The CO_2 Content of Consumption Across U.S. Regions: A Multi-Regional Input-Output (MRIO) Approach

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ABSTRACT

Using a multi-regional input-output (MRIO) framework, we estimate the direct and indirect carbon dioxide (CO_2) content of consumption across regions of the United States. We improve on existing estimates by accounting for emissions attributable to domestically and internationally imported goods using data describing bilateral trade between U.S. states and with international countries and regions. This paper presents two major findings. First, attributing emissions to states on a consumption basis leads to very different state-level emissions responsibilities than when attributed on a production basis; for example, California's emissions are over 25 percent higher. Second, heterogeneity of emissions across trading partners significantly affects the indirect emissions intensity of consumption (kg of carbon per $ of consumption), so regional differences in intensity across the U.S. go well beyond direct energy consumption. These findings have implications for evaluating the distributional impacts of national climate policies and for understanding differing incentives to implement state-level policies.

Keywords: CO_2 emissions, Emissions accounting, CO_2 content of consumption, Carbon tax incidence, Indirect emissions, Embodied emissions, United States

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1. INTRODUCTION

An extensive literature attempts to trace the full effect of consumption patterns on carbon dioxide (CO_2) emissions throughout the economy. There are many motivations for such studies, including attributing responsibility for emissions; guiding producers, consumers, or public policy to favor products and processes with lower emissions; and understanding how emissions pricing might affect households with different consumption patterns. One common approach relies on an engineering-based life-cycle methodology that identifies emissions related to a particular production process, including emissions related to the production of inputs, with the goal of identifying all emissions associated with a product through its full life cycle (e.g. ISO, 2006; Liamsanguan and Gheewala, 2009; US EPA, 2010a, b; Jones and Kammen, 2011). Engineering-based analysis typically stops somewhere along the production chain; it will measure the direct emissions caused by

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producing chemicals which are used to manufacture a product of interest, but will not necessarily measure the emissions associated with building the plant producing the chemicals, or the emissions related to the cement used to build the plant producing the chemicals. A second common approach relies on input-output (I-O) tables, which describe the entire production chain. Algebraic manipulation of I-O matrices is commonly used to attribute emissions occurring throughout the economy to individual consumption goods, and this manipulation does not arbitrarily truncate the emissions chain.

While these two approaches are similar in some respects—and at some levels, have the same general goal—in application they generally have different purposes. Engineering life-cycle analysis is best suited to evaluate different brands of the same product, or different processes used to produce an otherwise homogeneous product. The I-O approach, on the other hand, is difficult to resolve between different processes used to produce what otherwise is a homogeneous product, because of the relatively coarse level of aggregation in I-O tables. I-O analysis is better suited to estimate the full CO_2 implications of the consumption patterns of different regions. It can be used to understand whether, for example, per capita emissions in California are low compared to those in Texas because Californians consume different products than Texans, or whether they are low because the emissions related to their consumption patterns are embodied in goods produced elsewhere and imported into the state. One might attribute emissions from chemical and fuel production in Texas to Texans, and those emissions from the film industry in California to Californians, but it is possible that both Texans and Californians consume fuels and films at similar rates, resulting in similar indirect emissions.

I-O modeling has been used to track CO_2 emissions through the economy across countries, made possible by international trade data sets providing information on bilateral trade flows (see Wiedmann et al., 2007; Davis and Caldeira, 2010). It has also been used to compute the emissions embodied in trade across countries (e.g. Qi et al., 2014) and to compute the level of tariffs which would be based on the total carbon intensity of imports (e.g. Winchester et al., 2011). Our contribution is to improve on empirical estimates for states or regions within the U.S.—a timely issue, as recent Congressional efforts have focused on crafting legislation with mechanisms to “fairly” distribute the cost of a carbon policy among states.

As is common in this literature, we define as *direct* emissions those related to household fuel use and the production of electricity used by households; the emissions associated with the consumption of non-energy goods are termed *indirect* emissions. Hassett et al. (2009) find that roughly half of the CO_2 emissions related to final consumption in the U.S. are indirect emissions. While emissions associated with most non-energy goods and services are fairly low, the vast bulk of household spending goes toward the purchase of these items[1] and a large share of household emissions are thus embodied in non-energy goods and services. Previously, in making such calculations for U.S. states, studies have made the simplifying assumption that indirect emissions associated with the consumption of an imported product are uniform among different regional sources of the same product: a dollar’s worth of vehicle produced in Michigan has the same emissions as a dollar’s worth of vehicle produced in Tennessee, Germany or Japan, and a dollar’s worth of a haircut in Wyoming causes the same emissions as one purchased in California, although electricity purchased in California is much cleaner (e.g. Metcalf, 1999; Dinan and Rogers, 2002;

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[1] Direct consumer expenditures on energy (fuel oil, natural gas, electricity and motor vehicle fuels) accounted for only 9% of household expenditures in 2011–2012. Data are from the Consumer Expenditure Survey Midyear Tables at http://www.bls.gov/cex/tables.htm, accessed on Aug. 5, 2013.

Hassett et al., 2009; Mathur and Morris, 2012). This assumption was necessary because previous researchers lacked the full bilateral trade data needed to track domestic and international sources of imports.

Our contribution to the literature is to develop a multi-regional input-output (MRIO) model with over 100 countries and the United States disaggregated to the state level. This allows us to track the carbon embodied in imports and exports, as well as products domestically produced and consumed. We advance previous work by using available data for the U.S. on interstate and international trade flows to estimate a full matrix of bilateral trade flows—both interstate and between U.S. states and foreign countries. While the bilateral trade flow data are imperfect, we believe they allow us to challenge critical assumptions of previous work: specifically, that the emissions intensity of similar goods imported from different regions are identical, and that measures of regional emissions are not appreciably distorted by the first assumption. If the difference in carbon intensity does not depend on the origin of imports into a state (including consumption from within the state), then this simplifying assumption may be reasonable. However, if there are substantial differences among sources of consumption, we can at least conclude that further data collection or effort to estimate bilateral trade flows is needed—either to develop better estimates, or to make a compelling case for assuming identical emissions intensities of imports. To our knowledge, no previous studies on the regional incidence of U.S. carbon pricing policy have used MRIO modeling to determine differences in CO_2 consumption across regions of the U.S.

Apart from simply assigning responsibility, I-O analysis has also been used to assess the potential burden of emissions pricing on different consumers (e.g. Metcalf, 1999). Here, the idea is that a CO_2 emissions price will be reflected in the cost of products throughout the economy in proportion to the emissions incurred during production. The price of final goods in the economy will thus reflect the CO_2 cost of their production and use, carrying along the cost of all the CO_2 emissions associated with intermediate and primary production. While I-O analysis is widely used for such purposes, it assumes away any substitution possibilities and can thus at best provide an approximation of which demographics may bear the burden of emissions pricing. It does not either address what happens with the revenue from, or allowance value inherent in, a carbon pricing system, an important component of the distributional consequences of such policies (e.g., Rausch et al., 2010, 2011). Nevertheless, current consumption patterns are one of the ingredients necessary to determine relative CO_2 cost burdens. Accurately measuring the CO_2 intensity of consumption is vital to our understanding of how burdens may differ across states and regions.

In Section 2, we discuss the definition of "consumption" used in the analysis; we then describe the MRIO model and the data we used to compute CO_2 contents on a consumption basis. In Section 3 we discuss our findings. Two findings in particular stand out. First, attributing emissions to states on a consumption rather than production basis leads to very different state level emissions responsibilities; for example, when attributed on a consumption basis, California's per capita emissions are over 25 percent higher than when attributed on a production basis. Second, when attributing emissions on a consumption basis, heterogeneity of emissions across trading partners significantly affects emissions intensity. We offer some final thoughts in Section 4.

2. ESTIMATING THE CO_2 CONTENT OF CONSUMPTION IN A MULTI-REGIONAL INPUT-OUTPUT MODEL

2.1 Multi-Regional Input-Output

We develop a multi-regional input-output (MRIO) model and use it to estimate the CO_2 content of consumption across U.S. regions. Using the MRIO approach, we can track emissions—

on a consumption or production basis—through to final consumption, regardless of the origin of emissions or the number of intermediate production layers. For example, consider glass produced in Ohio that is exported to Michigan for assembly into automobiles, which in turn are exported to New York for sale. In consumption-based emissions accounting, the MRIO model allocates the emissions associated with the glass production to New York; under a production-based emissions framework, it would allocate the emissions to Ohio.

