individuals in these brackets but it also lowers the average tax rate for all other individuals.[17] We implement the personal income tax cut as follows: when household income is less than $70,000 (decile 1–6), we reduce the marginal labour tax rate; when household income is more than $70,000 (decile 7 to 10), we maintain constant the marginal tax rate and provide a lump-sum payment corresponding to the reduction in tax rate at the lower income brackets. The size of the tax cut is adjusted such that the total tax cut is equal to the reported tax cut in Table 1.

Direct lump sum payments funded by the carbon tax revenue include the BC low income action tax credit and the Northern and Rural Area Homeowner Benefit program. Only households in the first 4 deciles receive the low income climate action tax credit. We assume that each representative household receives an equivalent amount. Since eligibility for the Northern and Rural Area Homeowner Benefit program is not explicitly linked to an annual income (although the policy is generally targeted at lower income households), we distribute the benefit to each decile equally.[18]

We model business tax cuts as reductions in capital income tax rates. The size of the tax cut is adjusted such that the total tax cut is equal to the reported tax cut in Table 1. As Table 6 shows, the revenue recycling in the simulation represents well the existing revenue recycling.

[17] Income tax in Canada is levied on individual income not household income. Given the complexity of applying personal tax cut within the multi-household model, however, we conduct the personal income tax cut as if household income was personal income.

[18] Since the size of this program is not large, using alternate allocation of the benefit on distribution incidence does not change our qualitative results.

Table 8
Macroeconomic impacts. Welfare change and government deficit change are shown as a percent of benchmark income. "Adjusted" aggregate welfare is calculated by subtracting the increase in government deficit from welfare change. Change in GHG emissions of BC is shown as a percent change from the benchmark.

	No revenue recycling	With revenue recycling
"Adjusted" welfare	−0.13	−0.08
Welfare	−0.53	−0.01
Gov. deficit increase	−0.40	0.07
GHG	−9.22	−9.14

5. Results

5.1. Macroeconomic impacts

We begin by reporting aggregate impacts of the carbon tax. Table 8 shows the effects of the carbon tax on aggregate welfare and GHG emissions in scenarios with and without revenue recycling. In our model, welfare change is measured as the Hicksian equivalent variation and is shown as a percent of benchmark income (like other papers, we ignore the welfare gains from reduced greenhouse gases in this calculation; it should as a result be treated as a cost-effectiveness result rather than as a cost-benefit result). As explained earlier, actual implementation of the carbon tax in BC was associated with a net decrease in government revenue, since revenue recycling measures were larger than the carbon tax revenue. While assuming a flexible government deficit in the model has some merits (simulating "pure" distributional impact of carbon tax and implementing the existing revenue recycling scheme), the level of welfare change could be misleading (as a change in welfare is financed by an change in borrowing). Thus, we report both the welfare change and the change in government deficit that accompanied the policy. When we consider aggregate welfare as opposed to welfare for each household decile, a back-of-envelope calculation for "adjusted" welfare is straightforward (we simply subtract the increase in deficit from the aggregate income of BC).[19]

The carbon tax without revenue recycling worsens household welfare by 0.53%, whereas the carbon tax as actually implemented with revenue recycling worsens welfare by 0.01%. The change in welfare however, does not reflect the change in the government deficit, which increased in conjunction with the tax. If we adjust the welfare change to reflect the change in government deficit, aggregate BC welfare decreases by 0.13% without revenue recycling whereas it decreases by 0.08% with revenue recycling.[20] Our model exhibits a weak double dividend (revenue recycling improves welfare relative to no revenue recycling) but not a strong double dividend (welfare is still negatively affected). Table 8 also shows that the interim 2012 emission reduction target of 6% is met. The magnitude of GHG emissions reduction (9.1%) in our model is comparable to the one reported in Elgie and McClay (2013).

5.2. Distributional impacts

5.2.1. No revenue recycling

The heterogeneity in welfare impacts of the carbon tax is a result of heterogeneity of both spending and income. Carbon taxation affects the relative prices of energy goods and non-energy goods (spending side) and also changes the relative returns on household endowments such as labour, capital, and natural resources (income side). Carbon policy will affect factor prices in different ways because of the factor intensity of each sector, elasticities of substitution between different inputs to production, and the assumption of factor mobility. Depending on the relative contribution of the different endowments on household income, factor price changes will affect households to varying degrees.

[19] This "adjusted" welfare is an approximated estimate that ignores the difference between the households' consumption bundles and government spending bundle. That said, in the scenarios using a lump-sum payment to maintain the government balance in a sensitivity analysis, the change in aggregate BC welfare is similar to this approximated estimate.

[20] Although the revenue from the carbon tax is greater than revenue recycling measures in our simulation, other tax revenues become smaller because of the carbon tax, and the government deficit is increased to keep the government spending constant.

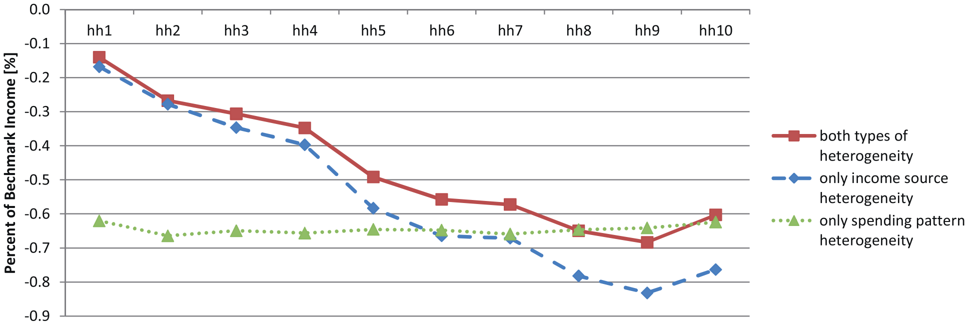

Fig. 5. Welfare impacts of household heterogeneity: Income source heterogeneity vs. spending pattern heterogeneity. Welfare impacts are measured as a percent of benchmark income.

