ABSTRACT

Title of Dissertation:	DEMAND-DRIVEN CLIMATE MITIGATION IN THE UNITED STATES: CHALLENGES AND OPPORTUNITIES TO REDUCE CARBON FOOTPRINTS FROM HOUSEHOLDS AND STATE-LEVEL ACTORS
	Kaihui Song, Doctor of Philosophy, 2022
Dissertation directed by:	Professor Giovanni Baiocchi Department of Geographical Sciences

Subnational and non-governmental actors have great potential to push for bolder climate actions to limit the global average temperature increase to 1.5 degrees Celsius above pre-industrial levels. A consistent and accurate quantification of their GHG emissions is an important prerequisite for the success of such efforts. Although an increasing number of subnational actors have developed their climate mitigation plans with medium- or long- term goals, whether these progressive commitments can yield effectiveness as planned still remains unclear. This dissertation research focuses on two large groups of climate mitigation actors in the U.S. – households and state-level actors –

to improve the understanding of potential mitigation challenges and shed light on climate policies.

This dissertation consists of three principle essays. The first essay reveals a key challenge of emission spillover among state-level collective mitigation efforts in the U.S. It quantifies consumption-based GHG emissions at the state level and analyzes emissions embodied in interstate and international trade. By analyzing major emission transfers between states from critical sectors, this essay proposed potential policy strategies for effective climate mitigation collaboration. The second essay addresses unequal household consumption and associated carbon footprints in the U.S., with a closer look at different contributions across income groups to the national peak-and-decline trend in the U.S. This analysis further analyzes changes in consumption patterns of detailed consumed products by income groups. The third essay proposed a framework to link people's needs and behaviors to their consumption and associated carbon footprints. This framework, built on existing models that connect carbon footprints with consumer behaviors, extends to people's needs with simulation over time. Such an extension provides a better understanding of carbon footprints driven by various needs in the context of real-world decision-making. Based on this framework, this essay selects a basket of behavioral changes driven by changing fundamental human needs and analyzes associated carbon footprints. The dissertation identifies opportunities and challenges in demand-driven climate mitigation in the U.S. Its findings provide implications for effective climate actions from state-level actors and households.

DEMAND-DRIVEN CLIMATE MITIGATION IN THE UNITED STATES: CHALLENGES AND OPPORTUNITIES TO REDUCE CARBON FOOTPRINTS FROM HOUSEHOLDS AND STATE-LEVEL ACTORS

by

Kaihui Song

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Advisory Committee:
Professor Giovanni Baiocchi, Chair
Professor Kuishuang Feng
Professor Laixiang Sun
Professor Leon Clarke
Professor Nathan Hultman

Foreword

Chapters 2-4 contain jointly authored work in which Kaihui Song is the primary author. Kaihui Song conducted data analysis and led manuscript drafting with advisory input from other authors who are named in the corresponding chapters.

Dedication

To my parents

For your unconditional love and support

Acknowledgement

It is with deep gratitude that I thank my mentors, colleagues, friends and family for their unwavering support and encouragement over the past four years.

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List of Abbreviations

ACA	Affordable Care Act
ASI	Avoid-Shift-Improve
BEA	U.S. Bureau of Economic Analysis
BTS	Bureau of Transportation Statistics
C2ES	Center for Climate and Energy Solutions
CARB	California Air Resources Board
CES	Consumer Expenditure Survey
CFS	Commodity Flow Survey
CH_4	Methane
CLA	Consumer Lifestyle Approach
CLCPA	Climate Leadership and Community Protection Act
CO_2	Carbon dioxide
COVID-19	Coronavirus Disease 2019
CPI	Consumer Price Index
DIIM	Dynamic Inoperability Input-output Model
EEIO	Environmentally-Extended Input-Output
EIA	U.S. Energy Information Administration
FAF	Freight Analysis Framework
FLIGHT	Facility Level Information on GreenHouse gases Tool
GDP	Gross Domestic Product
GGMCF	Gridded Global Model of Carbon Footprints
GHG	Greenhouse gas
GHGRP	Greenhouse Gas Reporting Program
GWP	Global Warming Potential
HFC	Hydrofluorocarbons
HVDC	High-Voltage Direct Current
IMPLAN	Economic Impact Analysis for Planning
IDA	Index Decomposition Analysis
IOA	Input-Output Analysis
IPCC	Intergovernmental Panel on Climate Change
LCA	Lifecycle Assessment
LMDI	Logarithmic Mean Divisia Index
MRIO	Multi-regional Input-Output
N_2O	Nitrous oxide
NAICS	North American Industry Classification System
NAM	National Association of Manufacturers
NDC	National Determined Contribution
NDC	National Determined Contribution

NEI	National Emissions Inventory
NIPA	National Income and Product Accounts
NSAs	Non-state and subnational actors
OECD	Organisation for Economic Co-operation and Development
PCA	Principal Component Analysis
PFC	Perfluorocarbons
PM	Particulate Matter
PPCA	Powering Past Coal Alliance
PPI	Producer Price Index
R & D	Research and Development
RGGI	Regional Greenhouse Gas Initiative
RMI	Rocky Mountain Institute
RPS	Renewable Portfolio Standards
SEDS	State Energy Data System
SF_6	Sulfur Hexafluoride
SUT	Supply-Use Table
U.S.	United States
UCC	Universal Classification Codes
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
USCA	United States Climate Alliance
USDA	United States Department of Agriculture
USDOE	United States Department of Energy
USEPA	United States Environmental Protection Agency
USITC	United States International Trade Commission
WCI	Western Climate Initiative
WID	World Inequality Database

Chapter 1 Introduction

1.1 Background and motivations

Limiting global average temperature increase to 1.5 degrees Celsius above pre-industrial levels pursues the hope of staving off severe climate disruptions that could exacerbate adverse impacts on human and social development (IPCC 2018). Achieving this climate target requires not only rapid and unprecedented transformations in energy systems from the supply side, but also urgent and collective efforts from the demand side which can be a low-cost complement to supply-side solutions (Creutzig et al. 2018; Dietz et al. 2009).

While national governments play dispensable roles in developing national climate targets and implementing top-down mitigation policy instruments to achieve the ambitious global climate goal, subnational and non-governmental actors can offer significant potential to deliver climate actions, and aid in closing the "emission reduction gap" between existing climate commitments and the needed efforts to meet the Paris Agreement goal (Hultman et al. 2020; Hale 2018; UNEP 2021; Kuramochi et al. 2020). By March 2022, 283 regions, over 11 thousand cities, and nearly 10 thousand companies have committed to climate actions (NAZCA 2022). The engagement of these diverse local actors opens opportunities for piloting innovative approaches that potentially scale up to broader practice (Hultman et al. 2020), designing solutions suitable to local needs (Jörgensen, Jogesh, and Mishra 2015), and leveraging local resources to foster demand-side actions (Sperling and Arler 2020). In addition, these concerted efforts can provide strong alternative support should national-level efforts prove to be inadequate or fail (Victor et al. 2017).

Another important potential contributor to climate mitigation is households. Studies have demonstrated the high potential of climate mitigation from households by switching away from carbon-intensive consumption, instead, adopting higher energy-efficiency technologies and low-carbon behaviors (Bjelle, Steen-Olsen, and Wood 2018; Moran et al. 2020; Ivanova et al. 2020; Creutzig et al. 2022). For example, an analysis of 113 behavior changes in Europe suggested that adopting pro-environmental options could yield a reduction of approximately 25% of European's carbon footprints (Moran et al. 2020). Another study found that demand-side options technically could reduce GHG emissions by 78% (6.8 $GtCO_2e$), 62% (5.8 $GtCO_2e$), 41% (7.3 $GtCO_2e$) and 41% (6.3 $GtCO_2e$) in the building, transport, food and industry sectors, respectively (Creutzig et al. 2022). Promisingly, achievement of the high climate mitigation potential is also suggested to be synergistic with an improvement in well-being (Creutzig et al. 2022). Although a combination of policy interventions, such as monetary incentives, information and feedback, are crucial to facilitate implementation, the consumption and behavioral change options indicate substantial contributions toward achieving the 1.5 degrees target, especially in high-income countries (Khanna et al. 2021; Ivanova et al. 2020).

The U.S., the largest national economy in the world, remains the largest cumulative CO_2 emitter since 1750, being responsible for about 25% of global historical emissions (Friedlingstein et al. 2021). Annual CO_2 emissions in the U.S. have been decreasing since around 2006, surpassed by China (Friedlingstein et al. 2021). Even though, Americans' annual carbon footprints per capita are still one of the largest around the globe, being nearly four times the world's average after 2015, down from five times during the period 1960 to 2007 (Friedlingstein et al. 2021). Although GHG emissions have been decreasing and the Biden Administration has rejoined the Paris Agreement, reaching a net-zero emission economy still remains challenging. On the state level, while around half of the states set climate targets to be consistent with the Paris Agreement, another half of the states whose economies are largely powered by resource extraction and manufacturing industries have not opted for climate commitments or developed clear decarbonization plans yet (USCA 2020b). This can lead to emission spillover, which is the major criticism of the Kyoto Protocol that shifts climate responsibility from regions that set stringent emission goals to regions that present lax emission regulations (Fischer and Newell 2008). At the household level, while there exists large mitigation potential, how to foster a more rapid behavior shift towards a lower-carbon society and how much people have achieved since the emission peak remain under-explored. In addition, the notably rising expenditure after the pandemic caused by coronavirus disease (COVID-19) has raised concerns in reducing carbon footprints, as increasing ownership of private vehicles and electronic equipment may lock people in carbon-intensive behaviors (Moody et al. 2021; EIA 2022a). Such concerns are also consistent with the growing evidence which shows that the sharp decrease in energy consumption and related CO_2 emissions after the breakout of COVID-19 pandemic is almost certain to be temporary and the direct effect of the pandemic-driven response is very likely to be negligible to long-term climate mitigation (Forster et al. 2020; Le Quéré et al. 2020b; Davis et al. 2022). Nevertheless, some consequential behavior changes and innovations of technology in response to the pandemic can have a middle- or long-term impact on global GHG emissions, thus policy interventions can be crucial for countries to “build back better” – a sustainable and resilient recovery after the pandemic (OECD 2020).

1.2 Literature reviews

1.2.1 GHG emissions accounting

Addressing climate change requires accurate, credible, standardized and widely-acceptable monitoring systems and accounting schemes to quantify GHG emissions from an individual, organization, jurisdiction and country (Hoepner and Rogelj 2021; Bellassen et al. 2015). They are cornerstones for developing multiple-level climate targets, quantifying the effectiveness of policy instruments and tracking climate mitigation progress (Steininger et al. 2016; Meinshausen et al. 2015; Rogelj et al. 2019). Emission scopes and allocation schemes are critical in quantifying climate responsibilities within the international community, but it remains contentious with regard to which one best reflects an organization’s or entity’s climate responsibility. The debates on climate responsibility related to boundary and scope have long existed in international climate discourse (Peters et al. 2011), and have become more challenging at higher spatial resolution with a growing body of diverse climate actors (Markolf et al. 2018; Hsu et al. 2019b). Without a uniformly standardized process, subnational actors can easily underreport their GHG emissions, leading to difficulties in evaluating their climate mitigation progress (Gurney et al. 2021).

The Kyoto Protocol sets binding emission reduction targets to reduce GHG emissions from industrialized countries (UNFCCC 2008). The national emissions were GHG emissions generated within countries’ territories, while the extraterritorial emissions, such as emissions generated in public aviation and shipping, are not considered in countries’ responsibility, nor are emissions embodied along supply chains included (UNFCCC 2008). The territorial emission accounting has still been used in National Determined Contributions (NDCs) that parties committed in the Paris Agreement (UNFCCC 2021). This accounting scheme is considered to be flawed in later studies as developed countries imported more carbon-intensive products from developing countries (Peters et al. 2011).

To overcome limitations of overlooking emissions embodied in internationally traded products, other emission accounting schemes are gaining increasing attention. One is the consumption-based accounting, which attributes emissions occurring along chains of production and distribution to final consumers of products (Wiedmann 2009; Davis and Caldeira 2010). This accounting scheme has been widely applied in attributing climate responsibility for its advantages of considering emissions across borders in the academic community (Peters 2008). This has also been applied to analyze other environmental burden shifting (Wiedmann and Lenzen 2018), including $PM_{2.5}$ (Zhao et al. 2019; Zhang et al. 2017), ammonia (Ma et al. 2021), sulfur dioxide (Lin et al. 2022), and mercury emissions (Chen et al. 2019), as well as biodiversity loss (Moran and Kanemoto 2017; Lenzen et al. 2012), land-use change (Hoang and Kanemoto 2021), resource extraction (Lenzen et al. 2022), and water use (Ridoutt et al. 2018; Serrano et al. 2016). These environmental pressures driven by consumption activities of an organization or subnational entities are usually referred to as “footprints” (Hua, Cheng, and Wang 2011). This accounting scheme, however, is not a panacea. One of the main concerns that the international community hesitated to adopt this principle lies in the incompleteness and inconsistencies in data sources among different databases to construct the global multi-regional input-output model where this principle is based on (Tukker, Wood, and Schmidt 2020). Recent studies have suggested that the differences in results were unlikely to have significantly higher uncertainty than production-based estimates as the differences mainly come from the different estimates of the latter (Peters, Davis, and Andrew 2012; Tukker, Wood, and Schmidt 2020). Another critic is that while consumption-based accounting takes the imported emissions into account, it does not credit countries for cleaning up emissions from their export products and overlooks the downstream lifecycle impacts of consumed products (Tukker, Pollitt, and Henkemans 2020).

Other attribution principles are also proposed by scholars, such as allocating emissions based on income (Liang et al. 2017; Marques et al. 2012), roles of industries in supply chains (Liang, Qu, and Xu 2016; Hu et al. 2021), and shared responsibility between producers and consumers (Gallego and Lenzen 2005). These perspectives are intended to overcome the limitations of the production-based and consumption-based allocation principles and to fill the gap in considering different roles that entities play in the supply chain. For example, the income-based approach allocates emissions to those who add values in production, according to the factor inputs, such as labor and capital (Steininger et al. 2016), while network-based approach emphasizes the important sectors and commodities (Liang, Qu, and Xu 2016). Hickel (2020) proposed to quantify national responsibility based on CO_2 emissions in excess of the planetary boundary; in this principle, the U.S. is responsible for the largest share (40%) of excess global CO_2 emission, followed by the European Union (29%).

1.2.2 U.S. subnational climate mitigation

Subnational climate actions in the U.S.

There has been a growing body of subnational and non-governmental actions increasing their impacts to achieve ambitious climate targets, which is broadly classified into Non-state Actor Zone for Climate Action (NAZCA) by UFCCCC. These efforts have the potential to bridge the "emission gap" left by insufficiently ambitious nationally determined contributions (NDCs). The subnational climate targets and policies are mostly centered around climate mitigation, although climate adaptation and resilience are critical components.

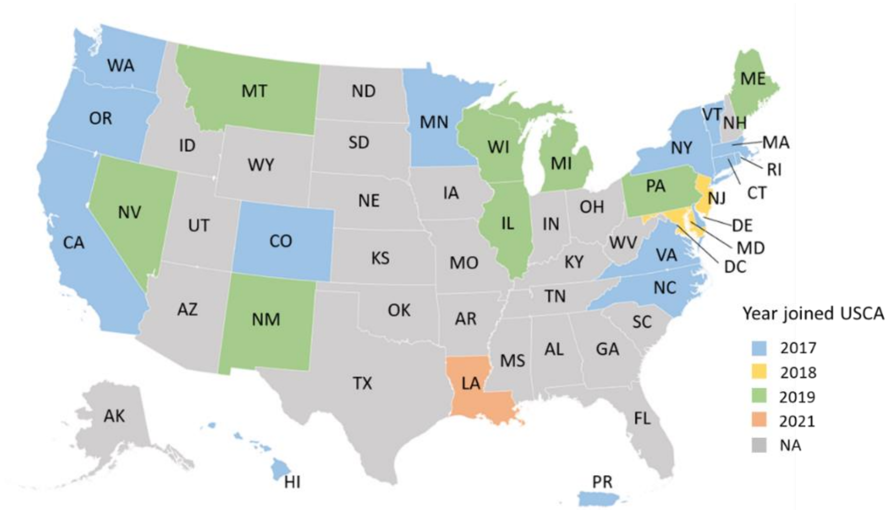

Figure 1-1 States and territories that joined U.S. Climate Alliance

In the U.S., since the 2000s, states have attempted to organize and make up for the lack of federal climate leadership. Early prominent efforts are mainly regional coalitions. For example, Regional Greenhouse Gas Initiative (RGGI) is a collective effort from eleven states in New England and Mid-Atlantic regions that have implemented a cap and trade program to mitigate carbon emissions from the power sector (RGGI 2021);

the Western Climate Initiative (WCI), founded in 2007, committed to reducing emissions and implementing an emission trading scheme between several U.S. states and Canadian provinces (WCI Inc. 2021); the Pacific Coast Collaborative, established in 2008 by pacific states to coordinate the implementation of climate change adaptation and mitigation policies cross borders and jurisdictional boundaries. Such arrangements have the potential for the member states to push for bolder national climate targets and provide best practices for others to follow in the implementation of climate agreements, especially in the absence or inadequacy of federal climate leadership (Hsu et al. 2020; van der Ven et al. 2017; Bordoff 2017).

US Climate Alliance (USCA), established in 2017, took the state-level climate leadership towards achieving climate goals of the Paris Agreement (USCA 2020b). The Alliance includes 26 states and territories as of 2021, as shown in Figure 1-1, representing 56% of the US population and 62% of GDP (USCA 2021). The multistate agreement is widely promoted as promising substitutive climate governance, considering that each of the top seven states in the USCA had an economic size that could be ranked global top 20 in 2017 and thus could make a significant contribution to achieving climate targets (BEA 2020). Considering spatial heterogeneity in geographical resource endowment and economic development in different states, state-initiated policies primarily focused on renewable energy transition (e.g., Renewable Portfolio Standards (RPS)) and upgrading outdated infrastructure with more energy-efficient technology (e.g., investing in clean technology projects to facilitate the energy transition) within their authorities (Martin and Saikawa 2017). Regionally, Eastern states' climate efforts concentrated on reducing the emissions from power grids, improving regional transportation systems and making regional progress on offshore wind, such as Pennsylvania, Virginia, and Rhode Island. Midwest states have been making progress in phasing-out coal-fired power plants, promoting clean cars and improving energy efficiency, including Illinois, Michigan, and Minnesota (C2ES 2020; USCA 2020a). For instance, Colorado signed coal-fired power plant retirement into law to cut fossil fuel consumption and promote a just transition (RMI 2018). Most western states have been dedicated to the clean energy transition, for example, California set the target of achieving carbon neutrality by 2045 and has reduced its carbon intensity by 41% between 2000 and 2017 (CARB 2019). In 2019, New York issued the Climate Leadership and Community Protection Act (CLCPA), which was one of the most ambitious climate legislation, committed to achieving 100% zero-carbon electricity by 2040, with consideration of upstream emissions associated with fossil fuels consumption outside of the state (NY State Senate 2019).

Quantifying subnational GHG emissions

Subnational GHG emissions are quantified according to various principles and scopes (Steininger et al. 2016). There is no sufficient research yet to track climate mitigation progress and compare subnational GHG emissions in a consistent manner with respect to the scope of emissions and quantification framework (Hale et al. 2021), and tracking countries' adaptation efforts have proven even more difficult (Berrang-Ford et al. 2019).

GHG emissions for subnational jurisdictions are mainly based on territorial emissions estimated according to the IPCC methodology, in earlier studies (Geng et al.

2011; Liu et al. 2012; Ambarita et al. 2018; Clarke-Sather et al. 2011; Cohen et al. 2019; Olale et al. 2018) and national statistics (Government of Canada 2022; EIA 2022c; Department of Industry Science Energy and Resources 2022). As emission spillover effects gain increasing attention, scholars have been striving to develop different models at multiple spatial scales to capture emissions along supply chains. The development of multi-regional input-output (MRIO) model has enabled scholars to quantify consumption-based GHG emissions at the subnational level and to analyze virtual emission transfer, further, to explain how different factors drive the differences (Feng et al. 2013; Ma et al. 2022; Pan et al. 2018). Recent studies also investigated the roles of investment (Hertwich 2021) and migration (Gao et al. 2021; Bu et al. 2022) in trade-related emission transfer at the regional level. At a high spatial resolution, studies utilized a commodity flow approach based on the gravity model to analyze GHG emissions from food supply chains (Lin et al. 2019; Vora et al. 2021; Escobar et al. 2020). At the city and metropolitan levels, several approaches have been applied and developed for city-scale GHG emission inventory, including IPCC-based approach (Cai et al. 2019), hybrid LCA approach (Jones 2020), entropy-based approach (Zheng et al. 2021), a top-down approach built with Gridded Global Model of Carbon Footprints (GGMCF) model (Moran et al. 2018), extensions of input-output approach (Mi et al. 2016; Harris et al. 2020), meta-analysis of case studies (Sethi et al. 2020) and others (Markolf et al. 2018; Moran et al. 2022)

1.2.3 Carbon footprints of households

In the U.S., households contribute nearly 80% of the national energy-related CO_2 emissions (Bin and Dowlatabadi 2005), responsible for approximately 20% of global

GHG emissions (Jones and Kammen 2011; Weber and Matthews 2008). Average U.S. household carbon footprint was about five times the world average between 1995 and 2009 (Ivanova et al. 2016; Song et al. 2019). Although per capita emissions decreased after the national emission peak, it is still twice those of China and Europe and more than triple the world average (Friedlingstein et al. 2021). The large U.S. household carbon footprints entail a large mitigation potential and require policy instruments. Research shows that U.S. household carbon footprints could be reduced by 20% within ten years under reasonably achievable and effective non-regulatory interventions by changing behaviors with potential financial savings and little or no reduction in household well-being (Dietz et al. 2009). There is extensive literature on reducing household carbon footprints by avoiding carbon-intensive consumption, shifting to low-carbon alternatives, and improving the resource efficiency of products, so-called Avoid-Shift-Improve (ASI) framework, ranging from macroeconomic level to individual level (Roy et al. 2021; Creutzig et al. 2022). Here I briefly summarize the household consumption patterns, influencing factors and inequality in carbon footprints.

Characterization of household consumption pattern

Existing studies address household carbon footprints by analyzing household consumption patterns across many dimensions, including consumption categories (what), consumer groups (who), spatial hotspots (where), temporal dynamics (change) and socioeconomic factors (drivers). Characterization of household consumption patterns varies in scales and approaches. A large body of literature focuses on detailed consumption products, typically GHG-intensive products, such as energy consumption (Yang, Ren, and Zhou 2018) and food diets (He et al. 2018). These studies are mostly based on survey data or smart metering (Yang, Ren, and Zhou 2018), combined with econometric or machine learning approaches.

On a large scale, the Consumer Lifestyle Approach (CLA) and a top-down Input-Output analysis (IOA) are mainly used in earlier studies to quantify the contribution of consumption categories to household carbon footprints (Bin and Dowlatabadi 2005; Weber and Matthews 2008). Recent studies combined Input-Output framework with Consumer Expenditure Survey (CES) to provide more details about consumer characteristics, such as income groups (Feng, Hubacek, and Song 2021; Hubacek, Baiocchi, Feng, and Patwardhan 2017; Wiedenhofer et al. 2017), age groups (Zheng et al. 2022), and race and ethnicity groups (Goldstein, Reames, and Newell 2022). Spatial analyses identified emission hotspots ranging from provincial level (Feng et al. 2013), to metropolitan area level (Markolf et al. 2017), to zip-code level (Jones and Kammen 2014). These studies improved our understanding of key contributors to household carbon footprints, but were limited in understanding the changes of contributors from a time-series perspective. These changes, resulting from the changes in preferences, demand volume, and technological development, are also important to be taken into consideration. Studies analyzing consumption patterns in time series that emerged in recent years are mainly based on: 1) national consumer expenditure survey data, 2) market segmentation data, 3) final demand of input-output data, and 4) national expenditure account data (such as National Income and Product Accounts (NIPA) data) (Steen-Olsen, Wood, and Hertwich 2016; Song et al. 2019; Yuan, Rodrigues, and Behrens 2019; Lubowiecki-Vikuk, Dąbrowska, and Machnik 2021).

Influencing factors on household consumption

Another challenge in modeling demand-side mitigation lies in the diversity of lifestyles and flexibilities in choosing what they want to spend money on. Household consumption is not only dependent on their affordability and energy efficiencies pertaining to where they live, but is also affected by their preferences, values, social norms, and other socioeconomic determinants (Caeiro, Ramos, and Huisingh 2012). Existing literature has analyzed the relationship between household carbon footprint and socioeconomic factors (Sommer and Kratena 2017; Wiedenhofer et al. 2013; Zhang et al. 2015; Long et al. 2017; Liu et al. 2019; Feng et al. 2021; Wiedenhofer et al. 2017), including income levels (Ivanova and Wood 2020; Kalaniemi et al. 2020), degree of urbanization (Muñoz et al. 2020; Ottelin et al. 2019), household size (Fremstad and Paul 2019) and car use (Ivanova et al. 2018; Kalaniemi et al. 2020); other studies focused on socio-cultural and psychological factors including social awareness (Li, Zhang, and Su 2019), and attitudes towards pro-environmental behaviors (Boucher 2016). In recent years, statistical approaches such as data mining and machine learning methods have been adopted to identify household consumption patterns with socioeconomic, demographic and attitude-related factors, as well as their impacts on household carbon footprints (Froemelt et al. 2018; Froemelt and Wiedmann 2020; Chen et al. 2019; Rolnick et al. 2019).

Unequal household carbon footprint

Among the socioeconomic factors, income presents a prominent impact on household carbon footprints. The term "carbon inequality" stems from "income inequality" in economics, which was coined when scholars adopted income inequality measurements to analyze different GHG emissions from different income groups (Kahrl and Roland-Holst 2007; Clarke-Sather et al. 2011). It gained growing attention as the gap between the large gap between the rich and the poor is found to be large that challenges sustainable consumption and poverty eradication goals. For instance, in 2010, the top 10% of global income earners should be responsible for 36% of household carbon emissions (Hubacek et al. 2017). Regionally, the very rich urban households in China, comprising 5% of the population, induced 19% of the total national carbon footprint from household consumption in 2012 (Wiedenhofer et al. 2017). In the United States, carbon footprints of households with higher than $150k annual income were over four times higher than households with $15k in 2009 (Song et al. 2019). Lifting more than one billion people out of poverty, theoretically, only increases global carbon emissions by 1.6–2.1% or less (Bruckner et al. 2022), but implementation at the national or local level still remains challenging. The importance of equality consideration in household climate action is based on the widely acknowledged argument that the reduction of GHG emissions should also ensure human’s needs and resource accessibility (Raworth 2017). In addition, people with low income who generate less emissions are more vulnerable to climate impacts and more sensitive to financial mitigation policies (Wang et al. 2016; Vogt-Schilb et al. 2019). In contrast, rich people with high consumption lifestyles are more capable of adopting low-carbon but potentially more expensive technologies.

1.2.4 Gaps in current literature

The subnational and household-level climate mitigation efforts are suggested to have great potential to facilitate achieving the 1.5 degrees climate goal, however, are still facing challenges in effective implementation.

As more subnational actors are committed to achieving climate goals, the effectiveness and sufficiency of subnational level climate mitigation efforts are underexplored. While states are credited for cleaning up their territorial manufacturing and industrial emissions, emissions along supply chains are rarely included in their climate mitigation plans. Methodological and knowledge supports are needed to reduce the transferred emissions. This proportion of emissions accounted for an average of 23% of total GHG emissions internationally (Davis and Caldeira 2010), and this number increases at more detailed spatial scales. For example, emissions embodied in imports accounted for 57% at the subnational level and approximately 70% at the city level based on the study of China (Feng et al. 2013; Mi et al. 2016; 2019). At the subnational level, the neglection of embodied emissions can result in considerable accounting bias, especially for states and cities that heavily rely on the trade of products with other regions. Historical international evidence has shown that displaced emissions among countries had increased under Kyoto Protocol where a subset of countries participated in climate efforts (Peters et al. 2011). Considering the resource endowment and growing labor specialization, more climate commitments from subnational jurisdictions could lead to more spatial heterogeneity in emission generation. While consumption-based accounting approach is applied in the international community to reallocate climate responsibility, such an approach is insufficiently developed and applied at a more localized level. It is not only because the local shipping is more frequent and more costly to track, but also because the local GHG emission account requires a more comprehensive coverage with respect to types of GHGs, clear scopes and integration process from multiple resources.

As existing studies highlighted the contribution of energy system transformation to decoupling national emission increase from economic growth (Hubacek et al. 2021; Le Quéré et al. 2019), whether households have contributed to this declining trend is not well-understood yet. Household contributions can be reflected in changing consumption patterns, such as avoiding carbon-intensive purchases and adopting low-carbon behaviors and technologies, against the backdrop of growing economy and population. However, few studies analyzed how consumption patterns have shifted at the national scale in a time series, despite that a large body of literature underscores the considerable mitigation potential and associated health benefits (Moran et al. 2020; Ivanova et al. 2020; Creutzig et al. 2022). Furthermore, who contributed to the emission decline requires more understanding than simply underscoring the top rich people being “pollute elites” (Ummel 2014; Kenner 2019). Since household carbon footprints are affected by not only socioeconomic factors, such as income, education, types of house, etc., but also affected by where they live and what they consume, understanding the effect reflected at the national level is important to shed light on national climate mitigation plans.

Finally, a rapid behavioral change from the demand side is essential to combat climate change but is rarely addressed. The COVID-19 pandemic offers an opportunity to investigate significant changes in people’s behaviors. This change, although resulting in a sharp decline of GHG emissions in its outbreak (Liu et al. 2020), cannot ensure a low-carbon behavioral transition, as they cause tremendous consequences in social development and wellbeing. There are certain behavioral changes, such as teleworking, online conferences and reduced leisure traveling, that gained unprecedentedly great attention opportunities for reducing carbon footprints as they achieved high adoption rates in a short period of time (Pabilonia and Vernon 2020; Burtscher et al. 2020; Leochico, Giusto, and Mitre 2021). On the flip side, for example, the increase in car purchases and decrease in the use of public transportation may lock people in carbon-intensive habits. While there is a heated debate on the effectiveness and feasibility of adopting certain behaviors in a longer term, it remains a question of what lessons we can learn from the decline in emissions and how we can achieve long-term low-carbon development through behavioral changes. Addressing this question will require considering not only carbon footprints of people's behaviors but also people's needs and willingness to change. A framework linking needs, behavior, consumption and associated carbon footprints will improve our understanding of green lifestyles.

1.3 Dissertation questions and objectives

This research aims at filling the gaps discussed above and improving the understanding of the effectiveness and contribution of subnational and household climate mitigation efforts. In order to achieve this goal, I analyze the consumption-based climate responsibilities for U.S. states, and examine how much households have contributed to emission reduction, with further exploration of emission reduction opportunities affected by the COVID-19 pandemic. This dissertation research addresses three main research questions that will be elaborated as follows.