Here, we estimate the carbon content of consumption using MRIO and provide two improvements on previous work. First, we account for differences in the CO_2 intensity of foreign imports and trace these to a destination state or region of the U.S., taking into account whether they are consumed in that region or further traded to other parts of the country. Second, intra-national trade patterns are based on interstate trade data, rather than assuming an homogeneous dispersion of products within the country.

International and intra-national regions are conceptually similar, and we denote them with the same index r. The model tracks flows for n sectors of the economy. We follow the notation from previous literature, in particular Peters (2008). Output in region r (x^r) is used in intermediate demand, final demand, and net exports:

$$x^r = A^r x^r + y^r + e^r - m^r \tag{1}$$

where each n by n matrix A^r tracks the use of output x^r as an intermediate input in region r, y^r is a vector of dimension n of final demand in region r, e^r is a vector of exports from region r, and m^r is a vector of imports to region r.

We decompose intermediate and final demand according to their origin. The input-output matrices A^r are decomposed into a matrix of industry requirements for domestic inputs (A^{rr}) and matrices of industry requirements for imported inputs from region s (A^{sr}). Exports out of region r are decomposed according to their destination region s in the e^{rs} vectors, such that $e^r = \sum_{s \neq r} e^{rs}$. Each of these are then decomposed into exports for final demand in region s (y^{rs}) and exports for use as intermediate inputs in region s (z^{rs}):

$$e^{rs} = z^{rs} + y^{rs} \tag{2}$$

where

$$z^{rs} = A^{rs} x^s$$

Letting y^{rr} represent the final demand in region r that is produced domestically, and noting that imports need not be tracked explicitly (since imports to region r from s are exports from region s to r), equation (1) can be rewritten as:

$$x^r = A^{rr} x^r + y^{rr} + \sum_{s \neq r} A^{rs} x^s + \sum_{s \neq r} y^{rs} \tag{3}$$

This system of equations can be stacked over the R regions:

$$\begin{bmatrix} x^1 \\ \vdots \\ x^R \end{bmatrix} = \begin{bmatrix} A^{11} & \cdots & A^{1R} \\ \vdots & \ddots & \vdots \\ A^{R1} & \cdots & A^{RR} \end{bmatrix} \begin{bmatrix} x^1 \\ \vdots \\ x^R \end{bmatrix} + \begin{bmatrix} \sum_s y^{1s} \\ \vdots \\ \sum_s y^{Rs} \end{bmatrix} \tag{4}$$

or

$$X = AX + Y \tag{5}$$

where X is an nR by 1 vector and so on. The Y vector is the vector of final demand both consumed domestically and imported.

The quantity of carbon dioxide emissions per unit of output associated with production in each region r is denoted by the row vector f^r of dimension n. These vectors can be stacked next to each other in the row vector F of dimension 1 by nR:

$$F = [f^1 \ldots f^R]$$

From these we compute the total CO_2 intensity of each good using the Leontief inverse of the multi-regional input-output matrix A. These are given by the vector $\mathrm{F^{tot}}$ of dimension 1 by nR:[2]

$$\mathrm{F^{tot}} = \mathrm{F(I-A)^{-1}}$$

The elements of this vector represent the total amount of carbon embodied in each dollar of sector i in region r, including that emitted in the production of domestic and imported intermediates.

2.2 Consumption-Related Emissions

Bilateral final demand in each region is represented by the nR vectors Y^r:

$$Y^r = \begin{bmatrix} y^{1r} \\ \vdots \\ y^{Rr} \end{bmatrix}$$

In this study, we use a broad definition of final demand, including not only the final use of goods and services by private households, but also government and investment-related final demand. Goods and services purchased by state and federal governmental entities are assumed to benefit households within the same region, and we attribute the CO_2 embodied in those goods to that region's consumption. The attribution of emissions embodied in final investment demand introduces an additional level of complexity and is typically overlooked in the input-output literature. Ideally, we would relate emissions associated with past investment (in today's capital stock) with current consumption; however, we cannot track the actual investments composing each sector's current capital stock. While for this reason we cannot provide an accurate attribution of emissions over time, we can—with some assumptions—attribute current investment emissions to consumption in each region. We do so by sharing out each sector's investment-related emissions proportionally to the regions in which the goods produced with that capital are finally consumed.

The final demand vectors are thus composed of final demand by private households H^r, government final demand G^r, and investment final demand I^r:

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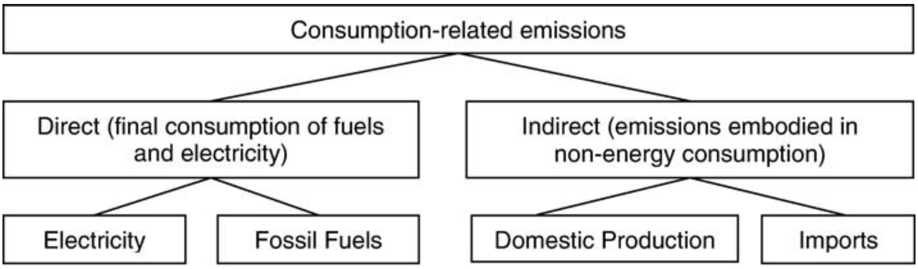
[2] This equation relies on the fact that $\mathrm{X = AX + Y \Leftrightarrow X - AX = Y \Leftrightarrow X = (I-A)^{-1}Y}$, so that total emissions per $ of final demand Y is given by $\mathrm{F(I-A)^{-1}}$.

Figure 1: Composition of Consumption-related Emissions



$$Y^r = H^r + G^r + I^r \tag{7}$$

We now define the emissions associated with this final demand. Consistent with Hassett et al. (2009), we separate consumption-based emissions into direct and indirect emissions. Direct emissions are defined as emissions arising from household, government or investment-related consumption of energy (fossil fuels and electricity). All other emissions embodied in the final demand for non-energy goods are categorized as indirect emissions (see Figure 1).

Specifically, direct household emissions are given by:

$$E^r_{H,Dir} = B^r H^r + E^r_{h,ele} \tag{8}$$

where B^r is a nR vector of CO_2 emission coefficients representing the quantity of CO_2 emitted per dollar of fossil fuel use by households in region r. The $E^r_{h,ele}$ term represents the emissions associated with the electricity consumed by households. It is attributed to direct consumption although it is computed using MRIO similarly to all other non-energy goods.

Indirect emissions embodied in region r's consumption are computed by multiplying the total CO_2 intensity vector $\mathrm{F}^{\mathrm{tot}}$ with the bilateral final demand vector and subtracting electricity emissions, as these are attributed to direct emissions:

$$E^r_{H,Indir} = F^{\mathrm{tot}} H^r - E^r_{h,ele} = F(I-A)^{-1} H^r - E^r_{h,ele} \tag{9}$$

Total emissions associated with household consumption are the sum of direct and indirect emissions: $E^r_H = E^r_{H,dir} + E^r_{H,Indir}$. Direct and indirect emissions associated with government and investment final demand (E^r_G and E^r_I) are computed in a similar manner. While we attribute to each region the emissions associated with households and governments in that region, the emissions embodied in final investment demand (E^r_I) are attributed not to region r but to regions in proportion to the final destination of the output of the sectors in which the investment occurred.

In our social accounting matrix, we observe final investment demand I^r (the value of each sector's output going to investment) as well as capital earnings in each sector i, V^r_i. We assume that investment per sector is proportional to capital earnings and use capital earnings to share out the CO_2 embodied in investment (E^r_I) to each sector. Assuming that investment in each sector has the same CO_2 intensity as aggregate investment, we compute E^{ri}_I, the investment-related emissions embodied in each sector i:

$$E_I^{ri} = \frac{V_i^r}{\sum_i V_i^r} E_I^r \tag{10}$$

We then attribute investment emissions to regions according to the destination of each sector's output. We assume that each region's future output will be exported to the same distribution of destinations as current production. These shares are computed using the elements of the inverted A matrix, $\alpha_{j,i,s,r}$, as $\theta_{i,s,r} = \sum_{j,r'} \alpha_{j,i,s,r'} y_{i,r',r}$. They assign production in each sector to the region in which it will ultimately be consumed and are used to compute the emissions embodied in investment for domestic production in region r as $E_{ID}^r = \sum_i \theta_{i,r,r} E_I^{ri}$, and the emissions embodied in imported investment as $E_{II}^r = \sum_{i,s} \theta_{i,s,r} E_I^{si}$.

