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Tracing toxic chemical releases embodied in U.S. interstate trade and their unequal distribution

Guangxiao Hu [a], Kuishuang Feng [a,*], Laixiang Sun [a,b], Giovanni Baiocchi [a]

[a] Department of Geographical Science, University of Maryland, College Park, MD 20742, USA

[b] School of Finance & Management, SOAS University of London, London WC1H 0XG, UK

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ABSTRACT

Toxic chemicals have severe impacts on ecosystem, climate change and human health, and the current toxic releases are inequitably distributed across regions. Investigating the toxic release embodied in final demand by states and income groups can reveal the responsibility transfer of different entities. In this paper, we extended the U.S. multi-regional input–output (MRIO) model with toxic chemical release data in 2017 to conduct the production- and consumption-based accounting of toxic release by each state, and the inter-regional transfer of embodied toxic release between states. In addition, this paper analyzed how the toxic releases and inter-state transfer of embodied toxic release have been driven by income groups across states. The results showed that the toxic release from production was highly concentrated on the central states and the Great Lakes Region, while the consumption-based accounting of toxic release was more equally distributed across regions in the US. The non-metallic and metallic products manufacturing sectors were the most important sectors for most states from both production and consumption-based perspectives and were also the most essential sectors for interregional flows of embodied toxic release from Great Lake Region to Southeast, Mid-Atlantic and Northeast. Our results also showed that the largest portion (41.88%) of embodied toxic releases were triggered by households' final demand, and that the consumption of the richest 35% of households contributed to more than 50% of the total toxic chemical releases triggered by total final demand of all households.

1. Introduction

Toxic chemicals have significant impacts on climate change (Conference of the Parties, 1998; Godal and Fuglestvedt, 2002), ecosystem quality (Gilbert et al., 2010), and human health (Balbus et al., 2013; Kaiser, 2000). Toxic chemical releases have caused severe disasters in both developing and developed countries. For example, thousands of people died of extremely toxic methylisocyanate gas escape and their exposure in Bhopal, India, in 1984, which is the world's worst industrial disaster in the recent decades (Taylor, 2014; US Environmental Protection Agency, 2022a). According to National Toxic Substances Incidents Program (NTSIP), during 2010–2014, nine participating states reported 22,342 incidents, of which 13,529 were acute toxic substance incidents, causing huge impact on human health (Melnikova et al., 2020).

The current distribution of toxic chemical releases (TCR) is largely unequal across regions within the US (US Environmental Protection Agency, 2021a). According to the Toxic Release Inventory (TRI), toxic release facilities are concentrated in the western coast, southeastern coast and the Great Lake's region, while midwestern regions have much fewer TRI facilities (see Fig. A1). Also, the total TCR differ significantly between regions in the US (see Fig. A3). Although Pacific Northwest, and Pacific Southwest have relatively smaller number of facilities, the region contributes a large amount of total releases. Many existing studies regarding TCR in the US focused on TCR from the production perspective, analyzing the inequality across regions and the health impacts across demographic groups. For example, Ard (2015) explored air pollution exposure across regions and demographic groups and found that the variation of the exposure have grown substantially in the United States over 1995–2004 using the United States Environmental Protection Agency (EPA)'s Risk Screening Environmental Indicators Geographic Microdata (RSEI-GM) and multilevel regression models. The results showed that African Americans are more exposed to air toxins than Whites even though the amount is decreasing for every-one. Using multilevel models, Ard and Smiley (2022) investigated the relationship between racialized poverty segregation and hazardous industrial sites,

* Corresponding author.
E-mail address: kfeng@umd.edu (K. Feng).

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and the results showed that counties with higher economic and racial segregation levels have a significantly higher density of facilities, which are disproportionately clustered at communities with higher percentages of poor African American and Hispanic people.

However, the products produced in one region are not only consumed by local consumers, but also traded to meet other regions' consumption. Therefore, consumption in one place may cause pollution in other places via interregional trade of goods and services (Zhang et al., 2018). The embodied TCR in regional trades may help us identify the transfer of responsibility hidden in products exchanged among regions. Consumption-based environmental accounting (Chen et al., 2018; Lenzen et al., 2007; Munksgaard and Pedersen, 2001; Peters, 2008) can allocate the production-based TCR to regions that consumes the final goods and services, thus demonstrating how the demands in consumer regions cause the environmental problems in producer regions (Hoekstra and Wiedmann, 2014; Wiedmann and Lenzen, 2018). Koh et al. (2016) calculated the toxicological footprint (consumption-based TCR) of the U.S. between 1998 and 2013. Fujii et al. (2017) also calculated the consumption-based toxicity of chemical emissions from the US industrial sector over the 1998–2009 period. These studies, however, only focused on toxic emissions at the national level. Through tracing TCR embodied in trade among U.S. states, consumption-based accounting is important for identifying the ultimate drivers of the releases, thus, open up opportunities for cooperative solutions among states (Nansai et al., 2020).

Aside from regional disparities, the consumption of different income and racial groups has contributed to TCR exposure and other criteria air pollution exposure disproportionately in the U.S. (Tessum et al., 2019). For example, Wang and Feliberty (2010) showed that minority and low-income groups are more likely to be located within buffers around the toxic release inventory facilities. Clark et al. (2014) also showed that low-income nonwhite young children and elderly people are disproportionately exposed to residential outdoor NO_2. Tessum et al. (2019) showed that PM2.5 exposure is disproportionately caused by consumption of goods and services of the non-Hispanic white majority, but disproportionately inhaled by black and Hispanic minorities. Thind et al. (2019) found that average exposures to PM 2.5 are the highest for blacks, and are higher for lower-income than for higher-income. Using EPA's TRI data, Charette et al. (2021) assessed residential clusters associated with pollutant releases, and results showed that the highest amount of releases were concentrated at clusters with high percentage of working class. Income inequality is extremely high in the U.S., for example, the mean household income in the top 20 % was 10.3 times greater than that in the bottom 20 % in 1975 while the gap was enlarged to 16.6 times in 2019 (Bor et al., 2017; Congressional Research Service, 2021). Income groups differ significantly in terms of consumption patterns, thus contributed to the environmental impacts very differently (Jorgenson et al., 2017). It is essential to understand consumption-based TCR or TCR footprint, which accounts for all toxic emissions (based on the TRI) along entire domestic supply chains (Koh et al., 2016), of different income groups so that policy decision-makers can be informed by demand-side toxic reduction policy recommendations with lower socioeconomic costs (Feng et al., 2021).

In summary, previous research mainly focused on TCR in the US from the production perspective, analyzing pollution exposure across regions and demographic groups (Ard and Smiley, 2022; Ard, 2015). A few researches calculated consumption-based toxicity of chemical emissions in the US (Fujii et al., 2017; Koh et al., 2016), however, these studies were conducted at the national level. There has been a lack of research attention to the flows of TCR embodied in interstate trade, which is termed consumption-based toxic chemical footprints. Consequently, there has been an absence of research analyzing the disproportionate exposure of consumption-based TCR faced by different income groups across states in the US. In this study, we fill the above gaps by first assessing regional consumption-based accounting of pollution inequalities and outsources of embodied TCR between states in the US; and then estimating the TCR footprint of different income groups at the state level. For this purpose, we developed an environmentally extended multi-regional input–output (MRIO) model for the US using the MRIO table from IMPLAN and the toxic chemical release inventory data in 2017 from US EPA, to calculate the production- and consumption-based TCR of each state, the inter-regional transfer of embodied TCR between states, as well as the TCR footprint across income groups. The MRIO model is a commonly used method to exam environmental impacts embodied in consumption and interregional trade (Brizga et al., 2017; Chen and Wemhoff, 2021; Foong et al., 2022; Lian et al., 2022; Wiedmann, 2009; Wiedmann et al., 2007). By using MRIO model, this paper provides quantitative information on how pollution inequality of toxic release varies across regions and income groups in the US. Such information can facilitate the formation of shared responsibilities between consumers and producers in the efforts to mitigate the adverse impact of toxic release on the environment and human health.

2. Model and data

2.1. Multi-regional input–output model

In a multi-regional input–output model, the product flows within a region and the product inflows and outflows among regions are taken into consideration. Suppose there are n regions and there are m producing sectors in each region. Z_{ij}^{rs} is the monetary flow from sector i in region r to sector j in region s. The elements of X are denoted as x_i^r, representing the total output of sector i in region r. The elements of the direct consumption coefficient matrix A are denoted as a_{ij}^{rs}, which is given by $a_{ij}^{rs} = z_{ij}^{rs}/x_j^s$, representing the amount of commodity i in region r directly required to produce per unit of sector j in region s. Y consists of intraregional (y^{rr} and y^{ss}) and interregional final demand y^{rs} and y^{sr}). The element y_i^{rs} represents the final demand for commodity i in region r from region s.

The basic equation of multi-region input–output model (MRIO) is

$$X = AX + Y \tag{1}$$

where

$$A = \begin{bmatrix} A^{1,1} & A^{1,2} & \cdots & A^{1,n} \\ A^{2,1} & A^{2,2} & \cdots & A^{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ A^{n,1} & A^{n,2} & \cdots & A^{n,n} \end{bmatrix}, X = \begin{bmatrix} x^1 & 0 & \cdots & 0 \\ 0 & x^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & x^n \end{bmatrix}, Y = \begin{bmatrix} y^{1,1} & y^{1,2} & \cdots & y^{1,n} \\ y^{2,1} & y^{2,2} & \cdots & y^{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ y^{n,1} & y^{n,2} & \cdots & y^{n,n} \end{bmatrix}.$$

To get X, the equation (1) can be rewritten as

$$X = (I - A)^{-1}Y \tag{2}$$

where $L = (I - A)^{-1}$ is the Leontief inverse matrix;I is the identity matrix.