Question 1: For U.S. states with climate targets, how much GHG emissions are spilled over to other places through trade networks? How much climate responsibility should each state take?

Among various subnational climate actors in the U.S., Climate Alliance is an important one in which some states jointly contribute to combating climate change to fill the lack of federal climate leadership. The effectiveness of such state-led efforts to tackle climate issues has not yet been well understood. This part of research will accomplish the three subsequent objectives as follows.

- *To quantify the production-based GHG emissions and consumption-based GHG emissions for each state in the U.S.,*
- *To quantify the virtual GHG emission transfer through supply chains between U.S. states, and*
- *To identify critical sectors and states that contribute to emission spillover.*

Question 2: How did U.S. household consumption contribute to the national emission peak-and-decline pattern? How did different income groups affect this pattern?

These questions will be addressed through a top-down approach using the Environmentally-Extended Input-Output (EEIO) analysis at the national level. I quantify the magnitude of changes in U.S. household carbon footprint caused by changes in consumption patterns from 2001 to 2015. The objectives are:

- *To quantify changes in household consumption with detailed products,*
- *To quantify the contribution of different income groups to the changes in overall GHG emissions induced by household consumption, and*
- *To analyze how the changes in household carbon footprint affected inequality in terms of carbon footprint and expenditures.*

Question 3: How did the COVID-19 pandemic affect U.S. household consumption and associated GHG emissions? What are the middle- or long-term impacts of potential behavior changes affected by the pandemic?

The COVID-19 pandemic is a human tragedy that has posed great threats to public health, considerably dented the economy and affected human activities and associated environmental impacts (Polyakova et al. 2020; Lenzen et al. 2020; Liu et al. 2020; Le Quéré et al. 2020; Guan et al. 2020). This chapter will explore a quantitative approach to analyzing people's behavioral change and associated carbon footprints, with a case study in the pandemic setting. The objectives are:

- *To develop a framework that links people's needs and behaviors to consumption and associated carbon footprints,*
- *To build quantitative tools to analyze behavior changes on the national level after the pandemic, and*
- *To develop scenarios based on a basket of behavior changes and analyze associated carbon footprints.*

1.4 Dissertation outlines

This dissertation is structured into five chapters. Chapter 1 describes the general background and articulates the motivations for my research topic. I summarize the growing literature on subnational and household climate mitigation efforts in the U.S., and conclude a few important knowledge gaps in the current literature. I propose the overarching question of this dissertation research and three break-down specific topics to address these gaps.

Chapter 2 focuses on addressing Question 1 by quantifying climate responsibility for each state in the U.S. It compares production-based and consumption-based emissions, then analyzes the emission transfer associated with interstate movements of goods and services. In this chapter, I develop a state-level GHG emission inventory from 536 sectors based on multiple sources, and construct a state-level emission Multi-Regional Input-Output (MRIO) table to capture interstate trade activities. The two datasets build the cornerstones for analyzing where the emissions are generated and where the products and services are consumed. As the U.S. is the largest emission importer worldwide, imported emissions are taken into account by linking the established state-level MRIO table to the international trade networks EXIOBASE. With an MRIO analysis, I identify the states with a considerable emission transfer and identify critical sectors where a large amount of emission transfer is present. I discussed the challenges of state-level climate mitigation policies posed by virtual emission transfer and potential solutions to address carbon spillover. This chapter maps the GHG emissions embodied in these trade activities and analyzes carbon spillover effects in the state-led climate governance system.

Chapter 3 examines Question 2 by analyzing changes in GHG emissions induced by changes in household consumption patterns. It inherits the methodological framework of Chapter 2. This chapter contributes to the literature by estimating the changes in GHG emissions driven by U.S. household consumption and its role in the national emission peak-and-decline trend. By isolating the effects of household consumption changes from supply-side factors, it focuses on the changes in direct and indirect emissions driven by household consumption through bridging a 536 sector-detailed input-output table and

Consumer Expenditure Survey (CES) from 2001 to 2015. It further analyzes the contributions from population, consumption volume per capita, and consumption patterns by quintile income groups by employing Logarithmic Mean Divisia Index (LMDI) decomposition approach. It examines the carbon-footprint inequality and sheds light on high-level policy-making processes pertaining to demand-side climate efforts.

Chapter 4 explores Question 3 by developing a framework that links people's needs, behaviors, consumption and associated carbon footprints. I propose a modifiable framework for estimating the economy-wide dynamics of consumer behavioral changes and associated carbon footprints affected by an abrupt economic system and shed light on low-carbon consumption. I employ this approach to a set of behavioral changes that are severely affected by the pandemic. The framework built in this chapter can be extended to explore the dynamics of carbon footprints caused by behavioral changes affected by exogenous shocks.

Chapter 5 summarizes and concludes the entire body of work. I revisit the key findings of Chapter 2-4, and discuss how each chapter improves the understanding of climate mitigation from subnational climate actors and households in the U.S. Finally, this chapter reveals the limitations of this dissertation and provides future directions to contribute to climate mitigation from subnational actors and households.

Chapter 2 Can multi-state climate mitigation agreements work? An embedded emission perspective for the U.S.[1]

Abstract: Subnational and non-governmental actors are expected to provide important contributions to broader climate actions. A consistent and accurate quantification of their GHG emissions is an important prerequisite for the success of such efforts. However, emissions embodied in domestic and international supply chains can undermine the effectiveness of climate agreements, add challenges to the quantification of emissions originating from the consumption of goods and services produced elsewhere. We examine emission transfers between the states that have joined the U.S. Climate Alliance (USCA) and the others. Our results show that states pledging to curb emissions consistent with the Paris Agreement were responsible for approximately 40% of total U.S. territorial GHG emissions. However, when accounting for transferred emissions through interstate supply chains of the goods they consume, Alliance's share increased to 52.4% of the national total GHG emissions. The consumption-based emissions for some Alliance states, such as Massachusetts and New York, could be more than 1.5 times higher than their production-based emissions. Reducing upstream emissions should be the current focus for states who have cleaned up their own manufacturing emissions. Our detailed sectoral analysis highlights the challenges facing such agreements to extend cooperation in the future for the larger joint benefit and the potential for interstate carbon leakage from member states implementing stricter environmental policies that could lead to

[1] The co-authors for this chapter include Giovanni Baiocchi, Kuishuang Feng, Klaus Hubacek, Laixiang Sun, Daoping Wang, Dabo Guan.

higher emissions from non-member states. It is critical for these arrangements to pay close attention to transferred emissions.

2.1 Introduction

Although addressing climate change can benefit from effective national and international responses, non-state and subnational actors (NSAs) play a critical role in delivering climate actions (Hsu et al. 2018; Roelfsema et al. 2018). The engagement of these diverse local actors opens opportunities for piloting innovative approaches that potentially scale up to broader practice (Hultman et al. 2020), designing solutions suitable to local needs (Jörgensen, Jogesh, and Mishra 2015), and leveraging local resources to foster demand-side actions. These opportunities embrace the merits of the emerging polycentric climate governance (Cole 2015; Ostrom 2009), offering significant potential to close the "emission reduction gap" arising from current commitments and the level required for meaningful mitigation in the face of accelerated climate risks, and provide strong alternative supports should federal efforts prove inadequate or fail (Hale 2018; Hultman et al. 2020; Masson-Delmotte et al. 2018; Lui et al. 2021).

The growing number and influence of subnational climate actors mostly feature in a voluntary process where these actors participate in climate mitigation or adaptation activities with proposed targets, ranging from alliances (e.g., Powering Past Coal Alliance, U.S. Climate Alliance) to individual cities. These self-selected initiatives demonstrate climate leadership and potentially provide best practices for others to follow. However, recent research highlights the problem of climate mitigation actors self-selecting into joining climate agreements because of access to lower-cost options, their capacity to bear the mitigation costs, and the presence of a functioning government capable of implementing policy decisions (Jewell et al. 2019). This raises the issue of how applicable lessons learned from these coalitions are to other potential members when efforts are scaled up if they apply only to specific circumstances.

Potential carbon leakage because of the interconnected nature of economic activities adds further complexities in quantifying the climate contributions from subnational actors, ignored by the currently proposed quantification framework (Hsu et al. 2018). GHG emissions embodied in trade are difficult to trace at higher spatial resolution due to the volume and number of traded products. Neglecting such embodied emissions from purchasing carbon-intensive products could exacerbate the underestimation of GHG emission inventories from self-selected climate entities by increasing the gap between estimated GHG emissions and actual emissions they should be responsible for (Gurney et al. 2021). So far, GHG emissions embodied in supply chains are well-quantified at national scales, however, are insufficiently analyzed within a country, even though the embodied emissions account for a large proportion of consumers' carbon footprints. For instance, more than half of GHG emissions in China are related to goods that are consumed outside of the province where they are produced (Feng et al. 2013). Quantifying embodied emissions will improve the effectiveness and accuracy of the climate contribution from subnational actors. More importantly, it provides scientific evidence to strengthen a safety net to continue building on the new momentum to address the climate challenge.

In this study, we analyze GHG emissions embodied in the supply chain for state-level climate actors in the United States (U.S.), as a case where subnational climate actors have relatively high administrative capability of implementing climate policies, under a broader background where subnational climate actions can yield different effects given their relationships with national authorities and mitigation potential of proactive actors. Prior studies have acknowledged the emergence of regional initiatives (such as Regional Greenhouse Gas Initiative, Western Climate Initiative, and Pacific Coast Collaborative) and state-level (such as California and New York) initiatives for their territorial contribution to climate mitigation that could provide best practices for others to follow (Bordoff 2017; Hsu et al. 2019). Additionally, for the U.S., the cost of state-driven, heterogeneous climate action has been shown to be not much higher than the theoretically least-cost, nationally uniform policy that could be ideally applied by the federal government (Peng et al. 2021). However, GHG emissions embodied in domestic and international supply chains are not well quantified, thus not sufficient information is provided to clarify climate responsibilities for these economic interactions. The evidence of division of labor and economic structural complementarity suggests that human activities continue hinging on regional trade networks, therefore, underscores the important role of emissions embodied in trade in assessing the effectiveness of subnational policies.

As an illustrative case, we examine the state-level climate actors following the U.S. Climate Alliance (USCA), one of the major coalitions pushing for a more coordinated effort to curb GHG emissions. It was established in 2017 and included 25 states and territories as of 2020, representing 55% of the U.S. population and 60% of GDP (USCA 2020b). Since its inception, the alliance member claims to have achieved absolute decoupling of territorial GHG emissions from growth: during the 2005-2018 period, Alliance members have collectively managed to cut their territorial emissions by

14% whilst growing per-capita economic output by 16% (USCA 2020b). The multi-state agreement is widely promoted as promising substitutive climate governance given the fact that each of the top seven states in the USCA had an economic size that could be ranked in the global 20 in 2017 and thus could make a significant contribution to achieving climate targets (BEA 2020). Considering resource endowment and economic development of each state, state-initiated policies primarily focused on accelerating the renewable energy transition (e.g., Renewable Portfolio Standards) and upgrading older infrastructure with more energy-efficient technology within their authorities (Martin and Saikawa 2017). Multi-state agreements constitute an effort to organize and improve upon previous individual state-level and fragmented efforts.

Current state policies enforced or planned mostly focus on reducing territorial emissions and involve only member states, ignoring emissions induced along domestic and global supply chains. Interstate movements of goods and services are considerable in the U.S. that reflect regional specialization, resource needs and endowments, highlighting the need for analysis in sectoral and spatial detail. Fossil fuels are by far the most shipped commodity within the U.S., representing one-third of all freight traffic (FAF 2021). Mining products, which are highly carbon-intensive in upstream processes, also contribute a significant proportion of interstate trade. For example, Minnesota, as the largest supplier of iron ore, provided 75% of the domestic iron ore demand in 2016 (USGS 2019). Moreover, different levels of economic and technological development, combined with local climate policies, reinforce differences in climate responsibility (Davis and Caldeira 2010; Peters and Hertwich 2008). Lower-income states that rely more on resource extraction and heavy industries usually set fewer regulations than higher-income states with less resource-intensive economic structure and access to clean technologies (Shea, Shields, and Hartman 2020). Given the current structure of production and trade between states and mitigation targets, it is of concern that the production of carbon-intensive goods could be further relocated from Alliance to non-Alliance states. There is mounting evidence of, as an example, companies moving from California to Texas to take advantage of lower taxes and laxer environmental regulation (Duggan and Olmstead 2021). Alliance states' unilateral policies aimed at reducing territorial emissions might have some effect at the state level but may be less effective or even counterproductive at the U.S. level. Consumption-based accounting, by attributing the responsibility for emissions to the final consumers of goods and services rather than its producers, is crucial in helping to judge the potential of such agreements (Davis and Caldeira 2010). Failure to consider GHG emissions embodied in interstate trade of goods and services may cause further carbon leakage beyond the state boundary.

Emissions embodied in supply chains are usually quantified by input-output analysis, where emissions induced from every lifecycle stage are attributed to consumers (Hertwich and Peters 2009). Gravity model has the advantage of generating more credible Type 2 multipliers compared to other local models and is used to capture detailed commodity flows (Feng et al. 2013; Riddington et al. 2006). We can use this approach to examine how interstate economic activities affect GHG emissions at the state level and their associated emission transfers by quantifying territorial GHG emissions and embodied emissions in interstate trade in the U.S. For this purpose, we build state-level GHG emission accounts for 536 economic sectors by combining GHG emission sources from the mandatory GHG Reporting Program (EPA 2019a) and EPA Greenhouse

Gas Emissions Inventory (EPA 2019b), and estimate emissions using energy flows based on state-level input-output tables. We then construct a state-level multi-regional input-output (MRIO) model linked with a doubly-constrained gravity model to quantify GHG emissions embodied in interstate trade (Riddington, Gibson, and Anderson 2006; Z. Zhang, Shi, and Zhao 2015). This model is linked to a global MRIO model (EXIOBASE v.3) to analyze emissions embodied in international trade to account for imports to the U.S. (Stadler et al. 2018). Then we zoom into the sectoral level to analyze the heterogeneity of GHG emissions from the Alliance and non-Alliance groups. Finally, we discuss the mechanism of current subnational agreements, the challenges of extending the current Climate Alliance to other states and potential carbon leakage. The results of our study reveal interstate emission transfers and shed light on the effectiveness of multi-state agreements to curb GHG emissions when considering the whole supply chain.

2.2 Methods and materials

2.2.1 Environmentally-extended MRIO framework

Construction of U.S. state-level MRIO

We used the multi-regional input-output (MRIO) approach to capture economic activities and associated emissions along domestic and global supply chains, based on monetary flows and virtual carbon flows between industrial sectors and countries or regions (Miller and Blair 2009a). Using this approach, we examined GHG emissions embodied between Alliance states and non-Alliance, based on their Alliance status by 2020.

We constructed the MRIO for 50 states and the District of Columbia and aggregated the 536 sectors into 147 sectors, resulting in 7497 region-sectors for 2017 (sector details shown in Table A-1). This aggregation preserves the sectors with high GHG emissions and facilitates the calculation (Steen-Olsen et al. 2014). The MRIO construction is based on single-regional input-output tables for 51 regions and the commodity flows between states, while the latter is derived from county-level commodity flows estimated by IMPLAN (IMPLAN Group LLC 2022). The commodity flows are calculated by the doubly-constrained gravity model, originally proposed by Leontief and Strout (1963), where the double constraints are used to ensure the supply-demand balance and the threshold of bilateral trade between regions. The model is then calibrated with Commodity Flow Survey (CFS) and Freight Analysis Framework (FAF 2021); these two databases provide information about the mode of transportation by commodity, ton-miles shipped and the origin and destination states. These commodities are classified according to the standard classification of transported goods at a two-digit level.

We constructed the state-level MRIO using the "Chenery-Moses" approach (Chenery 1953; Moses 1955; Miller and Blair 2009a). We first derived the balanced single-regional IO tables and the inter-county trade flows from IMPLAN. We aggregated the county-level trade data to the state level based on their origins and destinations of the trade activities and constructed a state-level MRIO table. This aggregation allows us to preserve sectoral flow details at the state level and can help cancel out uncertainties within states during the development of the gravity model (Fournier Gabela 2020; Lenzen, Pade, and Munksgaard 2004; Steen-Olsen et al. 2014). Based on interstate commodity flows, the total shipments of commodity *i* into that region *s* from all of the regions are expressed by T_i^s,

$$T_i^s = z_i^{1s} + z_i^{2s} + \cdots + z_i^{rs}$$

The proportion of all commodity i used in s that comes from each region r is denoted as vector $\boldsymbol{c^{rs}}$, in which each element is

$$c_i^{rs} = \frac{z_i^{rs}}{T_i^s}$$

Therefore, the interregional commodity proportion is

$$\hat{\boldsymbol{c}}^{\boldsymbol{rs}} = \begin{bmatrix} c_i^{rs} & 0 & \cdots & 0 \\ 0 & c_i^{rs} & 0 & 0 \\ \vdots & 0 & \ddots & \vdots \\ 0 & 0 & \cdots & c_n^{rs} \end{bmatrix}$$

Accordingly, when $r = s$, the matrix denotes the intraregional commodity proportion with each element being $c_i^{ss} = z_i^{ss}/T_i^s$. This could capture the proportion of goods i used in region s that comes within region s.

Expressed with c, the MRIO model is

$$(\boldsymbol{I} - \boldsymbol{CA})\boldsymbol{x} = \boldsymbol{Cf}$$

where, $\boldsymbol{A}$ is a matrix denoting technical coefficients; $\boldsymbol{I}$ is the identity matrix; $\boldsymbol{x}$ is the total output vector; $\boldsymbol{f}$ is the final demand matrix. In this study, the final demand matrix is composed of vectors of household consumption, federal government consumption (including defense and non-defense investment), state and local government expenditures (including education, noneducation, and investment), investment (capital stock formation), net inventory (stock) changes and foreign trade.

In the estimation, we assume that region r has the same proportions for allocating the intermediate and final consumption imported from region s (Miller and Blair 2009a).

While this is one of the best estimates we can get, this could still introduce uncertainties as intermediate trade and final demand consumers could have different preferences for the sources of goods and services.

RAS technique is then used to balance the input-output table (Miller and Blair 2009a; ten Raa, n.d.). This approach adjusts the columns and rows in an interactive process and corrects margin totals to zeros, which means the estimated interregional flows (imports and exports) are adjusted to the activity restrictions.

GHG emissions embodied in imports and exports

Environmentally extended MRIO (EE-MRIO) is widely used in analyzing environmental pressures along the supply chain by tracing all GHG emissions associated with consumed goods and services to final demand.

EE-MRIO is used to calculate the consumption-based GHG emissions, as expressed below.

$$\boldsymbol{E_{dom}} = \boldsymbol{e_{dom}} \times (\boldsymbol{I} - \boldsymbol{A_{dom}})^{-1} \times \boldsymbol{W_{dom}} + \boldsymbol{E_{dom\_dir}}$$

where $\boldsymbol{E_{dom}}$ represents GHG emissions from the domestic supply chain; $\boldsymbol{e_{dom}}$ represents territorial GHG emissions from state j, which is a vector in the length of $i \times j$ (*i* denotes the total number of sectors and *j* denotes the number of regions within the U.S.) ; $\boldsymbol{A_{dom}}$ is the technical coefficient matrix calculated by $a_{ij}^{rs} = z_{ij}^{rs}/x_{ij}^{rs}$, representing the amount of input from sector *i* required for producing one unit of output in sector j. $(\boldsymbol{I} - \boldsymbol{A_{dom}})^{-1}$ refers to the Leontief matrix that captures the direct and indirect effects along the supply chain. W_{dom} denotes the final demand associated with the domestic supply chain. $\boldsymbol{E_{dom\_dir}}$ is the direct emissions from fossil fuel burning by final consumers.

The U.S. is a large importer with imported GHG emissions accounting for approximately 18% of the total emissions in 2001 (Hertwich and Peters 2009). To estimate the GHG emissions embodied in international imports, we linked the state-level MRIO to the global input-output MRIO provided by EXIOBASE v.3 (Stadler et al. 2018). The latest version of EXIOBASE is for 2016, which covers 200 commodities for 49 countries or regions, representing about 90% of the world economy (Stadler et al. 2018). The GHG emissions that EXIOBASE covers include CO_2, CH_4, N_2O, SF_6, HFC, and PFC; they are expressed in $kgCO_2e$ based on 100-year time horizon global warming potentials (GWP) relative to CO_2 (Pachauri and Meyer 2014). We harmonized the 200 sectors in EXIOBASE with 147 sectors in IMPLAN for each state, to obtain the GHG emissions embodied in imports from the weighted global average for each sector. Due to the lag of data release, 2016 is the latest year of data we have access to. To make it consistent, we converted the monetary value of transactions from EURO to USD with an annual average exchange rate (IRS 2019), and converted it to the value of 2017 using an averaged deflator for each country (OECD 2019). The sector-specific GHG emission intensity coefficients we calculated from EXIOBASE are multiplied by imports derived from IMPLAN. Total GHG emissions embodied in imports are calibrated to be consistent with EXIOBASE.

Linking the global and national MRIO enables us to analyze emissions embodied in imports. While different states may import certain products from different countries, we assumed such difference is small and thus used the emission coefficients calculated by weighted global average for each sector. Although nesting the state-level input-output matrix would achieve this, there are many uncertainties involved, including scales of imports and exports, sector match, and table balance. Hereby, we include the imported emissions from other countries using a weighted global average to provide the global supply chain impacts of the consumption-based GHG emissions for each state.

Following the MRIO model, indirect emissions are calculated by

$$\boldsymbol{\varepsilon_{int}} = \boldsymbol{e_{int}} \times \boldsymbol{L_{int}} \times \boldsymbol{W_{int}}$$

where, $\boldsymbol{\varepsilon_{int}}$ is a vector of GHG emissions embodied in international imports, $MtCO_2e$; $\boldsymbol{e_{int}}$ is a vector of territorial GHG emissions from 7203 (147×49) country-sectors, $MtCO_2e$; $\boldsymbol{L_{int}}$ is the Leontief inverse calculated by $(\boldsymbol{I} - \boldsymbol{A_{int}})^{-1}$ using EXIOBASE; $\boldsymbol{W_{int}}$ is the international imports of each state, M$.

The GHG emissions capture embodied emissions from supply chains; whereas direct emissions from transportation and residents are directly added to the state. It is important to clarify the difference between the two accounting systems. Production-based accounting includes emissions that are generated from the production activities regardless of where they are consumed. However, consumption-based accounting attributes emissions to the final consumers of goods and services, even though the emissions generated in any step of upstream processes are located elsewhere. Compared to production-based accounting, consumption-based accounting of supply chain effects includes emissions embodied in imports and excludes emissions embodied in exports (Davis and Caldeira 2010).

2.2.2 State-level GHG emission account

We constructed a production-based state-level GHG emission account to analyze the interstate virtual GHG emissions embodied in interstate trade activities, including GHG emissions from electric power and industrial sectors, agriculture, transportation and the residential sector. We mapped the NAICS code (2007) of reported facilities into 536 IMPLAN sector codes via NAICS concordance and IMPLAN-NAICS Bridge (USCB 2018) and then aggregated them into 147 sectors. GHG emissions from electric power and industrial sectors are derived from Facility Level Information on GreenHouse gases Tool (FLIGHT), a bottom-up mandatory reporting program initiated by EPA (EPA 2019b; US EPA 2018). FLIGHT database covers 12 types of greenhouse gases (in CO_2e), including non-biogenic CO_2, methane (CH_4), Nitrous Oxide (N_2O), HFC, PFC, SF_6, NF_3, other fully fluorinated GHG, HFE, very short-lived compounds, other GHGs and biogenic CO_2 emissions. GHG emissions from agriculture mainly come from four sources, enteric fermentation from ruminants, manure management, crop planting (especially rice cultivation), and fuels used during crop and animal husbandry. GHG emissions from enteric fermentation, manure management and crop planting by state are derived from the EPA Inventory of US Greenhouse Gas Emissions and Sinks (EPA 2019b). Fuel usage during the cultivation process is derived from the USDA (2018). All emissions are converted to CO_2e according to GWP100 from the IPCC (Pachauri and Meyer 2014). Direct GHG emissions from transportation and residential sectors, as well as emission sources below the mandatory reporting threshold are estimated by the energy flow method described in Appendix A1.

2.3 Results

2.3.1 Territorial and consumption-based GHG emissions of Alliance and non-Alliance states

In this study, we divided U.S. states into two groups, the Alliance states committed to the Paris agreement and non-Alliance states, and analyzed their territorial and consumption-based GHG emissions. Our results show that the Alliance states representing 55% of the U.S. population and 60.3% of its GDP (USCA 2020b) account for just 40.2% of the U.S. territorial GHG emissions. When considering emissions embodied along supply chains, the Alliance states' total emissions increase to 52.4% of the national total.

We compared the ratio of consumption-based GHG emissions to production-based GHG emissions in 2017 for each state, as shown in Figure 2-1A, and found that most Alliance member states have a ratio value greater than 1. Consumption-based GHG emissions can be almost three times as high as territorial GHG emissions, ranging between about 3 for Massachusetts and 0.3 for Wyoming. The average ratio is about 1.5 for Alliance states and 0.9 for non-Alliance states. The net imported GHG emissions for each state are shown in Figure A-2.

We examined the composition of production-based GHG emissions in 2017 by six major aggregated production sectors for Alliance and non-Alliance states (as shown in the upper panel of Figure 2-1B), and the composition of consumption-based GHG emissions by location of emission occurrence (as shown in the lower panel of Figure 2-1B). The state details are shown in Figure A-1. Overall, non-Alliance states have a higher average share of GHG emissions from electricity generation, amounting to 31.3% of the total state-wide production-based emissions, as opposed to the 22.3% share of Alliance states. The shares of emissions from electricity generation are lower particularly for states like New England and Mid-Atlantic states, mostly Alliance states, as these states have been pursuing emissions reduction from power generation by expanding renewable energy sources (details of geographical locations shown in Table A-2). For example, emissions from electricity generation only contribute 1% of the total production-based GHG emissions in Vermont because of the high percentage of hydropower and wind power installed (EIA 2017b). On the other hand, Alliance states with low shares of electricity-related GHG emissions mostly have higher emissions associated with interstate trade or international trade in terms of consumption-based emissions (9% higher).

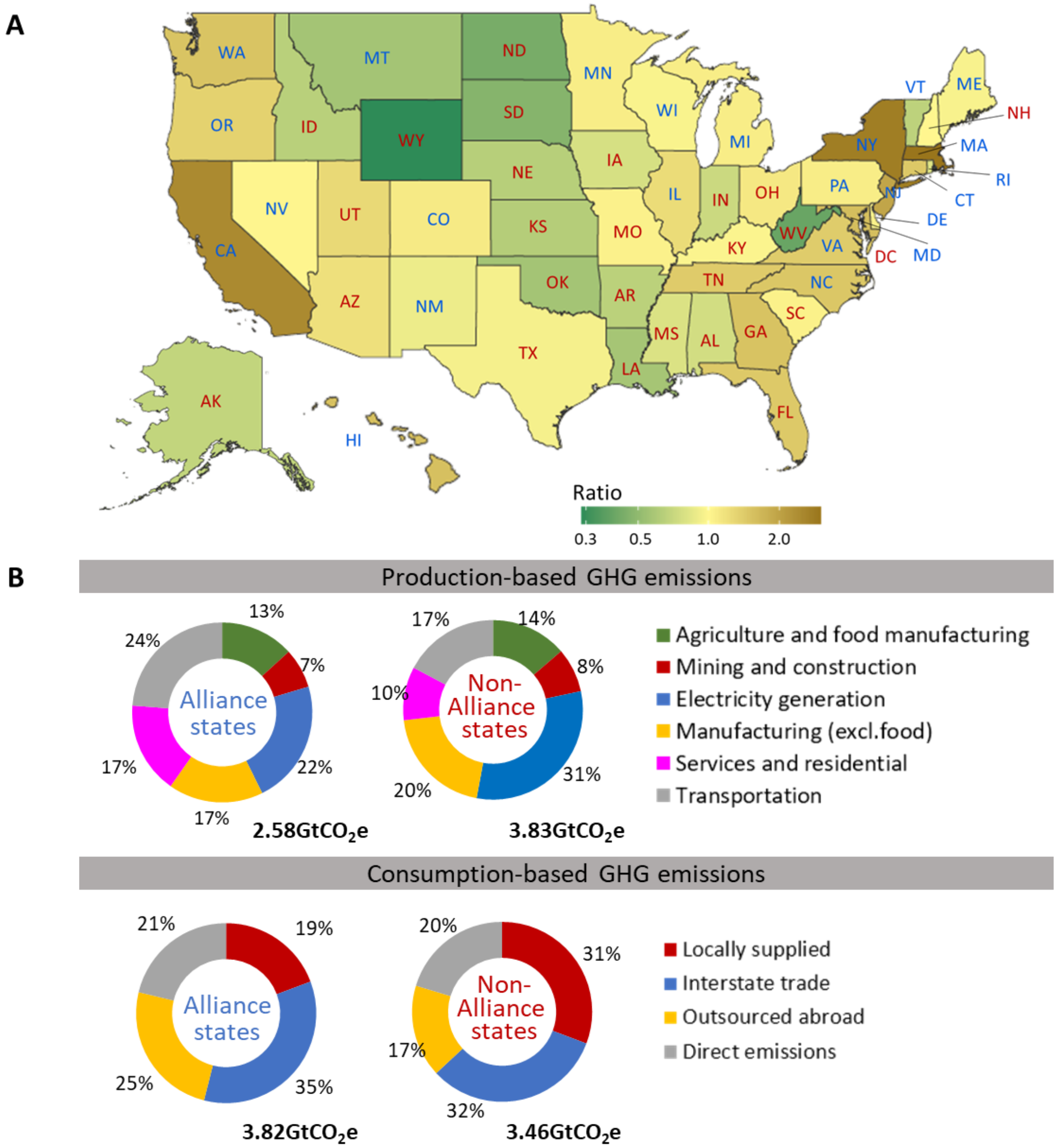

Figure 2-1 Consumption vs. territorial emissions for Alliance and non-Alliance states. (A) The ratio of consumption-based emissions to territorial emissions for each state; (B) The components of production-based GHG emissions for Alliance and non-Alliance states in terms of major production sectors (upper) and the components of consumption-based GHG emissions for Alliance and non-Alliance states in terms of three locations of production emission used to meet the state demand: local, other states, and abroad, as well as direct emissions from natural gas and gasoline-burning by final demand (lower).