Finally, emissions embodied in region r's consumption are the sum of household consumption emissions, government consumption emissions, and investment related emissions (both domestic and imported):

$$E_C^r = E_H^r + E_G^r + E_{ID}^r + E_{II}^r \tag{11}$$

2.3 Regional and Production-Related Emissions

We will compare consumption-based emissions to production-based emissions and regional emissions (the CO_2 emitted within region r). Direct production emissions caused by the burning of fossil fuels in industrial processes are given by:

$$E_{\mathrm{P,Dir}}^r = f^r x^r \tag{12}$$

Total production emissions, which correspond to both direct production emissions and the emissions embodied in all intermediate inputs are computed using F^{tot} as:

$$E_{P,Tot}^r = F^{\mathrm{tot}} x^r = F(I-A)^{-1} x^r \tag{13}$$

Finally, regional emissions (the CO_2 emitted within region r) include the emissions caused by the burning of fossil fuels in both final demand and production:

$$E_{\mathrm{R}}^r = B^r Y^r + f^r x^r \tag{14}$$

2.4 Emissions Intensity

From the total emissions embodied in consumption (E_C^r) we can compute the CO_2 intensity of consumption (or average physical amount of carbon per \$) as

$$k_C^r = \frac{E_C^r}{\sum_i y^{ir}}.$$

This measure of CO_2 intensity is closely related to the notion of carbon tax incidence computed in Hassett et al. (2009). Indeed, if the price shock caused by a tax on CO_2 emissions is assumed to completely pass through to consumers, the two metrics are equivalent.

We compare it to the average CO$_2$ intensity of gross output which is computed as $k^r_{P,tot} = \frac{E^r_{P,Tot}}{\sum_i x^{ir}}$ and the average CO$_2$ intensity of value added (GDP) which corresponds to $k^r_{P,dir} = \frac{E^r_{P,\mathrm{dir}}}{\sum_i va^{ir}}$.

2.5 Data

Construction of the *A*, *Y*, and *F* matrices requires combining data from a number of sources, including the Global Trade Analysis Project GTAP version 7 dataset (Narayanan and Walmsley, 2008), the U.S. Census Bureau Foreign Trade Statistics State Data Series, the EIA's State Energy Data System (SEDS), the Bureau of Transportation Statistics' Commodity Flow Survey (CFS), and state level input-output and consumption data compiled by the IMPLAN group (using the National Income and Product Accounts (NIPA), the BEA's output series, the U.S. Census Bureau's Annual Survey of Manufactures, Household Personal Consumption Expenditures (PCE) and the Consumer Expenditure Survey (CES)). Data preparation is discussed in an online Appendix, and more detail is available in Caron and Rausch (2013).

The resulting dataset includes input-output tables, final demand data and CO$_2$ emission coefficients for all 50 U.S. states as well as 113 countries and regions outside of the U.S. (see Table A4 of the online Appendix) for 2006. The dataset also includes the full matrix of bilateral trade between all regions, including U.S. intra-national trade and trade between U.S. states and their international trading partners. Our bilateral trade matrix does not, however, distinguish between trade in intermediate and final goods so these are shared out according to aggregate bilateral trade shares using a proportionality assumption.

Because the dataset we have constructed covers most of the global economy, we are able to compute the total CO$_2$ intensity of both internationally and domestically traded goods. Within states and countries, we track 52 sectors (see Table A2 of the Appendix) including agricultural, industrial and energy goods, as well as services. While we also compute results at the state level, we simplify exposition in the main body of this paper by aggregating states to 12 regions, as shown in Figure 2. Unless otherwise stated, all results are based on data from 2006.

3. RESULTS

We begin in Table 1 by reporting the elements of the F^{tot} vector, which correspond to the average amount of CO$_2$ (in kg) embedded in each dollar of output—the total CO$_2$ intensity of each sector—across regions of the U.S. for the 24 highest-emitting sectors in the dataset (representing over 90 percent of U.S. emissions). The intensity measure is the total amount of CO$_2$ required for the production of goods in each sector, divided by the value of gross output in that sector. For example, \$1 USD worth of Motor Vehicles/Parts sector in the Midwest region embodies an average of 0.58 kg of CO$_2$.

Table 1 reveals heterogeneity in carbon intensities across both regions and sectors. For example, New England and New York have less than half the carbon content per dollar of Electricity output than the Southeast and Central regions. The distribution of intensities is more homogenous in other sectors but large differences exist in almost all goods and services. These reflect differences in technology, prices, and the within-sector composition of production (these intensity measures use value as a denominator) as well as in the CO$_2$ intensity of intermediate inputs, electricity in particular.

Figure 2: Regional Aggregation of U.S. States

These sector-level intensity measures can be used to investigate the distribution of impacts that may be caused by carbon taxation policies. For example, if emissions were subject to a uniform tax t everywhere in the world (measured in terms of \$USD per kg), one could use this intensity measure to compute a first-order approximation of the effect of such a tax on the price of any good by multiplying its CO_2 intensity by t. Table 1 shows that electricity produced in New England contains an average of 4.59 kg of CO_2 per dollar of output; therefore, a fully passed forward carbon tax of $t = \$0.02/\text{kg}$ (\$20/metric ton) would increase the price of electricity by 9 percent of the value of output: $4.59 \times t = 0.09$. Of course, because these intensity indices capture the CO_2 emitted in all upstream sectors, multiplying intensity estimates by the value of output and summing across regions and sectors would lead to double-counting emissions as well as any associated tax revenue.

The final three columns of Table 1 relate to the total nation-wide emissions associated with each sector, in Mt CO_2. The first of these columns displays the total emissions embodied in each sector's output, both directly (in the production of that sector) and indirectly (through intermediate inputs, including electricity): the sum over all U.S. regions of $E^r_{P,Tot}$. The second-to-last column displays the amount of CO_2 directly emitted in the production of each sector:[3] the sum over all U.S. regions of $E^r_{P,\text{dir}}$. Comparing these columns shows that almost all emissions in the Electricity sector are direct production emissions—2305 Mt out of the total 2364 Mt. For many sectors, however, a large share of emissions is embodied in intermediate inputs. Very little carbon (77 Mt) is emitted directly in the production of the Recreational/Other Services sector, but its output is associated with a large amount of emissions (1028 Mt) when embodied emissions are included. The last column

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[3] The sum of these emissions over all sectors is 5309 Mt. This number does not include emissions occurring in final demand. According to the EPA GHG inventory, CO_2 emissions from fossil fuel combustion corresponded to 5753 Mt in 2005, 358 Mt of which were residential emissions.

Table 1: Carbon Intensity of Output by Region and Sector, Ordered by Total Emissions Embodied in Final Demand