Fig. 5 shows the welfare change from a carbon tax for a representative household in each income group. The line labeled "both types of heterogeneity" considers both income source and spending pattern heterogeneity. The downward slope of the line, which indicates greater welfare losses at higher levels of income, suggests that the carbon tax is a progressive policy. All households experience losses but households in higher deciles experience increasingly adverse impacts. The line labeled "only income source heterogeneity" eliminates the spending pattern heterogeneity to isolate the effect from income side. The distributional impact of the income-side effect is progressive and similar to the one with both types of heterogeneity. The line labeled "only spending pattern heterogeneity" eliminates the income source heterogeneity to isolate the effect from spending side. The distributional impact of the spending-side effect is neither progressive or regressive but proportional, and it is quite different from the one with both types of heterogeneity. In other words, the progressivity of the carbon tax comes from the income source heterogeneity.

The proportionality of the spending pattern heterogeneity might be surprising because the previous literature normally argues that the spending pattern heterogeneity leads to the regressivity (Rausch et al. (2010), Rausch et al. (2011), and Dissou and Siddiqui (2014)). These results are caused by the higher energy expenditure share of low-income households. For example, Rausch et al. (2011) shows the clear pattern of higher share of electricity and natural gas expenditure for low-income households in the US. However, in British Columbia, the heterogeneity in spending share is small especially for the spending share of natural gas, refined petroleum and transportation service. While the spending share of electricity is decreasing with income, the carbon tax does not increase the electricity price because the electricity in BC is mostly generated with hydro.[21] Thus, the heterogeneity in the spending pattern does not cause either progressive or regressive incidence.

Having established that income source heterogeneity is the driver of differential welfare impacts, we focus on which income source is contributing to the welfare change. Fig. 6 shows the decomposition of the welfare change for each income source.[22] Since welfare is calculated by dividing total income by the welfare price index (that consists of price of expenditure, saving and leisure), decomposing the total income into each income source gives us the welfare change attributed to each income source. Specifically, the welfare change from income source s for household decile hh is described as ΔW_{hh}^{s}

[21] Dissou and Siddiqui (2014) suggests that the spending pattern heterogeneity leads to the regressive incidence because of the higher expenditure share of energy including electricity for low-income households in Canada. However, their result is partly driven by the increase in price of electricity caused by the carbon tax. The electricity price rises because a larger share of Canada's electricity is generated with fossil fuel than British Columbia.

[22] Natural resource income is included into capital income since it is small.

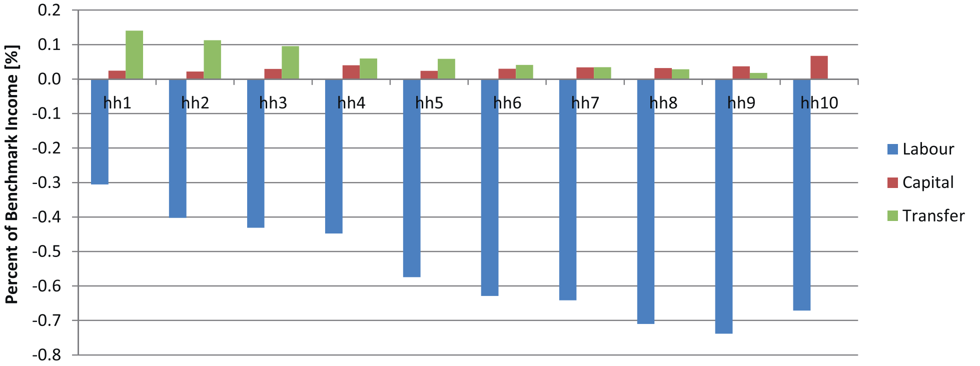

Fig. 6. Welfare impacts from each income source (without revenue recycling). Welfare impacts from each income source are measured as a percent of benchmark income.

in the following equation where income from source *s* before and after the carbon tax are denoted as $Income_s^0$ and $Income_s^1$, respectively:[23]

$$\Delta W_{hh}^{s} = \frac{Income_s^1 - Income_s^0}{\sum_s Income_s^0}.$$

The introduction of a carbon tax causes real wages (including leisure) to decline because the higher energy prices make mobile capital move out of BC. In contrast, labour is not mobile across provinces, and so bears the burden of the tax. Labour income falls across all income deciles with the carbon tax but higher-income households are more affected because labour income constitutes a larger share of their income in the benchmark scenario. The drop in labour income is responsible for reducing welfare by 0.3% for households in decile 1 and by nearly 0.7% for households in deciles 8, 9 and 10.

The impact of a carbon tax on real capital earnings depends on chosen parameter values for substitution elasticities (Fullerton and Heutel, 2010). Typically, carbon-intensive industries are capital intensive as well, which would imply a decrease in real capital returns. Yet our results indicate that the carbon tax has a small net positive effect on capital income across all households compared to the benchmark, which is due to our assumptions on labour and capital mobility between provinces. Labour is treated as fully immobile between provinces, while capital is assumed to be partially mobile (we test this assumption in a sensitivity analysis below). Capital mobility mitigates the decrease in capital return caused by the tax, so that the dropping welfare price index due to lower wages (and therefore lower leisure price) causes real capital income to increase compared to the benchmark. As a result, households across all income levels experience an increase in real capital income due to the carbon tax. The relative share of capital income in total household income is more equal across deciles than for labour income, with the exception of households at the top end of the income distribution that derives a comparably larger part of their income from capital endowments.

The real value of government transfers increases due to the carbon tax because they are indexed to Canadian consumer price index (CPI) (Rivers, 2012). The increase in CPI relative to the welfare prices in BC results in the increase in the value of transfers. Since lower-income households get a larger share of their income from transfers, this also contributes to the progressivity of the carbon tax.

To sum up, the progressive character of the carbon tax is mainly caused by the decline in real wages, coupled with the increase in the real value of transfer income. Households in the higher income deciles are more dependent on labour income than households in the lower deciles, which means they are hit harder by the drop in real wages. Households in the lower income deciles are more dependent on transfer income, and as such are the main beneficiaries of increases in the value of transfer income.

[23] Income here is a real value, or being adjusted with welfare price index.