While production-based emissions, as expected, reflect the geographical distribution of resource endowment, they are also consistent with states' roles along the domestic and international supply chains and thus can inform the discussion on climate responsibility. Alliance states have smaller shares of GHG emissions from upstream sectors (0.5% smaller, approx. 182 $MtCO_2e$, for agricultural and food manufacturing and 0.8% smaller, approx. 121 $MtCO_2e$, for mining and construction products) than non-Alliance states. Moreover, most Alliance states have higher shares of GHG emissions associated with downstream sectors such as transportation, service and residential sectors. These states have higher consumption-based GHG emissions than their territorial emissions due to out-of-state and international trade, except for a few states such as Montana and New Mexico which provide upstream products for other states. Differences in sectoral structure can account for the large gap in emissions between Alliance states and non-Alliance states, as non-Alliance states have a larger share of energy-related CO_2 emissions from the generation of energy needed to support their manufacturing sector (accounting for 64.6% of U.S. manufacturing in 1980 and 71.1% in 2018) (EIA 2020a). Our results show that manufacturing only accounted for 5.4% of territorial GHG emissions in California, however, it accounted for 18.8% of the consumption-based GHG emissions. This contrast is even more striking if we consider that consumption-based GHG emissions in California are more than twice the territorial GHG emissions in terms of magnitude.

Interstate trade plays an important role in the domestic economy and emission transfer. As shown in Figure 2-1B, a large proportion of the consumption-based GHG emissions are associated with out-of-state and international trade, ranging from 34.6% for Wyoming to 80.5% for Massachusetts. California is also a large emission importer, for example, nearly 72% of GHG emissions are generated outside of the state, where 38% are related to international trade. In many northern coastal states, a considerable fraction of the emissions associated with products consumed in these states occur in other regions, such as Massachusetts (80.5%), New York (72.5%), California (71.9%), Hawaii (74.3%), Washington D.C. (72.6%), Oregon (70.1%), New Jersey (64.5%), New Hampshire (62.4%),whereas for states located in the central parts of the country (e.g., Wyoming, North Dakota, Montana, Arkansas, West Virginia, Indiana, Oklahoma), the share is less than 40%. Three-quarters of Alliance states have higher consumption-based GHG emissions than territorial emissions (net importers), while this number for non-Alliance states (net exporters) is only 37%.

2.3.2 Heterogeneity within Alliance and non-Alliance groups

We also control for the size of the state aggregates and individual states by calculating GHG emissions per capita and GHG per unit of GDP (Figure 2-2) (with more details in Figure A-3). We found that Alliance states have lower production-based GHG emissions per capita than non-Alliance states (14.4tCO_2e/cap vs. 21.3 tCO_2e/cap). In comparison, the difference is rather small for consumption-based emissions. Alliance states have average per capita emissions of 21.33 tCO_2e, whereas non-Alliance states have an average of 23.64 tCO_2e/cap. A pronounced difference in production-based GHG emissions is observed between the two groups, which echoes that non-Alliance states play a significant role in upstream manufacturing industries and have higher emission intensities on average.

We also found that production-based GHG emissions per capita of Alliance states are not only lower on average but are also more homogeneous, ranging from 7.0 tCO_2e/cap to 66.9 tCO_2e/cap. In comparison, the non-Alliance states have production-based emissions ranging from 11.3 tCO_2e/cap to 175.2 tCO_2e/cap (Figure 2-2). A number of non-Alliance states located in central or mountainous areas tended to power their economy primarily with self-supplied fossil-fuel-based electricity and had a higher demand for space heating, resulting in high consumption-based GHG emissions per capita (Goldstein, Gounaridis, and Newell 2020). Such states include Wyoming, North Dakota, Alaska and Nebraska. These states have high fossil fuel resources without much regulation on extraction and emission that is used to support state-wide manufacturing, industrial and residential activities. States located in the north have relatively higher direct emissions from commercial and residential space heating. Space and water heating collectively contributed nearly two-thirds of the primary and secondary energy consumption in households (EIA 2018). In contrast, the grids have a larger share of renewable energy to power west and northeast coastal economies where the majority of Alliance states are located, which leads to a lower emission intensity in states located in these areas (NEI 2020). We used Principal Component Analysis (PCA) (Abdi and Williams 2010) to extract important emission sectors of Alliance states and non-Alliance states and found that Alliance states show a higher heterogeneity in agriculture and electricity production (more details in Figure A-4). The larger heterogeneity of non-Alliance states derives from contextual structural differences.

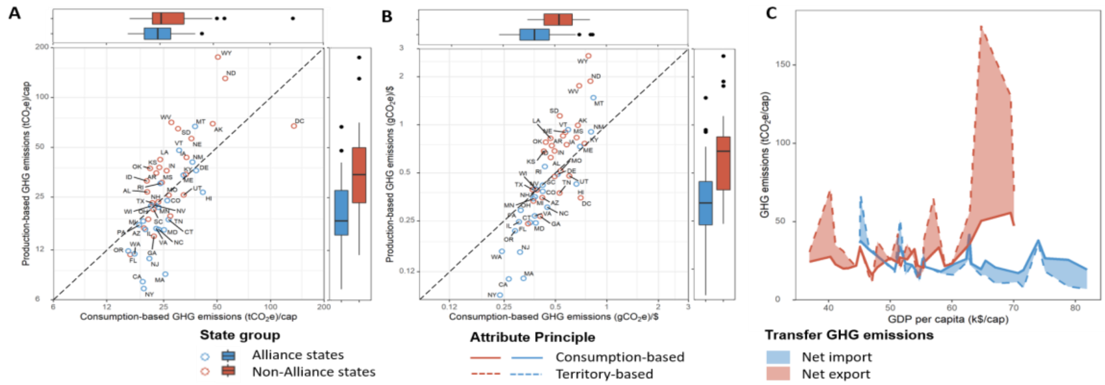

Figure 2-2 Per capita and per GDP production-based and consumption-based GHG emissions for Alliance and non-Alliance states. (A) Per capita production-based and consumption-based GHG emissions for Alliance and non-Alliance states; (B) Per GDP production-based and consumption-based GHG emissions for Alliance and non-Alliance states; (C) Patterns of GHG emissions vs. GDP per capita for Alliance states and non-Alliance states.

Figure 2-2C presents the relationship between GDP per capita and GHG emissions per capita, which highlights two opposite patterns. Both production-based and consumption-based GHG emissions from Alliance members decrease with increasing GDP per capita, while for non-Alliance states per capita GHG emissions are considerably higher for the most affluent states. This highlights structural differences in the economies where factors such as resource endowments, the impact on the state's GDP, and the relation with energy efficiency and fuel mix also play important roles in footprints. We can find that the affluent states with high per capita territorial emissions are mainly non-Alliance states whose economies are highly dependent on the energy and industrial sectors, while the affluent states with low emissions per unit of GDP are mostly Alliance states mainly based on service sectors (USITC 2016). The high carbon footprints of affluent non-Alliance states also demonstrate that carbon-intensive production in states with inadequate emission regulations could potentially cause carbon leakage. Alliance states with middle or high average per capita income seem to have a significant share of their consumption-based emissions generated elsewhere; however, they may have higher energy efficiency due to the shared commons and less carbon-intensive lifestyles of the residents (Jones and Kammen 2014; Markolf et al. 2017).

2.3.3 Net emission transfers via interstate trade flow of GHG emissions

Our results show that, in total, Alliance states imported 910 $MtCO_2e$ GHG emissions from non-Alliance states, while the non-Alliance states imported 401 $MtCO_2e$ emissions from Alliance states, resulting in a net transfer of 509 $MtCO_2e$ GHG emissions to Alliance states from non-Alliance states. To provide more detail on GHG emissions embodied in traded goods and services between states, we map the major domestic virtual emission flows (Figure 2-3). This map enables us to identify major trade flows between states. There are several major embodied emission links between Alliance states and non-Alliance states. For example, embodied emissions in trade from Texas to California (44.9 $MtCO_2e$, flow F1) are much larger than the embodied emissions in trade from California to Texas (9.4 $MtCO_2e$, flow F2). In addition, North Dakota is the second-largest embodied emission supplier to California (17.8 $MtCO_2e$). Another state with high net imported emissions is New York, having large virtual emission flows from non-Alliance states such as West Virginia (21.4 $MtCO_2e$), Indiana (12.5 $MtCO_2e$), Texas (12.0 $MtCO_2e$), and Alliance states such as Minnesota (10.9 $MtCO_2e$). Similarly, we can identify the major virtual GHG emission flows for other states: Indiana is the biggest embodied emission supplier to West Virginia and Wyoming is the biggest embodied emission supplier to Colorado. There are also some major partners between non-Alliance states whose trade activities embody a large amount of GHG emissions, for instance, the net flow from Texas to Florida, and from Florida to Georgia.

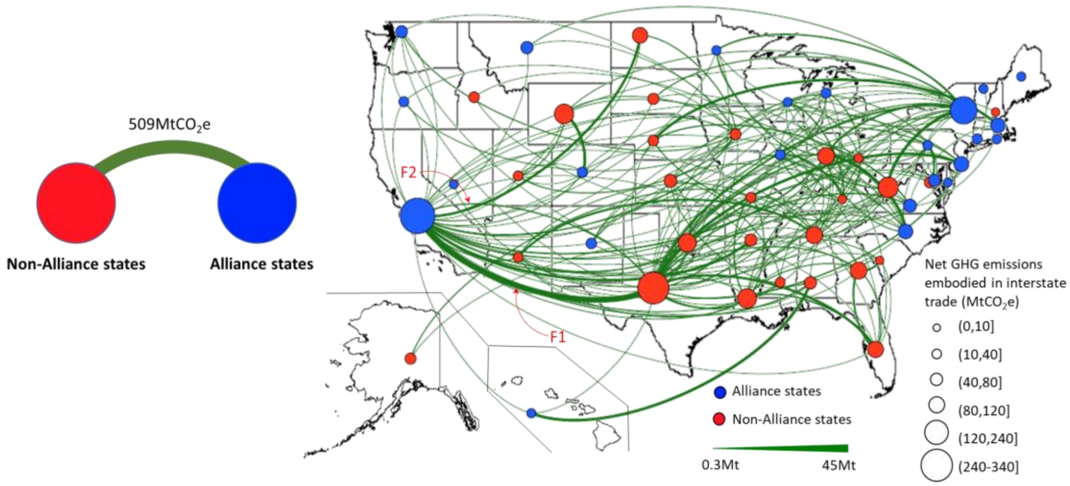

Figure 2-3 Virtual GHG emission flows within the U.S. (Note: The sizes of the circles represent net GHG emissions embodied in interstate trade. The width of the green-colored flows shows the amount of virtual GHG emission flows between states. This map only shows flows larger than 0.3MtCO2e. Exported flows are in a clockwise direction.)

2.3.4 GHG emissions embodied in interstate and international trade for Alliance and non-Alliance states

The transferred emissions can serve for producing intermediate goods and being traded as final products, where the latter was broken down into detailed sectors, as shown in Figure 2-4 (state details are shown in Figure A-5). For Alliance states, a substantial portion of the emissions embodied in imports is related to intermediate goods that serve for downstream production to meet the state demand or eventually to be traded to other states or countries. Alliance states have larger GHG emissions embodied in international imports (24.8%) than non-Alliance states (15.1%). In addition, higher income states tend to have a larger share of imports and associated emissions (Figure A-6). This indicates that the two groups tend to have a complementary division of labor where Alliance states tend to produce and export higher valued less carbon-intensive products such as services and high-tech products that use a higher proportion of low-carbon energy sources, while non-Alliance states specialize in primary commodities and the manufacturing of lower-valued more carbon-intensive products. As a result, products non-Alliance states produced and sold have significantly higher emission intensity (0.44 kgCO_2e/\$) compared to Alliance states (0.18 kgCO_2e/\$).

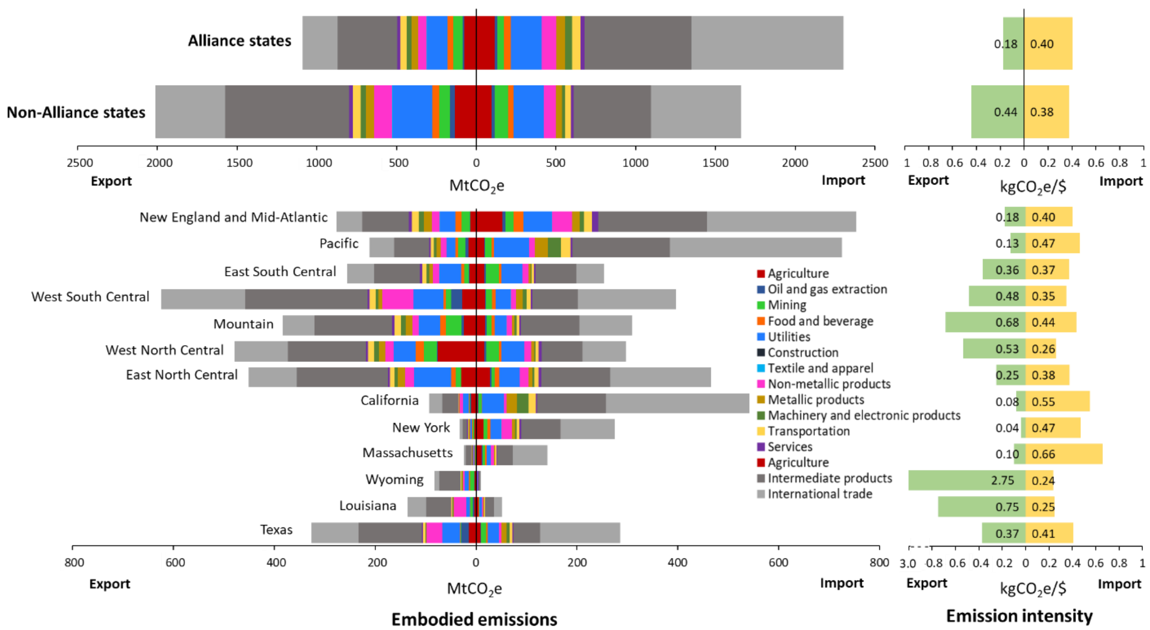

Figure 2-4 Magnitude and composition of GHG emissions and emission intensity of transferred products. Magnitude and composition of GHG emissions embodied in interstate and international trade by sectors for Alliance states, non-Alliance states, key geographical divisions and a few important individual states in the U.S. (left). GHG emission intensity of products imported to the states or state groups and exported from the states or state groups imports (right). Note: in this figure, "export" denotes GHG emissions embodied in selling products to other states and other countries, while "import" denotes GHG emissions embodied in buying products from other states and other countries.

In addition, non-Alliance states have a significantly higher proportion of emissions embodied in intermediate imports than Alliance states, 42.0% vs. 35.3%, respectively, while for proportion of emissions embodied in intermediate exports, non-Alliance states (42.9%) are slightly higher than Alliance states (40.4%). This implies that non-Alliance states have more imported emissions from producing their own final products rather than for export as intermediate goods for industries in other states. For example, the major value-added sectors in California are service sectors such as *finance*, *rental and leasing*, *professional and business services*, and *information* (BEA 2020). These specialized service sectors require high volumes of outstate purchases of motorized vehicles, transportation equipment, machinery, and electronics from upstream states, including Texas, Georgia, Alabama, and Illinois (FAF 2021). In contrast, *computer and electronic products*, *chemicals, food*, *beverage and tobacco products*, and *aerospace and other transportation equipment* are the top four manufacturing sectors in California (National Association of Manufacturers (NAM) 2021). The manufacturing of these high value-added products requires inputs of machinery products, metal and non-metal products, and plastic and rubber products purchased mostly from non-Alliance states (FAF 2021).

With the IO approach, we are able to identify the sectors that are associated with large emission transfers. Utility products embody the largest proportion of GHG emissions among the finished traded products. While Alliance states and non-Alliance states have similar amounts of GHG emissions embodied in products purchased elsewhere, non-Alliances have considerably more emissions embodied in products being sold to other states. These states are mainly located in East North Central and West South Central areas. In addition, agricultural products, non-metal products and mining products also embody a large amount of emissions through trade. For example, West North Central area presents to have the largest emissions embodied in selling agricultural products to other states, where major agricultural products producers are located, such as Iowa and Nebraska (USDA 2021). Texas and Louisiana are major producers of non-metal products, and most of the products embodying GHG emissions were traded elsewhere.

New England, Mid-Atlantic and Pacific regions, where most of the Alliance states are located, have large proportions of GHG emissions embodied from international trade and intermediate products from other states. Their emissions associated with purchasing final products from other states mainly concentrated on mining, non-metallic and utility products. New England and Mid-Atlantic regions have a large proportion of emissions embodied in agricultural products purchased from other states, while states in the Pacific region have large emissions embodied in utility, metal and machinery products purchased from other states. Most of the net emission exporters are non-Alliance states mainly located in West North Central and West South Central areas, which are important suppliers of coal and petroleum products serving for inputs for electricity and agricultural products to fill the demand in neighboring and coastal states; meanwhile, these states purchase more low carbon-intensive products such as electronics elsewhere.

In terms of emission intensity, the emission intensities of exports have higher variation than that of imports due to production specialization. States with high exporting emission intensities are highly dependent on fossil fuels and buy less carbon-intensive products elsewhere. Some states may have large amounts of embodied emissions, but relatively low intensity. For example, Texas was the largest emission exporting state to Mexico, Canada and East Asia, contributing 17.1% of U.S. exports in 2017, mainly concentrating on petroleum and gas products, non-metal products and agricultural products; meanwhile, Texas is also a large emission importing state, only second to California, as Texas relies heavily on manufacturing and agricultural products from abroad mainly from Mexico. While Texas has a large amount of GHG emissions embodied in interstate trade, the emission intensity remains relatively low.

2.4 Discussion

Our findings highlight two potential problems with multi-state agreements for large federal nations like the U.S. One is the challenge of extending the current Alliance due to the evidence of production specialization. The other is the potential carbon leakage through traded goods and services.

2.4.1 Challenges of extending the current Climate Alliance

We find that U.S. States have a wide range of emission transfers embodied in interstate and international trade activities. Our results show that more affluent coastal states in the U.S. tend to have higher embodied emissions than states located in central and mountainous regions. Coastal states, often subject to more stringent climate policies, tend to transfer net emissions to the inland states and international markets, where primary resources and industrial companies are located. States that have joined the Alliance tend to produce and export less emission-intensive products, compared to non-Alliance states, providing evidence of division of labor and economic structural complementarity with Alliance states specializing more in services and non-alliance in carbon-intensive manufacturing.

The main concern moving forward is that the members of a voluntary alliance of states pledging to curb emissions in line with the Paris or similar climate targets could have already been specializing in relatively cleaner industries and have thus self-selected themselves into the commitment. This issue has already been raised for international climate agreements like the Kyoto Protocol and the Powering Past Coal Alliance (PPCA), an alliance of national and subnational jurisdictions, which includes nine U.S. states (California, Connecticut, Hawaii, New Jersey, New York, New Mexico, Minnesota, Oregon, and Washington) that all are Alliance members, which committed to phasing out unabated coal plants, but happen to include mostly affluent national and subnational actors that already have a low cost of retiring coal plants or have already started such policies before joining (Jewell et al. 2019). This self-selection problem would limit the future potential of such agreements, as the prospect of other states joining would be limited. The literature on international cooperation has highlighted that a single dominant country, or a small group of countries, can effectively take the lead in addressing difficult global problems (Olson 1965). In climate change, however, eventually more states would need to become part of the effort to make a significant contribution to mitigation at the national level. Previous economic modeling has suggested that entities decide to participate in climate change agreements based on factors such as the perceived vulnerability to climate change, the level of income, natural endowment of alternative energy sources, and environmental policy preferences (Copeland and Taylor 2005).

Research on cooperation design literature has suggested that access to clean technologies, reduced air pollution and similar benefits could incentivize countries to join climate clubs (Nordhaus 2015; 2021; Obergassel, Wang-Helmreich, and Hermwille 2019). Technological cooperation that supports green innovations has been proposed as a policy to incentivize joining climate agreements and could be an option (Stewart, Oppenheimer, and Rudyk 2013; Urpelainen 2013). Technological cooperation is usually favored in policy discussions and plans over other options as it is typically perceived as more politically feasible as it emphasizes associated with opportunities for education, job training, and employment for disenfranchised communities (the sharing of expertise and best practices, technical cooperation, and clean energy jobs, are key components of the Alliance's plan). At the moment, agreements like the Alliance are more aspirational in nature when proposing further technological cooperation and lack the details and planning needed to match the rhetoric (USCA 2021). Such agreements need to be more ambitious and promote deeper, more transformative technological cooperation, especially in areas where economic forces are already driving change. As an example, large infrastructure multi-state efforts to build High-Voltage Direct Current (HVDC) bi-directional transmission lines could help promote renewable energy development and incremental decarbonization in areas rich in wind resources such as the Dakotas, Kansas, Oklahoma and Texas, where transmission has been already identified a key limiting factor in the development of renewable sources affected by intermittency and distributed generation (Gramlich, Goggin, and Gensler 2009).

Insufficient attention is usually given to co-benefits in climate change policymaking. Significant co-benefits for air quality from cutting emissions by increasing the efficiency of energy systems and shifting toward renewable energy sources could incentivize states to join the Alliance. Counties with the largest estimated percentage of mortality due to $PM_{2.5}$ and ozone tend to be located in the northeastern U.S., the industrial Midwest, and southern California (Fann et al. 2012). Long-term benefits could also play a part. The IPCC AR6 report has, for the first time, included a chapter assessing predicted changes in weather and climate extremes also on regional scales. Central and Western

North America are expected to experience increases in drought and fire weather and in extreme precipitation (IPCC 2021).

2.4.2 The issue of potential carbon leakage

Another problem highlighted by our research is potential leakage through traded goods and services.

Subnational climate actions, while having the potential to boost national climate contribution to achieving climate targets, should be aware of the pitfall of carbon leakage that can undermine the effectiveness of the current or future multi-state agreements. Stricter environmental policies applied to subnational members of an agreement might result in higher emissions elsewhere through changes in trade patterns and the relocation of pollution-intensive production. A similar issue is documented in the analysis of the effectiveness of the Kyoto Protocol that mandated that developing countries cut their emissions and became international law in 2005. The subsequent years were followed by significant increases in developed countries’ carbon embodied in imports from uncommitted developing countries that have been attributed by several researchers to leakage (Aichele and Felbermayr 2015; Peters et al. 2011; Hartl 2019). Some evidence of potential leakage can be found in the sectoral composition of the carbon flows. Hartl (2019) finds evidence that the sectors where the carbon trade deficit increases the most are within the energy-intensive sectors such as metals, machinery and transport equipment, consistently with the countries' specialization patterns. This sectoral footprint, that Hartl attributes to leakage, is also evident in our findings as these are the same sectors with the highest carbon trade imbalance between alliance and non-Alliance states. Obviously our findings of substantial emission transfers between members and nonmembers of the Alliance at one point in time do not provide *per se* evidence of carbon leakage. For carbon leakage to be a relevant factor, the environmental policies adopted would need to be stringent enough to make signatories states' production less competitive compared to others to begin with. After that, time-series data showing detailed emission transfer changes over time would be needed to assess the impact of the policies. Because of the large number of confounding factors, establishing carbon leakage in other settings has proven controversial and is still a matter of intense research (Naegele and Zaklan 2019; Sato and Dechezleprêtre 2015; Branger and Quirion 2014). To establish a causal relationship, advanced modeling showing what would have happened without the agreement would also be required. Models that are sophisticated enough for causal inference are not currently available. Because of these limitations, we can only suggest that adequate data collection and monitoring might be needed to make sure that emission transfers do not undermine efforts to achieve the agreed climate policy targets.

Past literature on traded emissions has explored policies that could mitigate these problems. A popular policy option suggested to counter the displacement of emissions because of the loss of competitiveness is a carbon adjustment tax for imports based on their embodied carbon (Elliott et al. 2010; Mckibbin et al. 2018). However, this policy would be practically and legally unfeasible in most subnational contexts, such as in the U.S. Because of general equilibrium effects, such policies could fail to reduce emissions, if, for example, supply chains once serving exports can be redirected to domestic consumption because of a border tax (Jakob and Marschinski 2013). Until such time as deeper cooperation between more states can be organized with the introduction of common carbon pricing mechanisms that would unlock larger potential joint benefits from climate change mitigation (Keohane and Victor 2016), consumption-based accounting can be used to support targeted interventions aimed at reducing emissions in key specific pollution-intensive sectors in non-member states through supply-chain leverage that can be wielded by consumers and importing industries (Skelton 2013). This approach could also lead to incrementally deeper sustainable cooperation in the longer run.

To support such policies and avoid adverse effects of one-sided interventions, one potential solution is to include the embodied emissions into subnational targets. At present, there is no uniform scope of emission accounting being used at the subnational level. Although the U.S. EPA provided the guidance on reporting GHG emissions in different scopes (US EPA Center for Corporate Climate Leadership 2021), the differences resulting from adopting different scopes of reporting could lead to inadequate subnational climate mitigation targets. In recent years, climate mitigation targets that Alliance states committed are mostly based on their territorial emissions. Some states initiated to include upstream emissions from electricity sectors which could be a leap step toward addressing the emission spillover. However, including the embodied emissions from only the electricity sector is greatly insufficient to address emission transfers of the magnitude we found. Since the Alliance and non-Alliance states tend to share grids within their group, even though the net interstate flow of electricity shares a large proportion of states' energy profile, it is still much less than the amount of emissions embodied in products between states (as seen in Appendix A). Therefore, we suggest that subnational targets include embodied emissions from all products participating in the supply chain.

To be able to capture the effect on the embodied emission in imports and exports between subnational climate actors, clear and accurate accounting will be required. The available data provides just a snapshot of the situation at the start of the agreement. To produce a consistent and timely time series, more frequent monitoring is needed to better capture the interstate movement of products and the provision of services, as the current datasets are updated every five years (FAF 2021). Better tracking of where the products are consumed and where associated emissions occurred would also benefit the accuracy of state- and city-level emission self-reporting programs (Gurney et al. 2021).

Chapter 3 Unequal household carbon footprints in the peak-and-decline pattern of U.S. greenhouse gas emissions[2]

Abstract: Greenhouse gas (GHG) emissions in the U.S. peaked and declined in the first decade of the 21st century, largely attributed to the increased use of natural gas and renewable energy replacing coal. However, if and to what extent household consumption also played a role in this trend is still debated. Finding demand-side options is necessary to hedge against the risks of technology solutions failing to materialize. To fill this gap, this study analyzes the change in GHG emissions driven by U.S. household consumption, and explores drivers of this change and the contribution of different income groups. To this end, we combined the U.S. consumer expenditure survey with an environmentally-extended multi-regional input-output framework to analyze changes in GHG emissions induced by household consumption between 2001 and 2015. We further analyzed how much population, consumption volume and consumption patterns drive emission changes by quintile income groups. Our results show that changes in household consumption contributed approximately one-third of the national emission decline. The decline in GHG emissions from U.S. households was mainly associated with a decrease in the consumption of carbon-intensive products, including gasoline, electricity, and animal-based food products. The top quintile income households were the main contributors to the emission increase before the peak, while the third and fourth income quintiles became emission mitigation leaders after 2010. Carbon inequality was increasing during the

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[2] The co-authors for this chapter include Giovanni Baiocchi, Kuishuang Feng, Laixiang Sun, Klaus Hubacek.

2001-2006 period, mainly driven by the increased wealth and consumption of high-income households, and was relatively stable after the peak.

3.1 Introduction

Reaching the peak of GHG emissions is an important milestone toward achieving climate goals of limiting global temperature increase to 1.5˚C above pre-industrial levels (Wang and Su 2020; Masson-Delmotte et al. 2018). GHG emissions in the U.S. reached a peak between 2005 and 2007 (Jackson et al. 2016). After the economic recession when the reduction of consumption volume primarily curtailed emissions (Feng et al. 2015; 2016), economic recovery and growth achieved absolute decoupling from GHG emissions in terms of both territorial emissions and consumption-based emissions (Hubacek et al. 2021; Le Quéré et al. 2019). As of 2019, U.S. territorial GHG emissions have declined by 8.7% since the peak year (USEPA 2021).

The current discourse attributes this emission decline mainly to the structural changes in the energy sector, including the decrease in fossil fuel mix and the switch from coal to gas given the increasing availability of shale gas since 2005 (Le Quéré et al. 2019), despite that coal consumption has been increasing after the pandemic (EIA 2022b). Such a transformation resulted in an observable decrease in energy intensity, dropping from 6.71 kBtu per chained (2012) dollar in 2005 to 5.05 kBtu per chained (2012) dollar in 2020 (EIA 2022b), which is acknowledged as a primary factor that drove the emission decline, despite increases in consumption volume and population (Wang et al. 2018). Other factors contributing to this decoupling trend include energy efficiency (Nadel, Neal, and Therese 2015), research and development (R&D) investment (Wang and Wang 2019), and urban form (Uhl et al. 2021). However, the contribution of household consumption, the most important component that ultimately drives the upstream emissions, has not been well addressed yet – in neither the composition of household consumption nor for different income groups (Ottelin, Ala-Mantila, et al. 2019; Heinonen et al. 2020). This study will focus on the changes in household consumption patterns per quintile in the U.S. for the time period 2001-2015.

Changing prices, consumption preferences, and changing lifestyles result in changes in consumption patterns and associated emissions (Semenza et al. 2008; Whitmarsh 2009; Zhou and Yang 2016), which can support or counteract efficiency gains in production and therefore contribute to or hinder a decoupling of economic growth and emissions, although population growth and increasing demands of carbon-intensive products can drive up consumption (Tortell 2020; Wynes and Nicholas 2017). Studies examining U.S. GHG emissions from household consumption (so-called carbon footprints) mostly focused on the contribution of different consumption categories for a particular year (Feng, Hubacek, and Song 2021; C. Jones and Kammen 2014; Jones and Kammen 2011; Markolf et al. 2017; Weber and Matthews 2008; Goldstein, Gounaridis, and Newell 2020), or explored specific behavioral changes via scenarios (Wolfram and Wiedmann 2017; Hitaj et al. 2019; Steinberg et al. 2017). While these studies offer insights into the composition of U.S. household carbon footprints and relevance to some socioeconomic factors at various spatial scales, few studies explored the changes in household carbon footprints over time. Such time-series based analyses can inform the contribution of household consumption to national emission trends, thus shedding light on effective demand-side climate mitigation strategies.

It is equally important to understand whether and by how much different income-earners contributed to the peak and decline in national GHG emissions, in order to explore mitigation policies that have the co-benefits of reducing inequality. This part of research is also lacking in the existing literature, despite a growing number of studies investigating carbon footprint inequality (e.g., Hubacek, Baiocchi, Feng, Muñoz Castillo, et al. 2017; Kenner 2019; Mi et al. 2020; Semieniuk and Yakovenko 2020; Sun et al. 2021). The concepts of “carbon inequality” (or “carbon footprint inequality”) emerged in the recent decade, which described the unequal ability to drive GHG emission generation, initially borrowed from the concepts of “income inequality” economic literature by employing the inequality measures, such as Gini index and Theil index (Kahrl and Roland-Holst 2007; Clarke-Sather et al. 2011; Kenner 2019; Chancel and Piketty 2015). Our study aims to bridge this gap by analyzing the changes in emissions driven by changes in household consumption of different income groups over time.