	F^{tot}: total CO_2 Intensity (Kg CO_2/\$)												Total U.S. Emissions – CO_2 (Mt)		
	NENG	NY	MATL	SEAS	FL	MWES	NCEN	SCEN	TX	MOUN	PACI	CA	Production (Total)	Production (Direct)	Embodied in final demand
Electricity	4.59	2.70	9.56	9.57	9.61	9.56	9.62	9.58	6.82	6.48	6.44	6.60	2364	2305	809
Recreational/Other Services	0.11	0.16	0.22	0.23	0.31	0.22	0.22	0.34	0.26	0.23	0.18	0.18	1028	77	275
Trade	0.13	0.15	0.22	0.24	0.27	0.21	0.21	0.30	0.25	0.17	0.14	0.14	459	36	268
Transport NEC	2.08	1.27	2.01	2.21	1.70	1.97	2.29	3.08	2.65	1.99	1.74	1.83	1240	899	202
Chemical/Rubber/Plastic Products	0.22	0.28	0.53	0.67	0.45	0.62	0.52	2.26	1.95	0.44	0.25	0.31	948	294	162
Petroleum/Coal Products	0.47	0.46	0.64	0.76	0.50	0.95	1.00	1.00	1.48	0.91	0.67	0.67	600	287	152
Public Admin./Defense/ Education/Health	0.07	0.07	0.09	0.10	0.11	0.11	0.11	0.15	0.11	0.08	0.07	0.06	305	22	147
Air Transport	2.53	2.85	3.85	3.43	3.86	3.36	2.73	3.86	4.46	3.31	4.44	3.28	436	336	145
Motor Vehicles/Parts	0.07	0.18	0.21	0.48	0.12	0.58	0.39	0.45	0.23	0.14	0.15	0.24	287	11	90
Food Products NEC	0.15	0.17	0.31	0.52	0.19	0.88	1.43	0.92	0.60	0.43	0.48	0.46	187	44	84
Manufactures NEC	0.20	0.10	0.20	0.38	0.18	0.31	0.32	0.44	0.17	0.19	0.16	0.25	75	3	80
Wearing Apparel	0.14	0.19	0.19	0.61	0.22	0.19	0.23	0.90	0.14	0.17	0.32	0.32	13	2	60
Electronic Equipment	0.22	0.15	0.21	0.25	0.29	0.17	0.28	0.24	0.44	0.46	0.47	0.32	248	10	56
Alcohol/Tobacco Products	0.15	0.10	0.37	0.54	0.36	0.35	0.38	0.63	0.50	0.69	0.20	0.35	68	13	54
Financial Services NEC	0.09	0.11	0.15	0.12	0.17	0.12	0.12	0.11	0.13	0.09	0.09	0.07	112	1	45
Communication	0.09	0.10	0.12	0.17	0.16	0.12	0.16	0.19	0.20	0.21	0.17	0.16	138	12	45
Bovine Meat Products	0.07	0.11	0.24	0.47	0.16	0.67	2.65	1.62	1.18	0.53	0.38	0.38	89	13	39
Meat Products NEC	0.09	0.02	0.27	1.71	0.21	0.21	0.78	2.38	1.01	0.05	0.59	0.35	64	14	27
Gas Production/Distribution	0.44	0.93	0.56	0.20	0.31	0.63	2.23	0.15	0.17	0.41	0.65	1.51	54	32	27
Leather Products	0.18	0.19	0.10	0.25	0.13	0.19	0.25	1.37	0.08	0.15	0.10	0.18	2	0	22
Business Services NEC	0.15	0.17	0.18	0.22	0.23	0.19	0.25	0.35	0.22	0.17	0.13	0.16	134	21	21
Water Transport	0.96	0.70	0.89	0.95	3.79	0.57	0.43	5.64	0.47	0.52	3.67	0.84	52	24	21
Sugar	0.14	0.09	0.48	0.30	0.40	0.70	5.24	4.88	1.05	1.54	0.36	0.40	30	16	20
Textiles	0.23	0.10	0.22	1.17	0.13	0.19	0.21	0.74	0.06	0.06	0.12	0.37	48	4	19
	Average CO_2 Intensity – All Sectors														
Gross output	0.20	0.18	0.33	0.53	0.33	0.54	0.59	0.86	0.68	0.51	0.33	0.23			
Value added	0.13	0.13	0.24	0.41	0.25	0.42	0.46	0.74	0.59	0.45	0.18	0.15			

displays the total amount of emissions embodied in the final demand of each sector: the sum over all U.S. regions of E^r_C. The Electricity sector constitutes the largest contributor to emissions in final demand, but again we see that sectors with considerably cleaner production (e.g., Recreational/Other Services, Trade) also contribute significantly to final demand emissions. The difference between total direct production emissions (summed across sectors) and those embodied in final demand is due to emissions embodied in international imports and exports. In some sectors, a large share of emissions embodied in final demand is imported—the consumption of Wearing Apparel, for example, is responsible for 60 Mt of CO_2 even though U.S. production of Wearing Apparel is only responsible for 13 Mt.

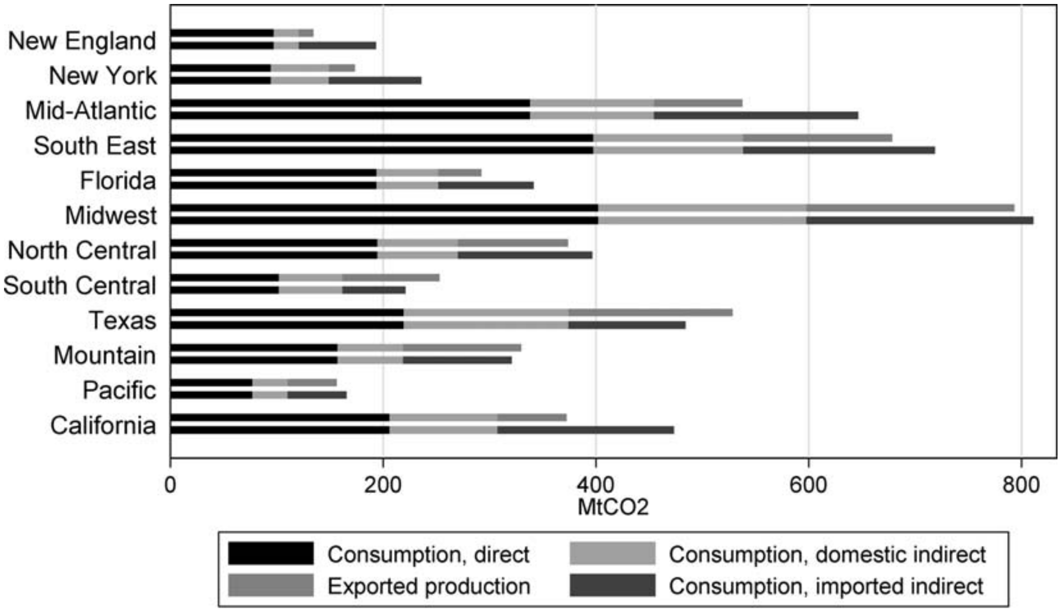
The last two rows of Table 1 illustrate how differences in each sector's CO_2 intensity and each region's composition of production relate to differences in the average CO_2 intensity of regional production. The first of these rows displays $k^r_{P,tot}$, the CO_2 intensity of gross output, and corresponds to the average of the sector-level intensities above it weighted by gross output. These values reveal very large differences between regions, ranging from an average of 0.18 kg CO_2/$ of output for New York, to an average of 0.86 for the South Central region. The last row of Table 1 shows $k^r_{P,dir}$, the CO_2 intensity of value added in each region (defined as the amount of CO_2 emitted directly in the production of all sectors, divided by value added—or GDP—in that region). We divide by value added rather than the gross value of output, relating in-region emissions to in-region economic activity. These values vary even more across regions than the gross output estimate, as the traded intermediates included in the gross output measure mitigate differences in direct CO_2 intensity between regions.

3.1 Regional CO_2 Inventories

Before switching our focus to measuring the CO_2 intensity of consumption, we find it informative to construct regional CO_2 inventories. We compute these both from a production and a consumption perspective, allowing for a differential attribution of responsibility for emissions. For each region, the top bar in Figure 3 corresponds to regional emissions: the CO_2 emitted within the region, E^r_R. The bottom bar corresponds to consumption-based emissions and are computed using the MRIO framework; these calculations include not only the carbon emitted in the production of final goods consumed in the region, but also the CO_2 emitted anywhere in the production of goods which are ultimately consumed in the region.

Both the regional and consumption-based calculations include direct consumption emissions (e.g., Midwest values include CO_2 emitted as households consume fossil fuels and electricity) as well as domestic indirect consumption emissions (e.g., Midwest values include CO_2 emitted during the production of glass in the Midwest used in cars that are ultimately purchased in the Midwest). However, the two metrics differ in terms of the CO_2 embodied in trade. Production estimates include the carbon emitted during the production of goods and services that are ultimately consumed outside of the region (e.g., Midwest production values include CO_2 emitted to produce glass in the Midwest for cars produced in the Midwest that were ultimately purchased in New York), while consumption estimates include imported indirect emissions—CO_2 emitted during production outside of the region of imported intermediate inputs or final goods (e.g., New York consumption values include CO_2 emitted to produce glass in the Midwest for cars that were ultimately purchased in New York). Neither bars include "re-exports" of CO_2—the emissions embodied in a region's imports of goods which are then transformed and ultimately exported to be consumed outside of the region. These emissions should not be attributed either to domestic consumption nor production, but the MRIO framework allows us to compute re-exports and we note that they comprise a rela-

Figure 3: CO_2 Accounting of Consumption, Compared to Regional Production Emissions



tively large share of CO_2 trade in most regions—on average 46% of total carbon exports, with a maximum of 76% in New England, and 36% of total imports (both domestically consumed and re-exported), with a maximum of 46% for the Midwest. Figure A1 in the Appendix displays CO_2 trade in each region, including re-exports.[4]

Comparison of the top and bottom bars in Figure 3 reveals whether a region is a net importer or a net exporter of CO_2. We find that the New England, New York, Mid-Atlantic, Florida and California regions are all significant net importers of embodied carbon. The Southeast, Midwest, North Central and Pacific regions are nearly balanced with imports of carbon very close to exports. The South Central, Mountain and Texas regions are exporters of carbon. These statistics include carbon imported or exported abroad and so do not net to zero as the U.S. as a whole is net importer of embodied carbon.