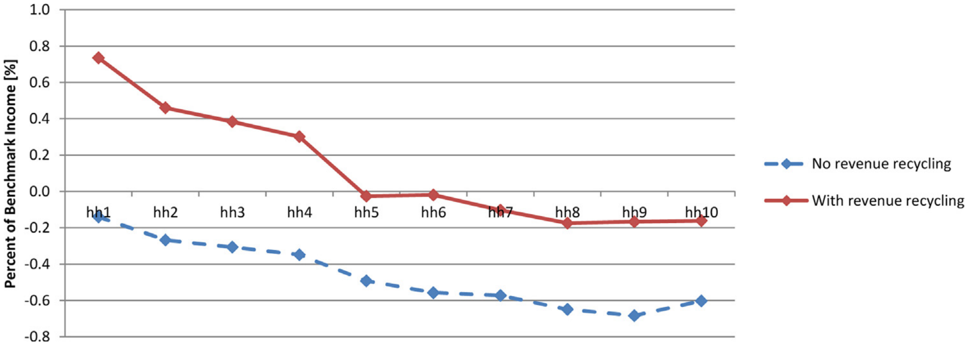

Fig. 7. Welfare impacts: No revenue recycling vs. With revenue recycling.

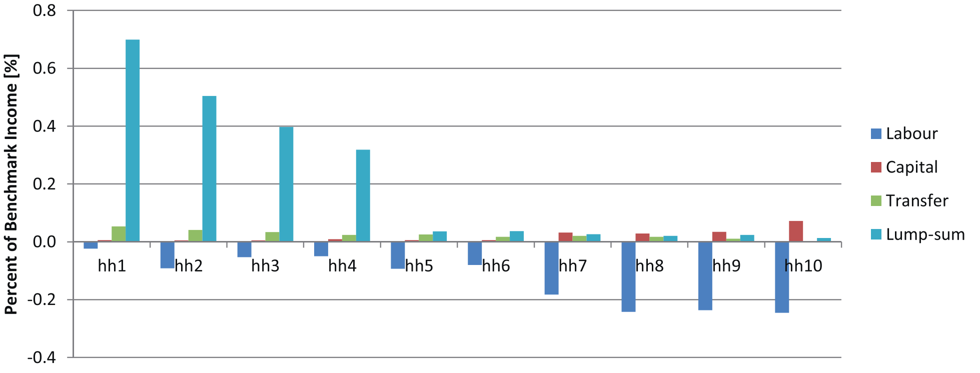

Fig. 8. Welfare impacts from each income source (with revenue recycling). Welfare changes from lump-sum payments include both the Northern and Rural Homeowner Benefit Program and the Low Income Climate Action Tax Credit Program.

Overall, lower income households are better off than high-income households because they are less affected by the wage drop but benefit from the slight increase in real transfer income.

5.2.2. *With revenue recycling*

The progressive character of the tax is enhanced when revenue recycling measures are introduced (Fig. 7). Revenue recycling benefits households across the entire income distribution, but lower income households (deciles 1–4) gain more from redistribution. The spread between the welfare gain of households in the lowest income decile and the burden for households in decile 10 is greater with revenue recycling than without. With the revenue recycling scheme in place, lower income households do better because of the carbon tax.[24]

Fig. 8 shows the decomposition of the welfare change for each income source. In the scenario with revenue recycling, we track labour income, capital income, transfers and lump-sum payments from both the Low Income Tax Credit or the Northern and Rural Homeowner Benefit in Table 7.[25] We have several findings in this figure. First, the lump-sum tax payment is the main source that improves the welfare of lower income households (deciles 1–4), and Table 7 shows that about 87% of the lump-sum payment to those households is Low Income Tax Credit. Second, the personal income tax cut is

[24] This is partly because we let government deficit increase while the increase in deficit is not reflected on the welfare. However, in a sensitivity analysis, we simulate the case where the government deficit is fixed by using the lump-sum payment to households, showing that low income households are still better off because of the carbon tax.

[25] Personal income tax cut for high income households (decile 7–10), which is conducted through the lump-sum payment, is included in the labour income.

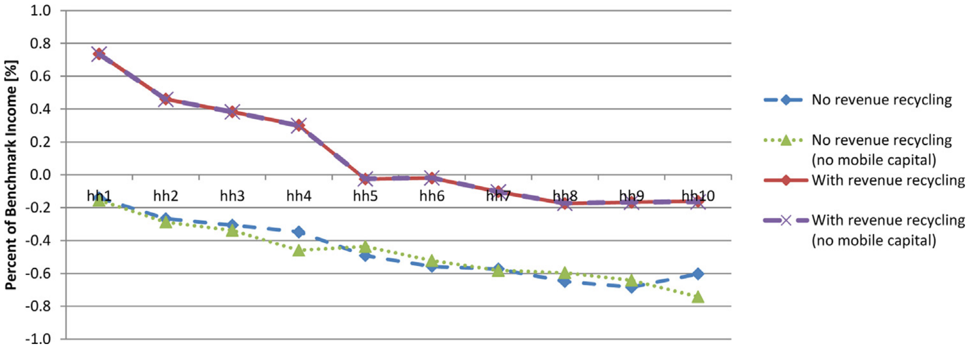

Fig. 9. Welfare impacts of regional (or provincial) capital mobility.

effective to mitigate the labour income decline for all households through the tax cut itself and wage increase. Although marginal personal taxes are only cut for households with incomes up to $70,000 (decile 1–6), leading to a wage increase, the wage increase is shared by all households.[26] For lower income households (decile 1–6), after tax wages are improved by the marginal personal tax cut on top of the wage increase. For higher income households (decile 7–10), not only personal tax cut through lump-sum return but also the wage increase mitigate the labour income decline. Since higher income households (decile 5–10) have higher share of labour income at the benchmark (Table 4), compared to Fig. 6, Fig. 8 shows that the benefit of the wage increase accrues more to them. Third, capital earnings are not improved much because capital is mobile between provinces and the benefit of capital tax cut on capital return is shared with capital in other provinces. To sum up, while Low Income Tax Credit increases the progressive incidence of the carbon tax, the personal income tax cut mitigates it. However, in total the existing revenue recycling scheme enhances the progressive nature of the tax, and renders it welfare-improving for low income households.

6. Sensitivity analysis

We examine how different model assumptions affect the distributional impact. We report results that test the assumptions about capital mobility and government deficit. We also check the robustness of our results by using different sets of production elasticities, but do not report results here as they are virtually unchanged from central case simulations.