To calculate the interregional TCR flows, a matrix t_c is needed to represent the direct TCR coefficient of different sectors in different regions. The interregional TCR flows can be calculated as follow:

$$TF = t_c(I - A)^{-1}Y \tag{3}$$

where TF is the TCR embodied in commodities flowing between regions; t_c is a matrix of sectoral direct TCR coefficient (total toxic chemical releases of sector j dividing by the total output of sector j in each state).

Production-based TCR of region r can be estimated as (Peters, 2008)

Table 1
Total household income for specified income group.

Specification	Explanation
Households LT15k	Those earning less than $15,000
Households 15–30 K	Those earning between $15,000 and $30,000
Households 30–40 K	Those earning between $30,000 and $40,000
Households 40–50 K	Those earning between $40,000 and $50,000
Households 50–70 K	Those earning between $50,000 and $70,000
Households 70–100 K	Those earning between $70,000 and $100,000
Households 100–150 K	Those earning between $100,000 and $150,000
Households 150–200 K	Those earning between $150,000 and $200,000
Households 200 K+	Those earning greater than $200,000

Source: Candi Clouse (2022).

$$TCR_P^r = \sum_{s=1}^{n}\sum_{i=1}^{m} TF_i^{rs} \quad (4)$$

Consumption-based TCR of region s can be estimated as (Peters, 2008)

$$TCR_C^s = \sum_{r=1}^{n}\sum_{i=1}^{m} TF_i^{rs} \quad (5)$$

To get the TCR related to each income group's final consumption by state level in US (Peters and Hertwich, 2004; Steen-Olsen et al., 2016), we can get

$$T_{incomegroup} = t_c(I-A)^{-1}HY_{incomegroup} \quad (6)$$

where $T_{incomegroup}$ is the embodied TCR associated with each income group's final consumption (TCR footprint) in each state. $HY_{incomegroup}$ is the household final demand for each income group in each state.

2.2. Data

The American multi-regional input–output (MRIO) tables was compiled using single-regional input–output tables for each of the 51 states and the trade flow data between states. The trade flow data between states was collected from the county-level trade data and aggregated to state-level. The MRIO data needed were extracted from the Economic Impact Analysis for Planning (IMPLAN) database (IMPLAN Group. LLC, 2021). There are 546 sectors in IMPLAN, representing all industries in the US classified by North American Industry Classification System (NAICS) codes ("Economic Impact Analysis for Planning | IMPLAN," n.d.).

The toxic release data was collected from Toxics Release Inventory (TRI) Program conducted by United States Environmental Protection Agency (EPA). TRI is a compilation of data submitted by certain facilities subject to the reporting requirements of Section 313 of the federal Emergency Planning and Community Right-to-Know Act (EPCRA) (US Environmental Protection Agency, 2021b). All facilities are required to report to TRI if they meet the reporting criteria: (1) are subject to EPCRA 313(b)2 determination; or (2) are in a covered industry sector and exceed the employee threshold (US Environmental Protection Agency, 2022b). Those facilities are mainly involved in hazardous waste treatment, manufacturing, electric power generation, and metal mining. The government passed EPCRA in 1986 in response to the disastrous gas leak in Bhopal, India, in 1984, which raised the concern about environmental and safety hazards of toxic releases. Toxics Release Inventory compiled information of certain toxic chemicals that may pose a threat to human health and the environment. The information includes how much of each chemical is released to the environment (air or water) and managed through recycling, energy recovery and treatment of each U.S. facilities. The current TRI toxic chemical list contains 775 individually listed chemicals and 33 chemical categories, which may cause cancer or other chronic human health effects, significant adverse acute human health effects or significant adverse environmental effects (US Environmental Protection Agency, 2022a).

EPA's Risk-Screening Environmental Indicators (RSEI) is a screening-level model incorporating TRI data with measures of human exposure and toxicity, which assesses the potential impact of industrial chemical releases from pounds-based, hazard-based, and risk-related perspectives (US Environmental Protection Agency, 2022a). The RSEI model uses reported data and information on facilities' on-site chemical releases and chemical transfers from these facilities to off-site facilities to model RSEI risk-related results. RSEI model can provide comparable values for each kind of toxic release using a continuous system of numerical weights developed by EPA. In this paper, we used "TRI Pounds", which reflect the number of pounds released or transferred that are reported to TRI, and are available for all releases and transfers. In order to make the sectors of TRI/RSEI data and IMPLAN data consistent, this paper matched the sectors between these two datasets using Primary-six-digit North American Standard Industry Classification System

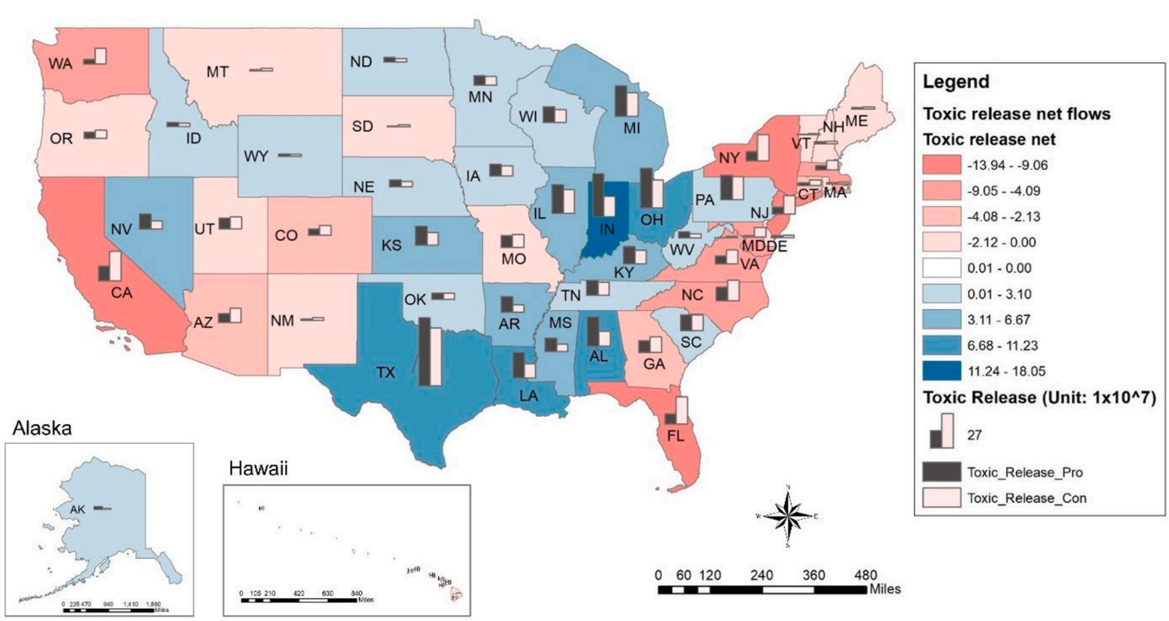

Fig. 1. Production-based and consumption-based TCR and net inflows (red) and outflows (blue) of embodied TCR across states in the US(USA states shapefile: https://www.arcgis.com/home/item.html?id=1a6cae723af14f9cae228b133aebc620).