Household income, directly related to household consumption, is the primary determinant that drives up carbon footprints (Wiedenhofer et al. 2017; Mi et al. 2017; Baiocchi et al. 2010; Ivanova et al. 2017; 2018; Jones and Kammen 2011; Sommer and Kratena 2017; Shigetomi et al. 2019). Other factors include family size (Ivanova et al. 2017; Baiocchi, Minx, and Hubacek 2010), urbanization (Jones and Kammen 2014; Ottelin, Heinonen, et al. 2019; Mi et al. 2020), dwelling attributes (Muñoz, Zwick, and Mirzabaev 2020b; Ma et al. 2019; Goldstein, Gounaridis, and Newell 2020b), and socio-psychological factors such as values, preferences and social norm (Li, Zhang, and Su 2019; Caeiro, Ramos, and Huisingh 2012).

Income distribution could explain unequal carbon footprint stemming from variabilities in consumption (Attanasio and Pistaferri 2016; Wunder 2012). In recent decades, income inequality in the U.S. has been increasing. The shrinking middle class is becoming a concerning phenomenon that highlights the enlarging income inequality in the U.S. While the share of aggregated income of the middle class decreased from 62% in 1970 to 43% in 2018, the upper-income tier increased wealth fastest after the Great Recession (Horowitz, Igielnik, Kochhar 2020). In 2019, people with the top 10% income before tax shared approximately 45% of the total national income (WID, 2020). The associated household carbon footprint across different income groups is, accordingly, different. Prior studies have demonstrated the disparity of household carbon footprint across different income groups (Wiedenhofer et al. 2017; Hubacek, Baiocchi, Feng, Muñoz Castillo, et al. 2017; Goldstein, Gounaridis, and Newell 2020; Kuishuang Feng, Hubacek, and Song 2021). In the U.S., carbon footprints of households with higher than $150k annual income were over four times higher than households with $15k in 2009 (Song et al. 2019), about 2.5 times on a per capita basis. Similarly, Goldstein et al. (2020) found that per capita carbon footprints of higher-income households related to residential energy consumption are about 25% higher than those of lower-income residents, primarily due to larger homes, and the difference increased to 15 times in especially affluent suburbs. Different income groups respond to climate intervention policies differently, given their respective perceptions on climate change and ability to adopt low-carbon alternatives (Zhou and Yang 2016; Semenza et al. 2008; Whitmarsh 2009). Understanding how different income groups changed their consumption patterns and how inequality in consumption of goods and services affects the emission peak-and-decline may offer further insights into sustainable consumption.

This research will contribute to the literature by estimating the changes in GHG emissions driven by U.S. household consumption and its role in the national emission peak-and-decline. To this end, this study fixes the effects of household consumption changes from supply-side factors, and focuses on the changes in direct and indirect emissions driven by household consumption through bridging a 536 sector-detailed input-output table and Consumer Expenditure Survey (CES) from 2001 to 2015. Carbon footprints abroad are estimated by multi-regional input-output analysis based on EXIOBASE (v.3) (Stadler et al. 2018). This study further analyzes the contributions from population, consumption volume per capita, and consumption patterns by quintile income groups by employing Logarithmic Mean Divisia Index (LMDI) decomposition approach. Additional details about the changes in consumption categories and their implications for emission changes are provided. Finally, this study analyzes the carbon-footprint inequality and its relationship with inequalities in consumption and income. Such analysis from a top-down approach could inform high-level policy-making processes pertaining to demand-side climate efforts.

3.2 Methods

3.2.1 Analytical approaches and models

Carbon footprint measures the total GHG emissions generated along the supply chain, occurring both domestically and abroad, due to human activities (Wiedmann and Minx 2008). This study first calculated the U.S. household carbon footprints related to household consumption change and then analyzed the drivers of this change and associated carbon footprint inequality. The analysis is based on U.S. residents while the U.S. citizen living abroad and tourists traveling to the U.S. is out of the scope of this study. In addition, construction is considered capital investment and thus not in the scope of study, but house repair and maintenance related GHG emissions are considered in this study. A research framework is provided in Figure 3-1. Further details are explained in the following sections.

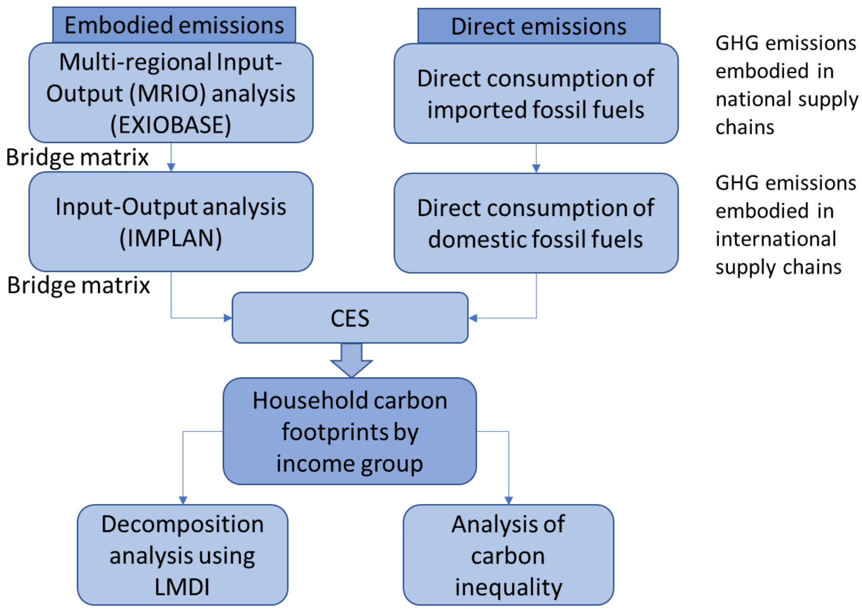


Figure 3-1 A research framework for quantifying U.S. household carbon footprints and analyzing their drivers and inequality

Input-output model

Total GHG emissions induced by household consumption by each income group (E^{tot}) is the sum of emissions directly generated from household activities (E^{dir}), such as driving and onsite natural gas combustion, and the indirect emissions generated along supply chains (E^{ind}). Direct and indirect emissions in the following equation are from a consumer's perspective (Bin and Dowlatabadi 2005).

$$\boldsymbol{E}^{tot} = \boldsymbol{E}^{dir} + \boldsymbol{E}^{ind}$$

Indirect GHG emissions (or indirect carbon footprints) are estimated by Environmentally Extended Input-Output (EEIO) analysis, which captures emissions from all economic activities along supply chains of goods and services consumed by households and institutions (Miller and Blair 2009). The supply-use tables (SUTs) are used in this research, where the supply table shows the total domestic supply of goods and services from both domestic and international producers that are available for use in the domestic economy and the use table presents the use of this supply by domestic industries as intermediate inputs and by final users as well as value-added by industry (Young et al. 2015). The SUT provides data linking industries and commodities, and the latter is matched with products and services consumed by households. More details on the structure of SUT can be found in Miller & Blair (2009) and details on mapping commodities to household consumption categories can be found in Wiedmann et al. (2006). Indirect carbon footprints could be estimated by

$$\boldsymbol{E}^{ind} = (\boldsymbol{\varepsilon}^{ind})' \times \boldsymbol{Y}^{cons} \times \boldsymbol{C} \times \boldsymbol{H}$$

where, $\boldsymbol{\varepsilon}^{ind}$ is a vector of indirect emission intensity of n commodities; $\boldsymbol{Y}^{cons}$ is the diagonal matrix representing household demand of *n* commodities in constant USD prices in year 2015, calculated by $\boldsymbol{Y} \odot \boldsymbol{P}$ where $\boldsymbol{Y}$ is the household demand vector of *n* commodities in the current year price, and $\boldsymbol{P}$ is a vector of deflators for *n* commodities from IMPLAN ($\odot$ denotes the Hadamard product, which takes the element-wise product of two matrices that have the same dimension); $\boldsymbol{C}$ is a concordance matrix, mapping the *n* commodities to *m* consumption categories (*m* refers to the categories in Table A-1); $\boldsymbol{H}$ is the matrix whose elements are the shares of *m* categories of household expenditure across *s* income groups. The development of the concordance matrix is further explained in section 2.2.1.

The indirect emission intensity is calculated with the assistance of supply-use table, as follows,

$$\boldsymbol{\varepsilon}^{\boldsymbol{ind}} = \boldsymbol{\varepsilon}^{\boldsymbol{p}} \,(\boldsymbol{I} - \boldsymbol{DB})^{-1}\boldsymbol{D}$$

where, $\boldsymbol{\varepsilon}^{\boldsymbol{p}}$ is the GHG emission intensity of n sectors in the supply table from the production perspective, with further information below; $\boldsymbol{I}$ is $n \times n$ identity matrix; $\boldsymbol{D} = [d_{ij}] = m_{ij}/q_{ij}$, represents the input amount of i industry in per unit output of j commodity, calculated by the output amount of j commodity from i industry (m_{ij}) over total output of j commodity (q_{ij}). $\boldsymbol{B} = [b_{ij}] = u_{ij}/x_j$, stands for the input amount of i commodity in per unit output of j industry, calculated by the input amount of i commodity in j industry (u_{ij}) over the total output of j industry (x_j). $(\boldsymbol{I} - \boldsymbol{DB})^{-1}$ in this equation is equal to the Leontief inverse (Leontief 1986).

The changes in household consumption are analyzed from 2001 to 2015, a period that covers the national emission peak and decline.

The GHG emission coefficients (for 2015) based on the production (ε^{p}) are calculated with reference to IPCC methodology (IPCC 2006), with more details in previous work (Kuishuang Feng, Hubacek, and Song 2021).

Direct emissions from households mainly come from gasoline consumption during driving and onsite natural gas combustion; other coal and petroleum products and bottled gas consumption are also included.

$$\boldsymbol{E^{dir}} = \sum_{i}^{n} \boldsymbol{fuel_i} \times \boldsymbol{\gamma_i} \times \boldsymbol{\delta_i} \times \boldsymbol{\rho_i} \times \boldsymbol{\epsilon_i}$$

where, $\boldsymbol{E^{dir}}$ is the direct GHG emissions from each income group, $\boldsymbol{fuel_i}$ denotes the household consumption of fuel i, including petroleum, natural gas, and other fuels such as industrial gases and other coal and petroleum products, in producer price of the current year; $\boldsymbol{\gamma_i}$ is the margin ratio converting producer's price to purchaser's price for fuel i, which is from IMPLAN margin dataset; $\boldsymbol{\delta_i}$ is the deflator that is converted to constant USD price of the year 2015 for fuel i; $\boldsymbol{\rho_i}$ is the sale price for fuels i from EIA; $\boldsymbol{\epsilon_i}$ is emission factors for fuel i from EPA (US EPA, 2016; 2018).

As imported emissions contribute a large part of U.S. embodied emissions, we linked our national-level analysis to global trade networks with the MRIO approach. A more detailed description of MRIO method is referred to Miller and Blair (2009). MRIO tables are derived from EXIOBASE from 2001 to 2015, which covers 49 countries and regions in the world with 200 commodities to calculate the imported emissions driven by household consumption (Stadler et al. 2018). GHG coefficients and production recipes for 2015 were used across the study period to isolate the contribution of household consumption. The commodities from EXIOBASE were matched with sectors in national IO tables.

Logarithmic Mean Divisia Method (LMDI)

The LMDI is a decomposition method that decomposes a target variable into several contributing factors with zero residual errors. It was proposed by Ang (1998) and initially employed to analyze sociodemographic factors that drove the changes in household GHG emissions. We analyzed the effects of emission intensity (ε), consumption structure (S), consumption volume (V, in \$2015 per capita) and population (P) on the changes in GHG emissions induced by changes in household consumption (E). The following IDA identity describes the total GHG emissions from household consumption of i consumption categories by *k* income groups.

$$E_k = \sum_i \frac{E_{i,k}}{V_{i,k}} \frac{V_{i,k}}{V_k} \frac{V_k}{P_k} P_k = \sum_i \varepsilon_{i,k} \cdot S_{i,k} \cdot V_k \cdot P_k$$

The LMDI in additive decomposition form was expressed as:

$$\Delta E_k = E_k^T - E_k^0 = \Delta E_{\varepsilon_k} + \Delta E_{s_k} + \Delta E_{v_k} + \Delta E_{p_k}$$

where E_k^T and E_k^0 are GHG emissions from demand-side household consumption during period *T* and the base year for *k* income group. Given our analysis isolated the effects from the demand side, the change in emission intensity ΔE_{ε_k} is zero.

The contribution from each effect to the changes in demand-side household GHG emissions was estimated by the following equations:

$$\Delta S_k = \sum_i \frac{E_{i,k}^T - E_{i,k}^0}{lnE_{i,k}^T - lnE_{i,k}^o} ln \frac{S_{i,k}^T}{S_{i,k}^T}$$

$$\Delta V_k = \sum_i \frac{E_{i,k}^T - E_{i,k}^0}{lnE_{i,k}^T - lnE_{i,k}^o} ln \frac{V_k^T}{V_k^T}$$

$$\Delta P_k = \sum_i \frac{E_{i,k}^T - E_{i,k}^0}{lnE_{i,k}^T - lnE_{i,k}^o} ln \frac{P_k^T}{P_k^T}$$

Inequality measures

Carbon inequality was first proposed by borrowing the idea of “income inequality” in economic literature. Multiple indicators have been developed by economists to quantify inequality of income; these indicators use different approaches to characterize the distribution of income (Cowell 2000). Gini index and 80/20 ratios are widely used among these indicators. The Gini index has the advantage of assessing overall inequality across income groups, while the 80/20 ratio stresses the role of the high-income group relative to low-income groups. This study uses both Gini index and 80/20 ratio for their individual strength. The Gini index is based on the Lorenz curve, calculated by the ratio of the areas between the ideal equality line and Lorenz curve to the total area under the line of equality (Dorfman 1979). 80/20 ratio takes the ratio of the households with the top 20% of incomes (top quintile) to the households with the lowest 20% of incomes (bottom quintile). In this study, the Gini index and the 80/20 ratio can also be used to quantify inequalities in GHG emissions, household consumption, and household income before tax.

3.2.2 Data

IMPLAN

The household consumption data were derived from Economic Impact Analysis for Planning (IMPLAN) (IMPLAN Group LLC 2022), which provides national supply-use tables of the U.S. in 536-sector detail during the study period. The household demand from IMPLAN database is estimated with a commodity-detailed benchmark table from the Bureau of Labor Statistics (BLS) with reference to PCE data from National Income and Product Accounts (NIPA) which are both in purchaser’s price, and converted to producer’s price with benchmark margins from BLS. To analyze the contribution of emissions from household demand over time, the SUT was employed for 2015 to control for price changes. Household demand data for 2001-2015 in constant prices of 2015. This approach used national-level accounting data NIPA published by BEA, which is one of the primary data sources to develop national Input-Output tables. The NIPA table was developed by the Bureau of Economic Analysis with imputations for missing data and misreported data to reflect household expenditure at the national level (BEA 2017). There is a parallel bottom-up approach using micro-level household expenditure survey data to estimate household carbon footprints (Steen-Olsen, Wood, and Hertwich 2016). While this approach provides a methodology that overcomes a time lag for getting the national IO table available, it has limitations of reporting bias. The reporting bias includes that richer households tend to underreport their consumption (Weber and Matthews 2008), and extremely high and low-income groups tend to have a larger share of non-responses (Donnelly and Pop-Eleches 2018). However, our analysis used quintile income groups thus the effect of underreporting of very high and low income households is less important in the larger quintile. In addition, we use a top-down approach from national IO tables with 536 sector details to avoid reporting bias from individual households.

Consumer expenditure survey (CES)

After performing EEIO analysis based on 536 sectors, emissions driven by households were disaggregated into income quintiles. However, while CES provides income quintiles, it presents in an aggregation of over 70 consumption categories for national average. The matching of the two data involves sectoral match and price conversion.

CES provides the best available data representing household consumption in the U.S., with details for over 70 categories, aggregated from approximately 850 separate products or services according to universal classification codes (UCC). However, the IMPLAN database with 536 commodities is based on the North American Industry Classification System (NAICS) and thus requires a concordance matrix to bridge IMPLAN trade data and CES consumption data. The core of the bridge is to express the emissions from consumption categories with price conversion so the emissions could be assigned to different groups of consumers. First, we map the commodities (except for margin sectors such as retails and wholesales, in producer's price) from IO tables to an aggregated 48 categories of household consumption with references of detailed UCC code. The 48 categories is an aggregation from over 70 consumption categories as some commodities match at least two consumption categories. Then, we allocate the retail and wholesale margins to corresponding household expenditures, where the margin ratios are derived from IMPLAN. Given the over-reporting and under-reporting problems of consumer expenditure data (Weber and Matthews 2008), for example, in 2015, the aggregate demand from the CES amounted to 7.19 trillion USD compared to 11.79 trillion USD of household consumption in IOT. We scaled the household expenditures to the IMPLAN national-level household final demand according to aggregated 48 categories (Tier 3 categories). Then emissions from the 48 consumption categories are allocated to quintile income groups (low income, low-middle income, middle income, middle-high income, and high income) based on CES data, where the population of each group represents 1/5 of the U.S. population. For example, the first quintile group represents 20 % of the population with the lowest income. The share of each consumption category is developed based on the quintile consumer expenditure data from the BLS. For presentation purposes, detailed household expenditures are aggregated into

20 categories. These categories are mutually exclusive; for example, “food away from home” accounts for expenditure on restaurants, take-out and food consumed on trips, while plant-based food, animal-based food and other food at home are all food consumed at home.

3.2.3 Research limitations

The modeling and analysis in this study are based on a few important assumptions and procedures linked price conversions, concordance matrix mapping commodities in IOT to Consumer Expenditure Survey (CES), and the representativeness of the CES. The first uncertainty regarding price conversion (from the current price to the constant price in 2015) came from the accuracy of deflators. To minimize the uncertainty, we checked the Producer Price Index (PPI) from the BLS for each commodity to ensure that the constant monetary values could represent the amount of national household consumption. Given that the sectors from IMPLAN are not exactly the same as available PPI, the best match for these sectors was chosen with reference to the detailed description of NAICS code and UCC code. In addition, the input-output framework only estimates the average carbon footprints of products from a sector, while it does not capture the price difference within the same sectors (Steen-Olsen, Wood, and Hertwich 2016). This may involve two issues. First, how money was spent (e.g., vehicle purchase with and without loans, whether utilities are paid separately from rent) can be considered in different sectors, which may involve uncertainty and rely on imputation (Heinonen et al. 2020). Second, the analysis is based on the assumption that consumption difference is reflected at the sectoral level, and whether products are purchased domestically or abroad is based on sectoral difference, rather than the difference of detailed products within the same sector.

This study used 536 commodities to quantify the carbon footprints but cannot fully address this issue.

Our inequality measurement is based on the average values of household expenditure and carbon footprints by five income groups. The quintile income group is the only consistent income grouping throughout the study period provided by CES, however, this high aggregation is limited to capture the detailed distribution of household carbon footprints. In addition, the variation within an income quintile and shifts in income quintile for individual households are not analyzed in this study.

3.3 Results

3.3.1 Changes in household consumption associated GHG emissions across income groups

In this section, we look at changes in GHG emissions driven by changes in household demand between 2001 and 2015 by quintile income groups (Figure 3-2). Prior studies that analyzed the drivers of carbon footprint change mainly have a mixed set of factors including both production-side and consumption-side perspectives, or only production-side factors such as fossil fuel mix and energy efficiency (Le Quéré et al. 2019). Since the current research focuses on the demand-side household consumption, effects from changes in production recipes, fuel mix, and energy efficiency are removed.

Figure 3-2A shows that GHG emissions from household consumption first peaked in 2007 and then quickly declined by 6% during the economic recession; this has a similar trend to the national territorial GHG emissions (USEPA 2021). However, the emission change driven by household consumption after the national emission peak bounced back to nearly the peak level in contrast to the steady decrease trend of national

GHG emissions. Our analysis on emissions embodied in international trade shows that Americans' overseas carbon footprints only slightly increased after the national peak (~0.1MtCO_2e), and the share of net emissions embodied in imports still decreased. In addition, the national consumption-based GHG has been decreasing after the peak (Friedlingstein et al., 2020). This implies that the increased GHG emissions driven by increased consumption were counteracted by supply-side technological factors.

For the overall GHG emission increase driven by household consumption change during the period of 2001–2015, the highest-income group is the major contributor, amounting to up to 66% of the cumulative total changes since 2004, compared to 2001 level. The highest contribution (66%) happened during the economic recession period (2008-2009), which suggests that although the top income quintile households have a substantial reduction in their consumption hit by the economic recession, they are still better off compared to the rest.

The decomposition analysis (Figure 3-2B) shows that although population growth is contributing to increasing household emissions as expected, consumption patterns play a major role in off-setting such an increase, especially in the years following the emission peak. Looking at income quintiles, our results show that different income groups contributed to changes in GHG emissions differently. For the low-income and low-middle income groups, household GHG emissions show generally increasing trajectories with no pronounced emission peaks or declines. The induced emissions from the low-income group even decreased before the economic recession, mainly driven by the significant decrease in consumption volume. Consumption patterns, however, hindered the emission decrease. These findings agree with the previous research showing a sharp increase in consumption inequality from 2001 to 2005, when low-income households reduced their expenditures on luxury purchases, resulting in a higher share of consumption on necessities such as homemade food and utilities (Meyer and Sullivan 2017; Henry 2014). GHG emissions have increased since 2013 from low- and low-middle income groups, driven by increased consumption volume, while consumption patterns were hampering this increase.

GHG emissions induced by consumption of households with middle- to high-incomes increased before the emission peak, and decreased during the economic recessions, and then rebounded again during the economic recovery in the post-recession period. The levels of emission increase after the economic recession, for middle income and middle-high income households, are still lower than the peak. Before their emission peaks, the emission increases were mainly driven by population growth. After the peak, changes in consumption patterns became the leading contributors that drove down the emissions for the two income groups. For the top quintile income group, the sharp increase in consumption volume and population had been driving up the emissions until they reached peak. Although the changes in consumption patterns negatively contributed to the emission increase after the peak, the emissions still increased with a tendency to surpass the peak.

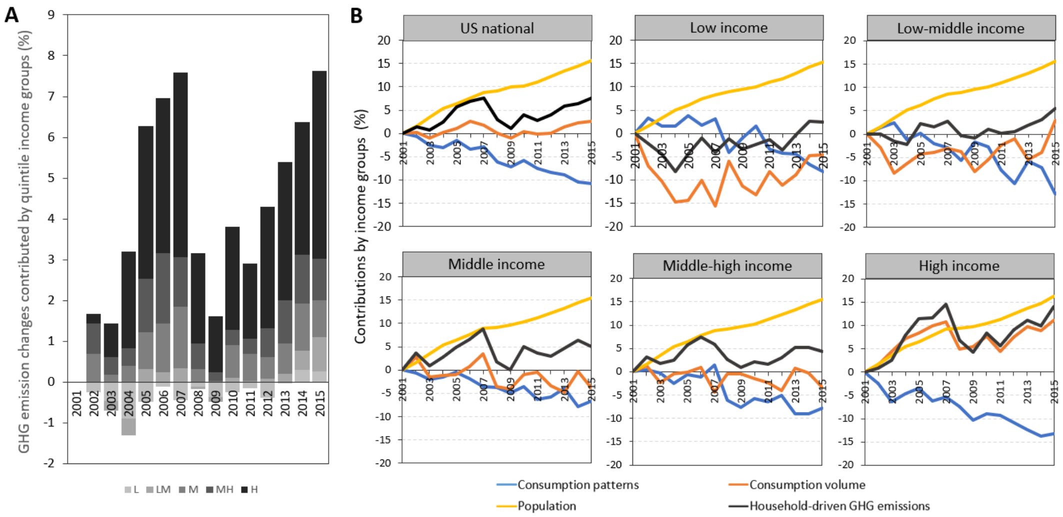


Figure 3-2 Changes in GHG emissions driven by changes in U.S. household consumption from 2001 to 2015 and contribution of consumption patterns, consumption volume, and population.

3.3.2 Carbon footprint changes across income groups

This section delves into the changes in per capita emissions (carbon footprints) to examine the contribution from each income group at the national level, and compares their contributions to national emission peak-and-decline temporal pattern. Household carbon footprints decreased between 2001 and 2015 across all income groups in the U.S., with an overall decrease of 7.5% for all income groups combined (Figure 3-3). Such a decrease is attributed to the changes in household demand and consumption structure. Prior studies show that consumption-based CO_2 emissions in the U.S. decreased approximately 20% from 2001 to 2015 (Friedlingstein et al. 2020). Accordingly, our study implies that about one-third of the household-driven GHG emissions were contributed from the demand side. This share remains roughly one-third when compared to the household-driven GHG emissions since roughly the peak year 2006. A detailed carbon footprints by consumption category and by income group in 2015 are provided in Figure B-2 and Figure B-3, respectively.

Analysis of changes in household carbon footprints for each income group from 2001 to 2015 shows that GHG emissions increased before the peak (between 2001 and 2007) were mainly contributed by the high-income group. Even during the period 2001–2004 when a small economic recession took place (Hugie 2014), the high-income group still increased their carbon footprints, driven by increased household demands (Meyer and Sullivan 2017). In contrast, the low-income and low-middle-income groups showed a sharp decrease in carbon footprint, approximately 1.9 tCO_2e/cap for low-income and 1.1 tCO_2e/cap for low-middle income households, during this period of time. This decrease was attributed to the reduction of total household consumption volume. The local peak of household consumption-related emissions was observed across all income groups from 2005 to 2007, but the peak was sharper for the top quintile. Although all income groups have increased carbon footprints after the economic recession, per capita GHG emissions rebounded across all quintile groups in 2010 with the high-income group increasing the most. After 2010, the middle-income and middle-high income groups were leading contributors to the GHG emission reduction, 0.9 tCO_2e/cap and 0.6 tCO_2e/cap, respectively.

From 2001 to 2015, carbon footprints of low-income and middle-high income groups decreased by 1.78 tCO_2e/cap and 1.93 tCO_2e/cap, respectively, which is equivalent to 12.1% and 10.3% reduction from their carbon footprint in 2001. The carbon footprint of the low-middle income and middle-high income groups decreased by 9%. While the high-income households had the most considerable emission reduction during the economic recession period, their total emissions during the 2001-2015 period were only reduced by 2%. When counting from the year when the demand-side peak occurred

(2007), our results suggest that the low-income group only reduced their carbon footprints by 0.04%. Low-middle income households reduced their carbon footprints more, being 3.8%. The middle-income reduced carbon footprints by 9.7%, and the middle-high and high-income households reduced their carbon footprints by 7.7% and 6.8%, respectively.

Our results suggest that different income groups play different roles in the national peak-and-decline transition of the national GHG emissions. Low-income and low-middle-income groups decreased their carbon footprints the most in 2001-2004, and high-income decreased greatest during the economic recession, while households with middle and middle-high incomes were leading contributors to the reduction, especially after 2010. After 2010, carbon footprints from low- and low-middle income groups slightly increased, driven by an increased consumption volume. A similar increasing trend was also observed for the top 20% income group, suggesting that they still led a carbon-intensive lifestyle and required more efforts in their climate mitigation actions.

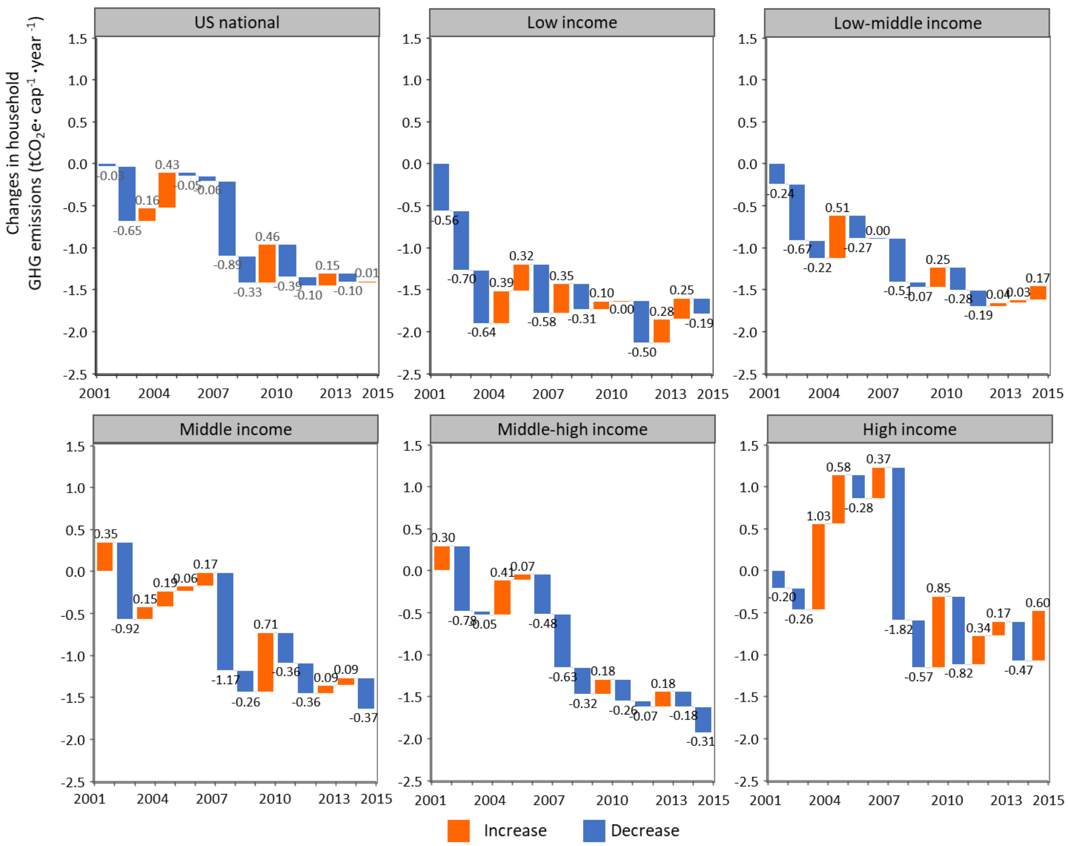


Figure 3-3 Changes in per capita U.S. household consumption induced GHG emissions across income groups from 2001 to 2015

3.3.3 Carbon footprints by household consumption category

Figure 3-4 shows the mean value of changes in household carbon footprints by different consumption category across five income groups (values with a range of 95% confidence level for aggregated 16 consumption categories from 2001 to 2015 are shown in Figure B-1, the composition of household expenditure for different quintile income groups are shown in Figure B-2). The carbon footprints of the majority consumption categories tend to behave similarly across the bottom four quintiles, with a very different consumption pattern from the top quintile (Figure B-1). From 2001-2004, per capita carbon footprints on food, housing and services decreased for low- and low-middle-income groups, while increased for the high-income group. The period of 2004–2007 is featured with an increase of household carbon footprints, mainly contributed by the increases in energy products (including electricity and gasoline) and financial services, agreeing with the existing literature and statistics (FRED, 2020; EIA, 2017).

