Global Environmental Change 77 (2022) 102596

Can U.S. multi-state climate mitigation agreements work? A perspective from embedded emission flows

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Keywords*:* Climate change; Climate mitigation; Embodied emissions; Climate Alliance; Carbon leakage; Multi-regional input–output analysis

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, that 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 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 international and interstate supply chains of the products they consume, the share of Alliance states 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. Our detailed sectoral analysis highlights the challenges facing such agreements to extend cooperation in the future for larger joint benefit given the potential for carbon leakage from member states implementing stricter environmental policies that could lead to higher emissions from non-member states. It is critical for these arrangements to pay close attention to transferred emissions.

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 (Jorgensen, Jogesh and Mishra, 2015), and leveraging local resources to foster demand-side actions. These opportunities embrace the merits of the emerging polycentric climate governance (Ostrom, 2009; Cole, 2015), 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 alternative strong supports should federal efforts prove inadequate or fail (Hale, 2018; Hultman et al., 2020; Kuramochi et al., 2020; Masson-Delmotte 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 their 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 are the lessons learned from investigating these coalitions to other potential members when efforts are scaled up if the lessons learned only apply to specific circumstances of each member.

Potential carbon leakage due to the interconnected nature of economic activities adds further complexities in quantifying the climate contributions from subnational actors; this factor has not been considered by the currently proposed quantification framework (Hsu et al., 2018). Greenhouse gas (GHG) emissions embodied in trade are difficult to trace at higher spatial resolution due to the volume and number of traded products. Given that self-selected climate entities are prone to underestimate their GHG emission inventories, neglecting such embodied emissions from purchasing carbon-intensive products could increase the gap between estimated GHG emissions and actual emissions they should be responsible for by adding net inflows of embodied emissions (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 capabilities 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 initiatives (such as California and New York) for their territorial contribution to climate mitigation. These initiatives could serve as a guide to identify 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 policies that could be ideally applied by the federal government (Peng et al., 2021). However, the 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 in curbing 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, 2020). 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, 2020). 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 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 (Peters and Hertwich, 2008; Davis and Caldeira, 2010). 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 effects 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 frequently quantified by input-output analysis, where emissions induced from every lifecycle stage are attributed to consumers (Hertwich and Peters, 2009). The gravity model has the advantage of generating more credible Type 2 multipliers (which accounts for direct, indirect and induced effects from supply chains) compared to other models and is used to capture detailed commodity flows (Riddington, Gibson and Anderson, 2006; Feng et al., 2013). This approach allows us 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; 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 chains.

2. Methods and materials

2.1. Environmentally-extended MRIO framework

2.1.1. Construction of US 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, 2009). Using this approach, we examined GHG emissions embodied between Alliance states and non-Alliance states, based on their Alliance status by the end of 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 S1). 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 its 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, 2009). 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 (Lenzen, Pade and Munksgaard, 2004; Steen-Olsen et al., 2014; Fournier Gabela, 2020). 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,

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

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

$$c_i^{rs} = \frac{z_i^{rs}}{T_i^s} \quad (2)$$

Therefore, the interregional commodity proportion is

$$\hat{\boldsymbol{c}}^{rs} = \begin{bmatrix} c_i^{rs} & 0 & \cdots & 0 \\ 0 & c_i^{rs} & & \vdots \\ \vdots & 0 & \ddots & 0 \\ 0 & 0 & & c_n^{rs} \end{bmatrix} \quad (3)$$

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

Expressed with *c*, the MRIO model is

$$(\boldsymbol{I} - \boldsymbol{CA})\boldsymbol{x} = \boldsymbol{Cf} \quad (3)$$

where, ***A*** is a matrix denoting technical coefficients; ***I*** is the identity matrix; ***x*** is the total output vector; ***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, 2009). This could 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 (ten Raa, no date; Miller and Blair, 2009). 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.

2.1.2. GHG emissions embodied in imports and exports

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

We use EE-MRIO to calculate the consumption-based GHG emissions, as expressed below.

$$\boldsymbol{E_{dom}} = \boldsymbol{e_{dom}} \times (\boldsymbol{I} - \boldsymbol{A_{dom}})^{-1} \times \boldsymbol{W_{dom}} + \boldsymbol{E_{dom\_dir}} \qquad (5)$$

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

The U.S. is a large GHG emission importer with net imported GHG emissions accounting for approximately 6.6 % of the total consumption-based GHG emissions in 2019 (Friedlingstein et al., 2021). 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 GWP100 conversion (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

EXIOBASE 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 tables 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

$$\boldsymbol{\varepsilon_{int}} = \boldsymbol{e_{int}} \times \boldsymbol{L_{int}} \times \boldsymbol{W_{int}} \tag{6}$$

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 $(I - A_{int})^{-1}$ 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. Comparing with 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. GHG emissions 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 (US EPA, 2018; EPA, 2019b). 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 Supplementary Information (SI).