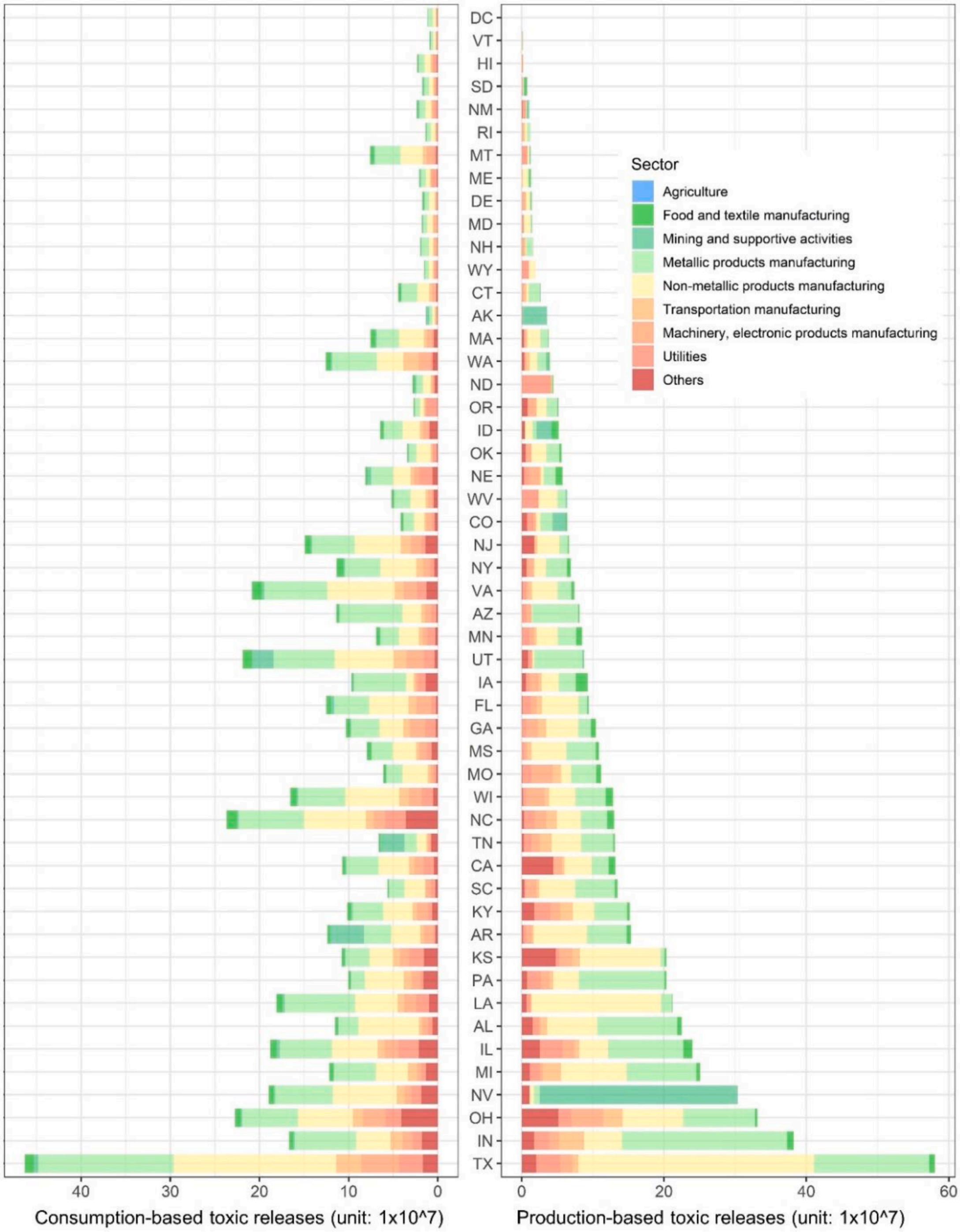

Fig. 2. Sectoral composition of production-based and consumption-based TCR in US states in 2017.

(NAICS) code.

Household number data of each state by income level was collected from American Community Survey (ACS) by United States Census Bureau ("2017 Data Profiles | American Community Survey | US Census Bureau,") (United States Census Bureau, 2017). The income groupings in ACS are different from the IMPLAN, thus matching groupings is needed between these two datasets. We assumed that the number of households within an income group is equally distributed, then re-aggregated the number of households in ACS according to the income grouping in IMPLAN dataset. The household income for specified income group is listed in Table 1.

3. Results

3.1. Production-based and consumption-based TCR inventories

Fig. 1 shows the production-based and consumption-based TCR and net flows of embodied TCR in each US state in 2017. The TCR from industrial production is unequally distributed across regions in the US with high concentration in a few south central and Great Lakes Region states. The TCR from the top 10 state accounts for about 53 % of the national total release. Texas is ranked the first with total amount of 54.34 million pounds TCR, which is 567 % higher than the TCR in Indiana, the second largest TCR state, and 70 % higher than that in Ohio

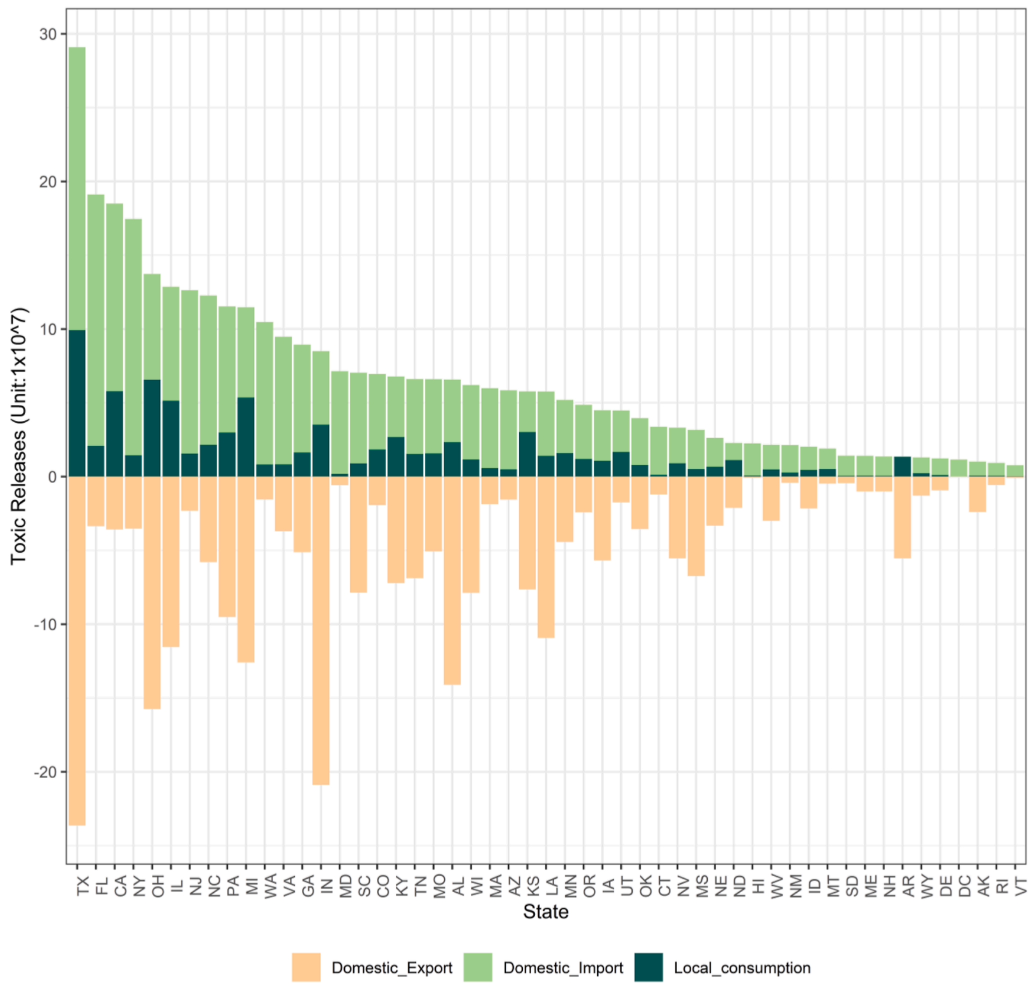

Fig. 3. Embodied TCR in local consumption and domestic export in 2017 Note: The abbreviations of states can be found in Table A1.

(the third largest TCR state). Michigan also produce large amount TCR and accounted for 18.15 % of the national total TCR in 2007. In sectoral detail, Fig. 2 presents a comparison of sectoral TCR from both the production and consumption perspectives for all states. From the production perspective, every state has its own dominant industries. For example, non-metallic and metallic products manufacturing sectors are the most important sources of the TCR for most states. Texas, as the highest production-based TCR state, have more than 80 % TCR from those two sectors. Mississippi, Louisiana, Arizona also have more than 80 % TCR from those non-metallic and metallic products manufacturing sectors. In addition, mining and supportive activities is the largest contributing sector to the TCR in Nevada and Alaska, and utilities is the largest TCR sector in North Dakota.

Compared with the production-based TCR, the consumption based TCR are less unequally distributed across regions in US. Texas still ranks the top state for consumption-based TCR with the amount of about 46.31 million pounds. Some west and east coastal states, such as Washington, California and North Carolina, and some Great Lakes Region states, including New York and Michigan, have similar number of consumption-based TCR. While most central states, such as Montana and Wyoming, produce and consume relatively small amount of TCR. In sectoral detail, non-metallic and metallic products manufacturing sector are the most important sectors, accounting for more than 50 % of the consumption-based TCR in most states.

From Fig. 1 we can see that net importers of embodied TCR are mainly focused on the east and west coastal areas, while net exporters are focused on central areas. For example, Indiana, Texas, Louisiana, and Alabama are among the largest net exporters of embodied TCR. Those states are also poor states with low per capita personal incomes (Table B2), while the coastal states, such as Washington, California, New York, New Jersey, and Florida, are the main net importers of embodied TCR with high personal incomes.

Fig. 3 showed the embodied TCR in local consumption and domestic trade in 2017. In this figure we can see that a large amount of embodied TCR flowed in and out of the states via inter-state trade, while the embodied TCR in local demand accounted for a very small proportion of total releases in every state. For example, local consumption of Texas cause only around 10 million pounds of TCR that were produced from its domestic firms, while the other 20 million pounds of TCR were imported from other states. In the meantime, a similar amount of TCR in Texas were caused by other states to meet the final demand in those states.