After the emission peak, during the economic recession period (2007-2010), GHG emissions associated with food, transportation and goods dented, especially for gasoline and motor oil, public transportation, and furnishing and equipment in the households. As our study traced household GHG emissions along supply chains, energy consumption and emission volume are different from existing statistics which only account for direct emissions with supply-side factors or only terrestrial emissions involved (EIA 2020c; 2020b). Nevertheless, the trends are similar; for instance, household consumption of gasoline and motor oil peaked before the economic recession (EIA 2017a), and emissions from public transportation decreased due to a drop in business trips and long-distance travel during the recession period (BTS 2020). The decline in carbon emissions from transportation and household supplies was higher at higher levels of income. Durable goods and non-durable goods, such as household supplies, furnishings and equipment, apparel and footwear, appear more sensitive to economic influence, both showing decreases across all consumer income groups. In terms of service sectors, GHG emissions associated with financial services of middle-high income households increased.

The household carbon footprints decrease after 2006 is largely due to a decrease in gasoline consumption. Such a decrease was primarily driven by increased gasoline prices and improved fuel economy (EIA 2017a). Since then, the imports of petroleum used for household consumption have also decreased, which decarbonized the gasoline supply chains imported from other countries. The gasoline price decreased after 2013 led to a slight increase in gasoline consumption. However, partially due to the increasing use of electric vehicles, especially among high-income households, the potential decrease in consumption of gasoline and its emissions can contribute to the decrease in high-income households (DOE 2020; Narassimhan and Johnson 2018).

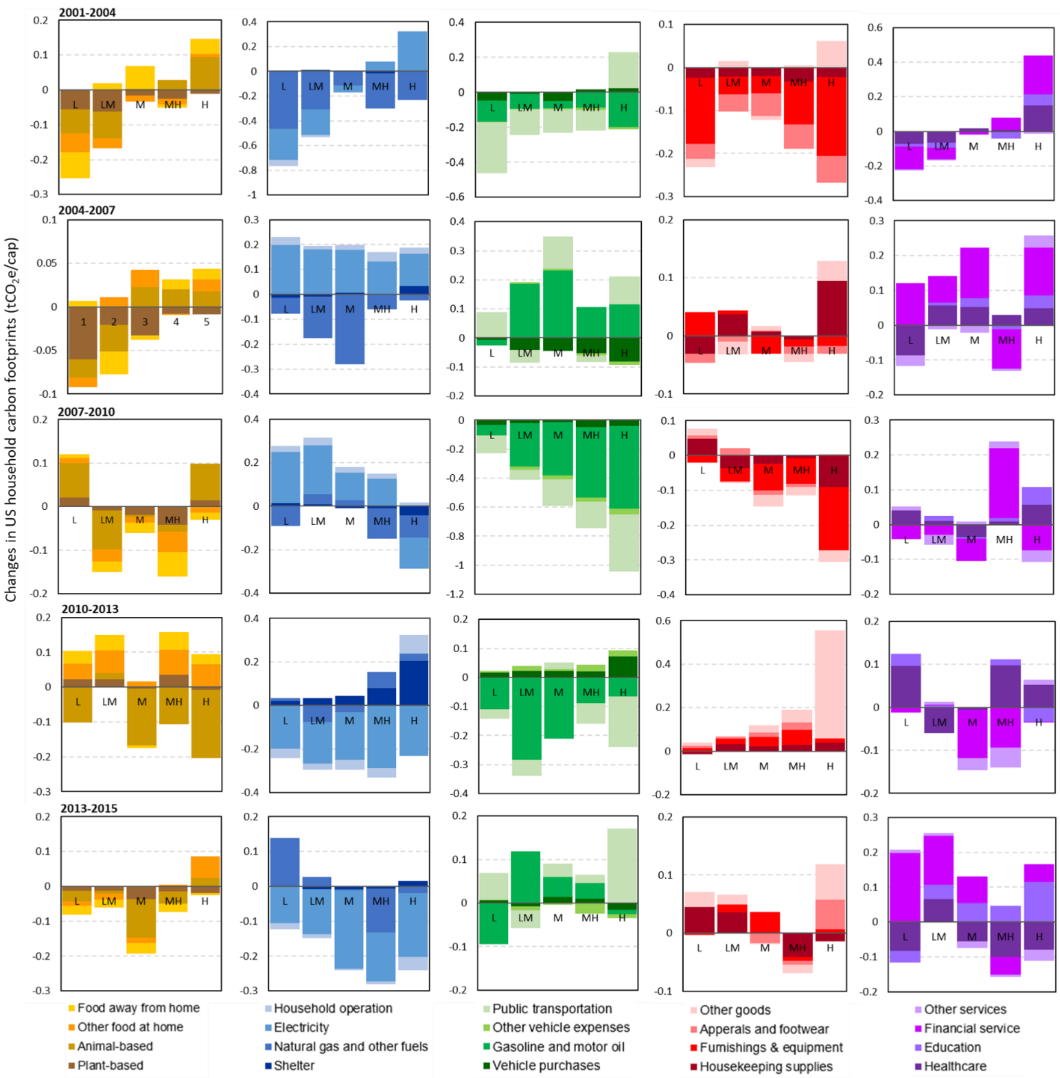


Figure 3-4 The change in carbon footprint from U.S. households by consumption type and income group from 2001–2015 ((Note: the aggregation of consumption categories is for presentation purposes)

Household carbon emissions only moderately rebounded immediately after the economic recession and slowly declined after that. In this period, the decline in electricity consumption played a dominant role in emission decrease, which corresponds with EIA's records that per capita residential electricity consumption in the U.S. has fallen since 2010 (EIA, 2017). The emission reduction from electricity would be even higher if we accounted for the supply side efforts, such as improved energy efficiency and a lower share of fossil fuel in energy supply. Given that our analysis isolated these supply-side effects, although supply and demand are mutually affected, consumers' adoption of high-energy-efficiency and low-carbon technologies will result in a decrease in demand for electricity in physical units (Creutzig et al. 2016; Zhang and Wang 2017). GHG emissions from animal-based food also decreased rapidly after the economic recession, which is consistent with the rapid decrease of red meat consumption from 2007 to 2014 (while the red meat consumption rebounded after 2015) (USDA 2022); however the decline was, to some extent, offset by a substantial increase of emissions from other foods (including packed food and canned food) and outside dining during the 2010-2013 period. While before the economic recession, the decrease in gasoline consumption was mainly driven by the increased price, the changes in gasoline consumption after the recession could be a combined effect of the increased market share of SUVs, improved fuel economy and increased use of electric vehicles (BTS 2020).

GHG emissions associated with mostly durable goods increased after the economic recession. Consumption of durable goods is associated with household incomes, as affluent households tend to acquire more durable goods, which results in higher shares of embodied emissions from their production processes rather than direct emissions from gasoline and natural gas (Vita et al. 2021). Therefore, the carbon footprint changes of durable goods are more significant for higher-income households. GHG emission changes associated with services show more variations. As the Affordable Care

Act (ACA) from the Obama Administration came into action in 2010, health care associated emissions from low-income consumers greatly increased during 2010-2013; the emissions from low-middle income consumers then significantly increased during 2013-2015 (USGOV 2010).

3.3.4 Carbon inequality change over time

We used both Gini index and 80/20 ratio to analyze the inequality changes in household emissions, household consumption, and household income (Figure 3-5). Our results show that changes in GHG emissions and changes in carbon inequality are positively associated. This implies that the increase in inequality in consumption may drive up the inequality of carbon footprint before the emission peak. Although more work is needed to draw causality, our results suggest that addressing the unequal emission responsibility should pay close attention to inequality in consumption.

Although income and expenditures are highly correlated and discussed interchangeably, consumption inequality is increasingly the focus of attention in the discourse of disparities in economic well-being (Attanasio and Pistaferri 2016). The literature and our study show that consumption is less unequal than income. There are several reasons that could explain this issue. First, household consumption, especially on necessities, tends to be relatively stable to ensure the well-being of households even if their income changes temporarily (Attanasio and Pistaferri 2016). Second, the savings and debts in households with different income levels are substantially different. Low-income households may also receive financial subsidies from governmental programs in various forms, including cash, tax credits, food stamps. Third, low-income people are willing to spend more time searching for low-price products (Arslan, Guler, and Taskin 2020).

Our results show that between 2001 and 2005 (as shown in Figure B-2), we observed sharp increases in carbon inequality driven by the increases in consumption inequality. The sharp increase in consumption inequality was documented in the literature (Attanasio and Pistaferri 2016; Meyer and Sullivan 2017; Han, Meyer, and Sullivan 2020). Across the consumption domains, consumption inequalities of service and transportation increased the most during this period, as they consumed more expensive items that wealthier households were inclined to purchase. In contrast, the inequalities of food and housing in both household consumption and carbon footprint are lower than other consumption categories as they contain more necessities rather than luxury purchases.

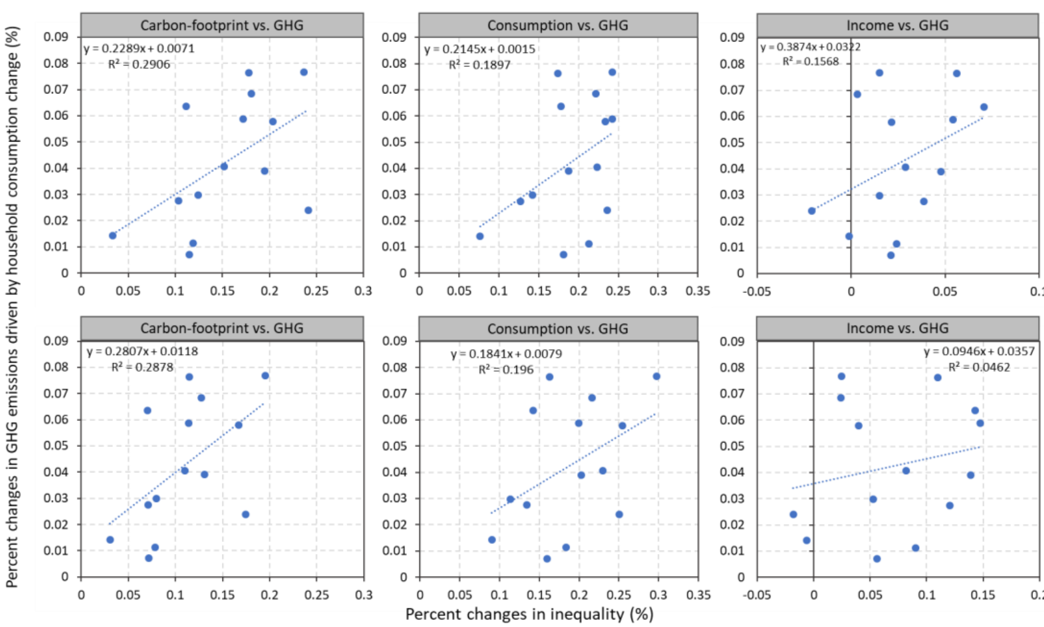


Figure 3-5 Relationship between changes in household-driven GHG emissions and changes in inequalities of GHG emissions, household consumption, and income from 2001 to 2015. The top three were measured by Gini index, and the bottom three figures were measured by 80/20 ratios.

3.4 Discussion

Most of the policies that aim to reduce household carbon footprints include two classes of options: infrastructure optimization and behavioral changes (Creutzig et al. 2016), where soft measures such as monetary incentives, nudges, and information are ubiquitous approaches. While these approaches are acknowledged to have great potential for reducing household carbon footprints in general (Creutzig et al. 2016; Grilli and Curtis 2021), different measures and combinations of interventions can also result in different outcomes. For example, monetary incentives tend to show on average a more pronounced effect (Khanna et al. 2021). In addition, outcomes of one behavioral change can also have high variation among individuals due to different responses and penetration. For example, only 34 out of 50 states in the U.S. require vehicle emission inspections but the implementation varies across states; LED lights still have a low penetration rate of 30% as of 2018 (DOE 2020). For low-carbon alternatives that can be scaled up to the national level with minimal costs, higher participation through stricter policies (e.g., a clear punishment policy for those who did not meet the requirement of vehicle emission inspection) and more effective incentive policies (e.g., targeting specific carbon-intensive behaviors like driving) should be considered.

It is equally important to consider the effects of policy intervention on different consumers, especially the monetary incentives and disincentives for different income groups. Our analysis sheds light on how consumption inequality drove the emission peak and decline and highlights the importance of targeting wealthier households as they have higher mitigation potential without deteriorating well-being. The increase in carbon inequality and the decrease in carbon intensity suggest the big mitigation potential for high-income groups and the wealth redistribution, given that rich people are getting richer, which requires more attention to inequity and emission mitigation. While our top-down approach implies consumption and carbon footprint disparity among different income groups, additional attention needs to be paid when developing interventions for different individual consumers. Since low-income households tend to be more sensitive to monetary incentives and disincentives in programs that promote pro-environmental behaviors (Chen, Xu, and Day 2017), as opposed to high-income consumers with higher flexibility due to their discretionary income, devising emission mitigation programs should consider the effects of policies on different income groups.

Analysis on carbon footprint inequality implies that addressing income inequality could help address carbon inequality. Although the implementation of a carbon tax is under debate, studies have suggested that using the revenue from carbon tax to subsidize the low-income households and to pay for the labor tax cuts have the potential to reduce inequality in terms of both consumption and carbon footprints (Fremstad and Paul 2019). Since companies can pass the costs of production-based carbon tax to consumers, an alternative carbon tax could be designed based on the GHG intensity of the industry from which the capital revenue is earned. Such a wealth-based tax can focus on the embodied emissions in certain types of wealth such as stock or bond ownership in GHG emission-intensive industries. Because the ownership of stock and bonds is highly concentrated among the richest households, such a tax could allocate more responsibility to those wealthiest households that are driving a disproportionate share of GHG emissions. In addition, such a tax could stimulate fiduciary fund managers to shift investment away from the taxed industries (Starr 2021).

Chapter 4 A framework for behavioral-associated carbon footprints[3]

Abstract: In response to the pandemic, restrictions and interventions aimed at modifying people's behavior were implemented to control the spreading of the coronavirus. This unexpected event tipped the US economy into an economic depression as it affected many aspects of normal activity including supply chains as well as people's behavior. When we talk about recovery, the framing is inevitably in terms of rejoining the previous path. However, we know that overall the previous path was unsustainable, and returning to it would not address the pressing need to prevent dangerous climate change. Policies during the pandemic such as school closures, lockdowns, and social distancing, have affected income, attitudes, values, beliefs and predispositions which in turn have affected individual's preferences and decision-making processes and thus the way people move, eat, learn, exercise, work, operate, etc. The response to the pandemic offers an opportunity to investigate the environmental effects of major changes in the way we live and behave. We develop a framework for linking human needs, behaviors to consumption and associated carbon footprints and apply this framework to a set of representative behavioral changes during COVID-19 pandemic to analyze recovery pathways. The case study integrates possible responses to the COVID shock in emissions and consumer behaviors to investigate emission impacts as well as options for a low-carbon behavioral change.

[3] The co-authors for this chapter include Giovanni Baiocchi.

4.1 Introduction

Coronavirus disease 2019 (COVID-19) pandemic posed acute threats to public health and jeopardized the economy and society (Guan et al. 2020; Josephson, Kilic, and Michler 2021; Friedman et al. 2021). The global and national supply chain was severely disrupted following the unprecedented lockdowns implemented to contain the spread of the coronavirus at the outbreak of the pandemic (Guan et al. 2020; Mandel and Veetil 2020). In response to the pandemic emergency, people significantly altered their behaviors to avoid gathering activities and keep social distance in almost all walks of life (Zhang 2021). As a consequence, personal consumption expenditure in the U.S. plunged by 16.5% and unemployment reached a high record of 14.8% in April 2020 (BEA 2021a). Transportation and service sectors were struck the hardest in this period of time, when the air transportation shrank by 93%, personal care services decreased by 77%, recreation services dropped by 61% and the food service sector declined by 52% compared to the pre-pandemic level in 2019 (BEA 2021a). Due to the contracted consumption, CO_2 emissions from transportation decreased sharply by 33.4% in April 2020 and CO_2 emissions from electric power generation and industrial sectors decreased by approximately 20% (EIA 2021). Since then, the economy in terms of GDP started to recover gradually. Emissions are following suit. National and local governments executed spending packages to relieve people's economic stress and buffer the loss from industrial companies with anticipation of economic recovery to the pre-pandemic "normal". Environmentalists are looking for lessons that can be learned from this devastating experience, to improve the environmental outcome.

The current discourse on social and economic recovery is mostly framed as rejoining the path, comparing economic indicators to the pre-pandemic level to develop national and local economic recovery plans. Scholars used economic structure and consumer demands of the pre-pandemic level as references to investigate the pandemic impacts and simulate economic pathways (Shan et al. 2021; Martin et al. 2020; Santos 2020; Dellink et al. 2021). However, the previous path was unsustainable (Griggs et al. 2013), and returning to it would not address the need to change but pose further threats to our human beings by overshooting the planetary boundary (Steffen et al. 2015). Taking a renewal path instead of recovering to the old one would benefit the economic and human development in the long term.

The response to the pandemic offers an opportunity to investigate the effect of major changes in the way we behave. Policies during the pandemic such as school closures, lockdowns, and social distancing, have affected income, attitudes, values, beliefs and predispositions which in turn have affected individual’s preferences and decision-making processes and thus reshaped the way people move, eat, learn, exercise, work, operate, etc. (Tchetchik, Kaplan, and Blass 2021; Groening, Sarkis, and Zhu 2018). These dramatic and unprecedented changes in economic activity driven by behavioral change have in turn affected global GHG emissions.

The pandemic and containment policies have impacted more than just economic indicators of activity but also people’s awareness of public health risks and consumption behaviors. The pandemic threats have affected people’s perception of various fundamental needs, for example, prioritizing safety needs, rethinking needs for freedom, and meeting needs for participation and affection under constraints. Such changes lead to emerging innovations and behavioral changes (Dahlke et al. 2021).

Needs-driven behavioral change. Consumption is ultimately motivated by satisfying consumers' various fundamental needs, which is conceptualized in many psychological theories, such as Maslow's hierarchy of needs theory (Maslow 1943) and Max-Neef's fundamental human needs (Max-Neef, Elizalde, and Hopenhayn 1992). People's values on different needs at a certain stage are reflected in their behaviors. At the beginning of the COVID-19 outbreak, people prioritized their safety needs and physiological needs and even sacrificed higher levels of need, such as stockpiling, avoiding gathering with families and friends, canceling trips and nonurgent in-person appointments. These immediate responses are intensively documented in the existing literature (Chenarides et al. 2021; Moya et al. 2020; Zhang 2021; Sabino-Silva, Jardim, and Siqueira 2020). While the supply chain and the employment rate are gradually recovering, people seek higher levels of needs such as connections with families and friends, and discussing values in the face of social events. At the same time, certain behaviors are also becoming habitual in the context of global social distance practice. The pandemic also increased some feasibility of rapidly changing behaviors, although in a less preferable way, to shape people's behaviors to low-consumption and potentially sustainable ones. While not all behaviors that yield environmental benefits are motivated by environmental concerns (for example, taking bicycles may be intrinsically motivated by fitness or joy reasons), some behaviors are indeed more sustainable and resilient to social or health risks such as pandemic shocks (e.g., cycling) (Fuller et al. 2021). Intrinsic motivations are more resilient to change and do not require governments and other institutions to pay the costs of providing incentives and regulations (Kinzig et al. 2013; Davis, Hennes, and Raymond 2018).

The passive and immediate behavioral changes in response to emergent lockdowns are more likely to be temporary; however, some behavioral changes during the recovery stage tend to last for a relatively long time. One of the most substantial impacts is switching from "physical transportation" (transportation of people and products) to "digital transportation" (transportation of information), highlighting the nationwide practice of teleworking, online education, and visual meetings (O'Brien and Aliabadi 2020). While people are still debating their efficacy and efficiency, these changes still provide opportunities to lower the lifecycle carbon footprints especially in transportation sectors (O'Brien and Aliabadi 2020; Thaler and Sunstein 2009; Isley et al. 2016) and provide at least an optimal alternative should pandemic persist. Another is the consumption reduction; on the one hand, people follow "everything in-home" logic to lower the risks of contracting coronavirus (Esposti, Mortara, and Roberti 2021; Sheth 2020), such as self-gardening and home-cooking; on the other, people sacrifice certain excessive needs, for example, avoiding buying excessive clothes, switching from long trips by flights to trips in nearby natural areas. While these behavioral changes were mainly targeted to tackle public health threats, they also yielded overall environmental benefits (Diffenbaugh et al. 2020; Shan et al. 2021; Le Quéré et al. 2021; Bashir et al. 2020). Some of these changes have the potential to rapidly reduce carbon footprint compared to technological improvement (Dietz et al. 2009; Creutzig et al. 2016). This potential can be achieved as the pandemic catalyzed a high adoption of certain behaviors and scaled them up to the national level.

However, not all behavioral changes can bring environmental benefits and the individual's impact on emissions is determined by the type of change adopted, the degree of the change, and its duration. Even though we observed a 7-8.8% decrease in global GHG emissions associated with energy consumption compared to the 2019 level (Le Quéré et al. 2021; Liu et al. 2020), the economy decreased disproportional to GHG emissions. It is mainly caused by the constraints on low emission-intensity but high value-added service sectors. These sectors would also take a longer time for recovery than secondary sectors. According to IEA, electricity demand rebounded sharply after the initial shock, already equivalent to pre-COVID-19 trends in the third quarter of 2020 (IEA (International Energy Agency) 2020). This could lead to a rebound in GHG emissions if the vast investments in economic recovery pay insufficient attention to cleaner and more resilient energy infrastructure. In addition, several changes may reverse to or even cement the old unsustainable paths and thwart the achievement of the Paris Agreement objectives (Obergassel, Hermwille, and Oberthür 2020). For example, sharing public facilities, such as public transportation, may take a longer time to recover; although people may show their willingness to take public transportation after the pandemic, more cars and second-hand cars were sold after the initial hit of the pandemic may lock more people in using private vehicles for transportation (DeWeese, Ravensbergen, and El-Geneidy 2022). In addition, many behavioral changes, even with environmental benefits, may confront people's priorities, values, and cultural recognition. Fully capturing these changes and determinants is challenging but could be best represented and analyzed under different scenarios.

Behavioral change over time. The aggregated effects in GHG emissions can also accumulate across time. The severity and duration of the COVID-19 pandemic are likely to shape people's behaviors and associated carbon footprints in a longer term than the pandemic lasts. In behavioral science, behavioral wedges are used to quantitatively estimate the near- and middle- term potential of carbon reduction from behavioral changes towards a desired objective based on a linear form (Dietz et al. 2009; Nielsen et al. 2020), highlighting the effects of cumulative national response into the future. In this framing, "behavioral plasticity" is often discussed (Dietz et al. 2009; Nielsen et al. 2020), which is used to measure the cumulative potential of certain rapid behavioral changes affected by internal or external stimuli in an extended period. Under the pandemic shock, people's behaviors are more plastic, more easily to be altered. In addition, technological innovations also allow people to adapt to alternative behaviors, such as teleworking and online conferences. Therefore, it is imperative to integrate behavioral changes, especially those affected by extreme events and potentially have middle- or long- term effects, into climate projection and developing high-level climate targets.

Simulation of emission mitigation pathways from behavioral changes. Decades of studies have demonstrated the importance of broader engagement of social and behavioral sciences in identifying opportunities for carbon footprint reduction (Stern et al. 2016). Certain behaviors are more plastic in face of extreme events, such as the pandemic calamity, and can reach a relatively high adoption level in a relatively short period of time. The cumulative effect of behavioral changes in response to extreme changes cannot be assumed as static and should be considered in the national climate mitigation pathways. While a sharply rising number of studies offer insights into behavioral changes in response to the COVID pandemic through survey and statistical analysis, the medium- and long- term environmental impacts of such behavioral changes are insufficiently analyzed. This chapter integrated people's needs and possible responses to the COVID shock into emission impacts to explore low-carbon options.

A key innovation is qualitative descriptions of behavioral responses to pandemic-induced changes in consumer behavior. Narratives are needed to narrow down the potentially infinite combinations of responses and other options that modulate the impact of consumption on emissions to a few representative stylized cases. This approach makes the complexity of the impact of behavioral change manageable while still allowing to explore different possibilities that can lead to a reduction in emissions as opposed to returning to the initial conditions, which is the focus of most recovery literature. We describe the methods used to develop the narratives as well as how these pathways are hypothesized to produce particular combinations of challenges to reduce consumer's impact and draw on expert opinion to identify key responses to change and to combine these different components in a consistent fashion. The behavioral response narratives are intended as a description of plausible responses, degree of adoption, and long term plasticity, that future conditions at the level of large world regions can serve as a basis for integrated scenarios of emissions and land use, as well as climate impact, adaptation and vulnerability analyses. This paper proposes a modifiable framework for estimating the economy-wide dynamics of consumer behavioral changes and associated carbon footprints affected by an abrupt economic system and sheds light on low-carbon consumption. This study can be extended to explore the dynamics of carbon footprints caused by behavioral changes affected by exogenous shocks.

4.2 A framework for quantifying carbon footprints from behavioral changes

This study built a framework for quantifying carbon footprints from behavioral changes (Figure 4-1), where people's activities (A) are driven by different levels of needs (N). These activities are affected by external interventions, such as policy, economic and cultural factors. For individuals, there could be several options that can meet their various needs; however, different people value different needs differently, constrained by different socioeconomic factors, and their executive activities are thus less than all options present to them. The activities executed by people are embodied in physical consumptions (C), which pose environmental impacts along supply chains (E).

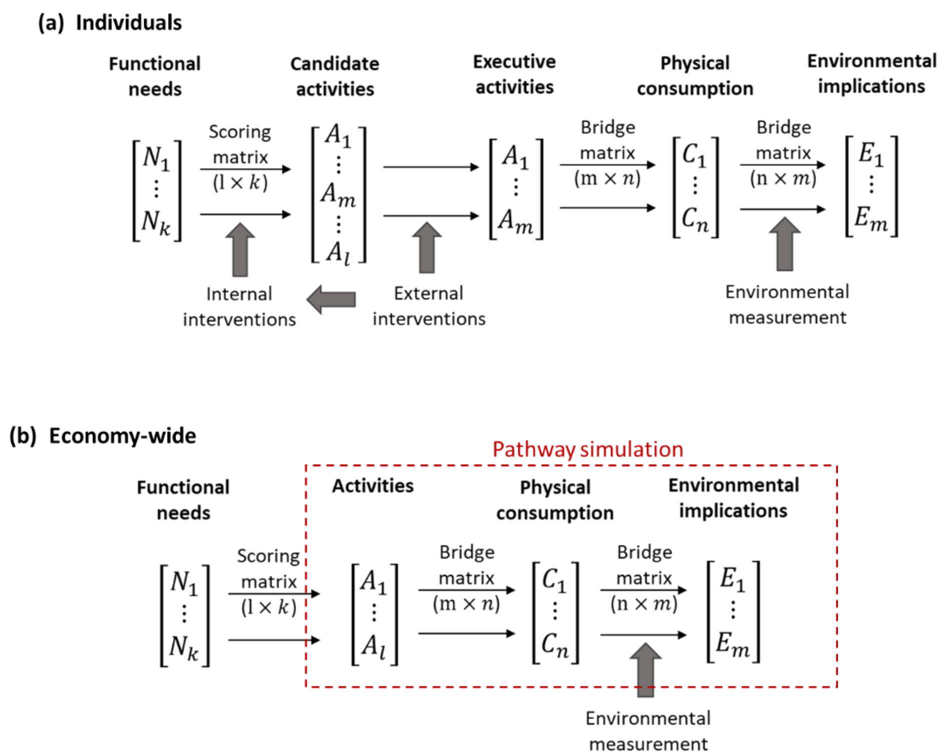


Figure 4-1 Framework of estimating dynamics of carbon footprints of behavioral changes.

In the context of the COVID-19 pandemic, people's motivations for adopting or abandoning certain activities are affected by various needs such as safety concerns, values of affection and freedom. It is also affected by external interventions such as social distancing orders and economic factors. The pandemic has altered people's behaviors which are scaled up to the national level and present prominent changes. Table C-1 provides an example of people's decision-making process to transform functional needs into candidate activities by scoring different activities.

The methods section below describes the process of pathway simulation depicted in the red box in Figure 4-1. It depicts the changes in behaviors affected by the pandemic and how it translates to carbon footprints.

4.3 Methods and materials

4.3.1 Environmentally Extended Input-Output model

Carbon footprint is widely used to measure the direct and indirect environmental impacts of human activities, usually calculated by Lifecycle Analysis (LCA) or Input-Output (IO) analysis or a hybrid method of the two. LCA approach concentrated on analyzing emission inventory in each stage of an activity or a product, while IO analysis focused on the economy-wide impacts based on supply chain networks. Both methods provide a systematic analysis of carbon footprints adherent to consumption, but both have their own limitations. While LCA provides more details in examining carbon footprints of behavioral changes, it usually suffers from intensive data collection, inconsistent scopes and underlying assumptions. IO approach sometimes can be coarse for behavioral change analysis, but it traces the economy-wide carbon footprints.

I aim to quantify economy-wide carbon footprints from behavioral changes, thus Leontief demand-driven open IO model was chosen to capture the direct and indirect effects of behavioral changes (Miller and Blair 2009). A detailed description of applying the demand-driven IO model to behavioral changes can be found in Wood et al. (2018).

$$\mathrm{F}_i = e_{ind} \cdot (I - A)^{-1} Y_i + e_{dir} \cdot Y_i$$

where, F is the carbon footprint of consumption i attached to a behavior; e_{ind} is GHG emission coefficient, kg/$; I is an identity matrix, A is the technical coefficient that describes product inputs per unit product output. $(I - A)^{-1}$ is also written as L, which is the Leontief inverse matrix. Y_i is the demand of product i involved in behavior.

The model is based on a few assumptions: first, changes in consumers' behaviors will reach an equilibrium consumption; second, the price of products is assumed to be stable (Wood et al. 2018); third, this analysis covers the direct and indirect emissions along the supply chain based on the whole economic system at the national level, but behavioral changes sometimes indirectly triggered other behavioral changes given the particular context (for example, people who choose to telecommute might move to a remote area that requires more driving to shopping, gym and restaurants), which is out of the scope of the present analysis. In addition, this study focuses on the recovery stage of a shock where GHG emissions are driven by demand, thus supply-side constraints are assumed to have negligible impacts on people's behavior change (Wood et al. 2018). In this behavioral reshaping and catastrophe recovery circumstance, it is assumed that the saved money from the reduction of a specific consumption is negligible compared to the negative economic impacts from the shock, thus the rebound expenditure on all other consumption is negligible.