6.1. When capital is not mobile between provinces

We change the assumption of capital mobility. Specifically, we assume that capital is immobile between regions (or provinces in our paper), as is common in single-country CGE analysis including Dissou and Siddiqui (2014). With capital not able to move between regions, the return on capital in the regulated region drops because of carbon tax.

Fig. 9 adds two more scenarios with no capital mobility between provinces to Fig. 7. First, we look at the scenarios with no revenue recycling. The overall progressive incidence holds whether capital is mobile between the provinces or not. One difference is that the household decile 4 and 10, which have the higher income share of capital (Table 4), have larger welfare decrease when capital is immobile between the provinces. Fig. 10 confirms that capital return goes down and that the households with higher capital income share have larger decrease. Also, we can see that the decrease in labour income is smaller because the burden of the carbon tax falls on both capital and labour once we assume that capital is immobile.

[26] If we would like to differentiate the wage change by each household decile, we need to know the share of labour input by each household decile for each production sector, which is beyond the scope of this paper.

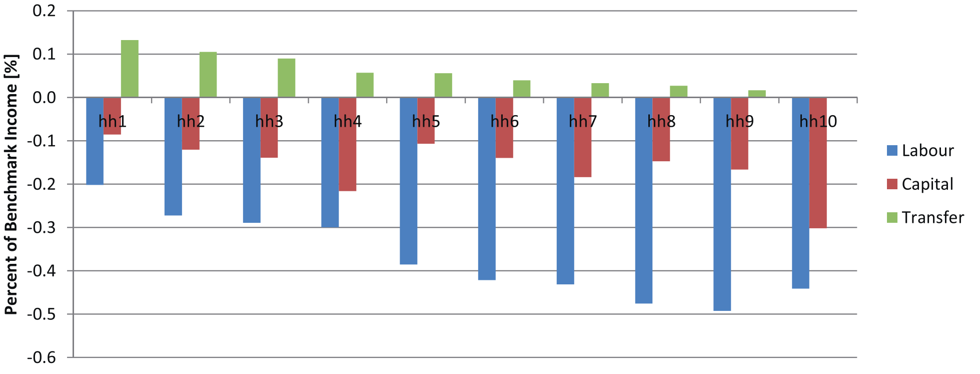

Fig. 10. Welfare impacts from each income source (with no revenue recycling and no regional capital mobility).

Regarding the scenarios with revenue recycling, the distributional impact is almost the same regardless of the assumption of capital mobility. This is because the existing revenue recycling (including capital tax cut) makes the capital return in BC quite similar to the capital return in other provinces. Since the gap of capital returns between provinces is the driver of capital movement, if the gap does not exist, capital is not moving out of (or into) BC even though we allow capital mobility. Thus, the capital mobility assumption is irrelevant in this case.

6.2. When government deficit is fixed

In our central case scenarios, we mimic the actual carbon tax by allowing the government deficit to be flexible (in the scenario without revenue recycling, the government deficit is decreased, while in the scenario with revenue recycling, the government deficit is increased). In this sensitivity analysis we fix the government deficit by using lump-sum payments to households such that the lump-sum payment does not distort the distributional impact. Specifically, the allocation of lump-sum payment to each household is proportional to the benchmark income.

Fig. 11 shows how the level of welfare is affected by the assumption that government deficit is fixed. First, we look at the scenarios with no revenue recycling. In our central case where government deficit is flexible, carbon tax revenue is kept by government to reduce the deficit, whereas in this sensitivity analysis where government deficit is fixed, carbon revenue is returned to households as a lump-sum payment. With the lump-sum payment from government to households, the welfare of all households is equally improved from our central case, and lower income households (decile 1–4) are better off with carbon tax.

Second, we look at the scenarios with revenue recycling. In our central case where government deficit is flexible, since recycling measures exceed carbon tax revenues, government deficit increases.

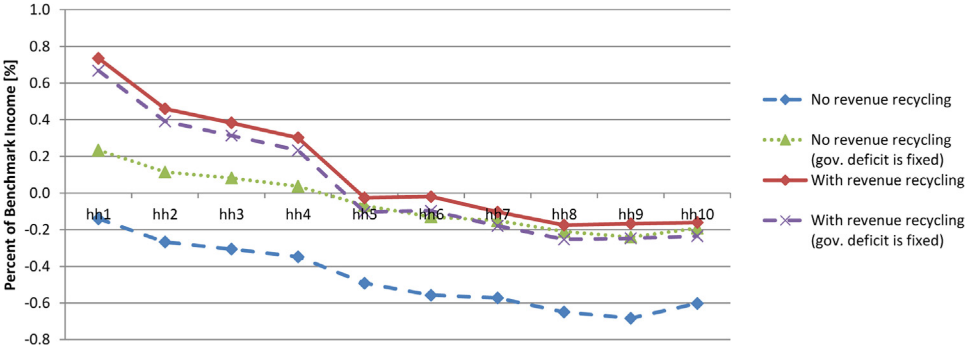

Fig. 11. Welfare impacts of fixed government deficit.

In this sensitivity simulation, households conduct lump-sum payment to government so that government deficit is unchanged. With the lump-sum payment from households to government, the welfare of all households is equally declined. The small decline reflects the relatively small increase in government deficit in our central case.

7. Conclusion

There has been much attention on the equity implications of the revenue-neutral carbon tax in BC and some analysts have criticized the program for not fully compensating low-income households for the additional burden due to higher energy prices. Our analysis suggests that this criticism is unfounded. Our analysis focuses on the equity and efficiency effects of the provincial carbon tax with its accompanying revenue recycling program, making every effort to represent the provisions of the policy program as closely as possible. Our key findings relate to the progressivity of the scheme (both with or without recycling). Even without a revenue recycling system in place, our model suggests that the carbon tax is progressive. The policy's revenue recycling measures, including labour tax cuts, tax benefits, and capital tax cuts, enhance the progressive incidence.