3.2. Inter-state transfers of embodied TCR

Fig. 4 showed the inter-state transfers of embodied TCR in the US EPA regions (see Fig. A2). The results showed that the main outsourcing of embodied TCR is from release-intensive central regions to rich coastal regions. For example, the largest interregional transfer of TCR is from Great Lake Region to Southeast (16.2 million pounds). Although Great Lake Region (including Illinois, Indiana, Michigan, Minnesota, Ohio, and Wisconsin) only has 16 % of the U.S. population, it owns 25 % of all the TRI facilities, most of which are concentrated in toxic release-intensive sectors of the fabricated metals (i.e., manufacture of metal products) and chemical manufacturing sectors (US Environmental

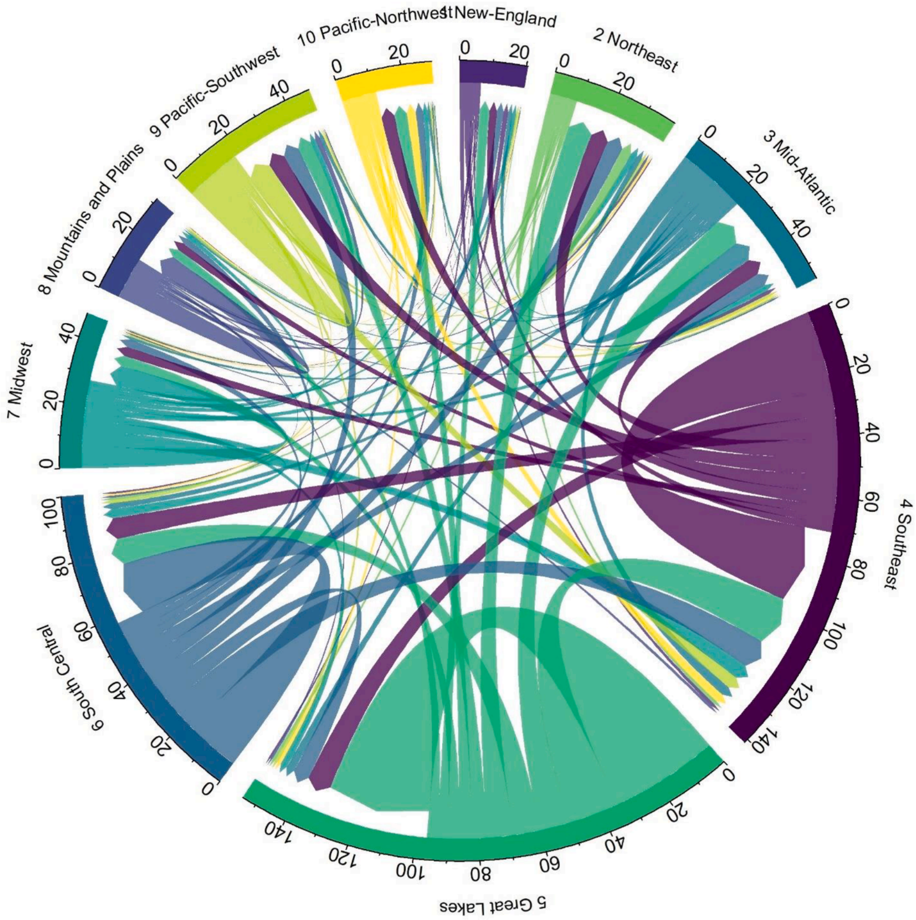

Fig. 4. Inter-regional embodied TCR flows between the US EPA regions (unit: 1x10ˆ7).

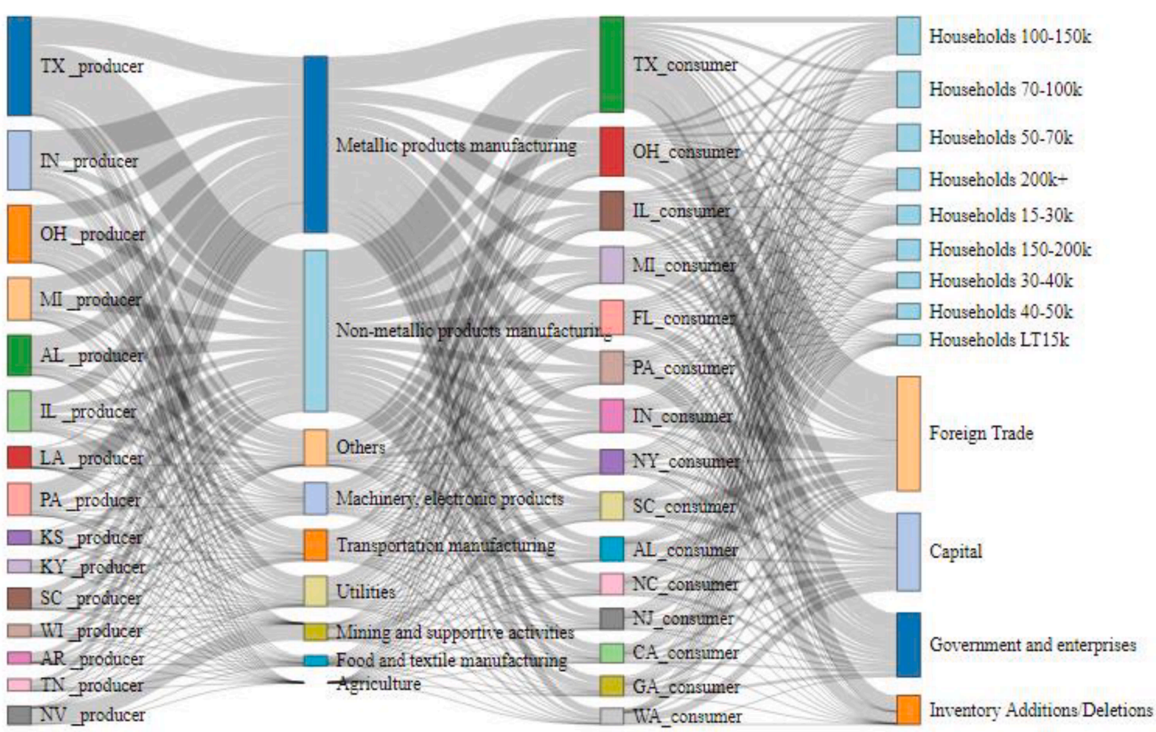

Fig. 5. Flows of embodied TCR from top 15 release producing states to the final consumers in the top 15 consuming states.

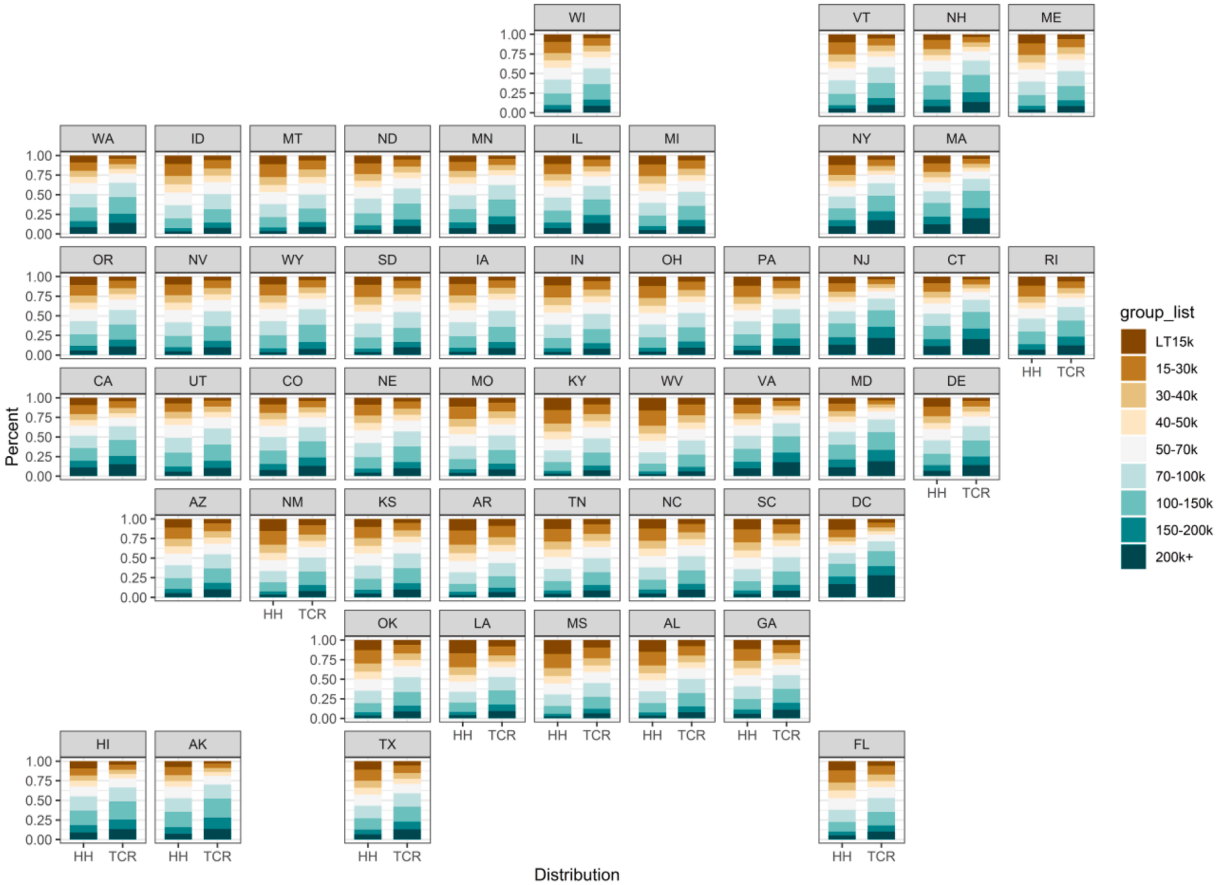

Fig. 6. The distribution of TCR footprints in each state (household number and corresponding shares of total TCR). Note: HH means household number.