Figure 3 highlights the extent to which measures of CO_2 can differ when computed on a consumption rather than a production basis. Consider California, for example: its consumption-based emissions are about 100 Mt larger than its production-based emissions; California imports 1.85 times more embodied CO_2 than it exports. Although we do not trace emissions over time in this analysis, this difference suggests reason for caution about drawing policy conclusions from curves such as the Rosenfeld Curve, which shows a marked decline in California's per capita energy consumption from 1963–2009 (Rosenfeld and Poskanzer, 2009), but may largely underestimate the amount of emissions for which the state is responsible as the decline may be partially attributed to the state importing more emissions.

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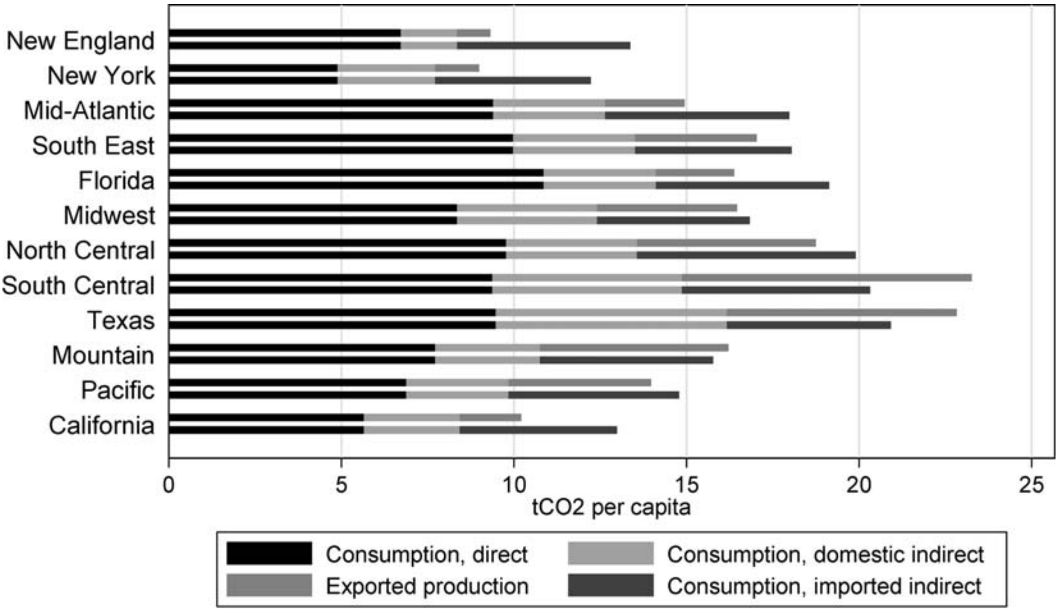
[4] To illustrate the role of bilateral trade flows in generating these estimates, Table A7 of the online Appendix displays the CO_2 embodied in bilateral trade flows (in Mt CO_2) of US regions, between regions as well as with their major international trading partners.

Figure 4: CO_2 Emissions per Capita (tonnes)



Overall, Figure 3 highlights the importance of tracking trade flows: almost all regions consume more imported CO_2 (*imported indirect*) than domestically emitted CO_2 (*domestic indirect*), and most regions export a majority of the CO_2 they emit in the production of goods.

Of course, the values in Figure 3 also reflect differences in region size. In Figure 4, we normalize them by population. Shifting to per capita emissions, two things stand out. First, the ranking of regions changes significantly: South Central region is revealed to have the highest production emissions per capita, whereas Texas has the highest consumption emissions per capita; New York has both the lowest production- and consumption-based emissions. California, even with its substantial imported emissions, remains among the lower-emitting regions. Second, although accounting for size differences causes the variation in emissions to drop significantly, it is still quite large—particularly when measured on a production basis. The ratio of highest to lowest production emissions per capita is still roughly two to one—a considerable amount, especially since we display results at a relatively high level of aggregation. The variation in consumption emissions per capita is lower, as trade between regions partially equalizes emission rates; however, large differences remain between regions' per capita consumption of CO_2.

3.2 Decomposing the CO_2 Content of Final Demand

Figure 5 shows the total CO_2 content of consumption of each final demand type as defined in Equation (13). Private household demand dominates, but government and investment demand account for non-negligible shares of consumption emissions. On average, household final demand accounts for 70% of emissions, government demand for 15%, domestic investment (emissions embodied in domestic investment that are attributed to domestic consumption) for 7% and imported investment (emissions embodied in out-of-region investment that is attributed to domestic con-

Figure 5: Percentage of Each Final Demand Type in Consumption Emissions, by Region

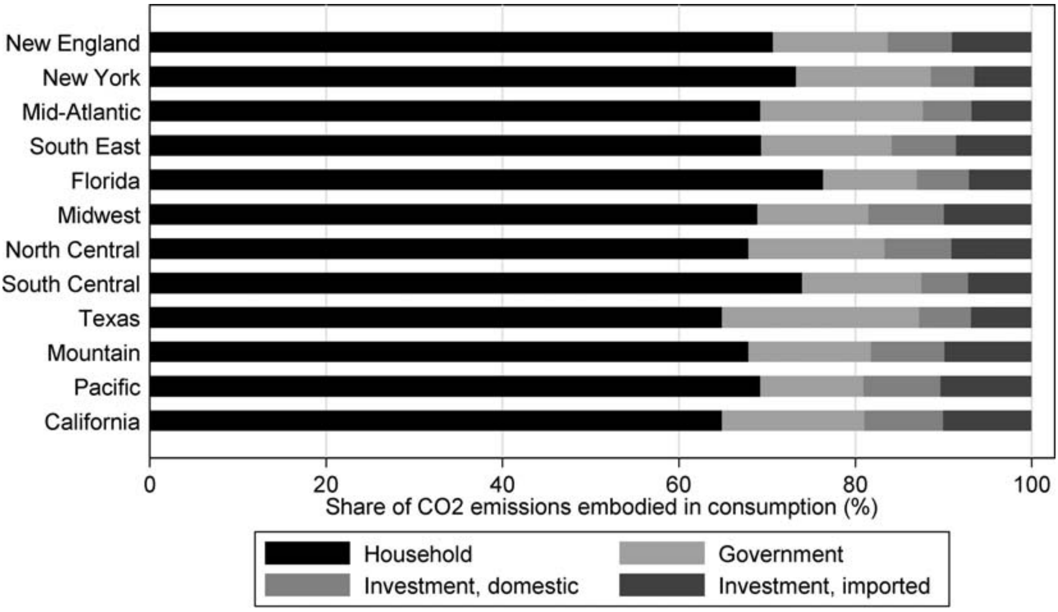
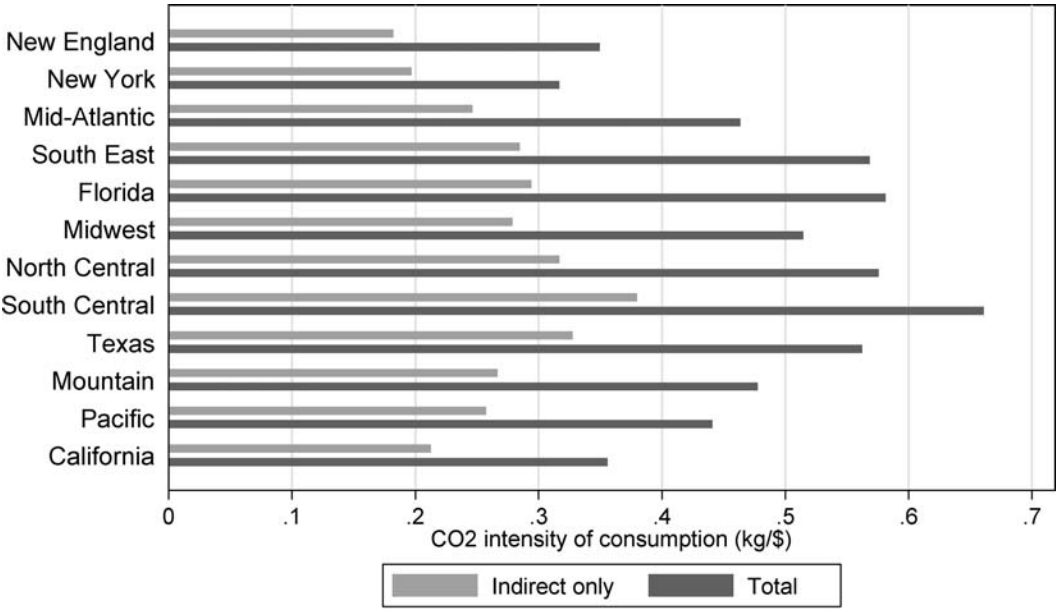


Figure 6: Total vs. Indirect-only CO_2 Intensity of Consumption



sumption) for 8%. Overlooking investment-related consumption emissions would therefore lead to a substantial underestimation of the emissions embodied in final demand.