4.3.2 Consumer behavioral changes

There are six major consumption behavioral changes to adapt to the pandemic that covers six domains: food, housing, transportation, goods, services, and work. Prior studies examining household carbon footprints mostly classify consumption into the first five domains (Wiedenhofer et al. 2017). However, behavioral changes also involve work-related consumption when a disaster occurs, such as teleworking and reducing business trips during the pandemic.

Behavioral changes are classified into four groups based on sector relationships in the IO framework: 1) activities with replacement between sectors, 2) activities with replacement within a sector, 3) activities with partial (out-of-market) replacement, and 4) activities without replacement. These consumption behavior shifts can drive changes in production recipes and/or changes in energy efficiency.

The Avoid-Shift-Improve framework characterized the process of carbon footprint reduction into the so-called three components. Avoiding certain behaviors results in a reduced level of consumption of certain products, which is calculated as follows, referring to Wood et al. (2018).

$$\boldsymbol{y}^{red}(t) = \boldsymbol{y} \circ (1 - \boldsymbol{r}(t))$$

where y^{red} is the reduced level of demand for products, as a result of behavior change, $\boldsymbol{y}$ is the household demand at the pre-disaster level, and $\boldsymbol{r^t}$ is the reduction rate of household demand for this product caused by the disaster at t time. The notation $\circ$ represents the element-wide product.

$$\boldsymbol{y}^{sub}(t) = p(\boldsymbol{y} - \boldsymbol{y}^{red}(t)) \circ \boldsymbol{y}^{mar}$$

$\boldsymbol{y}_o^{sub}(t)$ is the reduced level of demand at t time. p is price ratio, taking values of consumer's price. $\boldsymbol{y}^{mar}$ is marginal shares for the corresponding sectors taking the value between 0 and 1.

If there is more than one sector as substitute, for example, people may switch from consumption of *Full-service restaurants* to *Limited-service restaurants* and *All other food and drinking places.* From public transportation to bicycles, driving private cars, and even canceling the trip.

The total substitute demand is then

$$y^{sub}(t) = \sum_i \alpha_i y_i^{sub}(t)$$

$$0 \leq \sum_i \alpha_i \leq 1$$

$y^{sub}(t)$ is the total substitute demand at t time. α_i is adoption rate for purchasing type i alternative products, taking the value typically between 0 and 1. When $\sum_i \alpha_i = 0$, it is the case when the changes of activity have no replacement following specific patterns, or all the activity is substituted by out-of-market consumptions, for example, canceling flights or canceling parties to avoid close contact with people. $\sum_i \alpha_i = 1$, there are i sectors that fully substitute the changes in the initial sector. When $0 < \sum_i \alpha_i < 1$, there are partial out-of-market substitutions; for example, when gyms are closed during the pandemic, people may instead buy sports equipment at home or run outside, or even stop working out.

4.3.3 Dynamic behavioral changes

The pandemic posed unprecedented challenges as a shock to change people's behaviors in a relatively short time. We assume that people tend to go back to their pre-pandemic consumption behaviors. Existing models on the impacts of disaster and recovery (for example, Dynamic Inoperability Input-output Model (DIIM) (Lian and Haimes 2006; Santos et al. 2014) and flood footprint model (Zeng et al. 2019; Shan et al. 2021)) mostly assume that the economy will recover to the exact pre-disaster level. However, it is usually not the case, as we observe that people change their behaviors to adapt to the new conditions. The natural logarithm form was taken to model the tendency of behavior recovery. However, given the behavioral plasticity that people change their behaviors in response to exogenous factors (e.g., pandemic), some behavioral changes can have long-term effects (Dietz et al. 2009). As a result, demands for some products may reach a level (lower or higher than the pre-pandemic level) when the market reaches a new equilibrium. It is different from the existing studies that examine the effects of economic recovery that assume the demand and economic structure will reach the same as pre-pandemic level. Let the changed rate *R(t)* be

$$R(t) = 1 - r_i(\mathrm{t})$$

The changed rate in exponential form is

$$R_i(\mathrm{t}) = \left(R_i^{ini} - R_i^{end}\right)e^{\omega_i t} + R_i^{end}$$

when t = 0, it takes the value of the initial reduction rate at the shock (R_{ini}), and approach to the renewal demand level at the new equilibrium (R_{end}). The initial and new reduction rate is based on the level of shocks and behavioral plasticity. When the change reaches to λ, the change tends to be stable. Therefore, we get the reduction parameter ω_i for sector i, $\omega_i < 0$.

where, r is the demand reduction rate at t time. The government typically has plans for the economic recovery period (T), thus T is a modifiable parameter. As $R_i(\mathrm{t})$ is approaching R_i^{end}, we assume at time T, the difference between the changed rate and the new equilibrium is λ = 0.01. Then

$$\omega_i = \frac{1}{T} ln \frac{\lambda}{(R_i^{ini} - R_i^{end})}$$

4.3.4 Modification of production recipe

The changes in consumer behavior not only can change the demand for particular products but also can drive the changes in production and distribution along the supply chain. For example, during the pandemic, although the demand for restaurant service overall decreased, people who chose take-outs instead of dining in the restaurants would cause a higher use of food packages and single-use utensils. Therefore, the production and distribution systems are changed. In order to model this scenario, we divided the sector into two parts, with one part unchanged, while the other part has a change in the production systems.

Hence, we adopt the modifiable changes of the technical coefficients from Wood et al. (2018)

$$\mathbf{A} = [\boldsymbol{a_1}, \boldsymbol{a_2}, \dots \boldsymbol{a_n}]$$

$$\boldsymbol{a_n^{chg}} = \boldsymbol{a_n} \circ (1 - \boldsymbol{r_n^A})$$

$\boldsymbol{r_n^A}$ is the change of the production system driven by consumer behavioral changes.

4.4 Case study: Carbon footprints of a basket of behavioral changes in post-COVID

4.4.1 GHG emission trajectories from a basket of behavioral changes

Table 4-1 A basket of behavioral changes in post-COVID and associated parameters

ID	Behavioral changes	Substitutes	Needs priority	Share of behavior substitution adoption	Initial penetration	Scenarios		
						S1 Pandemic stagnancy	S2 Minor policy nudges	S3 Social diving
1	Dining in full-service restaurants	Take-out or food delivery	Protection	0.1	0.8	0.3~0.4	0~0.1	-0.1~-0.2
		Consuming at limited-service restaurants	Freedom	0.2				
		Cooking at home	Creation	0.7				
2	Going to gym	Home gym	Protection	0.2	0.8	0.3~ 0.4	0~0.1	-0.1~-0.2
		Working-out without equipment	Creation	0.5				
		Stop working-out	Idleness	0.3				
3	Commuting with public transportation	Commuting with private cars	Protection	0.2	0.4	0.3	0.1~0.2	0
		Commuting by bikes	Identity	0.3				
		Telecommuting	Freedom	0.5				
4	Commuting with private cars	Telecommuting	Freedom	1	0.4	0.3	0.1~0.2	-0.1~0
5	Leisure trips by flights or ferries	Leisure at nearby natural areas	Affection	0.8	0.8	0.4~0.5	0.1~0.2	-0.2~-0.1
		Canceling trips with no substitutes	Protection	0.2				

COVID-19 has transformed consumer spending habits in different consumption domains. We selected five major frequently occurring behavioral changes and their substitutes in response to the pandemic and investigated their potential in reducing carbon footprints. This basket of behavioral changes is a subset of total behavioral changes in economic recovery stage following the COVID-19 outbreak. We use it as a case study to investigate the GHG emission pathways from a combination of behavioral changes. These frequently occurring behaviors can achieve aggregated effects by repetitions and are more likely to have long-term effects. Although some one-time and high-impact low-carbon technologies are acknowledged to have positive long-term effects, we assume that people's adoption of these technologies is constant given that green investment is usually expensive and it involves in-person installation against the background of sluggish economy and social distancing. In other words, we assume people stop increasing their green investment at home, such as purchasing energy-efficient equipment and electric vehicles.

We develop three scenarios for a basket of behavioral changes in the economic recovery stage of the COVID pandemic, as shown in Table 4-1: pandemic stagnancy (Scenario 1), back-to-normal with minor policy nudges (Scenario 2), and social diving (Scenario 3), highlighted by the levels of penetration rate when behaviors reach a stable status. In this part of analysis, we assume that people have a preference for substitutes for a changed behavior among the population, reflected in a fixed share of behavior substitute adoption. The results show that the selected basket of behavioral changes drove emission reduction of 90.1 $MtCO_2e$ at the initial pandemic shock, approximately 1.1% of the national household GHG emissions. If the behavioral changes caused by the pandemic persist (Scenario 1), there is 46–62 $MtCO_2$ emission reduction can be achieved. However, the overshoot scenario (Scenario 3) suggests that the household consumption rebound can potentially increase GHG emissions by 4-20 $MtCO_2$ emissions. The back-to-normal scenario with minor policy nudges can potentially achieve GHG emission reduction of 2-18 $MtCO_2$ at the national level.

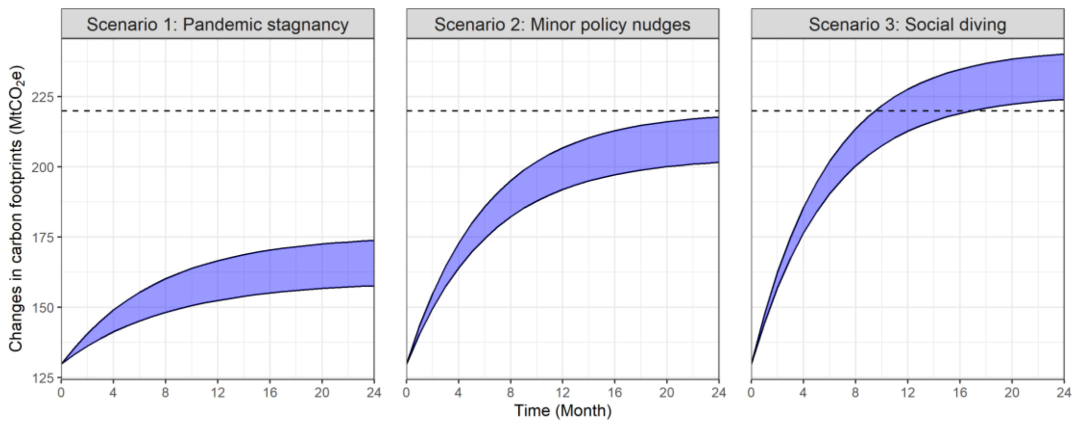


Figure 4-2 Changes in carbon footprints of a basket of behavioral changes following COVID-19 pandemic

4.4.2 Carbon reduction potential with different alternatives

Scenario 4 and Scenario 5 simulated the first three behavioral changes described in Table 1 under the circumstances of flexible substitutes, where people switch away from old behaviors but are open to different substitutes. More details regarding data and assumptions are shown in Appendix C. Our results suggest among the three alternative options to replace dining in full-service restaurants, adding additional take-out or food delivery services will increase carbon footprints by 0.73% at the initial hit of the pandemic, and smooth to an increase by up to 0.38% under behavioral stagnancy scenario and decrease by 0.17% by abdicating additional delivery services and embracing pre-pandemic full-service dining. In contrast, consuming at limited-service restaurants and cooking at home lowered carbon footprints by approximately 15% when the penetration rate reached 80% at the initial hit of the pandemic and the latter has slightly higher emission reduction effects.

In workout activities, adding sports equipment at home overall increases GHG emissions which are generated from the upstream manufacturing process, while alternative options – working out without equipment and stopping working out – would yield emission reduction effects. It is also important to notice that although some low-carbon alternatives have similar carbon reduction potentials (for example, going to gyms is replaced by going to open spaces for jogging and stopping working out), people's sense of belonging, mental health and well-being can be different. In this regard, working out in open space without equipment could achieve both environmental and health benefits. However, attention should be paid to people's priorities and other needs, for example, the effectiveness of muscle build-up by different means of working-out can be different. Instead of home gyms and centralized gym buildings, research suggested that open gym spaces in communities, mostly popular in Asian countries, can improve urban resilience and promote sustainable cities (Safrilia and Poerwoningsih 2021; Ling 2021).

In terms of means of commuting, driven by safety concerns, people who have to go to the office would opt for driving instead of public transportation. Our results suggest that, for people who used to take public transportation to work now have the choice of driving to the office, biking to the office and teleworking because of the pandemic; biking to the office has the most substantial emission reduction effects. Teleworking also contributes to emission reduction by reducing gasoline use but a rebound in residential electricity consumption was observed. Our results further show that the shift from public transportation to private cars has the potential to increase GHG emissions by up to 173%, if 40% of the population who has the possibility to telework actually drive private cars to the office. It is important to note that our results are based on economy-wide supply chain effects measured by consumption level, the secondary effects (for example, research suggests that telecommuters tend to move to suburban areas living in spacious houses which eventually increase their energy consumption overall) are beyond the scope of the current analysis. Driving private cars to replace public transportation is the largest contributor to the increase of GHG emissions in the examined basket of behavioral changes.

Figure 4-3 depicts the trajectory of GHG emissions by adopting carbon-intensive substitutes (Scenario 4) and the low-carbon options (Scenario 5). They are simulations of what if all people adopt a certain behavior as their alternative to meet their needs. While a large body of literature suggests the opportunity for the transition to lower carbon consumption following the pandemic, our model suggests that certain behavioral changes in response to the pandemic can deteriorate the goal of sustainable consumption, such as adding food packaging and delivery services and increasing the use of private cars. A combination of the investigated three behavior changes we investigated can increase up to 78 Mt CO_2e, up 5-15% of associated carbon footprint depending on different levels of adoption. Although they are driven by safety concerns during the pandemic, additional policy nudges may be needed to discourage people from unsustainable behaviors they developed during this period. A decrease in public transportation ridership can also make it a less green travel mode (Sui et al. 2020). Scenario 5 depicts the pathways of consumers adopting low-carbon alternative behaviors in response to the pandemic shock, with an overshooting scenario considered. The combination of the low-carbon substitutes could reduce up to 8.4 Mt CO_2e GHG emissions. The two scenarios show that different alternatives to the three behaviors can lead to an aggregated 18.4 MtCO_2e emission difference, highlighting the importance of considering the effects of emission reduction from behavioral changes. Although our model does not aim to address how policy guidance can lead to the emission reduction pathways, it underscores emission mitigation that can be reasonably achieved following the shock of the pandemic.

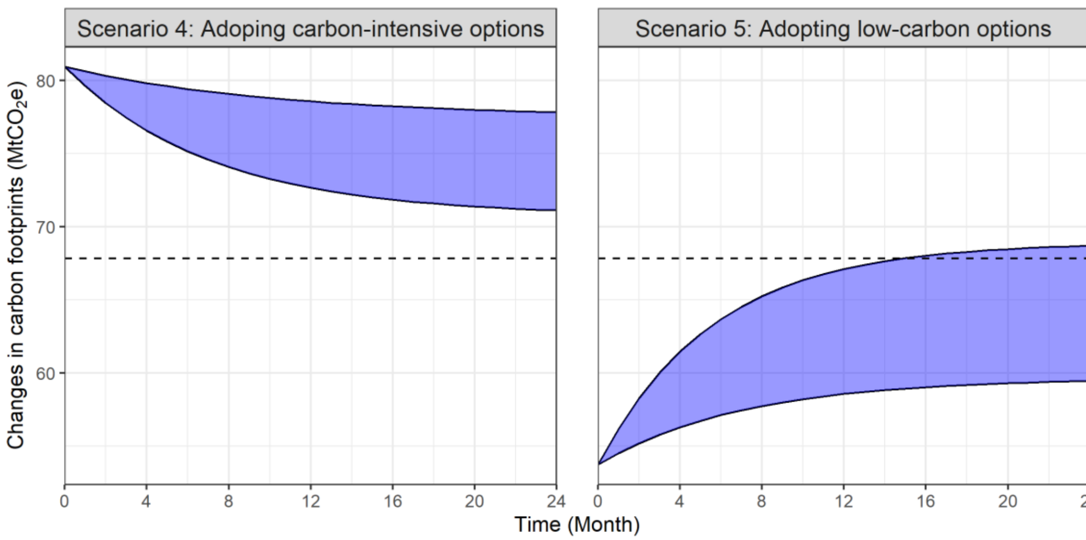


Figure 4-3 Pathways of GHG emission changes by adopting carbon-intensive options (Scenario 4) and low-carbon options (Scenario 5)

4.5 Discussion

Behavioral changes can yield significant environmental benefits only are they organically combined with financial and other interventions (Stern 2020; Nisa et al. 2019). While we observed an emission reduction during the pandemic outbreak, it is disproportional to the economic dent largely due to the severe shock on service sectors. It indicates that emission reduction is mainly contributed by consumption decrease instead of energy intensity improvement. While debunking consumerism is gradually proposed by recent environmental economists for sustainable consumption, the increase in energy intensity due to the lag of improvement in economic structure would backfire in a longer term. In addition, although abstained consumption has made achieving the 2020 climate goal easier, the decreased green investment (such as renewable energy) could also delay the climate mitigation progress in the medium and long term.

While consumer behaviors are easy to shape after the pandemic shock, policies targeting the promotion of sustainable consumption and encouraging low-carbon practices are still lacking. Research suggested that the positive effects of decoupling policy on GDP are even stronger during the pandemic than compared to the pre-COVID-19 period (Lahcen et al. 2020). At this point, the recovery packages open a channel to mobilize this funding to shift away from carbon-intensive institutions, and instead, shape consumer behaviors towards sustainable consumption (Obergassel, Hermwille, and Oberthür 2020). It is imperative to explicitly gear the recovery packages to support the long-term sustainable transformations (Fischedick and Schneidewind 2020).

In addition, the lack of modeling tools from the scientific realm adds difficulties for a targeted low-carbon recovery program. Prior studies offer insights into environmental impacts on behavioral changes mainly focused on individual levels, however individual behavioral changes are highly dependent on the economic and cultural context. Additionally, behavior wedges are proposed to depict the potential of behavioral changes in a linear form, but when external shocks challenge people's basic needs (according to Maslow's Hierarchy of needs). Combining behaviorally sensitive features with financial incentives and information has the potential to achieve a considerable amount of carbon reduction. Rather than providing policy guidelines, this paper highlights the importance of integrating

Our study summarized the importance of behavioral changes in climate mitigation pathways, especially following extreme events like the pandemic, and the complexity of modeling environmental impacts from behavioral changes. We developed a framework for linking and quantifying people's behavior changes and estimated the aggregated effects of carbon footprints from behavioral changes, as well as simulated GHG emission pathways associated with a basket of behavioral changes during pandemic as a case study. The framework facilitates the translation from people's hierarchical needs to carbon footprint impacts, with case analysis to simulate pathways under different scenarios of behavioral changes. While we have been careful to explore the consumption change and behavioral plasticity in parametrization, our analysis is still based on different scenarios due to different possibilities and is dependent on policy guidance and efficacy. Further efforts to couple behavioral change into climate models should explore the interactions and robustness.

Chapter 5: Conclusions

5.1 Major findings

As emerging subnational and individuals participate in climate mitigation actions, decision makers are eager to design policies that promote mitigation practices and evaluate the effectiveness of their mitigation approaches. Knowledge is needed to quantify their contributions to climate mitigation and identify challenges and opportunities for future mitigation practices. While literature is growing on this topic, this dissertation fills several gaps in current research that aid in effective climate policies by exploring the virtual emission transfer between subnational climate actors and how different income groups change their consumption patterns. In Chapter 2, the dissertation focused on analyzing consumption-based GHG emissions of U.S. states and analyzed emission spillover among states. In Chapter 3, it improved our understanding of how different income groups changed their consumption patterns and associated carbon footprints. Chapter 4 built a framework for linking fundamental human needs, behavioral change, consumption to footprints to explore low-carbon opportunities for households.

Chapter 2 highlights the importance of using consumption-based accounting to measure subnational-level GHG emission transfers to assess climate responsibilities and as a complementary tool to aid in the design of adequate mitigation policies through wider alliances. This piece of study pioneers in the framing of subnational climate responsibilities – not only the territorial emissions but also embodied emissions generated elsewhere along the supply chain. I found that emissions embodied in interstate and international imports can be significant at a subnational scale, as they can be nearly twice as large as the production-based emissions at the state level in the U.S. case, especially for more fluent states with stricter climate policies. Emissions embodied in trade because of wide production and interstate specialization can undermine the effectiveness of current subnational climate actions and pose challenges to extending alliances and deepening cooperation for greater joint gains. Also the results suggest that subnational actors should be mindful of potential carbon leakage through trade and relocations as a result of territory-centered climate policies. I discussed the challenges, based on the findings for the U.S. case, of extending the Climate Alliance to other states and the potential carbon leakage and suggested possible venues to address them.

By analyzing emission transfer, we can identify the major emission partners at the state level, which can provide a scientific base for deeper multi-state level cooperation. As an example, I found that several key sectors deserve more attention as they involve significant emission transfer between states. Emissions from several energy-intensive sectors are easier to monitor and trace than those resulting from the production and trade of many light-weight products, thus opening opportunities for states to substantially reduce supply-chain emissions and incrementally increase cooperation with non-member states using these analytic tools. I suggest that subnational targets should include embodied emissions from all products participating in the whole supply chain.

Chapter 3 analyzed how changes in household consumption affected national GHG emissions in the U.S., focusing on changes in consumption patterns across quintile income groups. This study is the first one, to my knowledge, that analyzed how different income groups change their consumption patterns at the national level. I observed that, at the national level, the changes in GHG emissions attributed to changes in U.S. household consumption do not follow the same patterns as the national GHG emissions

(Friedlingstein et al., 2020). This difference mainly manifested after the economic recession, which suggests that while household consumption was increasing, the consumption-based GHG emissions were decreasing mainly due to supply-side factors. My further analysis confirms that the difference between the national trend and the consumer one was mainly due to technological factors rather than an increased reliance by consumers on carbon-intensive imports. This highlights the dangers of relying only on supply-side policy approaches as opposed to a policy portfolio that includes demand-side options to prevent potential rebounds from technological efficiency gains.

By analyzing consumption change among different income groups, this research found that the emission increase before the national peak was mainly contributed by high-income households. During the period under study, consumption patterns played a major role in emission reduction especially after the emission peak, and this effect was much more evident in middle-high- and high-income groups.

Chapter 4 filled the knowledge gap by linking human needs to climate mitigation research. Human wellbeing is one of the Sustainable Development Goals (SDG 3), which can be ensured by meeting various fundamental human needs in addition to physical health. It is not sufficiently analyzed in climate mitigation research yet. This chapter enriched the literature in this branch by proposing a modifiable framework for estimating the economy-wide dynamics of consumer behavioral changes and associated carbon footprints. The innovation of integrating needs and behaviors into demand-driven carbon footprint analysis adds more perspectives to analysis of low-carbon lifestyles. The results of this study suggested dynamic human needs in the face of social incidence, and certain human needs such as affection and participation induce low carbon footprints. The application to a basket of behavioral changes during the pandemic reveals that not all major behavioral changes during the pandemic reduced carbon footprints. In addition, opting for low-carbon behaviors could buffer potential emission overshoot caused by excessive consumption. This study can be extended to explore the dynamics of carbon footprints caused by behavioral changes affected by exogenous shocks.

5.2 Limitations and future work

Substantial work is required in promoting rapid and effective climate actions from households and subnational jurisdictions, from scientific analysis and implementation. First and foremost, an accurate, credible and standardized emissions scheme is essential, which requires the establishment of various databases and monitoring systems. In Chapter 2, I established a state-level emission account and used freight data to trace virtual emission flows through a consumption-based approach. The available data provides just a snapshot of the situation at the start of the agreement. Recent research has started to monitor GHG emissions at the subnational level, such as near-real-time Carbon Monitor (Liu, Ciais, Deng, Davis, et al. 2020), ClimActor (Angel Hsu, Yeo, et al. 2020), and Vulcan (Gurney et al. 2021). These databases mainly improved data at spatial and time scales but lack attention to Scope 3 emissions. To produce consistent and timely emission flows, more frequent monitoring of freight and trade is needed to better capture the interstate movement of products and the provision of services, as the current datasets are updated every five years (FAF 2021). Better tracking of where the products are consumed and where associated emissions occurred would also benefit the accuracy of state- and city-level emission self-reporting programs.

To better understand household carbon inequality, a harmonized approach is needed to combine carbon footprints and socioeconomic factors. At present, different results are generated from different studies due to different approaches and data being used. While national Consumer Expenditure Surveys from different countries provide more details in terms of demographic and socioeconomic factors, they usually suffer from misreporting issues and lack of geographical details due to privacy concerns. Other databases, such as IO-based data, do not offer sufficient details about household characteristics. Chapter 3 analyzed how different income groups changed their consumption patterns and associated GHG emissions. While the innovation of this research is to look at the contribution from different income groups for policymakers to include inequality in devising climate policies, quintile income groups are selected in analysis due to data consistency issues. Substantial work is required to include the detailed income, consumption and footprints of individual households to improve the resolution and target most carbon-intensive consumers while reducing carbon inequality. In addition, socioeconomic factors are important to be considered in future work to devise feasible plans to reduce carbon footprints at the household level.

The implementation of climate policies should consider not only inequality but also human needs, which mainly focuses on Sustainable Development Goal 3. The framework that links human needs to carbon footprints is pilot and exploratory research. Given the nature of complexity in human behaviors, the model proposed is under several assumptions and based on the consumption level. There are certain limitations of this model. First, behavioral changes are context-specific and dependent on socioeconomic and psychological factors. The interactions and causal effects among these factors are still not well quantified in the existing literature. The model translated the impacts of the pandemic to consumption levels based on survey and statistical data, then translated to associated GHG emissions based on the open IO model. However, it is still limited in capturing the interactions and feedback between consumption and other factors. Second, given the COVID emergency, I assume that people's adoption of one-time and high-impact low-carbon technologies are constant, although they have the potential for long-term effects. In other words, we assume people stop increasing their green investment at home, such as purchasing energy-efficient equipment and electric vehicles. It is because these adoptions are usually expensive with a relatively long energy payment period, while people are in economic struggling due to sluggish economy; and people would try to keep social distance and avoid in-person contact with installation and maintenance people. In addition, structural and institutional constraints need to be considered. Future work should pay more attention to capturing and quantifying the interactions between consumption and socio-psychological factors. While analyzing the interlinkage between these factors and human behaviors is labor-intensive with high uncertainty, context-specific results are still needed to fully understand this complicated issue. There are emerging studies using meta-analysis to summarize results from case studies, which could draw general results to inform nationwide effects. Agent-based models are also increasingly used to simulate the process of consumer decision-making.

Appendices A Supplementary information for Chapter 2

A1 Supplementary methods

Details of methods and materials

Scholars introduced three scopes to clarify the emission boundaries in subnational administrative areas, including direct in-boundary GHG emissions from energy and industrial sectors (Scope 1), electricity import emissions from other states (Scope 2) and emissions from both upstream and downstream as a result of human activities (Scope 3). In our study, we analyzed all the three scopes – both direct and indirect emissions along supply chains – for Alliance and non-Alliance states and individual states, and their emission transfers. We constructed a state-level GHG account based on territorial emissions by state and then modeled GHG emissions driven by consumption, including direct emissions from consumers, embodied emissions from electricity transmission and upstream manufacturing activities. When building a production-based emission account, we cited different data sources and avoided double accounting.

GHG emissions from electric power and industrial sectors

The state-level GHG emissions from electric power and industrial sectors are derived from Facility Level Information on GreenHouse gases Tool (FLIGHT), a bottom-up mandatory reporting program initiated by EPA (US EPA 2018). FLIGHT database covers 12 types of greenhouse gases (in CO_2e), including non-biogenic CO_2, methane (CH_4), Nitrous Oxide (N_2O), HFC, PFC, SF_6, NF_3, other fully fluorinated GHG, HFE, very short-lived compounds, other GHGs and biogenic CO_2 emissions. All the emissions are converted to CO_2 equivalent (CO_2e), referring to EPA GHG conversion (EPA 2019b). More than 8,000 facilities whose GHG emissions are larger than 25,000 $MtCO_2e$/year are mandatory to report to this program. We mapped the NAICS code (2007) of reported facilities into 536 IMPLAN sector code via NAICS concordance and IMPLAN-NAICS Bridge (IMPLAN Group LLC 2022; USCB 2018), and then aggregated them into 147 sectors we used for analysis.

It is important to note that GHG emissions from transmission pipelines and local distribution companies (LDC) may cause emissions displacement to another state. We assign the emission to occurrence states accordingly based on information provided by the FLIGHT database and manual checks. Another note is that the mandatory reporting system does not include emissions from agriculture, land use, or direct emissions from sources that are below the reporting threshold. It also does not include sinks of GHGs.

There are many GHG emission databases initiated by different programs, having different rules and serving different purposes, thus they are not comparable. In detail, the EIA focused on energy-related CO_2 emissions and reported territorial CO_2 emissions by five major sources at the state level. Both GHGRP and National Emission Inventory (NEI) are initiated by EPA; however, they are under different rules (the former under 40 CFR Part 98, while the latter under 40 CFR part 51). Although NEI included part of GHGRP data, NEI point sources are primarily based on state-reported data, with GHGRP as a supplementary. The NEI has a requirement for criteria pollutants thus does not target GHG emissions. In addition, different reporting administrations (EPA GHGRP, EPA air pollutants, EPA GHG inventory, and IEA energy-related CO_2 emissions) have different reporting scopes (Fong, Doust, and Deng-Beck 2014). While most cities reported territorial emissions, some cities, for example, Seattle, included embodied emissions of asphalt, and embodied emissions of foods and construction materials (Coven, Krishnan, and Morgenstern 2019), and the majority only considered emissions produced within the state.

This study used the FLIGHT database launched by GHGRP that covered most types of greenhouse gases, compared to EIA which only covers energy-related CO_2 emissions and NEI which covers four major GHGs. The four major GHGs (CO_2, CH_4, N_2O, and SF_6) in FLIGHT are 100.8% of the GHG emissions from NEI point sources. Even though the NEI covers some emission points that are below the reporting threshold that the mandatory reporting program cannot capture, the NEI has a requirement for criteria pollutant reporting but GHG emissions are not required. Another reason is that the FLIGHT database also has information about GHG emission displacement, for example, the locations of emissions from pipelines and local distribution companies occurred and the locations of the companies. Besides, given the FLIGHT database has the best coverage of greenhouse gases and specifically serves for GHG emissions accounting, we use the FLIGHT database of GHGRP initiated by EPA for our analysis.