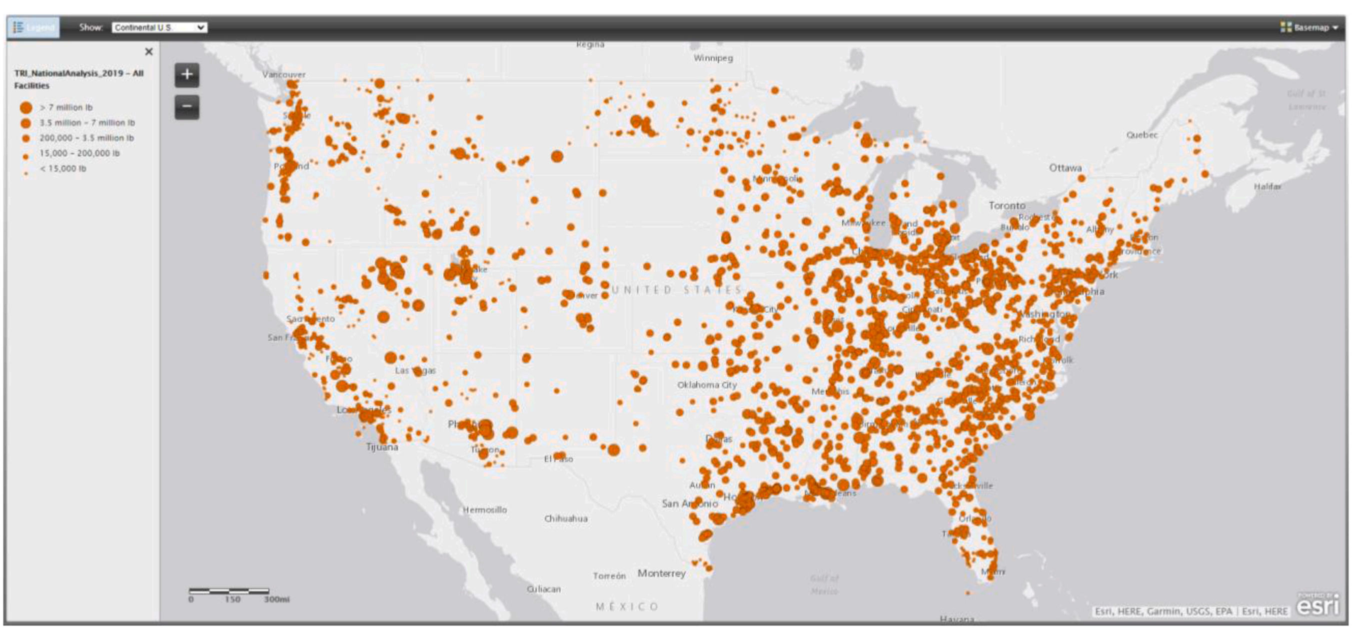

Fig. A1. Geographic Distribution of TRI-Reporting facilities in 2019.
Source: https://gispub.epa.gov/trina2019/facilities.html?webmap=90002265bec645dfbf0703c55d03093e.

Protection Agency, 2021d). Except for Southeast, Great Lake Region also outsourced to neighboring rich regions like Mid-Atlantic (9.52 million pounds) and Northeast (8.19 million pounds). On the contrary, final demand consumption in Southeast region (including Alabama, Florida, Georgia, Kentucky, Mississippi, North Carolina, South Carolina, Tennessee, and 6 tribes), which accounting for 1/5 of the U.S. population, is mainly being supported by production and associated releases occurring in neighboring regions, including Great Lakes (16.2 million pounds) and

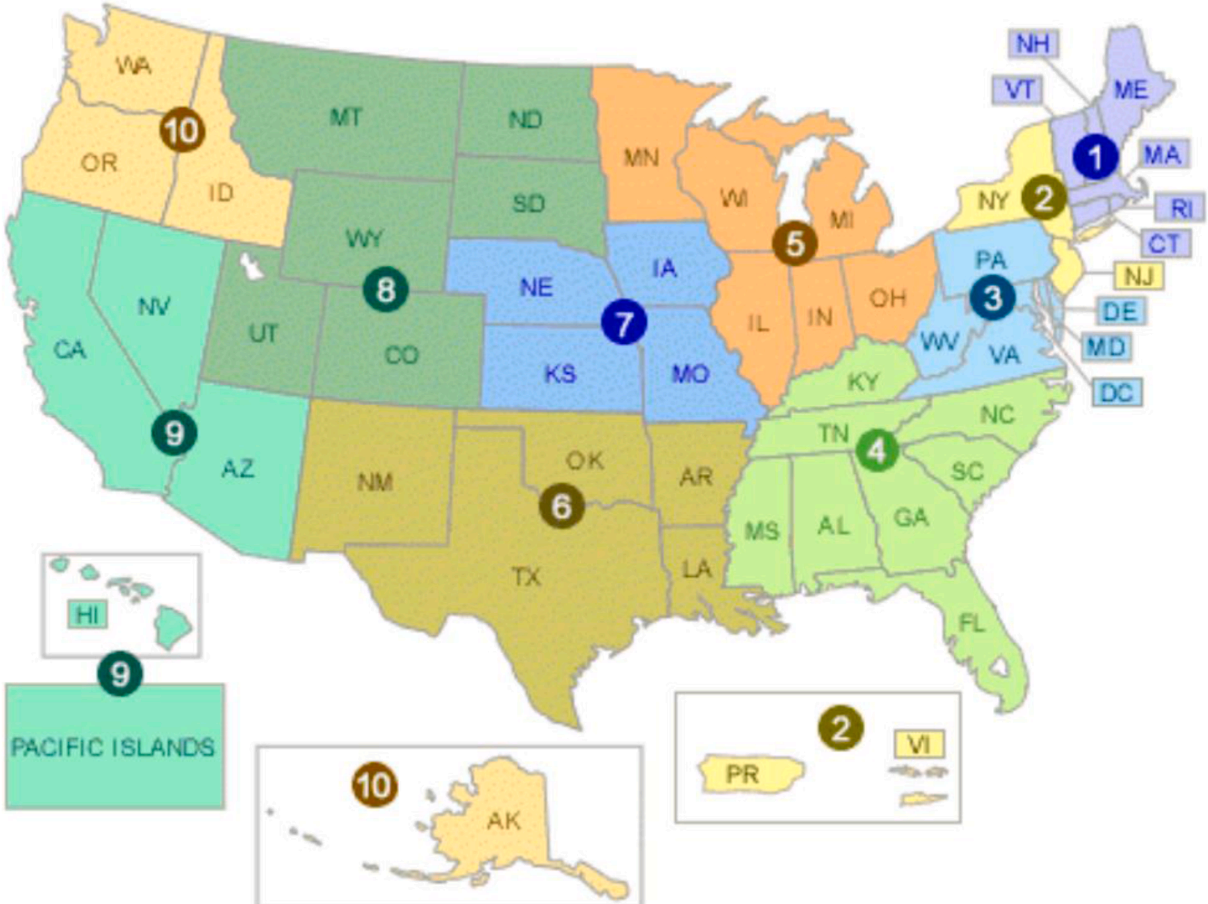

Fig. A2. Map for 10 EPA Regions. Source: https://www.epa.gov/aboutepa/regional-and-geographic-offices. Note: The EPA regions are distinct administrative units with different bureaucratic cultures, state regulations, and data sources. Region 1 (New England) includes CT, ME, MA, NH, RI, and VT; Region 2 (Northeast) includes NJ, NY, Puerto Rico, and the U.S. Virgin Islands; Region 3 (Mid-Atlantic) includes DE, DC, MD, PA, VA, WV and 7 federally recognized tribes; Region 4 (Southeast) includes AL, FL, GA, KY, MS, NC, SC, and TN; Region 5 (Great Lakes) includes IL, IN, MI, MN, OH, and WI; Region 6 (South Central) includes AR, LA, NM, OK, and TX; Region 7 (Midwest) includes IA, KS, MO, and NE; Region 8 (Mountains and Plains) includes CO, MT, ND, SD, UT, and WY; Region 9 (Pacific Southwest) includes AZ, CA, HI, NV, American Samoa, Commonwealth of the Northern Mariana Islands, Federated States of Micronesia, Guam, Marshall Islands, and Republic of Palau; Region 10 (Pacific Northwest) includes AK, ID, OR, WA and 271 native tribes.

South Central (9.89 million pounds).

In Fig. 5, we selected top 15 states in production, which produced the greatest TCR (first column) and top 15 states in consumption, whose consumption triggered the largest amount of TCR (third column) to show the main embodied TCR flows between producers and final consumers. The top 15 toxic release producing states, including Texas, Illinois, Ohio, Michigan and etc., account for 63.15 % of total TCR, and it is intuitive that they are net exporters of the embodied TCR (see Fig. 1). The top 15 toxic release "consuming" states can be divided into two types of groups: one group includes the top producing states, for example, Texas, Ohio, and Illinois; another group is the top net importers of embodied TCR, for example, California, Florida, New York and Washington. The sectoral embodied TCR flows show different patterns between these two groups. In the first group, Texas is the largest state in TCR production, and non-metallic products manufacturing accounts for the largest percentage of the production (53.25 %), followed by metallic products manufacturing (27.90 %). Meanwhile, a great majority of TCR from non-metallic and metallic products manufacturing are consumed by Texas. The similar patterns showed in other states in this group. For another group, non-metallic and metallic products manufacturing are also major consumption sectors in California, Florida, New York and Washington, accounting for around 70 % of total consumption in each state. Although these states are not major TCR production states, they import large amount of TCR from producing states with high TCR intensity.

From final demand side, the largest portion of embodied TCR is triggered by households' final demand of all income groups (41.88 %) for top 15 consuming states, followed by foreign trade (23.39 %) and capital formation (15.88 %). In detail, Illinois's households with income 100–150k triggered the largest amount of TCR, around 1.593 million pounds, followed by Ohio's households with income 70–100k (1.574 million), 100–150k (1.567million), and Florida's households with income 70–100k (1.412 million). Foreign trade is also a major part that causes the embodied TCR, and Texas's export accounts for the largest proportion of embodied TCR (20 %), followed by Ohio (13.99 %) and Indiana (13.27 %).