3. Results

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, 2020) account for 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 Fig. 1A, and found that most of the 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 Fig. S2.

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 Fig. 1B), and the composition of consumption-based GHG emissions by location of emission occurrence (as shown in the lower panel of Fig. 1B). The state details are shown in Fig. S1. 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 S2). 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, 2017). 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).

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 economic 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 sectors (accounting for 64.6 % of U.S. manufacturing in 1980 and 71.1 % in 2018) (EIA, 2020). 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.

A large proportion of the consumption-based GHG emissions are associated with interstate and international trade (as shown in Fig. 1B). California is 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 %, with the lowest one being 34.6 % for Wyoming. 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 %.

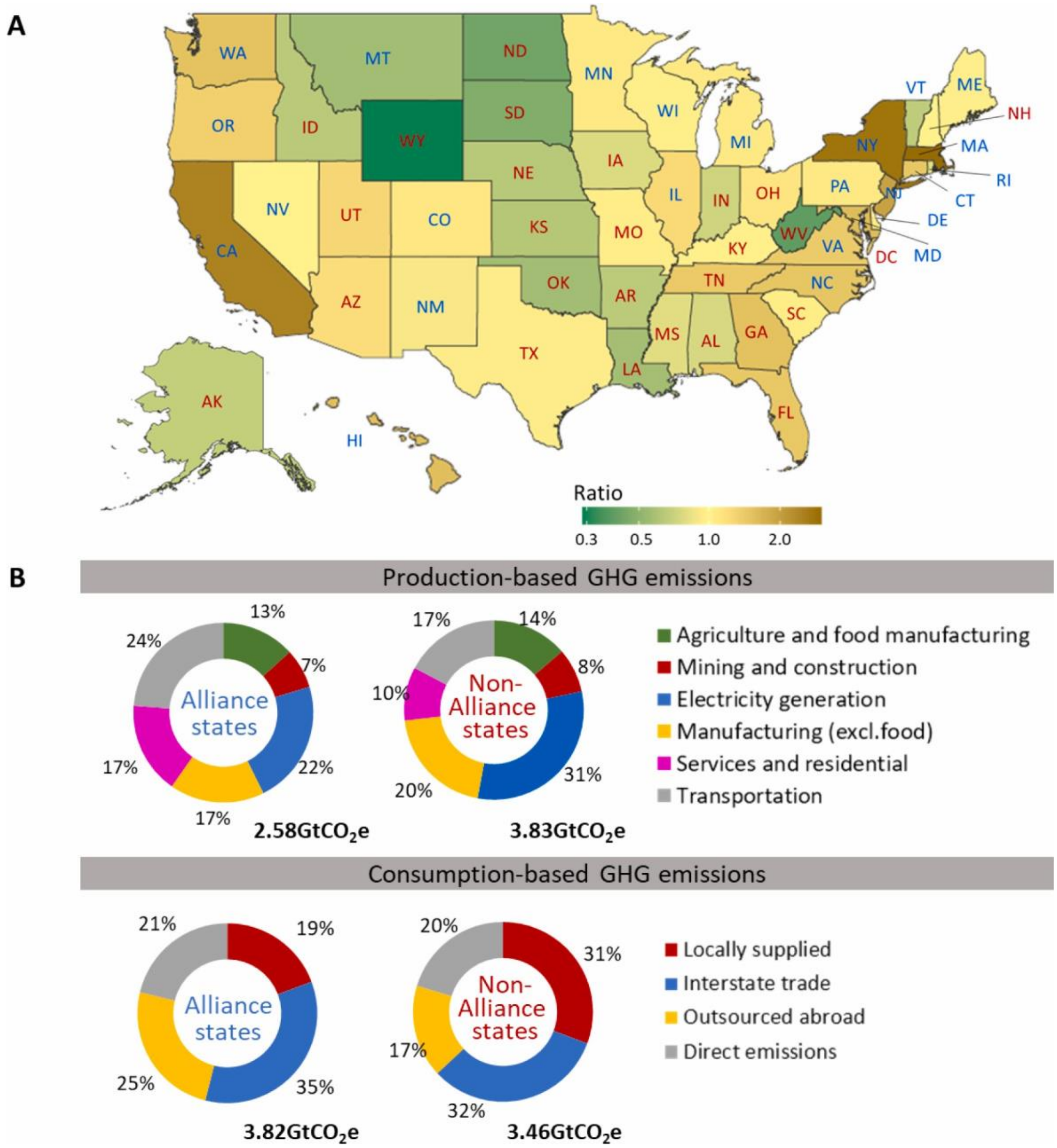

Fig. 1. Consumption vs territorial emissions for Alliance and non-Alliance states. (A) The ratio of consumption-based emissions to territorial emissions for each state; (B) The components of production-based GHG emissions for Alliance and non-Alliance states in terms of major production sectors (upper) 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).