We compared mandatory CO_2 emissions by state with state-level CO_2 in 2017 released from EIA, and found that over 97% of the CO_2 emissions in EIA are captured by the GHGRP. Figure A-7 illustrates the share of CO_2 emissions from GHGRP to the CO_2 emissions from EIA. For the 50 states, the mean is 0.977 and the standard deviation is 0.135.

The total GHG emissions GHGRP captured, including non-CO_2 GHG, is 106.58% of the CO_2 emissions by state from EIA. Facility-level GHG emissions are mapped to corresponding sectors in each state. The FLIGHT dataset covers 1212 out of 7497 region-sectors.

GHG emissions from agriculture

Some entire sectors, such as the agricultural and land-use sectors, are not required to report to the GHG mandatory reporting program. However, according to EPA Inventory of US Greenhouse Gas Emissions and Sinks, agriculture accounts for approximately 9% of the total national GHG emissions. We exclude the seven self-reporting facilities related to agricultural sectors in the GHGRP database, and fill the GHG emissions from agriculture with data from EPA (EPA 2019b) and USDA (USDA 2018).

GHG emissions from agriculture mainly come from four sources, enteric fermentation from ruminants, manure management, crop planting (especially rice cultivation), and fuels used during crop and animal cultivation. The GHG emissions from enteric fermentation, manure management and crop planting by state are derived from EPA Inventory of US Greenhouse Gas Emissions and Sinks (EPA 2019b). Fuel usage during the cultivation process is derived from USDA. All emissions are converted to CO_2e according to GWP100 from IPCC (Pachauri and Meyer 2014). Agriculture accounts for about 8.5% of national GHG emissions (GHG Inventory). In addition, the fuels used in agriculture are not included in 9% accounting, estimated by Fuel Usage from the Census of Agriculture the 2017 and The Farm Production Expenditures 2018 Summary (USDA 2018).

Estimation of GHG emissions from other sectors that are below the threshold of the mandatory reporting program

We screened primary energy sectors that serve as upstream energy inputs to the rest of region-sectors during the operation, in order to estimate the GHG emissions of the sectors that the mandatory reporting program cannot capture. The ten primary sectors and CO_2 emission coefficients to estimate associated GHG emissions are shown in Table A-3. The CO_2 coefficient is derived from the EIA methodology for estimating energy-related CO_2 emissions for different states in 2017.

The energy price we used is derived from the State Energy Data System (SEDS) (EIA 2018). The price for different types of energy is at the state level (EIA 2017b). We then used the margin data from IMPLAN to convert the price into producer's price for the ten sectors.

One of the limitations of using energy flow to estimate GHG emissions in other sectors below the threshold of the mandatory reporting program is that we can only estimate the CO_2 emissions from the primary energy sources due to data limitations. The assumption based on this is that the non-CO_2 emissions from energy consumption are much less compared to the CO_2 emissions.

Prior research usually calculated energy consumed and associated emissions for each region-sector based on fossil fuel inputs (Davis and Caldeira 2010). However, given the commodity flow data used in the gravity model to estimate the interstate trade flows, this method has its limitations in accurately quantifying regional emissions. The facility-level GHG emission database we used in this study greatly improved the level of closeness of state-level GHG emission accounts to where it actually occurs.

Direct emissions from transportation in final demand and residential sectors

Direct GHG emissions from the transportation and residential sectors, mainly from driving and natural gas burning, are also significant components of national GHG emissions, although they are not directly related to the regional GHG transfer. The emissions from transportation and buildings per capita could reflect the energy efficiency and should be included in the emission accounting (Ramaswami and Chavez 2013).

The direct GHG emissions from the gasoline and other fuel combustion from transportation generated from final demand are estimated by energy flow based on primary fuel inputs. Four sectors are identified to provide primary energy for final demand transportation, as shown in Table A-4.

The GHG emissions from residential sectors are derived from EIA (EIA 2018). Residential emissions (302 $MtCO_2e$) are mainly from the use of fuels for heating and power.

Visualization

The maps are developed with ArcGIS. We further visualized the interstate GHG emission flows by an open-source graphing program (*Gephi v0.9.1*) and an external plug-in (*Geolayout*). The size of nodes represents net GHG emissions embodied in interstate trade. The strength and degree of the inter-state flows represent the volume of the GHG emissions embodied in the interstate trade activities. The direction of the emissions transferred from one state to another is shown clockwise.

A2 <u>Supplementary discussion</u>

Scenarios of emission reduction from Alliance States

Alliance states have committed to reducing their GHG emissions at least consistent with the Paris Agreement goal within their jurisdictions, involving electric power generation, transportation, energy efficiency, climate finance and climate resilience. Among these, targets regarding electric power are usually gained considerable attention and formalized with clear and quantitative goals; in addition, many also committed to being responsible for emissions from their upstream electricity grids to achieve middle- and long-term decarbonization. This section investigates how much emissions embodied in the upstream electricity generation will be mitigated if these states make substantial progress in their electricity decarbonization. It is important to note that the current power transmission systems in the U.S. are divided into multiple wide area synchronous grids. Electricity is usually transmitted within their interconnected grid regions (de Chalendar, Taggart, and Benson 2019).

We simulated the GHG emissions (in terms of both production-based emissions and consumption-based emissions) under the scenarios that Alliance states reduce the GHG emission intensity of electric power generation within territories (by either implementing Carbon Capture and Storage or deploying renewable energy), with no changes in non-Alliance states, the international markets and demands (Figure A-8). This simulation assumed each grid region is closed without further extensions or connections in the next several decades. We also assumed that the economic structure is similar to the study year (2017) and no macroeconomic equilibrium is further adjusted in these scenarios. This assumption was made following two lines of reasons. First, the production recipe usually does not change dramatically in relatively stable economic development, and this assumption has been used in many studies (Shan et al. 2021; Wang et al. 2021). Second, the economic structure in the reference year represents the best available data.

Our results show that even if the Alliance states achieved net-zero emissions in their power grid, their production-based emissions would be reduced by nearly 22%; however, their consumption-based emissions would only be reduced by 2.3%. In terms of composition, Alliance states' share of production-based emissions will decrease from 39.2% to 33.6%; however, their share in consumption-based emissions will increase by 0.3% (from 51.5% to 51.8%). Given that electricity generation sectors from the Alliance states generate 570 Mt, which means that Alliance states account for 32% of national power sector emissions, full decarbonization of the electric power sector from the Alliance states will cut emissions equivalent to one-third of the whole sector. Without efforts on decarbonizing power sectors in non-Alliance states, the promotion of electric vehicles in Alliance states potentially increases the carbon leakage further, as the non-Alliance states locate a large proportion of upstream vehicle manufacturing sectors.

While some Alliance members consider seeking clean sources for electric power generation to decarbonize the power grids, such expanded climate responsibility would not make a big difference. It is because Alliance and non-Alliance states tend to cluster geographically, electric power generation is usually used for local demands and shared with neighboring states in the same Alliance group. While there is a considerable amount of GHG emissions embodied in inter-state transmission, the net emissions embodied in the electricity trade are only less than 30Mt from non-Alliance states to Alliance states.

This is in agreement with the study (de Chalendar, Taggart, and Benson 2019). Although inter-regional coordination in electricity generation and transmission has the promise to reduce the cost of decarbonizing the electricity system (Brown and Botterud 2021), potential carbon leakage should be aware of and could backfire the electricity decarbonization in the near term. In summary, our results demonstrate that only decarbonizing the upstream electricity is insufficient to achieve substantial climate mitigation. State governors should act boldly on climate legislation and pay attention to emissions embodied in the trade of products; in addition, we also highlight the importance of climate efforts from the non-Alliance states.

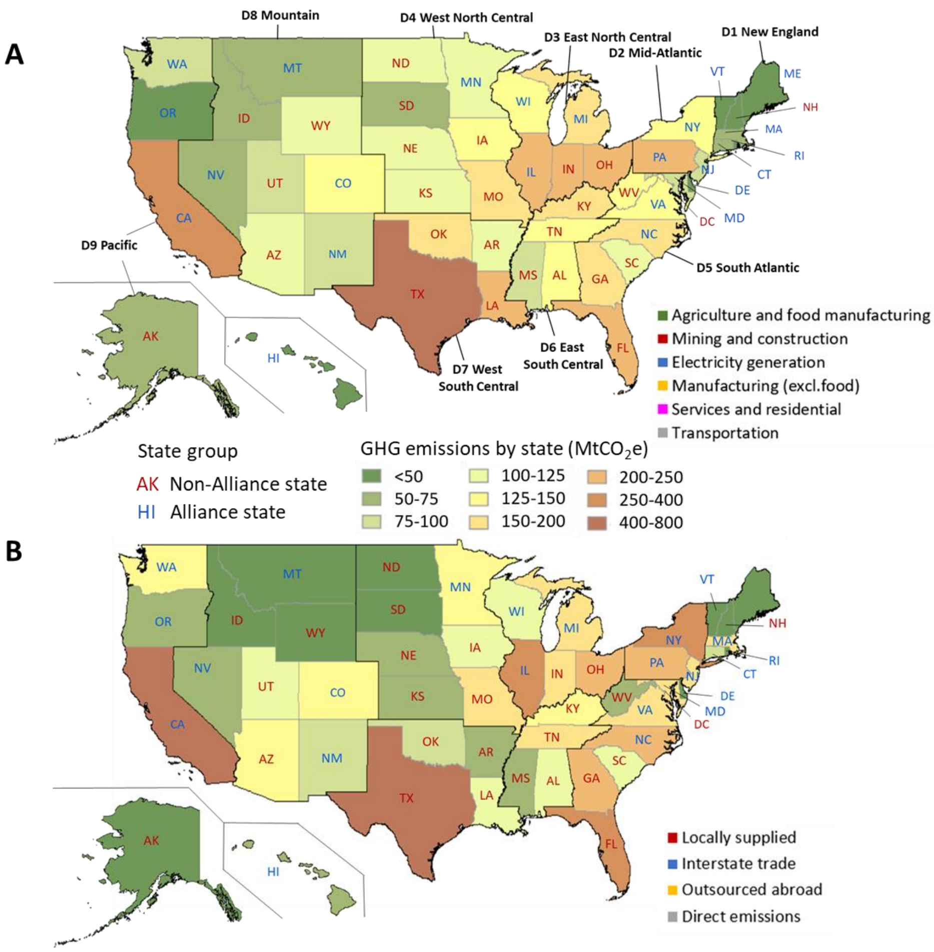
Discussion on data comparison and limitations

Total territorial GHG emissions for the U.S. amounted to 6.410 $GtCO_2e$ in 2017, representing 99.4% of the gross GHG emissions reported in the national emission inventory (EPA 2019b). Emissions from industrial and energy sectors serving for manufacturing accounted for 45.2% of total territorial emissions. The agriculture sector accounted for 8.5% of the total territorial GHG emissions. Taking emissions embodied in imports and exports into account, the U.S. is responsible for a total of 7.279 $GtCO_2e$ emissions, 13.5% more than territorial GHG emissions. The difference in national GHG emissions between our study and national inventory comes from different data sources and different analytical systems. The national emission inventory from EPA is based on national energy consumption and other GHG emission sources like agriculture. While our analysis derived data of non-energy-related agricultural GHG emissions from EPA inventory, we focus on total GHG emissions with production-based emissions by each state when developing emission accounts. To this end, we obtain GHG emissions from different emission sources and match them to different sectors by state, meanwhile estimating emissions that current emission statistics failed to capture and avoiding double accounting.

The state-level territorial or production-based emission account we developed is based on where the emissions occur, regardless of the location of the companies. The shares of different sectors' contributions to the total state emissions are different from currently published statistics within range. For example, transportation share for each state is generally smaller than that published by EIA because we also counted other GHG emissions other than CO_2 from energy and emissions from agriculture sectors. While some states' environmental protection programs publish their annual emission sources, they have different accounting scopes. In addition, we use the energy flow method to estimate emissions under the reporting threshold to fill the gap of missing data for each state.

Our model is built based on the Freight Analysis Framework (FAF) and Commodity Flow Survey (CFS) from the Bureau of Transportation Statistics, which are the two best available datasets that describe the interstate movements of products. However, there are still limitations and uncertainties in the estimation of GHG emission spillovers in terms of data accuracy and model construction. The first limitation comes from the gravity model. Gravity model requires inputs of commodity volume and distance. This model used distance which is based on weighted averages of different modes of transportation, which significantly improves the model accuracy compared to an ideal Euclidean distance. However, the CFS data, which this gravity model relies on, report shipment origins rather than manufacturing origins. While it is a small difference, it can still cause an underestimation of the average distance, which occurred from the movement of commodities from manufacturing companies to concentrated shipping stations such as warehouses (Thorvaldson and Squibb 2019). The second limitation comes from MRIO construction. The aggregation of sectors from 536 to 147 for each state may bring bias in this process. Although our aggregation is roughly based on the carbon intensity, which means we try to preserve carbon-intensive sectors and aggregate low carbon-intensive sectors, this aggregation process still leads to differences. In addition, we assumed that states purchased products of the specific sectors from a globally averaged mix of products. Although this process accounted for different emission intensities from the production process of different countries, it does not allow us to know which country the state purchased products from. It brought uncertainties, especially when different states have specific trading partners. Third, uncertainties exist in emission estimation using the energy flow approach, which is based on the MRIO model we constructed. Because the GHGRP program has a mandatory reporting threshold 25,000 metric tons, emissions from facilities below this threshold should be estimated. Although we follow the IPCC processes, the accuracy of emission from fuel combustion relies on the MRIO we developed.

A3 *Supplementary figures*



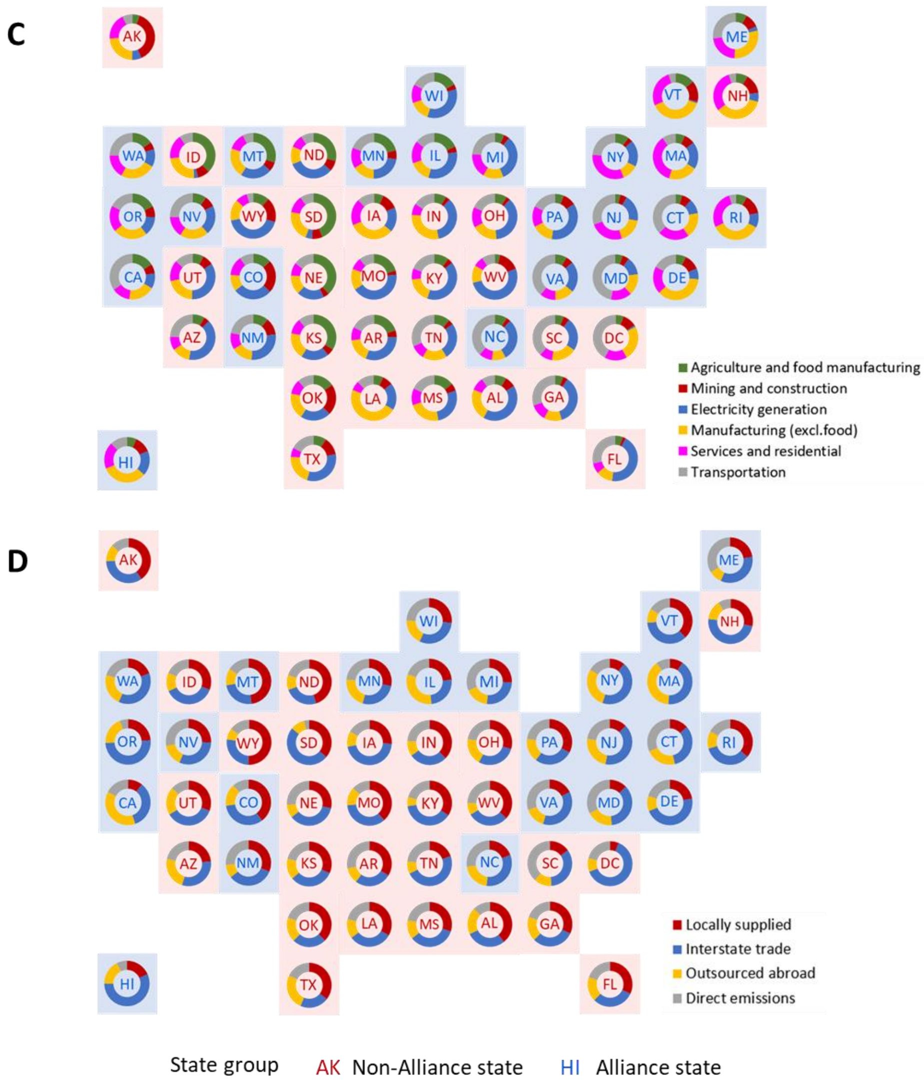


Figure A-1 Production-based and consumption-based GHG emissions for Alliance and non-Alliance states, and for all US states.

(A) Production-based GHG emissions for Alliance and non-Alliance states and individual state; (B) Consumption-based GHG emissions for Alliance and non-Alliance states and individual state; (C) Shares of six aggregated major production sectors in terms of production-based GHG emissions from individual state; (D) shares of three origins of production emission used to meet the state demand: local, other states, and abroad, as well as direct emissions from natural gas and gasoline-burning by final demand in terms of consumption-based GHG emissions from individual state.

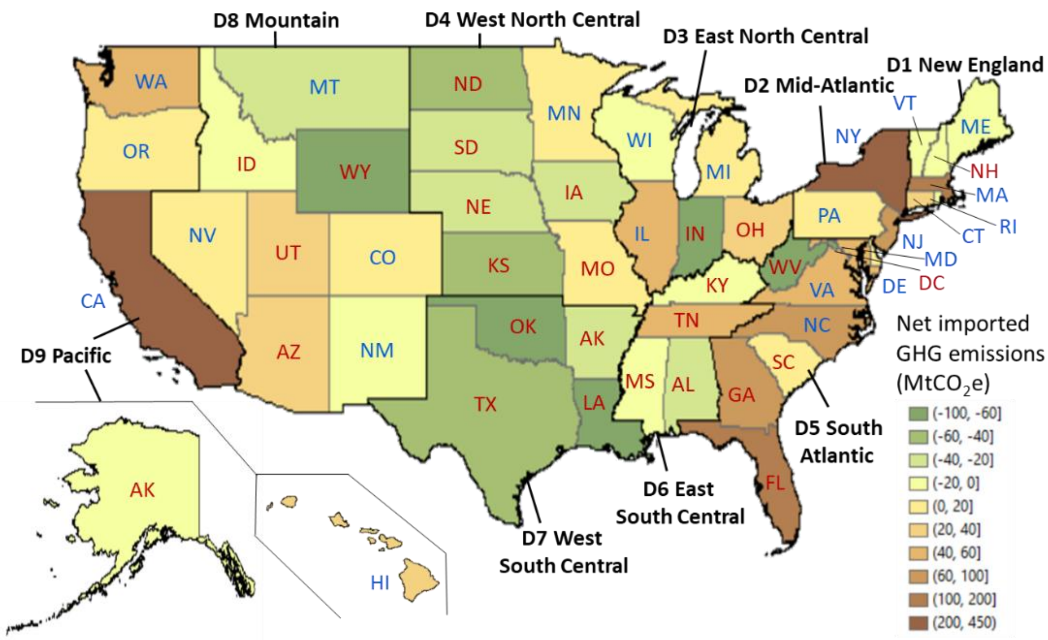


Figure A-2 Net imported GHG emissions for each U.S. state, including emissions embodied in both interstate and international trade

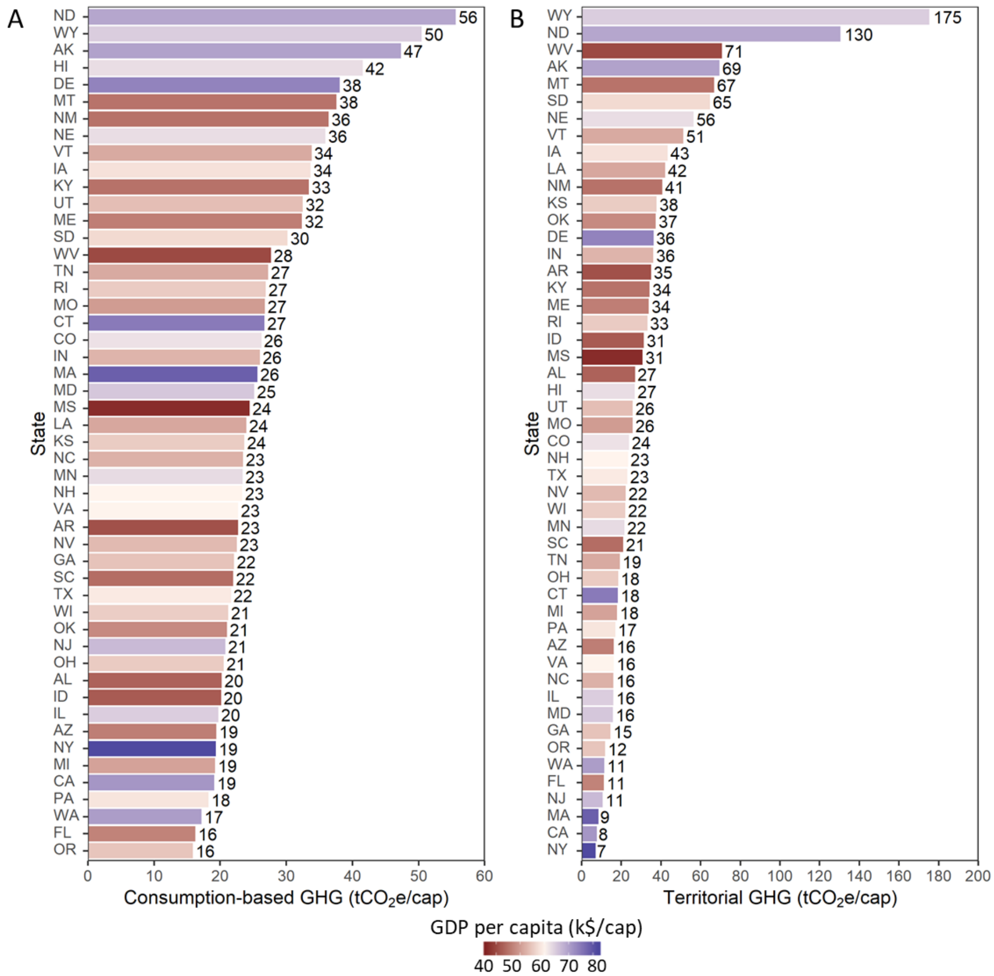


Figure A-3 Consumption-based and territorial GHG emissions per capita and GDP per capita for individual state in the U.S. in 2017

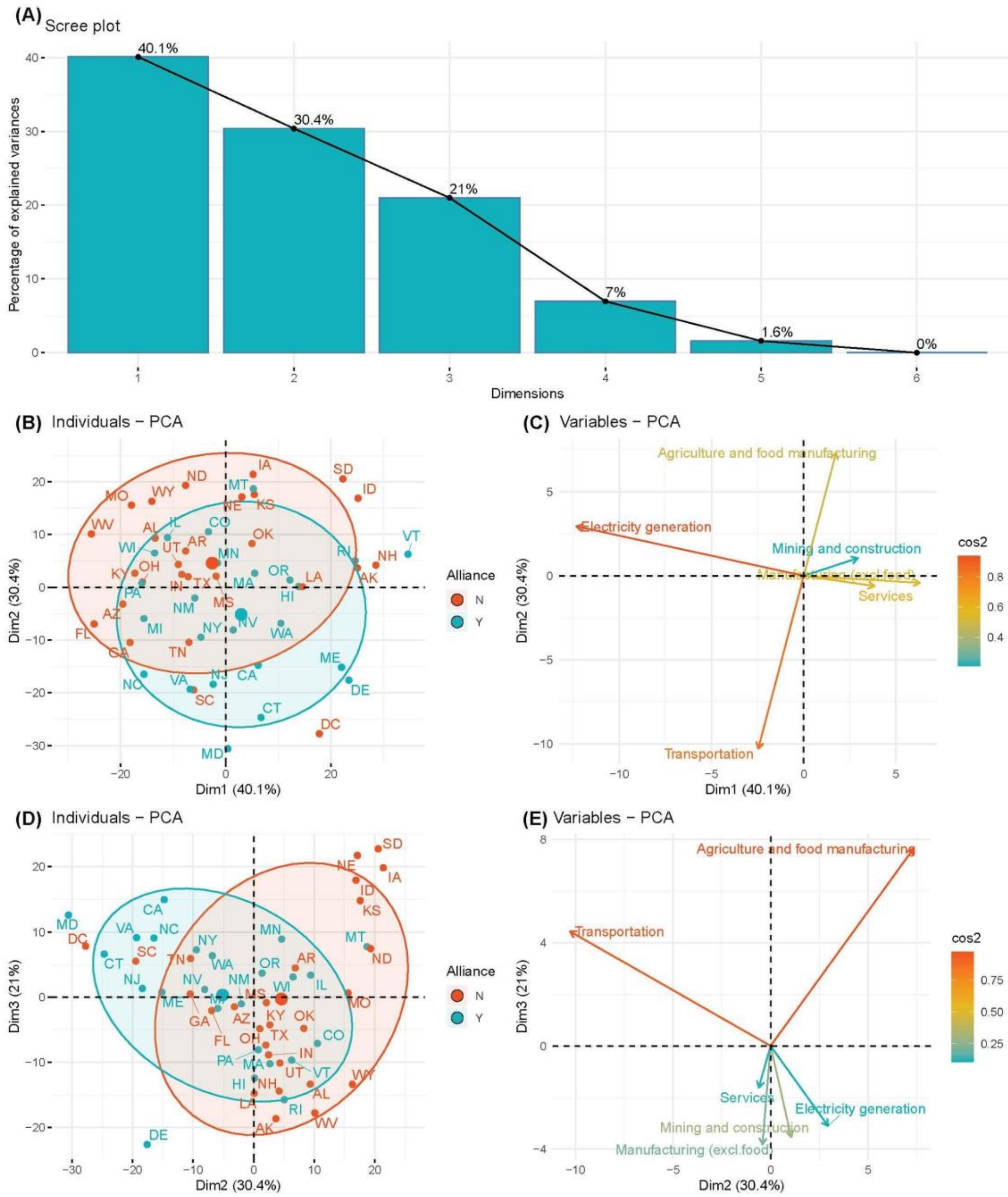


Figure A-4 Principal Component Analysis of territorial emissions from Alliance states and non-Alliance states

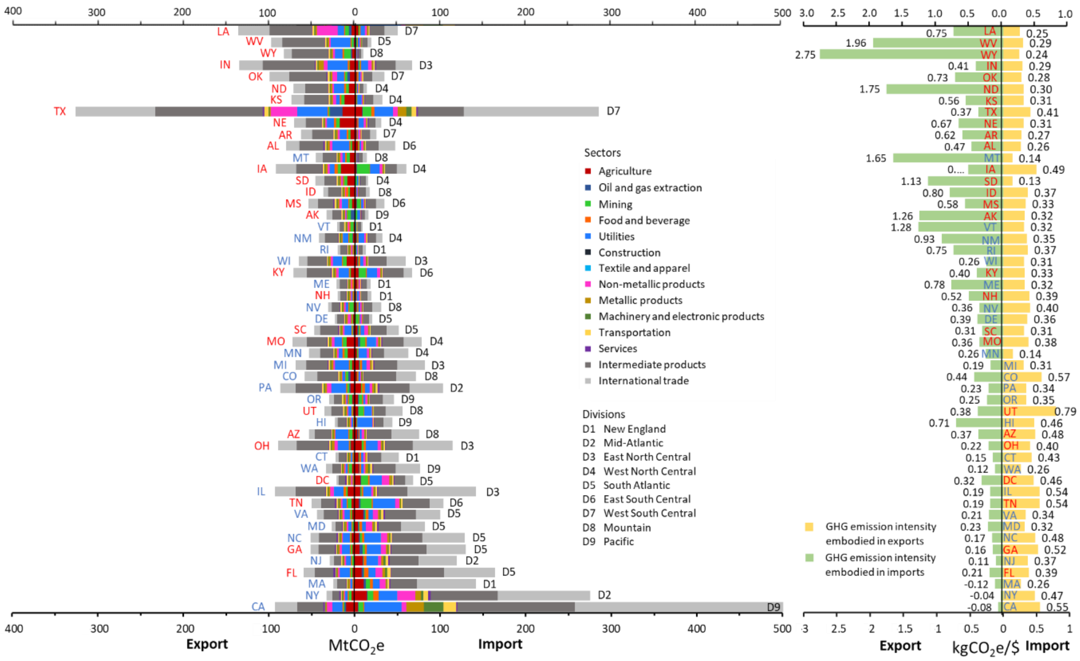


Figure A-5 Magnitude and composition of GHG emissions embodied in interstate and international trade by sectors for individual states in the U.S. (left). GHG emission intensity of products imported to the states exported from the states (right)

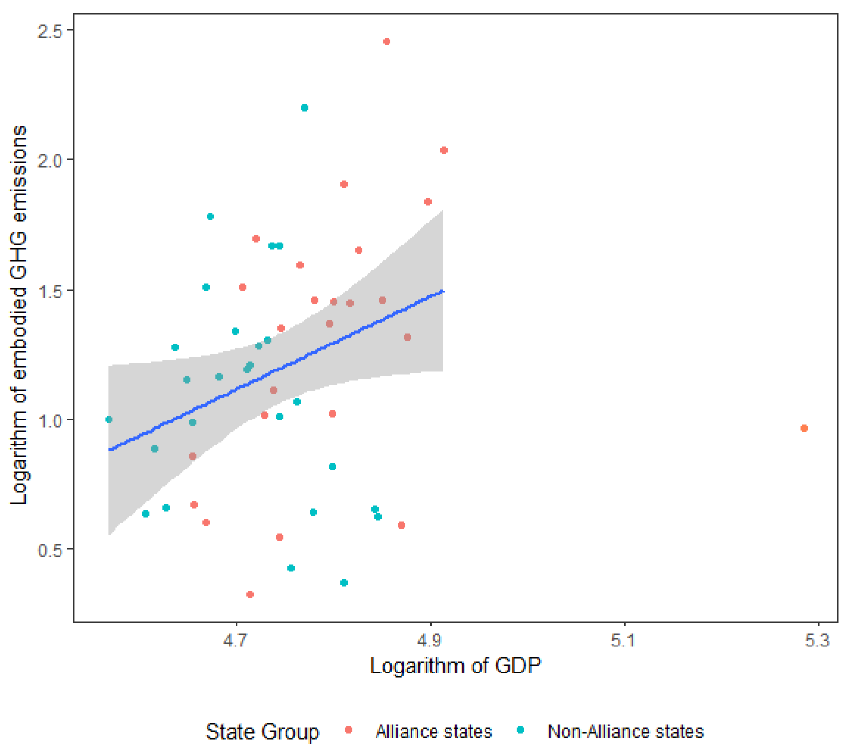


Figure A-6 Relationship between GDP and GHG emissions embodied in products purchased outside of the state

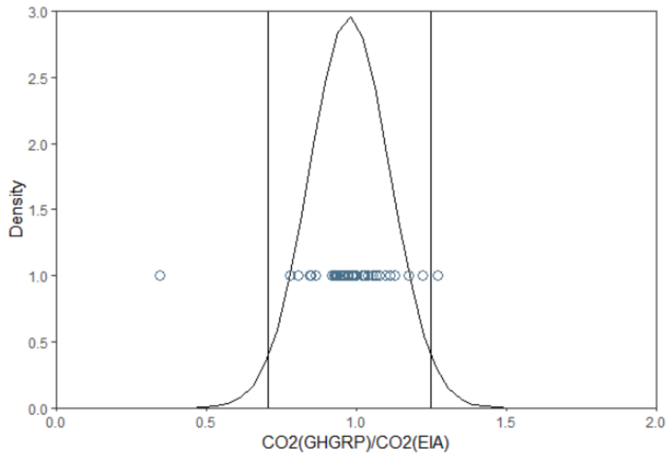


Figure A-7 Comparison between CO_2 emissions from mandatory GHG reporting program and CO_2 emission by state from EIA

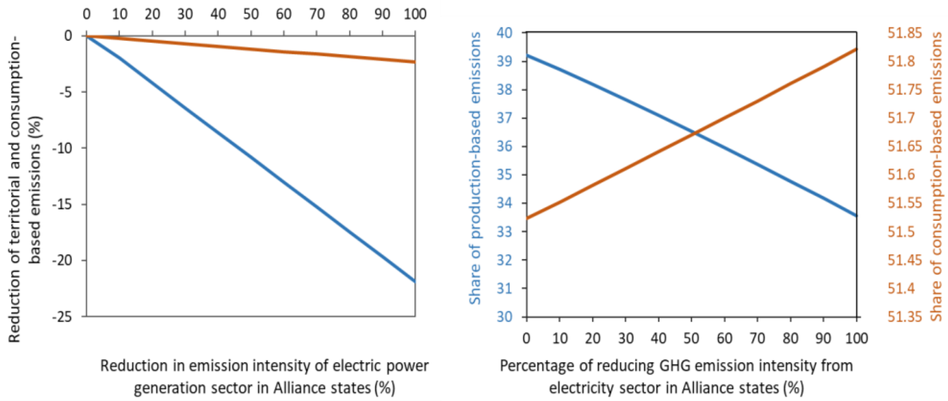


Figure A-8 Scenarios of reducing GHG emissions from climate Alliance states

(A) Percent of reduction of territorial and consumption-based GHG emissions (compared to 2017 level) under the scenario of reducing emission intensity of the electric power generation sector by 0-100% in Alliance states. (B) Shares of production-based and consumption-based GHG emissions from Alliance states under the scenarios of decarbonizing electric power generation (reducing emission intensity by 0 to 100%) within their territory. Scenario setting: reducing territorial emission from power generation in Alliance states, emission shares of Alliance states in terms of production-based emissions are shown on the left y-axis, emission shares of Alliance states in terms of consumption-based emissions are shown on the right y-axis.