3.3. TCR footprint by income groups

Since households' final demand contributed to about half of the total TCR, in this section, we provide a detailed analysis on household's consumption and associated TCR across income groups. Fig. 6 showed the unequal distribution of TCR footprint by income groups in each state. In general, high-income groups, although with small population, account for high percent of total TCR footprint; while low-income groups with large population account for low percent of total TCR footprint. For example, the consumption of top 35 % of rich household (groups of larger than 100k) contributes to more than 50 % of total TCR

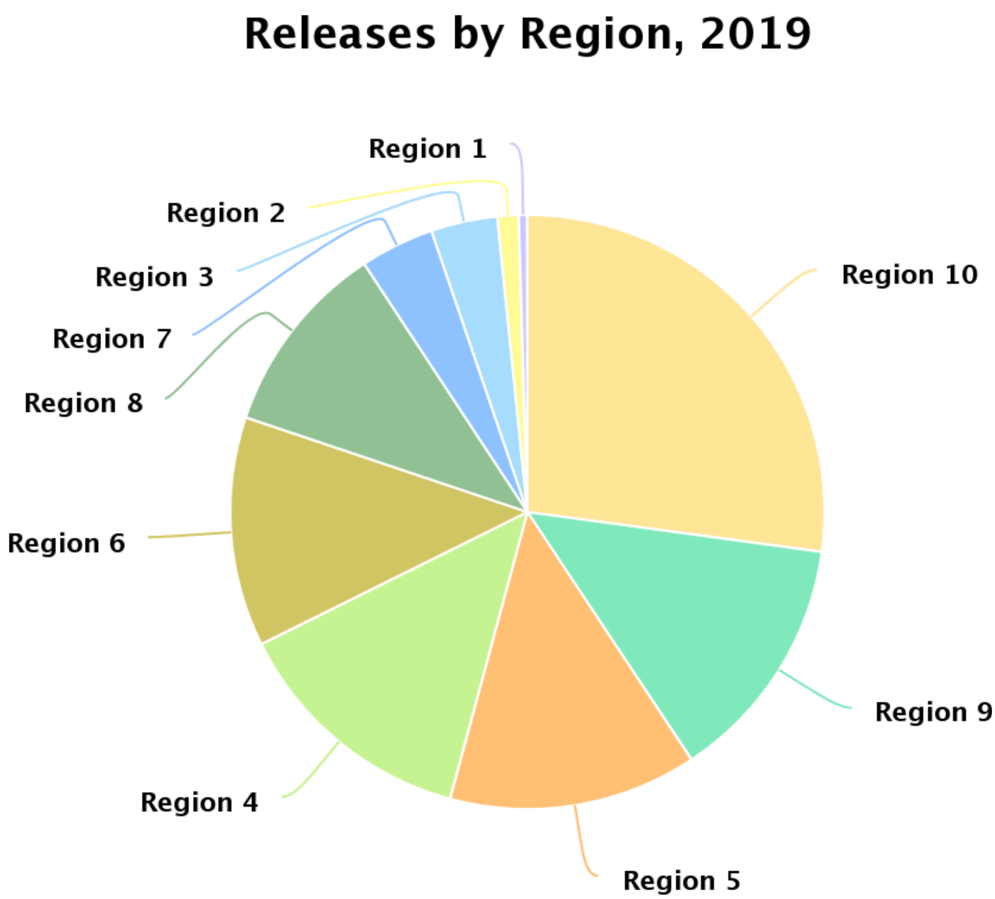

Fig. A3. Releases by Region in 2019. Source: https://www.epa.gov/trinationalanalysis/regional-profiles. Note: In 2019, Region 1 has 950 facilities, Region 2 has 1040 facilities, Region 3 has 1905 facilities, Region 4 has 4586 facilities, Region 5 has 5330 facilities, Region 6 has 2956 facilities, Region 7 has 1515 facilities, Region 8 has 718 facilities, Region 9 has 1641 facilities, and Region 10 has 742 facilities.

Table A1
State abbreviations for US states.

US state	Abbreviation	US state	Abbreviation	US state	Abbreviation
Alabama	AL	Kentucky	KY	North Dakota	ND
Alaska	AK	Louisiana	LA	Ohio	OH
Arizona	AZ	Maine	ME	Oklahoma	OK
Arkansas	AR	Maryland	MD	Oregon	OR
California	CA	Massachusetts	MA	Pennsylvania	PA
Colorado	CO	Michigan	MI	Rhode Island	RI
Connecticut	CT	Minnesota	MN	South Carolina	SC
Delaware	DE	Mississippi	MS	South Dakota	SD
District of Columbia	DC	Missouri	MO	Tennessee	TN
Florida	FL	Montana	MT	Texas	TX
Georgia	GA	Nebraska	NE	Utah	UT
Hawaii	HI	Nevada	NV	Vermont	VT
Idaho	ID	New Hampshire	NH	Virginia	VA
Illinois	IL	New Jersey	NJ	Washington	WA
Indiana	IN	New Mexico	NM	West Virginia	WV
Iowa	IA	New York	NY	Wisconsin	WI
Kansas	KS	North Carolina	NC	Wyoming	WY

triggered by the final demand of all households in the U.S., where the similar unequal distribution occurs in most states (Fig. 6). The main reason is that the TCR footprint per household in high-income groups is larger than that in low-income groups (Figure C2).

We also found that the distributions of population and TCR footprint between rich and poor states show different patterns. On the one hand, poor states with low per capita income (Table B1) have larger percent population of low-income groups (groups of less than 30k) and thus have higher percent of corresponding TCR footprint than national average level. For example, the population of low-income groups in poor states Kentucky, Mississippi and West Virginia account for more than 30 % of total population, while the national percent is only 17.95 %. The corresponding percent of TCR footprint in the above three states are more than 20 %, comparing to the national average of 8.78 %. In contrast, the population of high-income group (groups of larger than 100k) are smaller than the national average level, so are the corresponding TCR footprint. On the other hand, it is intuitive that the rich states have larger percent of high-income groups than the national average (35.44 %), for

Table B1
Total and per capita production- and consumption-based TCR (pounds) in each state.

State	Total population	Toxic_Release_Pro	Toxic_Release_Con	Toxic release net	Toxic_Release_Pro_Per_Capita	Toxic_Release_Con_Per_Capita
Alabama	4,874,747	233,808,162	121,492,661	112,315,501	47.96	24.92
Alaska	739,795	31,534,061	12,967,801	18,566,260	42.63	17.53
Arizona	7,016,270	72,859,780	113,722,699	−40862919	10.38	16.21
Arkansas	3,004,279	122,867,135	56,151,052	66,716,083	40.90	18.69
California	39,536,653	118,482,933	236,947,901	−118464968	3.00	5.99
Colorado	5,607,154	50,487,427	81,247,495	−30760068	9.00	14.49
Connecticut	3,588,184	22,076,865	44,552,622	−22475757	6.15	12.42
Delaware	961,939	15,506,966	17,728,952	−2221986	16.12	18.43
District of Columbia	693,972	25,031	11,605,257	−11580226	0.04	16.72
Florida	20,984,400	79,418,307	218,774,632	−139356325	3.78	10.43
Georgia	10,429,379	93,968,718	125,120,126	−31151408	9.01	12.00
Hawaii	1,427,538	1,731,134	23,028,576	−21297442	1.21	16.13
Idaho	1,716,943	35,103,619	28,201,165	6,902,454	20.45	16.43
Illinois	12,802,023	229,417,357	187,787,683	41,629,674	17.92	14.67
Indiana	6,666,818	347,155,269	166,698,855	180,456,414	52.07	25.00
Iowa	3,145,711	95,135,201	79,617,362	15,517,839	30.24	25.31
Kansas	2,913,123	150,532,441	100,183,460	50,348,981	51.67	34.39
Kentucky	4,454,189	138,829,920	107,814,275	31,015,645	31.17	24.21
Louisiana	4,684,333	202,663,856	114,969,841	87,694,015	43.26	24.54
Maine	1,335,907	14,106,821	17,264,401	−3157580	10.56	12.92
Maryland	6,052,177	9,566,975	75,698,300	−66131325	1.58	12.51
Massachusetts	6,859,819	33,926,799	75,539,334	−41612535	4.95	11.01
Michigan	9,962,311	244,077,661	189,564,648	54,513,013	24.50	19.03
Minnesota	5,576,606	76,224,133	69,131,620	7,092,513	13.67	12.40
Mississippi	2,984,100	108,430,915	60,943,031	47,487,884	36.34	20.42
Missouri	6,113,532	94,652,829	102,828,580	−8175751	15.48	16.82
Montana	1,050,493	11,553,453	20,663,348	−9109895	11.00	19.67
Nebraska	1,920,076	54,676,616	41,512,708	13,163,908	28.48	21.62
Nevada	2,998,039	120,273,796	65,960,856	54,312,940	40.12	22.00
New Hampshire	1,342,795	15,748,648	19,702,819	−3954171	11.73	14.67
New Jersey	9,005,644	57,019,800	149,112,567	−92092767	6.33	16.56
New Mexico	2,088,070	8,560,383	23,383,439	−14823056	4.10	11.20
New York	19,849,399	71,637,264	208,351,483	−136714219	3.61	10.50
North Carolina	10,273,419	108,436,041	165,448,692	−57012651	10.56	16.10
North Dakota	755,393	35,489,631	26,978,540	8,511,091	46.98	35.71
Ohio	11,658,609	319,124,401	227,318,509	91,805,892	27.37	19.50
Oklahoma	3,930,864	53,534,537	51,597,497	1,937,040	13.62	13.13
Oregon	4,142,776	49,665,956	64,679,148	−15013192	11.99	15.61
Pennsylvania	12,805,537	193,826,430	180,902,867	12,923,563	15.14	14.13
Rhode Island	1,059,639	9,301,657	13,524,080	−4222423	8.78	12.76
South Carolina	5,024,369	127,203,285	123,946,087	3,257,198	25.32	24.67
South Dakota	869,666	6,399,468	17,209,967	−10810499	7.36	19.79
Tennessee	6,715,984	121,152,077	107,187,299	13,964,778	18.04	15.96
Texas	28,304,596	543,392,297	463,178,225	80,214,072	19.20	16.36
Utah	3,101,833	84,737,873	96,659,248	−11921375	27.32	31.16
Vermont	623,657	1,464,338	8,948,821	−7484483	2.35	14.35
Virginia	8,470,020	62,601,179	113,504,842	−50903663	7.39	13.40
Washington	7,405,743	34,962,060	125,533,983	−90571923	4.72	16.95
West Virginia	1,815,857	49,824,787	34,332,298	15,492,489	27.44	18.91
Wisconsin	5,795,483	124,056,438	101,351,332	22,705,106	21.41	17.49
Wyoming	579,315	18,530,092	15,191,837	3,338,255	31.99	26.22