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 (Fig. 2) (with more details in Fig. S3). We found that Alliance states have lower production-based GHG emissions per capita than non-Alliance states (14.4 tCO_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.

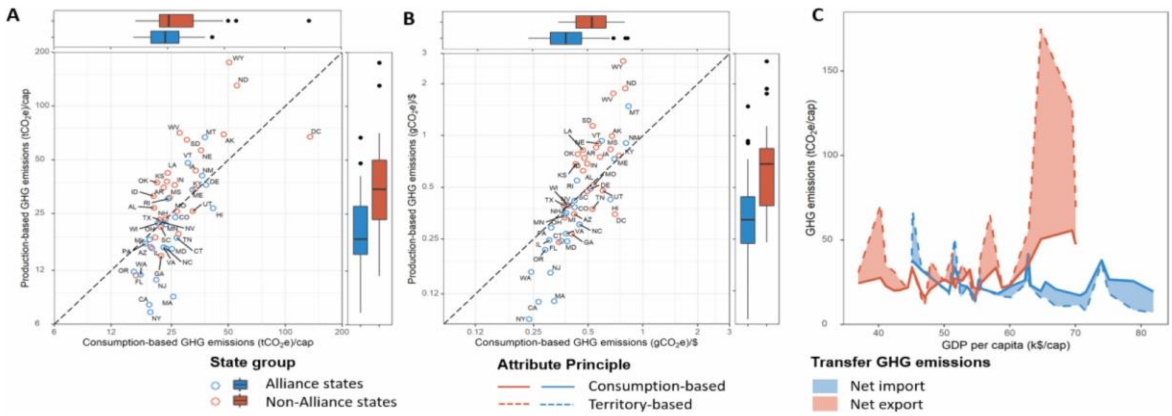

Fig. 2. Per capita and per GDP production-based and consumption-based GHG emissions for Alliance and non-Alliance states. (A) Per capita production-based and consumption-based GHG emissions for Alliance and non-Alliance states; (B) Per GDP production-based and consumption-based GHG emissions for Alliance and non- Alliance states; (C) Patterns of GHG emissions vs GDP per capita for Alliance states and non-Alliance states. The boxplots e the distribution of per unit GDP and per capita production-based and consumption-based GHG emissions for Alliance states and non-Alliance states.

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 (Fig. 2A and B). 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 the agricultural sector and electricity production (more details in Fig. S4). The larger heterogeneity of non-Alliance states derives from contextual structural differences.

Fig. 2C presents the relationship between GDP per capita and GHG emissions per capita, which highlights two opposing 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, GDP, energy efficiency and fuel mix 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 shared commons and less carbon-intensive lifestyles from the residents (Jones and Kammen, 2014; Markolf et al., 2017).

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 (Fig. 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.

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

Transferred emissions are associated with the production of intermediate goods and being traded as final products, where the latter was broken down into detailed sectors, as shown in Fig. 4 (state details are shown in Fig. S5). 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 (Fig. S6). 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 $kgCO_2e/\$$).