3.3 The Direct and Indirect CO_2 Intensity of Consumption

Figure 6 displays both the average indirect and total CO_2 content per dollar—or CO_2 intensity—of consumption for each region. The difference between the two bars corresponds to the

Table 2: CO_2 Intensity of Consumption—Summary Statistics across U.S. Regions

	CO_2 intensity of consumption (kg/$)				
	Mean	**Std. dev.**	**C.V.**	**Min**	**Max**
Direct	0.218	0.054	0.248	0.120	0.287
Fossil fuel	0.120	0.022	0.180	0.081	0.157
Electricity	0.099	0.050	0.505	0.024	0.207
Indirect	0.265	0.048	0.182	0.182	0.380
Emitted domestically	0.125	0.043	0.340	0.049	0.213
Emitted in other U.S. regions	0.076	0.014	0.192	0.050	0.105
Emitted internationally	0.064	0.010	0.157	0.048	0.079
Total	0.484	0.098	0.202	0.317	0.661

CO_2 intensity defined as the physical quantity of CO_2 in kg per dollar of consumption; all values weighted by total regional consumption; The coefficient of variation (C.V.) is the standard deviation divided by the mean.

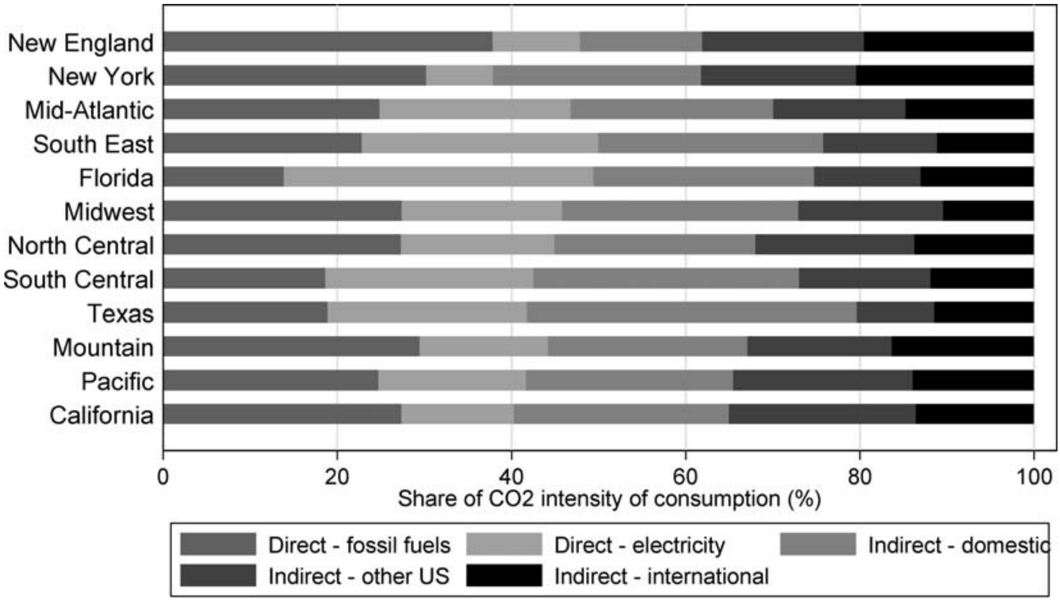
emissions due to the direct final consumption of fossil fuels and electricity. Table 2 provides summary statistics on these intensity measures, weighted by total consumption in each region such that the mean value corresponds to the U.S. mean value. Table A1 in the Appendix displays this intensity for each individual U.S. state.

In Figure 6, we observe that the indirect component of consumption accounts for more than half of the total intensity. On average over the whole country, each dollar of consumption contains 0.218 kg of direct emissions and 0.265 kg of indirect emissions. While policy makers tend to focus on the impact of carbon pricing on energy goods that cause direct emissions through consumption (e.g., gasoline, home heating fuels and electricity), most consumer spending is on non-energy goods where embodied emissions occurred during production.

Importantly, we find that both the direct *and* indirect emissions vary across regions. The direct emissions intensity of consumption is found to range from 0.12 to 0.29 kg/$ (generally, northern states have greater fossil fuel requirements for heating, and southern states have greater electricity requirements for air conditioning). The literature had already identified this variability and this range is roughly consistent with that found by Hassett et al. (2009) and Mathur and Morris (2012). Focusing only on direct emissions overstates the geographic disparity in emissions—though not as much as previous authors have argued. Indeed, indirect emissions are found to vary considerably more than suggested by the aforementioned studies, which argued that the variance of the geographic distribution of indirect emissions is much lower than that of direct emissions. We find that indirect carbon intensity varies from 0.18 to 0.33 kg/$—a ratio of almost two to one. In contrast, Mathur and Morris (2012) find that the CO_2 intensity of the most emissions-intense region is less than 25% higher than that of the least intense region, and that direct emissions vary twice as much between regions as indirect emissions. While direct comparison is difficult due to slight differences in regional aggregation relative to Mathur and Morris (2012), there is clearly considerably more variation in the indirect emissions statistics computed using MRIO.

Figure 7 displays the locus of emission for the carbon embodied in consumption, displaying the composition of emissions in each region. Emissions are categorized as direct, if stemming from the combustion of fossil fuels in final demand (*Direct—fossil fuels*) or from the final demand for electricity (*Direct—electricity*), or indirect, if having occurred within the region (*Indirect—domestic*), in other regions of the U.S. (*Indirect—other US*), or internationally (*Indirect—international*). Figure 7 suggests that, even at this level of aggregation, most indirect emissions are non-domestic: domestically emitted indirect emissions correspond to just 0.13 kg/$ of consumption on average, while imported emissions account for 0.14 kg/$ of consumption on average, with nearly half of

Figure 7: Composition of the CO_2 Intensity of Consumption



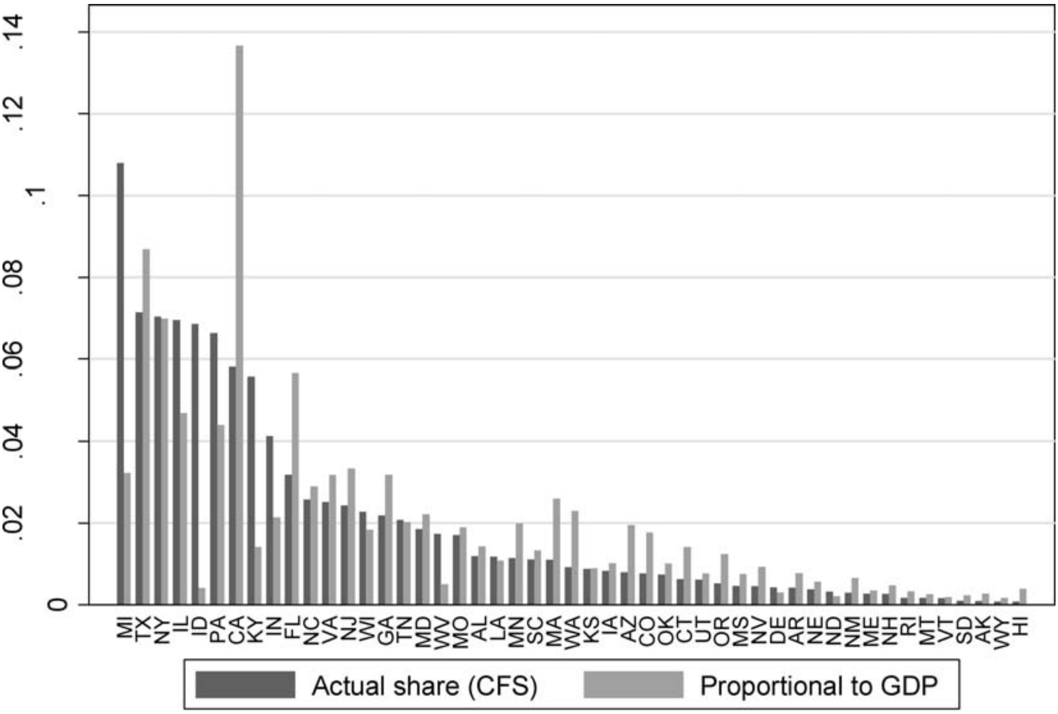
that (0.06 kg/$) coming from international sources. There is slightly less variation in the *Indirect—international* intensity than in the *Indirect—other U.S.* intensity, indicating that the composition of international imports varies less from region to region than that of domestic imports.