example, high-income groups account for 42.57 %, 40.17 % and 40.33 % of total population in District of Columbia, Maryland and New Jersey, respectively. Although the per household TCR footprints in rich states are smaller than poor states like Mississippi (Figure C2), the high number of populations in rich states still make high percent of TCR footprint. The consumption of high-income groups in District of Columbia, Maryland and New Jersey are contributing 58.82 %, 56.21 % and 57.05 % of total TCR footprint, respectively (comparing to the national mean 52.20 %).

4. Discussion and conclusion

From the previous analysis, we gain some new insights regarding the regional distributional patterns of production-based and consumption-based TCR, the outsourcing of embodied TCR, the unequal distribution by regions and demographic groups. This analysis is useful for the distribution of pollution reduction responsibility between different entities, such as states and demographic groups.

The production of TCR is unequally distributed across regions in the US, mainly concentrating on certain central and southern states and the Great Lakes Region, such as Texas, Indiana, Ohio, and etc. The disparities of production-related TCR in each region can be partly explained by the types of main sectors located in each region. The production activities of certain type products are geographically concentrated and generate large quantities of TRI chemical. For example, almost all the mining and supportive activities are concentrated in Nevada and Alaska. Non-metallic products manufacturing is mainly focused in Texas, Louisiana, Kansas, and Michigan (Fig. 2). These states produce products to not only meet their own final demand, but also satisfy final demand in other states. In order to enjoy the benefit from economies of scale, industrial concentration occurs in the US, thus causing the concentration of TCR. Under the production-based principle, producer is responsible for the TCR from the production of goods and services (Munksgaard and Pedersen, 2001). In order to reduce the TCR, the states with high

Table C1
Per capita personal income (dollars) in US in 2017.

State	Per capita personal income	State	Per capita personal income	State	Per capita personal income
New York	455997.1	North Dakota	52,610	Missouri	45,307
District of Columbia	78,974	Rhode Island	52,600	Indiana	45,217
Connecticut	71,699	Vermont	51,632	Tennessee	45,193
Massachusetts	68,405	Delaware	50,738	Georgia	44,865
New Jersey	64,964	Nebraska	50,617	North Carolina	44,376
Maryland	60,714	South Dakota	49,738	Utah	44,142
California	60,581	Wisconsin	49,239	Louisiana	43,903
New Hampshire	58,689	Kansas	48,846	Oklahoma	43,769
Washington	58,400	Oregon	48,719	Arizona	42,566
Alaska	57,295	Florida	48,473	Idaho	42,218
Wyoming	56,421	Texas	48,402	South Carolina	42,178
Virginia	55,582	Iowa	47,629	Arkansas	41,622
Colorado	55,550	Nevada	47,615	Alabama	41,000
Minnesota	54,930	Ohio	46,804	Kentucky	40,874
Illinois	54,247	Maine	46,525	New Mexico	39,727
Hawaii	53,382	Montana	46,138	West Virginia	38,891
Pennsylvania	53,277	Michigan	45,931	Mississippi	36,510

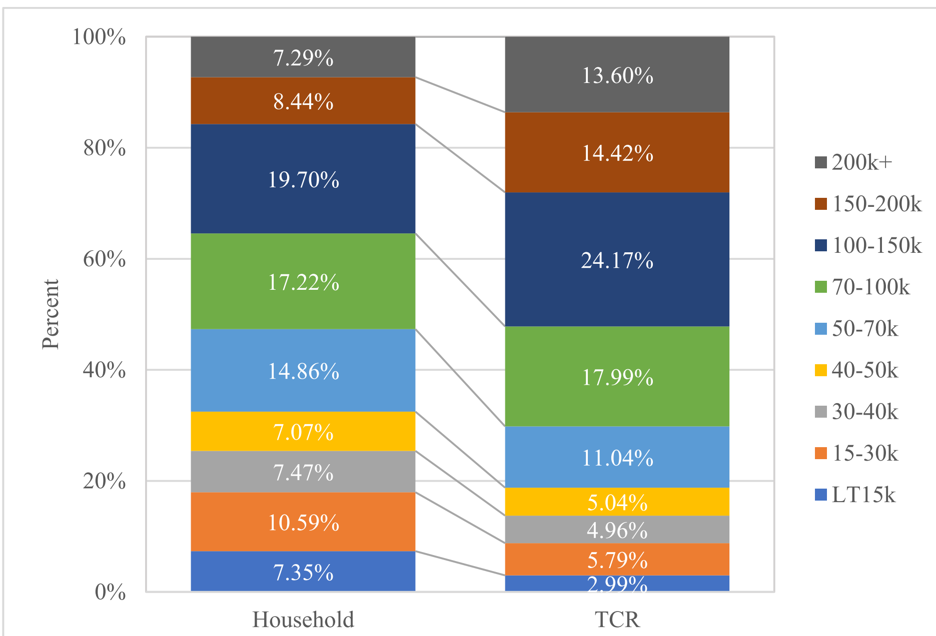

Fig. D1. The distribution of household number and TCR footprint across income groups of all states.

releases should implement effective measures. For example, in 2019, 5 % of facilities in Arkansas, Louisiana, New Mexico, Oklahoma and Texas have reported implementing new source reduction activities (US Environmental Protection Agency, 2021c): a motor vehicle parts manufacturer improved the effectiveness of the producing system by updating the zinc rinse system and reducing zinc waste. Similar to EPA's "good neighbor" plan, which requires more than 20 states, including Texas, Louisiana and others, to cut ozone pollution from power plants and industrial sources that contribute to ozone pollution in neighboring states (US Environmental Protection Agency, 2022c), under production-based principle, the government could propose plans that control toxic emissions from large TCR producers. However, there are limits to production-based principle, which cannot distinguish the consumption between export and domestic, thus exacerbating the responsibility of producer (Munksgaard and Pedersen, 2001).

The consumption-based TCR is less unequally distributed across regions in the US (Fig. 1). From previous analysis, we found that the production activities of particular goods and services are geographically concentrated. Thus, in order to fulfill the final demand, states have to import products they don't produce enough from other states, and thus triggering the embodied TCR of other states. For example, the main economic sectors in California and New York are tertiary industries such as finance, insurance, real estate, rental, and leasing, professional and business services, and information. (Statista, 2022a, 2022b), thus, CA and NY need to import necessary goods like metallic and non-metallic products to fulfill their intrastate demand (Fig. 1). In the US, local consumption accounted for a small percentage of total consumption-based TCR, while inter-regional transfer between states accounts for a large proportion (Fig. 3). Therefore, policies under consumption-based principle, which take inter-regional trade into account, would be more appropriate. Under consumption-based principle, the consumer is responsible for the TCR from the production of goods and services (Munksgaard and Pedersen, 2001; Peters, 2008), even if they are imported from other states. The net importers of embodied TCR are mainly the coastal states (Fig. 1), which means they should shoulder more TCR reduction responsibility from consumption-based principle than production-based principle. For example, Texas, Florida, Illinois, New York, New Jersey, Pennsylvania, California etc. are main consumers (Fig. 5) of TCR, and their demand triggered other states' production, such as Texas, Indiana, Ohio, Michigan, Alabama, Illinois etc. Those