This finding is clearly different from other studies that estimate the incidence of carbon taxes considering only the spending-side effect, because the missing income-side effect is the driver of the progressive incidence. On the other hand, our finding is in line with other studies considering both spending-side and income-side effects (Rausch et al. (2010), Metcalf et al. (2010), and Dissou and Siddiqui (2014)), showing that the progressive incidence of the income-side effect can dominate the regressive incidence of spending-side effect. However, which effect dominates the other effect depends on the characteristics of the regulated region or country. In the case of the BC carbon tax, the regressive incidence of spending-side effect is very weak or neutral because the electricity in BC is mostly generated from hydropower and the fossil fuel spending share is not significantly different between households. Whether our finding holds or not in other provinces in Canada or other countries depends on the characteristics of income source and spending pattern of households. For example, in the countries where the transfer income share is high for low income households, which is the case for other provinces in Canada and most (if not all) OECD countries, the income-side effect is expected to be progressive because carbon tax affects other types of income. In contrast, if the electricity is generated mostly from coal, the spending-side effect is expected to be regressive, since the electricity spending share tends to be high for low income households.

Appendix A. Summary of elasticities

Table 9

Table 9
Key parameters in the model. Elasticity of substitution with the resource (σ^R) is calibrated to the empirical estimates of fossil fuel supply elasticities. Other production elasticities are from Okagawa and Ban (2008) and vary by sector. Elasticity of substitution between consumption and leisure is calibrated as explained in the text.

Parameter	Value	Description
Trade elasticities		
σ^{DM}	4	Armington substitution elasticity between domestic and imports
σ^{MM}	8	Armington substitution elasticity between foreign and other province imports
Production elasticities		
σ^{M}	Varies	Elasticity of substitution between capital-labour-energy and materials
σ^{D}	0	Elasticity of substitution between materials
σ^{E}	Varies	Elasticity of substitution between capital-labour and energy
σ^{L}	Varies	Elasticity of substitution between capital and labour
σ^{ELE}	0.25	Elasticity of substitution between electricity and other fuels
σ^{COA}	0.5	Elasticity of substitution between fossil fuel inputs
σ^{OIL}	0.75	Elasticity of substitution between oil and natural gas

Table 9 (*Continued*)

Parameter	Value	Description
Consumption elasticities		
σ_C^E	0.5	Elasticity of substitution between energy and other goods
σ_C^M	0.5	Elasticity of substitution between non-energy goods
σ_C^{ELE}	0.25	Elasticity of substitution between electricity and other energy
σ_C^{COA}	0.5	Elasticity of substitution between fossil fuel inputs
σ_C^{OIL}	0.75	Elasticity of substitution between oil and natural gas
Welfare elasticities		
σ^{LS}	Calibrated	Elasticity of substitution between consumption and leisure
σ^{I}	1	Elasticity of substitution between consumption-leisure and investment

Appendix B. Algebraic model summary

The model is formulated as a system of nonlinear inequalities. The inequalities correspond to the three classes of conditions associated with a general equilibrium: (i) exhaustion of product (zero profit) conditions for constant-returns-to-scale producers, (ii) market clearance for all goods and factors and (iii) income-expenditure balances. The first class determines activity levels, the second class determines prices and the third class determines incomes. In equilibrium, each of these variables is linked to one inequality condition: an activity level to an exhaustion of product constraint, a commodity price to a market clearance condition and an income to an income-expenditure balance.[27] Constraints on decision variables such as prices or activity levels allow for the representation of market failures and regulation measures. These constraints go along with specific complementary variables. In the case of price constraints, a rationing variable applies as soon as the price constraint becomes binding; in the case of quantity constraints, an endogenous tax or subsidy is introduced.[28]

In our algebraic exposition of equilibrium conditions below, we state the associated equilibrium variables in brackets. Furthermore, we use the notation Π_{gr}^{Z} to denote the unit profit function (calculated as the difference between unit revenue and unit cost) for constant-returns-to-scale production of item g in region r where Z is the name assigned to the associated production activity. Differentiating the unit profit function with respect to input and output prices provides compensated demand and supply coefficients (Hotelling's Lemma), which appear subsequently in the market clearance conditions.

We use g as an index comprising all sectors/commodities including the final consumption composite of each household, the public good composite and an aggregate investment good. The index r (aliased with s) denotes regions. The index h denotes household and household consumption. The index EG represents the subset of all energy goods except for crude oil (here: coal, refined oil, gas, electricity) and the label X denotes the subset of fossil fuels (here: coal, crude oil, gas), whose production is subject to decreasing returns to scale given the fixed supply of fuel-specific factors. Tables 10–17 explain the notations for variables and parameters employed within our algebraic exposition. Figs. 1–4 provide a graphical representation of the functional forms. Numerically, the model is implemented under GAMS (Brooke et al., 1996)[29] and solved using PATH (Dirkse and Ferris, 1995)[30].

Zero profit conditions:

[27] Due to non-satiation expenditure will exhaust income. Thus, the formal inequality of the income-expenditure balance will hold as an equality in equilibrium.

[28] An example for an explicit price constraint is a lower bound on the real wage to reflect a minimum wage rate; an example for an explicit quantity constraint is the specification of a (minimum)target level for the provision of public goods.

[29] Brooke et al. (1996).

[30] Dirkse and Ferris (1995).

1 Production of goods except for fossil fuels ($Y_{gr}|_{g\notin X}$):

$$\Pi_{gr}^{Y}=\left(\theta_{gr}^{EX}\left(\frac{P_{gr}^{Y}(1-tp_{gr}^{Y}-tf_{gr}^{Y})}{\bar{P}_{gr}^{Y}}\right)^{1+\eta}+\left(1-\theta_{gr}^{EX}\right)\left(\frac{\mu(1-tp_{gr}^{Y}-tf_{gr}^{Y})}{\bar{\mu}_{gr}}\right)^{1+\eta}\right)^{\frac{1}{1+\eta}}$$
$$-\left(\theta_{gr}^{M}P_{gr}^{M^{1-\sigma^{M}}}+(1-\theta_{gr}^{M})\left(\left(\left(\theta_{gr}^{E}P_{gr}^{E^{1-\sigma^{E}}}+(1-\theta_{gr}^{E})\left(\theta_{gr}^{L}P_{r}^{L^{1-\sigma^{L}}}+(1-\theta_{gr}^{L})P_{gr}^{K^{1-\sigma^{L}}}\right)^{\frac{1}{1-\sigma^{L}}}\right)^{1-\sigma^{E}}\right)^{\frac{1}{1-\sigma^{E}}}\right)^{1-\sigma^{M}}\right)^{\frac{1}{1-\sigma^{M}}}\leq 0$$