3.4 The Importance of Accounting for International and Sub-National Trade Flows

The large differences in the indirect CO_2 intensity of consumption revealed by Figures 6 and 7 have an important implication regarding the incidence of carbon taxation: the extent to which households will be affected will vary across regions not only because of differences in the consumption of fossil fuels and electricity, but because of differences in non-energy consumption as well.

In the online appendix, we propose a decomposition of results in order to better understand the source of this variability. Among other things, we compare consumption-related emissions computed using full MRIO to those computed using the key assumption made by recent studies including Hassett et al. (2009) (that we thus define as *HMM)* that commodities produced in and exported out of any given state are equally likely to be consumed in any other given state. This assumption is clearly not supported by the data: Figure 8 illustrates that the proportion of exports from Ohio going to each state depends not only on the importing state's size, but also on geographical proximity. While the source of data we use, the Commodity Flow Survey, may be capturing flows of goods which are further transported without transformation (warehousing) and may thus exaggerate the effect of distance on trade, there is good evidence that trade costs—including transport costs—play a role in limiting trade. Thus, regional differences in production CO_2 intensities (see Table 1) can lead to differences in the overall CO_2 intensity of consumed goods across states. We find that computing the CO_2 intensity of consumption using the HMM assumption yields a coefficient of variation of 0.119—considerably lower than the 0.202 found with MRIO: the sourcing of domestic and international imports clearly matters. We also find that differences in consumption

Figure 8: Share of Exports from Ohio, by Destination State



patterns do not explain a large part of the heterogeneity, which is better explained by differences in production intensities.

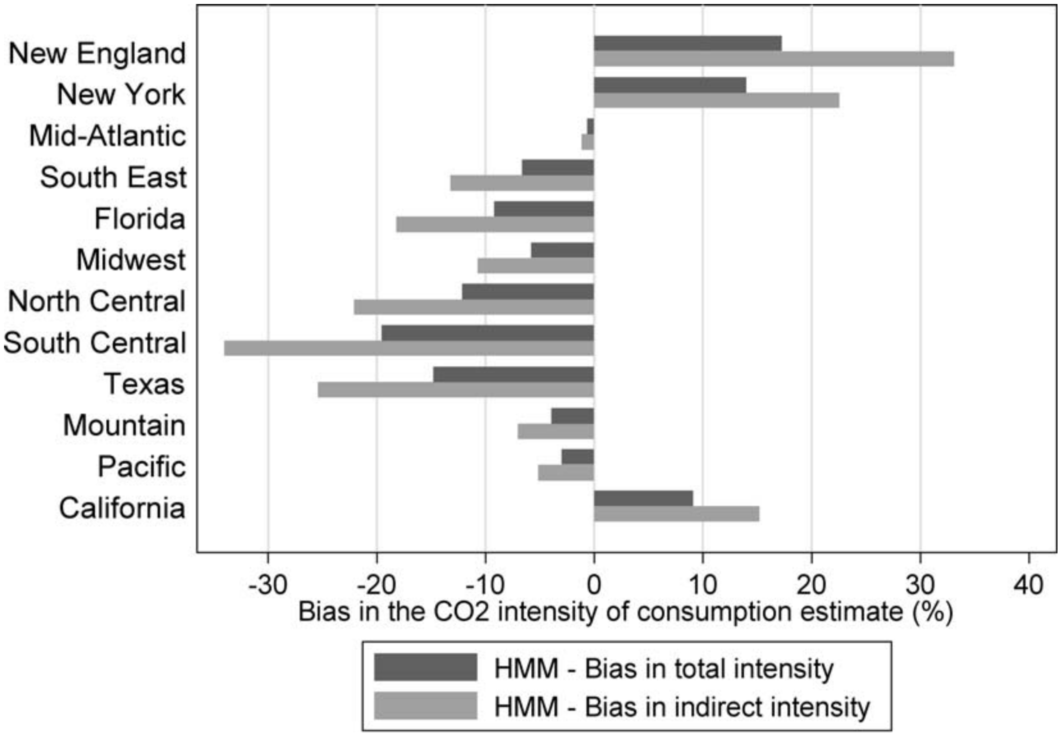
From a practical standpoint, the most important aspect to consider when comparing methodologies might be the precision of estimates for particular regions that policy makers may care about. To investigate this, we also express differences across methodologies by comparing the HMM intensity estimates to MRIO estimates. These differences are measured as 100 × (HMM neutrality assumption estimate / MRIO estimate −1) and shown in Figure 9. Estimates of these differences for all 50 states are shown in Appendix Table A1. Over all states, the median absolute difference for indirect emissions is 17%; however, the error arising from not accounting for differences in the carbon intensity of trade flows is much higher in particular states. Using the HMM assumption would overestimate the indirect CO_2 intensity of consumption by more than 37% in Massachusetts, while simultaneously underestimating that of households in North Dakota by about 70%.

4. CONCLUSIONS

We have used a multi-regional input-output (MRIO) model to understand the patterns of embodied CO_2 consumption in the U.S. Our first significant finding is that state level responsibility for emissions differs substantially when emissions are allocated on a consumption basis rather than a production basis. For example, California's per capita emissions are much higher when allocated on a consumption basis, due to the large net inflow of emissions embodied in the goods it imports.

Our second finding is that there is significant regional heterogeneity in emissions per dollar of consumption, even when focused on the carbon embodied in non-energy consumption. This

Figure 9: Difference between the HMM and MRIO Methodologies



result contrasts sharply with previous studies which made an homogeneity assumption that has led them to underestimate differences in the CO_2 intensity of consumption across states. We thus find good reason to believe that disparities in the impact of carbon pricing go well beyond direct energy consumption.

This matters. Even though non-energy goods and services have low emissions intensities relative to that of energy goods, emissions related to their production amount to a large share of consumption emissions because such a large portion of the household budget is spent on these goods. One implication, then, is that while the impact of carbon pricing might be most obviously seen in the price of energy goods, household budgets will also be impacted by the accumulation of very small, individually unremarkable increases in the cost of all other goods.

Our results are important for understanding the regional patterns of CO_2 intensity in consumption and contribute to explaining regional variation in support for climate policy. Our findings are also relevant for the analysis of state-level carbon policy which, given the failure to enact carbon pricing at the national level, is growing in importance. The carbon intensity of production and consumption in different sub-national regions could help determine the likelihood of enacting policy at the sub-national level, as well as inform the design of that policy—including, for example, whether carbon pricing should be enacted on an upstream (production) or a downstream (consumption) basis.