A4 *Supplementary tables*

Table A-1 Aggregated sectors in MRIO model

Sector Code	Sector Name	Sector Code	Sector Name
1	Crop production	75	Coating, engraving, heat treating, and allied activities
2	Beef cattle ranching and farming, including feedlots and dual-purpose ranching and farming	76	Other fabricated metal product manufacturing
3	Dairy cattle and milk production	77	Agriculture, construction, and mining machinery manufacturing
4	Poultry and egg production	78	Industrial machinery manufacturing
5	Animal production, except cattle and poultry and eggs	79	Machinery manufacturing
6	Forest products and logging	80	Metalworking machinery manufacturing
7	Commercial fishing and hunting	81	Engine, turbine, and power transmission equipment manufacturing
8	Support activities for agriculture and forestry	82	Other general purpose machinery manufacturing
9	Extraction of natural gas and crude petroleum	83	Computer and peripheral equipment manufacturing
10	Extraction of natural gas liquids	84	Communications equipment manufacturing
11	Coal mining	85	Audio and video equipment manufacturing
12	Iron ore mining	86	Semiconductor and other electronic component manufacturing
13	Gold and silver ore mining	87	Navigational, measuring, electromedical, control instruments manufacturing and optical media
14	Copper, nickel, lead, and zinc mining	88	Electric lighting equipment manufacturing
15	Other metal ore mining	89	Household appliance manufacturing
16	Stone mining and quarrying	90	Electrical equipment manufacturing
17	Sand, carvel, clay, and ceramic and refractory minerals mining and quarrying	91	Other electrical equipment and component manufacturing
18	Other nonmetallic mineral mining and quarrying	92	Motor vehicle manufacturing
19	Support activities for mining	93	Motor vehicle body and trailer manufacturing
20	Electric power generation	94	Motor vehicle parts manufacturing

21	Electric power transmission, control and distribution	95	Aerospace product and parts manufacturing
22	Natural gas distribution	96	Railroad rolling stock manufacturing
23	Water, sewage and other systems	97	Ship and boat building
24	Nonresidential building construction	98	Other transportation equipment manufacturing
25	Residential building construction	99	Household and institutional furniture and kitchen cabinet manufacturing
26	Specialty trade contractors	100	Office furniture (including fixtures) manufacturing
27	Animal food manufacturing	101	Other furniture related product manufacturing
28	Grain and oilseed milling	102	Medical equipment and supplies manufacturing
29	Sugar and confectionery product manufacturing	103	Other miscellaneous manufacturing
30	Fruit and vegetable preserving and specialty food manufacturing	104	Wholesale trade
31	Dairy product manufacturing	105	Retail - motor vehicle and parts dealers
32	Animal slaughtering and processing	106	Retail - furniture and home furnishings stores
33	Seafood product preparation and packaging	107	Retail - electronics and appliance stores
34	Bakeries and tortilla manufacturing	108	Retail - building material and garden equipment and supplies stores
35	Other food manufacturing	109	Retail - food and beverage stores
36	Beverage manufacturing	110	Retail - health and personal care stores
37	Tobacco manufacturing	111	Retail - gasoline stores
38	Textile mills	112	Retail - clothing and clothing accessories stores
39	Textile product mills	113	Retail - sporting goods, hobby, musical instrument and book stores
40	Apparel manufacturing	114	Retail - general merchandise stores
41	Leather and allied product manufacturing	115	Retail - miscellaneous store retailers
42	Wood product manufacturing	116	Retail – non-store retailers
43	Paper manufacturing	117	Air transportation
44	Printing and related support activities	118	Rail transportation
45	Petroleum refineries	119	Water transportation
46	Asphalt manufacturing	120	Truck transportation

47	Petroleum lubricating oil and grease manufacturing	121	Transit and ground passenger transportation
48	Other petroleum and coal products manufacturing	122	Pipeline transportation
49	Petrochemical manufacturing	123	Scenic and sightseeing transportation and support activities for transportation
50	Industrial gas manufacturing	124	Couriers and messengers
51	Synthetic dye, pigment and other basic inorganic chemical manufacturing	125	Warehousing and storage
52	Basic chemical manufacturing	126	Publishing Industries (except Internet)
53	Resin, synthetic rubber, artificial, synthetic fibers and filaments manufacturing	127	Motion picture, sound recording and broadcasting industries
54	Pesticide, fertilizer, and other agricultural chemical manufacturing	128	Telecommunications and data processing
55	Pharmaceutical and medicine manufacturing	129	Other information services
56	Paint, coating, and adhesive manufacturing	130	Finance and insurance
57	Soap, cleaning compound, and toilet preparation manufacturing	131	Real estate
58	Other chemical product and preparation manufacturing	132	Rental and leasing services
59	Plastics product manufacturing	133	Professional, scientific, and technical services
60	Rubber product manufacturing	134	Management of companies and enterprises
61	Clay product and refractory manufacturing	135	Administrative and support and waste management and remediation services
62	Glass and glass product manufacturing	136	Educational services
63	Cement and concrete product manufacturing	137	Ambulatory health care services
64	Lime and gypsum product manufacturing	138	Hospitals
65	Other nonmetallic mineral product manufacturing	139	Nursing and residential care facilities and social assistance
66	Iron and steel mills and ferroalloy manufacturing	140	Arts, entertainment and recreation
67	Steel product manufacturing from purchased steel	141	Accommodation

68	Alumina and aluminum production and processing	142	Food services and drinking places
69	Nonferrous metal (except Aluminum) production and processing	143	Repair and maintenance
70	Foundries	144	Personal and laundry services
71	Forging and stamping	145	Religious, grantmaking, civic, professional and similar organizations and private households
72	Cutlery and hand tool manufacturing	146	Public administration services
73	Architectural and structural metals manufacturing	147	Others
74	Metallic products manufacturing		

Table A-2 Geographical regions and divisions of each state and the District of Columbia, designated by US Census Bureau

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

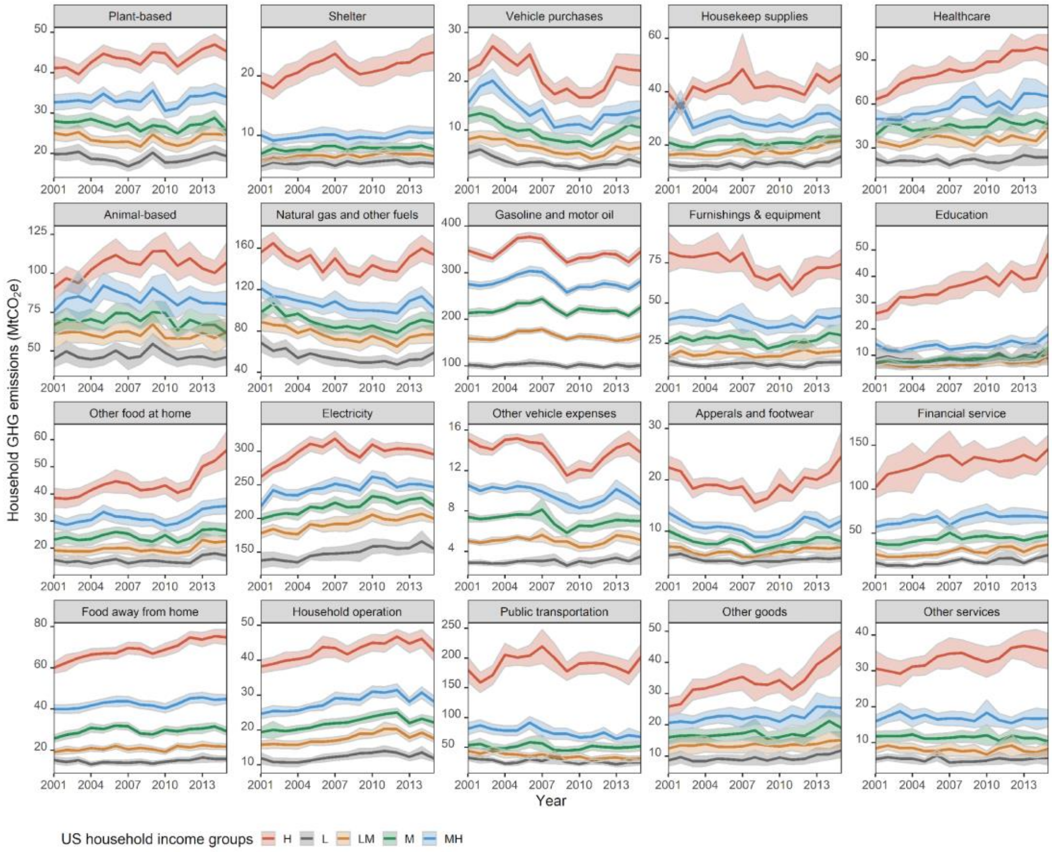
Table A-3 Sectors and CO_2 coefficients used for estimating GHG emissions from sectors under the threshold of the mandatory reporting program

Sector Code	Sector Name	CO_2 coefficient ($kgCO_2$/MBtu)	Energy price (Dollar per Btu)
9	Extraction of natural gas and crude petroleum	73.15	DFTXD
10	Extraction of natural gas liquids	61.82	HLTXD
11	Coal mining	94.28	CLTXD
22	Natural gas distribution	53.06	NGTXD
45	Petroleum refineries	71.26	MGTXD
47	Petroleum lubricating oil and grease manufacturing	74.21	LUTXD
48	All other petroleum and coal products manufacturing	74.84	OPTXD
49	Petrochemical manufacturing	68.37	FOICD
50	Industrial gas manufacturing	64.2	NGTXD
52	Other basic organic chemical manufacturing	74.54	PATXD

Table A-4 Sectors and CO_2 coefficients used for estimating direct emissions from final demand transportation

Sector Code	Sector Name	CO_2 coefficient ($kgCO_2$/MBtu)	Energy price code (Dollar per Btu)
45	Petroleum refineries	71.26	MGTXD
47	Petroleum lubricating oil and grease manufacturing	74.21	LUTXD
48	All other petroleum and coal products manufacturing	74.54	PATXD
49	Petrochemical manufacturing	68.37	FOICD

Appendices B Supplementary information for Chapter 3



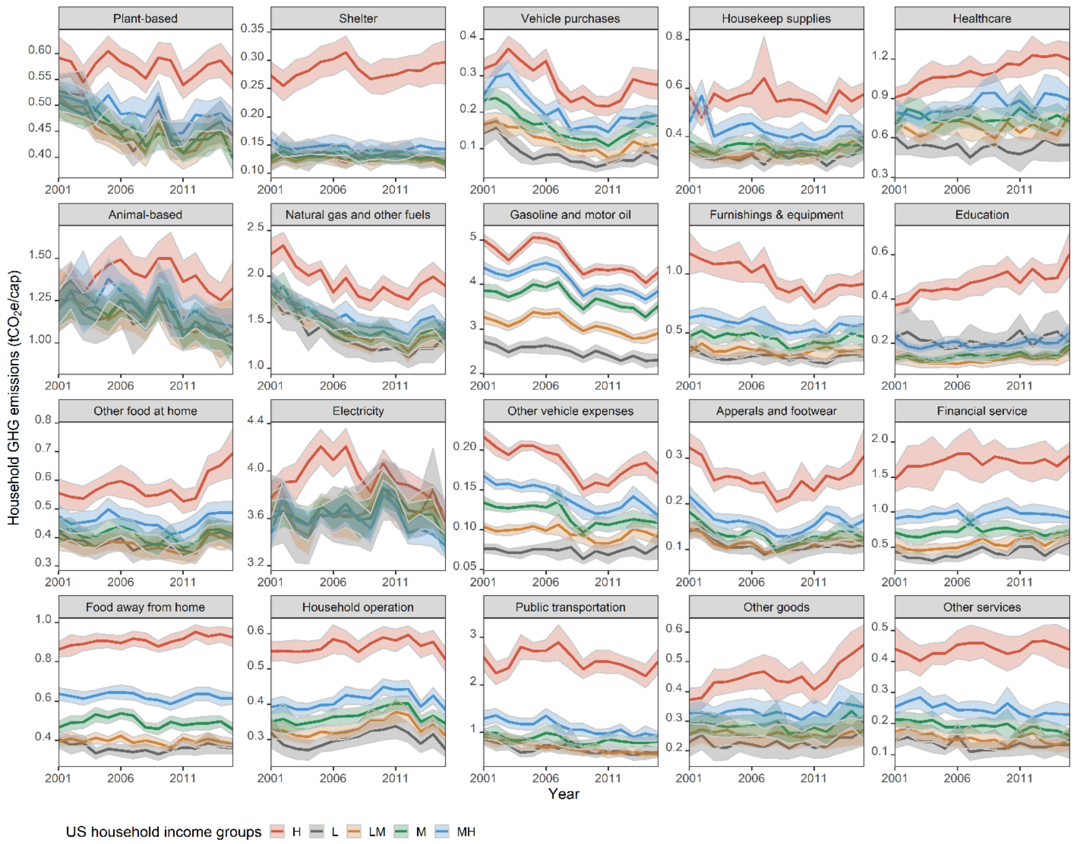


Figure B-1 GHG emissions from U.S. household consumption by quintile income groups based on national total and GHG emissions per capita

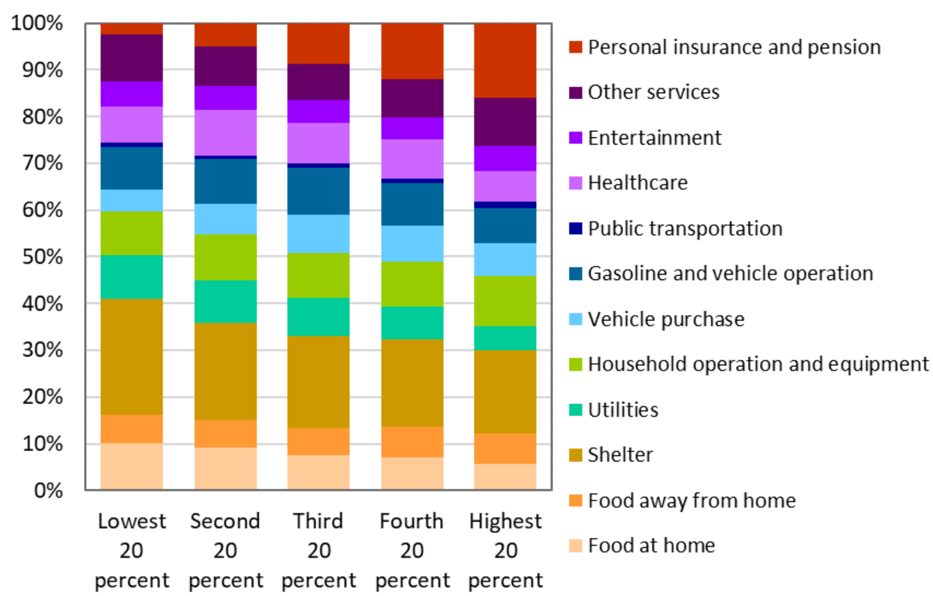


Figure B-2 Composition of household expenditure by quintile income group in the U.S.

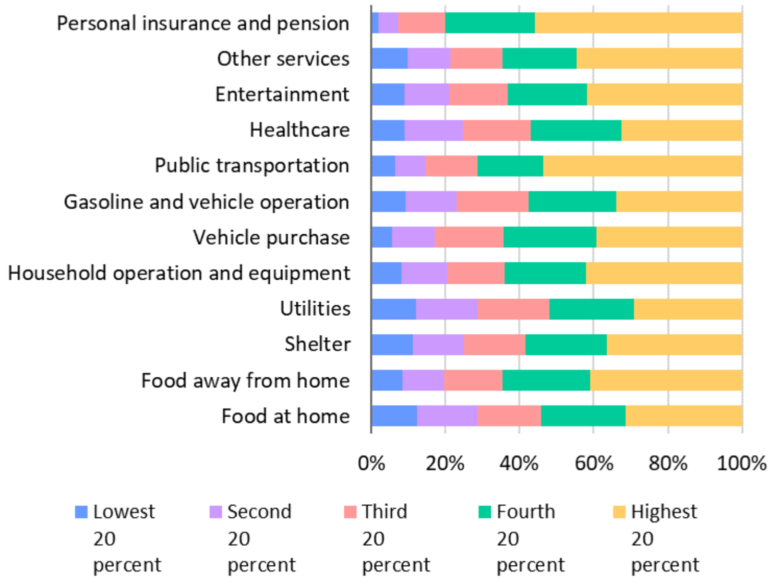


Figure B-3 Household expenditure distribution among different income groups

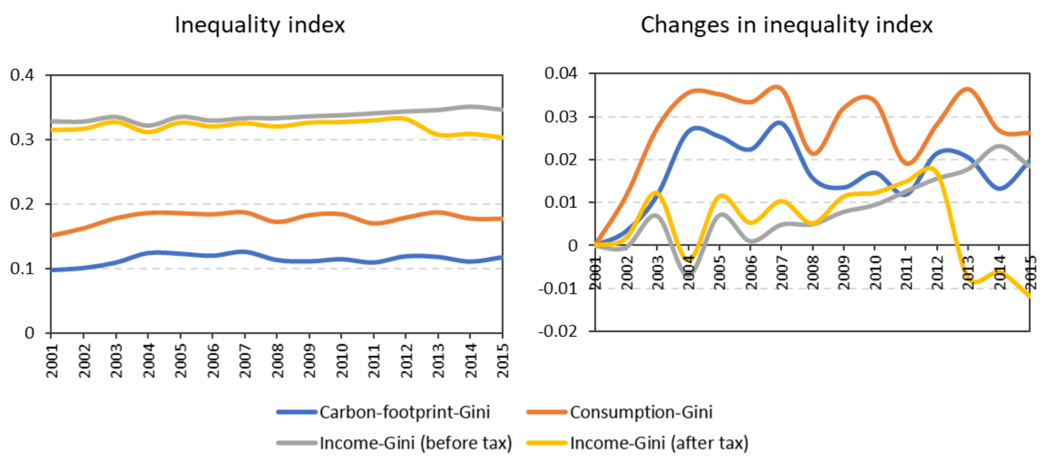


Figure B-4 Inequality indices and their changes from 2001 to 2015

Appendices C Supplementary information for Chapter 4

Table C-1 An example of needs-driven behavioral choice from individuals

Behavior group 1				
Needs	Dining in full-service restaurants	Take-out or food delivery	Consuming at limited-service restaurants	Cooking at home
Subsistence	0	0	0	0
Protection	0	0.3	0.1	0.3
Affection	0	0	0	0.1
Understanding	0	0	0	0
Participation	0	-0.1	0	0
Idleness	0	0	0	-0.1
Creation	0	0	0	0.1
Identity	0	0	0	0
Freedom	0	0.1	0	0
Wellbeing	0	0.3	0.1	0.4
				Behavior adopted
Behavior group 2				
Needs	Going to gym	Home gym	Working-out without equipment	Stop working-out
Subsistence	0	0	0	0
Protection	0	0.3	0.3	0.1
Affection	0	0.1	0	0
Understanding	0	0	0	0
Participation	0	0	0	-0.2
Idleness	0	0	0	0.1
Creation	0	0	0.2	0
Identity	0	0	0	-0.2
Freedom	0	0	0	0
Wellbeing	0	0.4	0.5	-0.2
			Behavior adopted	
Behavior group 3				
Needs	Commuting with public transportation	Commuting with private cars	Commuting by bikes	Telecommuting
Subsistence	0	-0.2	0	0
Protection	0	0.2	0.1	0.2
Affection	0	0	0	0
Understanding	0	0	0	0
Participation	0	0	0	-0.1

Idleness	0	0	0	0.2
Creation	0	0	0	0
Identity	0	0	0.1	0
Freedom	0	0.1	0.1	0.1
Wellbeing	0	0.1	0.3	0.4
				Behavior adopted

Behavior 1: Switching from dining in full-service restaurants to limited-service restaurants and home cooking.

Before the pandemic, food services (chained value) has been increased by 38% from 2002 to 2019 (BEA 2021b), and people's caloric intake from food away from home grew from 17% in the late 1970s to 34% in 2013-2014 (Mackie and Wemhoff 2020). During the pandemic, people avoided eating at full-service restaurants, instead, they switched to *Take-out or food delivery* (Substitute 1.1), *Consuming at limited-service restaurants* (Substitute 1.2), or *Cooking at home* (Substitute 1.3). We simulated their carbon footprints from an initial 80% reduction in full-service restaurant at the pandemic shock to a recovery level of 0-60% of pre-pandemic level to an overshoot of 20% more than pre-pandemic level. Additional details are shown in Table C-1.

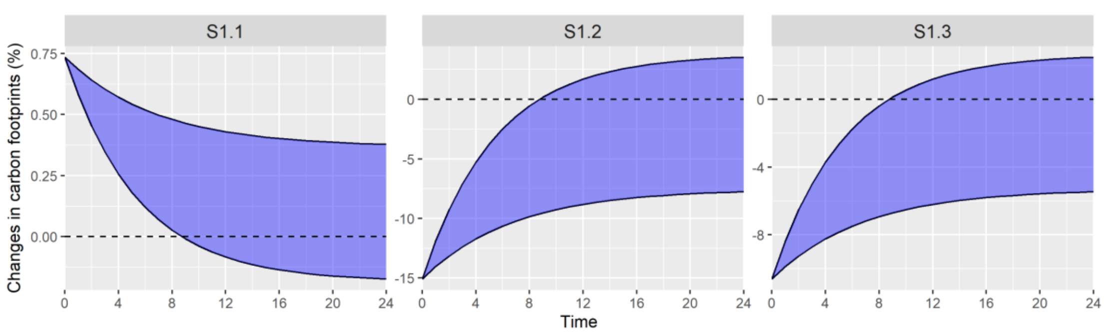


Figure C-1 Changes in carbon footprints of switching from dining in full-service restaurants to adding food-delivery services (S1.1), consuming in limited-service restaurants (S1.2) and cooking at home (S1.3).

Our results show that among the three substitutes to eating in full-service restaurants, eating at home has the largest potential of reducing carbon footprints from the economy-wide perspective, followed by eating in limited-service restaurants, while adding food delivery services would increase carbon footprints. Dining in full-service restaurants have the highest carbon footprints as people tend to order high-calorie food with drinks (Mackie and Wemhoff 2020). From an economy-wide perspective, switching to limited-service restaurants lowered people's footprints with less consumption and less food wastes (ReFED 2018). However, if 40% consumers intended to consume in full-service restaurants with additional food delivery service, increase carbon footprints by approximately 0.38%. More attention should also be paid to the overshooting scenarios for potential short-term and long-term

Behavior 2: Switching from going to gym to alternative workout plans

Consumer expenditure on gym and sports decreased by more than 95% in April 2020, up until early 2021, it has recovered to only approximately 15% compared to the pre-pandemic level (BEA 2021b). Sports and gym sectors are the ones that bear the brunt of the pandemic hit. While gym-related activities are not large carbon footprint contributors, they are an essential part of people's daily life and substantially changed during the pandemic. We simulate the carbon footprints of switching from gyms to alternative workout plans, including *Home gym* (Substitute 2.1), *Working-out without equipment* (Substitute 2.2), and *Working-out cancellation* (Substitute 2.3). Although people who switched from gym activities to various home sports equipment are dependent on their home space, economic status, etc., we assume they spend on sports equipment an average of twice times compared to gym memberships.

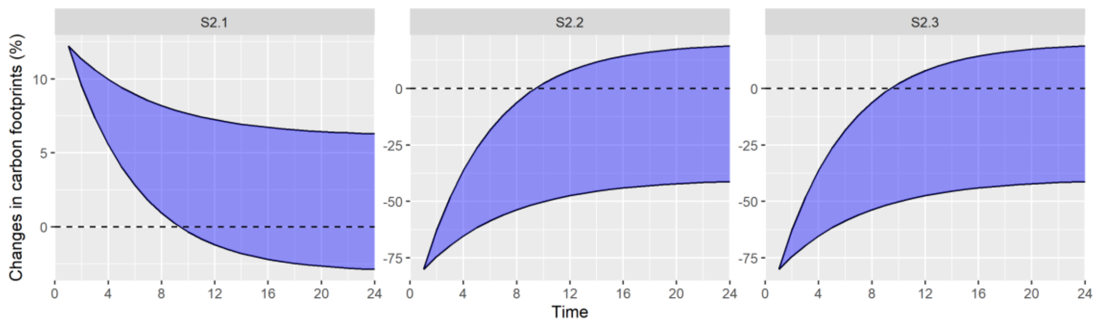


Figure C-2 Changes in carbon footprints of switching from public gyms to home gym (S2.1), working-out without equipment (S2.2) and working-out cancellation (S2.3).

Behavior 3: Commuting

Telecommuting has been perceived as a more sustainable and time-saving mode of working for its merits of reducing dependency on transportation and centralized office space (O'Brien and Yazdani Aliabadi 2020). The COVID-19 pandemic has accelerated its wide practice. As people become more acclimated with online interfaces for working, many companies are also likely to consider extending teleworking practices after the pandemic. Although the switching from working in offices to teleworking involves contextual details, here we provide a fast tool to roughly estimate the carbon footprints of such behavioral changes, assuming other social factors remain unchanged. Thus the main sectors involved, also the majority of studies suggested, are the decreased use of transportation and increased consumption of electricity at home (O'Brien and Yazdani Aliabadi 2020), despite inconsistent research methods and scopes.

Studies investigated the residential energy consumption after the lockdown. In Japan, 32% of households reported a household energy increase compared to 5% of households that reported a decrease at the beginning period of lockdown (Zhang 2021). Rouleau et al. studied the changes in residential energy and water consumption between and after the partial lockdowns in Canada (Rouleau and Gosselin 2021) and found that residential electricity increased by less than 2% during the lockdown period, but increased 17.5% in the first month of the lockdown. This implies a good sign that the more people stay at home, the more they may pay attention to the household energy use, such as adjusting home temperature and adopting more energy-efficient devices. Given that O*NET shows that 37% of jobs in the U.S. can be performed entirely at home (Dingel and Neiman 2020) and American Time Use Survey shows that American Time Use Survey shows that nearly 44% of workers had the ability to telework (Pabilonia and Vernon 2020), we assume stay-at-home order achieved the full potential of telecommuting at a level of 40%, and gradually recovered to a level of 30-10% compared to pre-pandemic level. According to DOT, driving private cars as commuting tools with single ridership increased approximately 20% between 2000 and 2017. In addition, commuting accounted for 18.6% person-miles of travel (USDOT 2018). Figure C-3 shows changes in carbon footprints by switching from public transportation to driving own cars (S3.1), switching from driving own cars to teleworking (S3.2), and switching from taking public transportation to teleworking (S3.3).

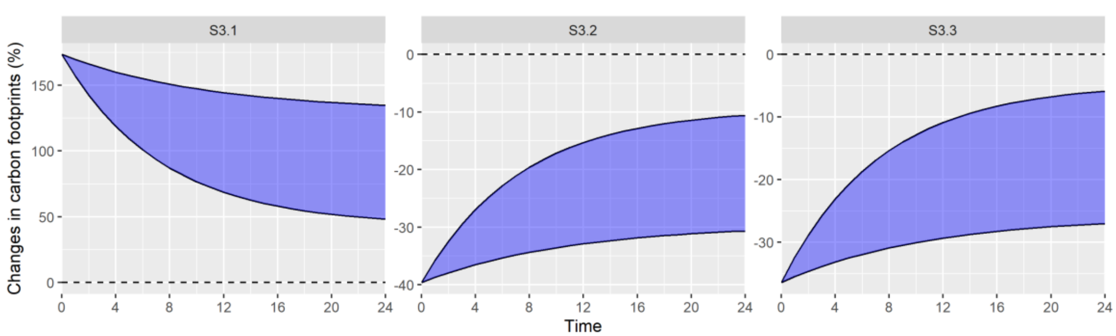


Figure C-3 Changes in carbon footprints of switching from public transportation to driving own cars (S3.1), cycling (S3.2) and teleworking (S3.3).

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