2 Production of fossil fuels ($Y_{gr}|_{g\in X}$):

$$\Pi_{gr}^{Y}=\left(\theta_{gr}^{X}\left(\frac{P_{gr}^{Y}(1-tp_{gr}^{Y}-tf_{gr}^{Y})}{\bar{P}_{gr}^{Y}}\right)^{1+\eta}+\left(1-\theta_{gr}^{X}\right)\left(\frac{\mu(1-tp_{gr}^{Y}-tf_{gr}^{Y})}{\bar{\mu}_{gr}}\right)^{1+\eta}\right)^{\frac{1}{1+\eta}}$$
$$-\left(\theta_{gr}^{R}\left(\frac{P_{gr}^{R}(1+tp_{gr}^{R}+tf_{gr}^{R})}{\bar{P}_{gr}^{R}}\right)^{1-\sigma_{gr}^{R}}\right.$$
$$\left.+\left(1-\theta_{gr}^{R}\right)\left(\theta_{gr}^{L}P_{r}^{L}+\sum_{i}\theta_{igr}^{R}\frac{(P_{ir}^{A}(1+tp_{igr}^{D}+tf_{igr}^{D})+a_{igr}^{CO_2}P^{CO_2})}{\bar{P}_{igr}^{A}}\right)^{1-\sigma_{gr}^{R}}\right)^{\frac{1}{1-\sigma_{gr}^{R}}}\leq 0$$

3 Sector-specific material aggregate (M_{gr}):

$$\Pi_{gr}^{M}=P_{gr}^{M}-\left(\sum_{i\notin EG}\theta_{igr}^{M}\left(\frac{P_{ir}^{A}(1+tp_{igr}^{D}+tf_{igr}^{D})}{\bar{P}_{igr}^{A}}\right)^{1-\sigma^{D}}\right)^{\dfrac{1}{1-\sigma^{D}}}\leq 0$$

4 Sector-specific energy aggregate (E_{gr}):

$$\Pi_{gr}^{E}=P_{gr}^{E}-\left(\left(\left(\theta_{ELEgr}\left(\frac{P_{ELEr}^{A}(1+tp_{ELEgr}^{D}+tf_{ELEgr}^{D})}{\bar{P}_{ELEgr}}\right)^{1-\sigma^{ELE}}\right.\right.\right.$$
$$+(1-\theta_{ELEgr})\left(\left(\theta_{COAgr}\left(\frac{P_{COAr}^{A}(1+tp_{COAgr}^{D}+tf_{COAgr}^{D})}{\bar{P}_{COAgr}}+a_{COAgr}^{CO_2}P^{CO_2}\right)^{1-\sigma^{COA}}\right.\right.$$
$$+(1-\theta_{COAgr})\left(\theta_{OILgr}\left(\frac{P_{OILr}^{A}(1+tp_{OILgr}^{D}+tf_{OILgr}^{D})}{\bar{P}_{OILgr}}+a_{OILgr}^{CO_2}P^{CO_2}\right)^{1-\sigma^{OIL}}\right.$$
$$\left.\left.\left.\left.\left.+(1-\theta_{OILgr})\left(\frac{P_{GASr}^{A}(1+tp_{GASgr}^{D}+tf_{GASgr}^{D})}{\bar{P}_{GASgr}}+a_{GASgr}^{CO_2}P^{CO_2}\right)^{1-\sigma^{OIL}}\right)^{\frac{1}{1-\sigma^{OIL}}}\right)^{1-\sigma^{COA}}\right)^{\frac{1}{1-\sigma^{COA}}}\right)^{1-\sigma^{ELE}}\right)^{\frac{1}{1-\sigma^{ELE}}}\leq 0$$

5 Armington aggregate (A_{ir}):

$$\Pi_{ir}^{A} = P_{ir}^{A} - \left(\left(\Theta_{ir}^{DM} \mu^{1-\sigma^{DM}} + \left(1 - \Theta_{ir}^{DM}\right) \left(\sum_{s} \Theta_{isr}^{MM} P_{is}^{Y^{1-\sigma_i^{MM}}} \right)^{\frac{1}{1-\sigma^{MM}}} \right)^{1-\sigma^{DM}} \right)^{\frac{1}{1-\sigma^{DM}}} \leq 0$$

6 Labour supply (L_{rh}):

$$\Pi_{rh}^{L} = \frac{P_r^L \left(1 - tp_{rh}^L - tf_{rh}^L\right)}{\bar{P}_r^L} - P_{rh}^{LS} \leq 0$$

7 Mobile capital supply (K):

$$\Pi^{K} = \left(\sum_{r} \Theta_r^K \left(\frac{P^K \left(1 - tp_r^K - tf_r^K\right)}{\bar{P}_r^K} \right)^{1+\epsilon} \right)^{\frac{1}{1+\epsilon}} - P^{KM} \leq 0$$

8 Welfare (W_{rh}):

$$\Pi_{rh}^{W} = \left(\Theta_{rh}^{I} P_r^{I^{1-\sigma_r^I}} + \left(1 - \Theta_{rh}^{I}\right) \left(\left(\Theta_{rh}^{LS} P_{rh}^{LS^{1-\sigma_{rh}^{LS}}} + \left(1 - \Theta_{rh}^{LS}\right) P_{rh}^{Y^{1-\sigma_{rh}^{LS}}} \right)^{\frac{1}{1-\sigma_{rh}^{LS}}} \right)^{1-\sigma_r^I} \right)^{\frac{1}{1-\sigma_r^I}} \leq 0$$

Market clearance conditions:

9 Labour (P_r^L):

$$\sum_{h} L_{rh} \geq \sum_{g} Y_{gr} \frac{\partial \Pi_{gr}^{Y}}{\partial P_r^L}$$

10 Leisure (P_{rh}^{LS}):

$$\bar{L}_{rh} - L_{rh} \geq W_{rh} \frac{\partial \Pi_{rh}^{W}}{\partial P_{rh}^{LS}}$$

11 Mobile capital (P^{KM}):

$$\sum_{rh} K\bar{M}_{rh} \geq K$$

12 Sector-specific capital (P^K_{gr}):

$$\sum_h \bar{K}_{grh} + K\frac{\partial \Pi^K}{\partial P^K_{gr}} \geq \sum_g Y_{gr}\frac{\partial \Pi^Y_{gr}}{\partial P^K_{gr}}$$