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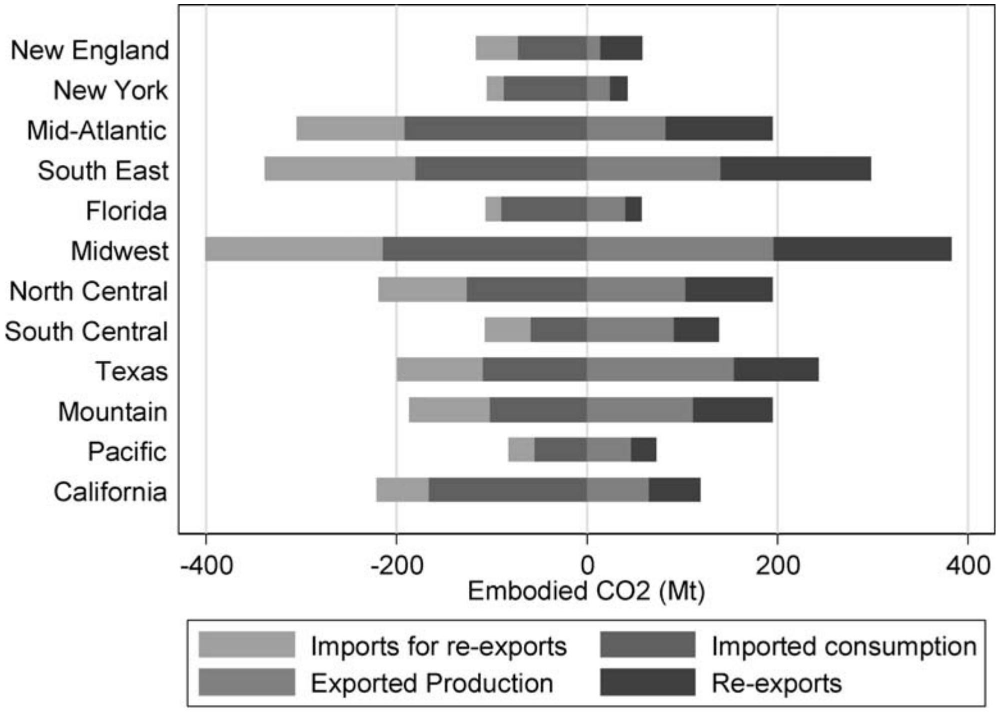
APPENDIX

Table A1: The CO_2 Intensity of Consumption, by State (kg/$)

		CO_2 Intensity of Consumption (kg/$)				HMM vs MRIO (% Diff.)	
State		Direct – Fossil	Direct – Electricity	Indirect Non-Energy	Total	Indirect Non-Energy	Total
Alaska	AK	0.168	0.065	0.646	0.88	-53.8	-39.5
Alabama	AL	0.117	0.163	0.356	0.63	-26.3	-14.7
Arkansas	AR	0.122	0.151	0.381	0.65	-31.4	-18.3
Arizona	AZ	0.098	0.104	0.227	0.42	7.5	4.0
California	CA	0.097	0.045	0.209	0.35	19.5	11.6
Colorado	CO	0.121	0.054	0.257	0.43	-2.3	-1.4
Connecticut	CT	0.117	0.038	0.180	0.33	35.4	19.1
Delaware	DE	0.104	0.129	0.275	0.50	-8.1	-4.4
Florida	FL	0.081	0.207	0.298	0.58	-17.9	-9.1
Georgia	GA	0.152	0.156	0.262	0.57	-5.1	-2.3
Hawaii	HI	0.074	0.116	0.406	0.59	-39.5	-26.9
Iowa	IA	0.183	0.102	0.300	0.58	-16.8	-8.6
Idaho	ID	0.477	0.076	0.302	0.85	-15.9	-5.6
Illinois	IL	0.126	0.078	0.248	0.45	0.6	0.3
Indiana	IN	0.138	0.112	0.285	0.53	-10.9	-5.8
Kansas	KS	0.115	0.107	0.333	0.55	-24.5	-14.7
Kentucky	KY	0.125	0.122	0.283	0.53	-9.5	-5.1
Louisiana	LA	0.126	0.180	0.460	0.76	-44.5	-26.7
Massachusetts	MA	0.128	0.024	0.180	0.33	37.8	20.5
Maryland	MD	0.102	0.122	0.249	0.47	-2.6	-1.4
Maine	ME	0.237	0.059	0.274	0.57	-7.0	-3.4
Michigan	MI	0.160	0.089	0.291	0.54	-9.6	-5.2
Minnesota	MN	0.193	0.088	0.275	0.55	-7.6	-3.8
Missouri	MO	0.146	0.120	0.299	0.56	-15.9	-8.4
Mississippi	MS	0.129	0.196	0.383	0.70	-32.8	-17.8
Montana	MT	0.179	0.071	0.561	0.81	-53.8	-37.3
North	NC	0.124	0.150	0.247	0.52	0.5	0.3
North Dakota	ND	0.192	0.106	0.852	1.15	-69.5	-51.4
Nebraska	NE	0.120	0.102	0.296	0.51	-15.7	-9.0
New	NH	0.154	0.063	0.219	0.43	12.8	6.4
New Jersey	NJ	0.131	0.092	0.254	0.47	-2.1	-1.1
New Mexico	NM	0.128	0.052	0.330	0.50	-14.9	-9.7
Nevada	NV	0.089	0.067	0.209	0.36	20.0	11.4
New York	NY	0.096	0.024	0.198	0.31	24.0	14.9
Ohio	OH	0.135	0.109	0.276	0.52	-8.3	-4.4
Oklahoma	OK	0.120	0.142	0.346	0.60	-26.4	-15.0
Oregon	OR	0.099	0.071	0.215	0.38	15.0	8.4
Pennsylvania	PA	0.118	0.097	0.250	0.46	1.6	0.9
Rhode Island	RI	0.039	0.026	0.208	0.27	16.8	12.8
South	SC	0.137	0.165	0.276	0.57	-10.1	-4.8
South Dakota	SD	0.104	0.176	0.371	0.65	-32.8	-18.7
Tennessee	TN	0.112	0.153	0.303	0.56	-16.4	-8.8
Texas	TX	0.106	0.129	0.332	0.56	-24.8	-14.5
Utah	UT	0.143	0.050	0.247	0.44	2.7	1.5
Virginia	VA	0.112	0.114	0.253	0.48	-3.4	-1.8
Vermont	VT	0.194	0.053	0.247	0.49	2.2	1.1
Washington	WA	0.121	0.069	0.218	0.40	15.0	8.0
Wisconsin	WI	0.167	0.099	0.276	0.54	-7.8	-4.0
West Virginia	WV	0.114	0.111	0.314	0.53	-18.2	-10.6
Wyoming	WY	0.134	0.067	0.449	0.65	-42.7	-29.5

Figure A1: CO_2 Embodied in Trade



Note: graph displays imports (for re-exports and domestic consumption) left of the zero-axis, and exports (from domestic production and re-exports) on the right of the zero-axis. It reveals whether a region is a net importer or a net exporter of CO_2, and can also be used to compute the share of the CO_2 in imports that will be re-exported, and the share of CO_2 in exports which were imported.

Table A2: Sectors in the Dataset

Code	Description
ATP	Air Transport
B T	Beverages and Tobacco Products
C B	Sugar Cane/Sugar Beet
CMN	Communication
CMT	Bovine Meat Products
CNS	Construction
COL	Coal
CRP	Chemical, Rubber and Plastic Products
CRU	Crude Oil/Natural Gas
CTL	Bovine Cattle, Sheep, Goats, Horses
DWE	Dwellings
EEQ	Electronic Equipment
ELE	Electricity
FMP	Metal Products
FRS	Forestry
FSH	Fishing
GAS	Gas Manufacturing and Distribution
GRN	Grains (paddy rice, wheat, and cereal grains NEC)
I S	Ferrous Metals
ISR	Insurance
LEA	Leather Products
LUM	Wood Products
MIL	Dairy Products
MVH	Motor Vehicles and Parts
NFM	Metals NEC
NMM	Mineral products NEC
OAP	Animal products NEC (e.g., raw milk, wool,
OBS	Business Services NEC
OCR	Crops NEC
OFD	Food Products NEC
OFI	Financial Services NEC
OIL	Petroleum/Coal Products
OME	Machinery and Equipment NEC
OMF	Manufactures NEC
OMN	Minerals NEC
OMT	Meat products NEC
OSD	Oil Seeds
OSG	Public Administration, Defense, Education, Health
OTN	Transport Equipment NEC
OTP	Transport NEC
PCR	Processed Rice
PFB	Plant-based Fibers
PPP	Paper Products, Publishing
ROS	Recreational/Other Services
SGR	Sugar
TEX	Textiles
TRD	Trade
V F	Vegetables, Fruit, Nuts
VOL	Vegetable Oils and Fats
WAP	Wearing Apparel
WTP	Water Transport
WTR	Water