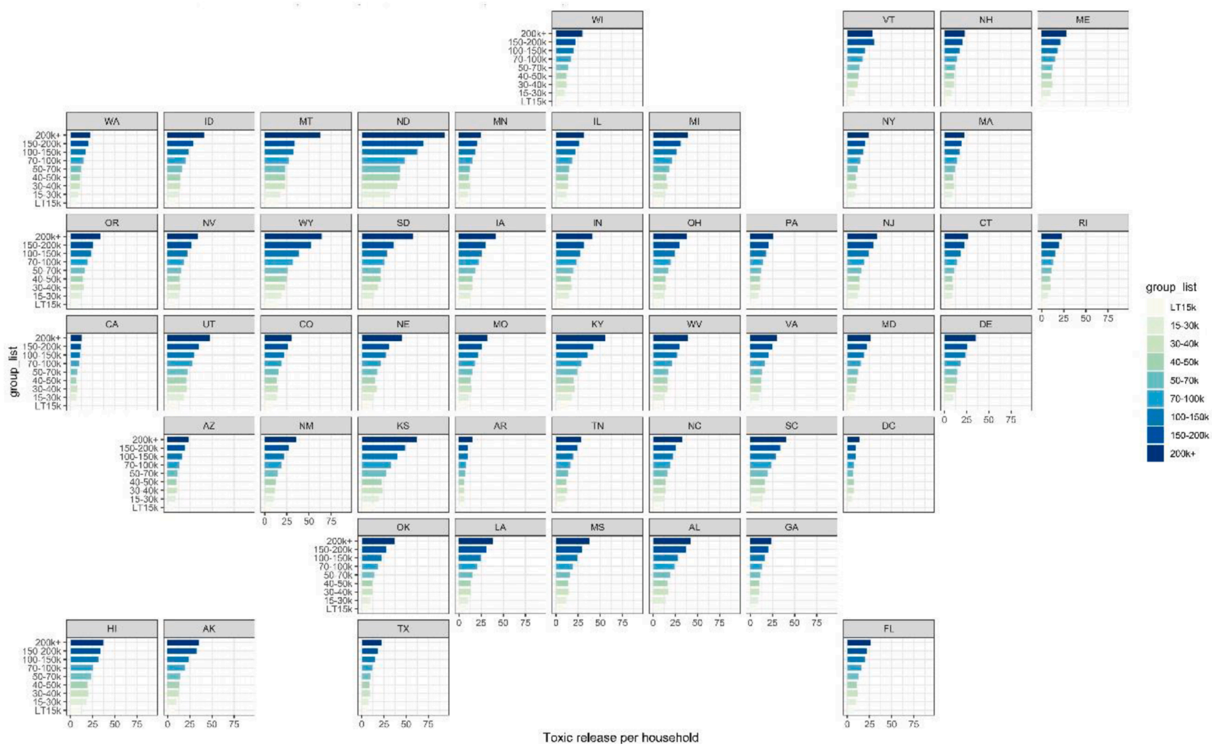

Fig. D2. TCR embodied in household consumption across states and income groups.

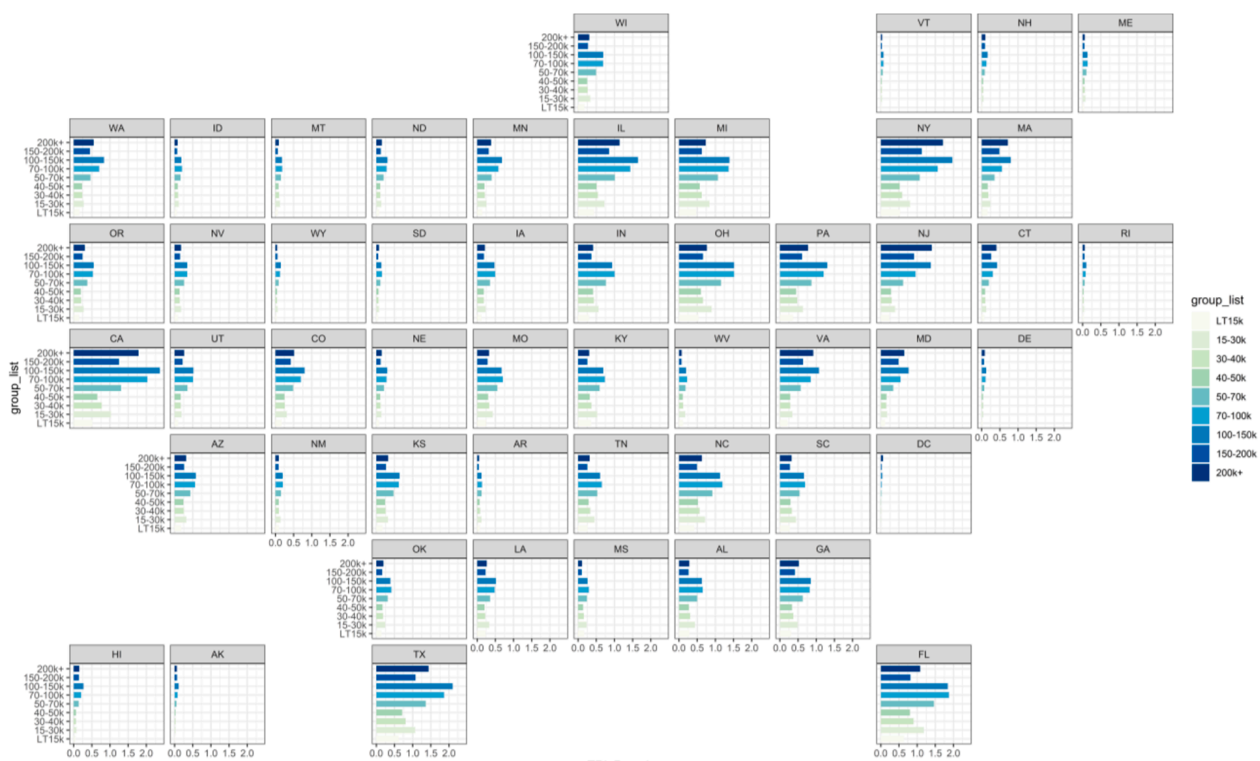

Fig. D3. Total TCR across income groups in each state to meet household consumption.

consumer states have generated the demand for the exported products and thus caused the production for export to take place, therefore, they should shoulder the responsibility for the TCR reduction. However, consumer responsibility requires political decision making of other regions. The United States is a federal republic where federal government has certain control over states' policies, but state governments also have significant authority in their respective states (Forum of Federation, 2021). It is hard to make certain consumer states shoulder TCR responsibility without a unanimous agreement between states. Some researchers brought up new insights of shared-responsibility –

responsibility for impacts can be shared between producer and consumer – to make a fair distribution of TCR reduction responsibility (Lenzen et al., 2007; Peters, 2008).

Our results showed that the largest portion of embodied TCR is triggered by households' final demand of all income groups and for example, Illinois's households with income 100–150k triggered the largest share of TCR in comparison other income groups in the state (Fig. 6). It is interesting to dig into the unequal distribution of TCR footprint between different income groups in each state. The consumption of the top 35 % of households (groups of >100k) contributes to more than 50 % of total TCR in the U.S. The TCR footprint per household in high-income groups is larger than that in low-income groups (Figure C2), which is very intuitive since rich income groups consume more goods and products than poor income groups and thus trigger more TCR during the production process of goods and services. Rich states, such as New York, District of Columbia, and California, have larger percent of high-income groups than national average, thus have higher TCR footprint than national one (Fig. 6). The income inequalities in those states had gaps wider than the national gap (Sommeiller and Price, 2018), with rich people spending more money on housing, transportation and etc., which triggered disproportionally larger share of TCR footprint in the total. Given the high inequality, in order to solve this problem, the government need to propose policies that increase the bargaining power of low-income groups and promote political participation by all citizens in economic and environmental issues. More interestingly, although rich states have high total household TCR footprints (Figure C3), the per household TCR footprints are pretty low (Figure C2). Poor states, in contrast, have high per household TCR footprints (Figure C2) despite the low total household TCR footprints. The regional disparities may be partly explained by the household consumption patterns in different states. For poor states, such as Mississippi, Alabama, Kentucky, the population densities are relatively low (Statista, 2021). People in these states usually have larger house, more vehicles,[1] and more other resources per capita, thus, the large number of final demands from these states' households triggers more TCR. Therefore, in order to reduce household TCR, it is necessary to promote green consumption patterns in all households, especially in high-income groups in poor states, since they have larger TCR reduction potential.

In conclusion, this paper filled two important gaps in the literature: The lack of research attention to the interstate-flows of consumption-based toxic chemical footprints and the absence of analyzing the disproportionate exposure of consumption-based TCR exposure by income groups across states in the US. This paper provided qualitative information about spatial disparities of TCR in terms of pollution transfer triggered by final consumption across states and income groups. This new set of information can facilitate the government and other stakeholders to propose mitigation policies and actions from both production-based and consumption-based perspectives.

There are some limitations that should be addressed in future studies. First, the toxic release inventory only includes the number of TCR but does not include concentration information of chemical substance in air, water and land. In the future study, the concentration of the toxic chemicals should be estimated in order to achieve more accurate results. Second, TRI does not include all industrial sectors, and does not include all facilities in these sectors. TRI only includes large facilities in manufacturing, metal mining, electric power generation, chemical manufacturing and hazardous waste treatment that meet TRI reporting criteria. Third, this paper does not study temporal dimensions of pollution inequality. When years of MRIO tables are available, the analysis of embodied TCR trend over time can be conducted and the decomposition analysis can be proposed to investigate the driving forces of changes.

[1] https://capitol-tires.com/how-many-cars-*per*-capita-in-the-us.html.

CRediT authorship contribution statement

Guangxiao Hu: Conceptualization, Methodology, Visualization, Formal analysis, Software, Writing – original draft, Writing – review & editing. **Kuishuang Feng:** Conceptualization, Methodology, Writing – review & editing, Supervision. **Laixiang Sun:** Conceptualization, Writing – review & editing, Supervision. **Giovanni Baiocchi:** Conceptualization, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Regional disparities for toxic chemical releases

Figs. A1-A3 and Table A1.

Appendix B. Total and per capita production- and consumption-based TCR in each state

See Table B1.
Appendix C Per capita income in US states.
See Table C1.

Appendix D. Household toxic chemical releases

See Figs. D1-D3.

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