13 Fossil fuel resources ($P^R_{gr}|_{g\in X}$):

$$\bar{R}_{gr} \geq Y_{gr}\frac{\partial \Pi^Y_{gr}}{\partial (P^R_{gr}(1+tp^R_{gr}+tf^R_{gr}))}$$

14 Energy composite (P^E_{gr}):

$$E_{gr} \geq Y_{gr}\frac{\partial \Pi^Y_{gr}}{\partial P^E_{gr}}$$

15 Material composite (P^M_{gr}):

$$M_{gr} \geq Y_{gr}\frac{\partial \Pi^Y_{gr}}{\partial P^M_{gr}}$$

16 Armington good (P^A_{ir}):

$$A_{ir} \geq \sum_g E_{gr}\frac{\partial \Pi^E_{gr}}{\partial (P^A_{ir}(1+tp^D_{igr}+tf^D_{igr})+a^{CO_2}_{igr}P^{CO_2})} + \sum_g M_{gr}\frac{\partial \Pi^M_{gr}}{\partial (P^A_{ir}(1+tp^D_{igr}+tf^D_{igr}))}$$

17 Commodities (P^Y_{ir}):

$$Y_{ir}\frac{\partial \Pi^Y_{ir}}{\partial (p^Y_{ir}(1-tp^Y_{ir}-tf^Y_{ir}))} \geq A_{ir}\frac{\partial \Pi^A_{ir}}{\partial P^Y_{ir}}$$

18 Private good consumption (P^Y_{rh}):

$$Y_{rh} \geq W_{rh}\frac{\partial \Pi^W_{rh}}{\partial P^Y_{rh}}$$

19 Investment (P^Y_{Ir}):

$$Y_{Ir} \geq \sum_h W_{rh}\frac{\partial \Pi^W_{rh}}{\partial P^{Ir}}$$

20 Public Consumption (P^Y_{Gr}):

$$Y_{Gr} \geq \frac{INC^p_r}{P^Y_{Gr}} + \theta^G_r\frac{INC^f}{P^Y_{Gr}}$$

21 Welfare (P^W_{rh}):

$$W_{rh} \geq \frac{INC^{RA}_{rh}}{P^W_{rh}}$$

22 Carbon emissions (P^{CO_2}):

$$\bar{CO_2} \geq \sum_r \sum_{i \in EG} \sum_g E_{gr} \frac{\partial \Pi^E_{gr}}{\partial (P^A_{ir}(1 + tp^D_{igr} + tf^D_{igr}) + a^{CO_2}_{igr} P^{CO_2})}$$

Income-expenditure balances:

23 Income of representative consumer (INC^{RA}_{rh}):

$$INC^{RA}_{rh} = P^{LS}_{rh} \quad \bar{L}_{rh} + \sum_{x \in g} P^R_{gr} \quad \bar{R}_{grh} + P^{KM} \quad \bar{KM}_{rh} + \sum_g P^K_{gr} \quad \bar{K}_{grh} - P^Y_{Ir} \quad \bar{I}_{rh} + \mu \quad \bar{BOP}^{RA}_{rh} + \bar{LUMP}_{rh}$$

24 Income of provincial government (INC^p_r):

$$\begin{aligned} INC^p_r = & \sum_h L_{rh} P^L_r tp^L_{rh} + \sum_{g \in x} \bar{R}_{gr} P^R_{gr} tp^R_{gr} + \sum_g Y_{gr} \frac{\partial \Pi^Y_{gr}}{\partial P^K_{gr}} P^K_{gr} tp^K_r \\ & + \sum_i \sum_g \left(E_{gr} \frac{\partial \Pi^E_{gr}}{\partial (P^A_{ir}(1 + tp^D_{igr} + tf^D_{igr}) + a^{CO_2}_{igr} P^{CO_2})} P^A_{ir} tp^D_{igr} \right. \\ & \left. + \ M_{gr} \frac{\partial \Pi^M_{gr}}{\partial (P^A_{ir}(1 + tp^D_{igr} + tf^D_{igr}))} P^A_{ir} tp^D_{igr} \right) + \sum_g Y_{gr} \frac{\partial \Pi^Y_{gr}}{\partial (p^Y_{gr}(1 - tp^Y_{gr} - tf^Y_{gr}))} P^Y_{gr} tp^Y_{gr} \\ & + \sum_g Y_{gr} \frac{\partial \Pi^Y_{gr}}{\partial (\mu(1 - tp^Y_{gr} - tf^Y_{gr}))} \mu tp^Y_{gr} + P^{CO_2} \theta^{CO_2}_r \bar{CO_2} - \varepsilon_r + \mu BOP^p_r \chi_r - \sum_h \bar{LUMP}_{rh} \end{aligned}$$

25 Income of federal government (INC^f):

$$\begin{aligned} INC^f = & \sum_{rh} \left(L_{rh} P^L_r tf^L_{rh} + \sum_{g \in x} \bar{R}_{gr} P^R_{gr} tf^R_{gr} + \sum_g Y_{gr} \frac{\partial \Pi^Y_{gr}}{\partial P^K_{gr}} P^K_{gr} tf^K_r + \sum_i \sum_g \right. \\ & \times \left(E_{gr} \frac{\partial \Pi^E_{gr}}{\partial (P^A_{ir}(1 + tp^D_{igr} + tf^D_{igr}) + a^{CO_2}_{igr} P^{CO_2})} P^A_{ir} tf^D_{igr} + M_{gr} \frac{\partial \Pi^M_{gr}}{\partial (P^A_{ir}(1 + tp^D_{igr} + tf^D_{igr}))} P^A_{ir} tf^D_{igr} \right) \\ & \left. + \sum_g Y_{gr} \frac{\partial \Pi^Y_{gr}}{\partial (p^Y_{gr}(1 - tp^Y_{gr} - tf^Y_{gr}))} P^Y_{gr} tf^Y_{gr} + \sum_g Y_{gr} \frac{\partial \Pi^Y_{gr}}{\partial (\mu(1 - tp^Y_{gr} - tf^Y_{gr}))} \mu tf^Y_{gr} + \mu \bar{BOP}^f + \varepsilon_r \right) \end{aligned}$$

26 Equal-yield for provincial government demand (χ_r):

$$\frac{INC_r^P}{P_{Gr}^Y} \geq \bar{G}_r^P$$

27 Equal-yield for federal government demand (ε):

$$\sum_r \theta_r^G \frac{INC^f}{P_{Gr}^Y} \geq \sum_r \bar{G}_r^f$$

B.1. Notation

See Tables 10–17.

Table 10
Sets.

Symbol	Description
i	Goods excluding final demand goods
g	Goods including intermediate goods ($g=i$) and final demand goods, i.e. private consumption ($g=h$), investment ($g=I$) and public consumption ($g=G$)
r (alias s)	Regions
EG	Energy goods: coal, refined oil, gas and electricity
X	Fossil fuels: coal, crude oil and gas

Table 11
Activity variables.

Symbol	Description
Y_{gr}	Production of good g in region r
E_{gr}	Production of energy composite for good g in region r
M_{gr}	Production of material aggregate for good g in region r
A_{ir}	Production of Armington good i in region r
L_{rh}	Labour supply of household h in region r
K	Capital supply
W_{rh}	Production of composite welfare good

Table 12
Price variables.

p_{gr}^Y	Price of good g in region r
p_{gr}^E	Price of energy composite for good g in region r
p_{gr}^M	Price of material composite for good g in region r
p_{ir}^A	Price of Armington good i in region r
p_r^L	Price of labour (wage rate) in region r
p_{rh}^{LS}	Price of leisure of household h in region r
P_{gr}^K	Price of capital services (rental rate) in sector g and region r
p_{gr}^R	Rent to fossil fuel resources in fuel production in sector g ($g \in X$) and region r
p^{CO_2}	CO_2 price
p^{KM}	Price of interregionally mobile capital
p_{gr}^K	Price of sector-sector specific capital
p_{rh}^W	Price of composite welfare (utility) good
μ	Exchange rate

Table 13
Income variables.

Symbol	Description
INC_{rh}^{RA}	Income of household *h* in region *r*
INC_{r}^{p}	Income of provincial government in region *r*
INC^{f}	Income of federal government

Table 14
Tax rates and reference prices.

Symbol	Description
tp_{gr}^{Y}	Provincial taxes on output in sector *g* and region r
tf_{gr}^{Y}	Federal taxes on output in sector *g* and region *r*
tp_{gr}^{R}	Provincial taxes on resource extraction in sector *g* and region *r*
tf_{gr}^{R}	Federal taxes on resource extraction in sector *g* and region *r*
tp_{igr}^{D}	Provincial taxes on intermediate good *i* in sector *g* and region*r*
tf_{igr}^{D}	Federal taxes on intermediate good *i* in sector *g* and region*r*
tp_{rh}^{L}	Provincial taxes on labour of household *h* in region *r*
tf_{rh}^{L}	Federal taxes on labour of household *h* in region *r*
tp_{r}^{K}	Provincial taxes on capital in region *r*
tf_{r}^{K}	Federal taxes on capital in region *r*
$\bar{P}_{gr}^{Y}$	Reference price of good *g* in region *r*
$\bar{\mu}_{gr}$	Reference value of exchange rate
$\bar{P}_{gr}^{R}$	Reference price of fossil fuel resource *g* in region *r*
$\bar{P}_{ir}^{A}$	Reference price of Armington good *i* in region *r*
$\bar{P}_{r}^{L}$	Reference price of labour (wage rate) in region *r*
$\bar{P}_{r}^{K}$	Reference price of capital in region *r*

Table 15
Cost shares.

Symbol	Description
θ_{gr}^{EX}	Value share of international market exports in domestic production of good *g* in region *r*
θ_{gr}^{E}	Value share of energy in the production of good *g* in region *r*
θ_{gr}^{M}	Value share of the material aggregate within the composite of value-added and material in the production of good *g* in region *r*
θ_{gr}^{L}	Value share of labour in the value-added composite of good *g* production in region *r*
θ_{gr}^{R}	Value share of fossil fuel resource in fossil fuel production ($g \in X$) in region *r*
θ_{gr}^{ELE}	Value share of electricity in the energy composite of good *g* production in region *r*
θ_{gr}^{COA}	Value share of coal in the coal-oil-gas composite of good *g* production in region *r*
θ_{gr}^{OIL}	Value share of oil in the oil-gas composite of good *g* production in region *r*
θ_{ir}^{DM}	Value share of domestically produced inputs to Armington production of good *g* in region *r*
θ_{isr}^{MM}	Value share of imports from region *s* in the import composite of good *i* to region *r*
θ_{r}^{K}	Value share of capital supply to region *r* in overall (mobile) capital supply
θ_{rh}^{LS}	Value share of leisure demand of household *h* in region *r*
θ_{rh}^{I}	Value share of investment demand of household *h* in region *r*
θ_{r}^{G}	Share of region *r* in overall public good consumption
$\theta_{r}^{CO_2}$	Share of region *r* in overall CO_2 emission endowment

Table 16
Endowments and emissions coefficients.

Symbol	Description
$\bar{L}_{rh}$	Aggregate time (labour and leisure) endowment of household h in region r
$\bar{K}_{grh}$	Sector-specific capital endowment of household h in region r
$\bar{R}_{gr}$	Endowment of fossil fuel resource g by region r ($g \in X$)
$B\bar{O}P_{rh}^{RA}$	Balance of payment deficit or surplus of household h in region r
$B\bar{O}P_r^p$	Provincial government's balance of payment deficit or surplus in region r at the benchmark
$B\bar{O}P^f$	Federal government's initial balance of payment deficit or surplus
$\bar{CO}_2$	Endowment with carbon emission rights
$a_{igr}^{CO_2}$	Carbon emissions coefficient for fossil fuel i ($i \in X$)in good g production of region r
$\bar{G}_r^p$	Exogenous provincial government demand
$\bar{G}_r^f$	Exogenous federal government demand
$LU\bar{M}P_{rh}$	Exogenous lump-sum return of carbon revenue recycling of household h in region r

Table 17
Additional variables.

Symbol	Description
χ_r	Coefficient of provincial government deficit or surplus to warrant equal-yield constraint for provincial government r
ε_r	Lump-sum transfers to warrant equal-yield for federal government

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