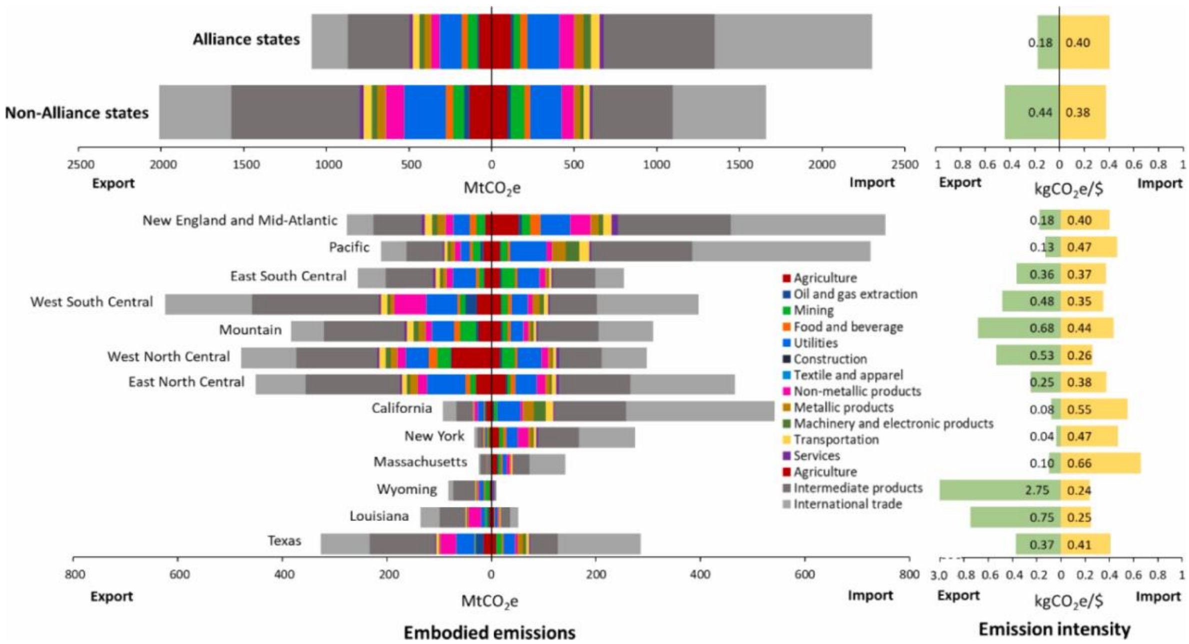

Fig. 3. Virtual GHG emission flows within the U.S. The sizes of the circles represent net GHG emissions embodied in interstate trade, with Alliance states coded with blue and non-Alliance states coded with red. The width of the green-colored flows shows the amount of virtual GHG emission flows between states. This map only shows flows larger than 0.3 $MtCO_2e$. Exported flows are in a clockwise direction. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

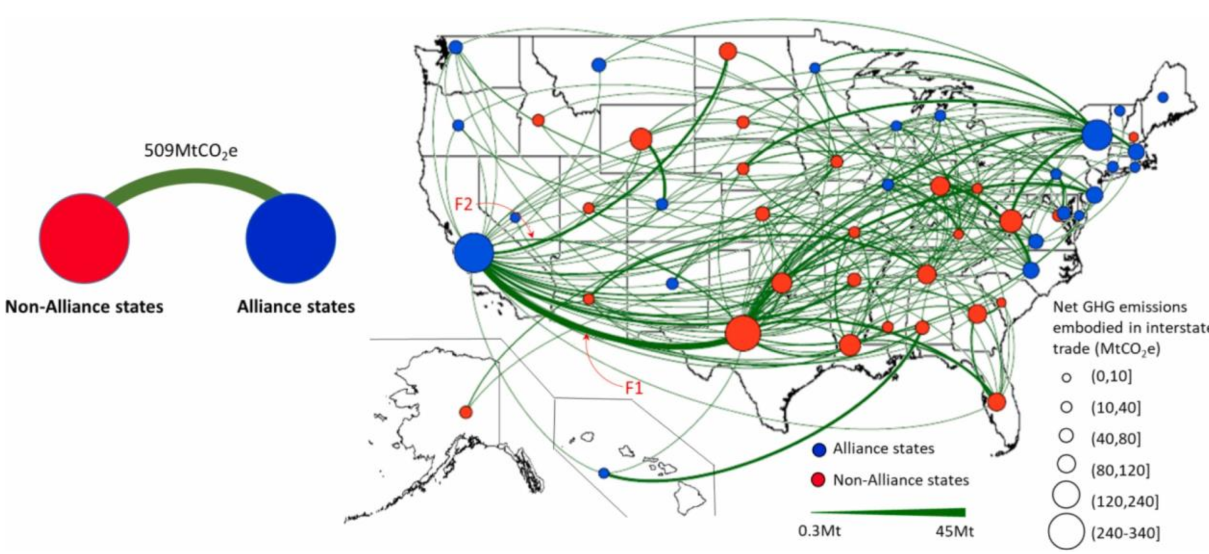

Fig. 4. Magnitude and composition of GHG emissions and emission intensity of transferred products. Magnitude and composition of GHG emissions embodied in interstate and international trade by sectors for Alliance states, non-Alliance states, key geographical divisions and a few important individual states 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 in terms of 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 embody a large amount of emissions through trade. For example, West North Central area, where major agricultural producers are located, such as Iowa and Nebraska (USDA, 2021), presents to have the largest emissions embodied in selling agricultural products to other states. 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 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.

4. Discussion

Our analysis quantified GHG emissions driven by the consumption of goods and services from each state in the U.S. and examined interstate GHG emission transfer. We compared the country-level total consumption-based GHG emissions from our analysis with that calculated from EXIOBASE (v.3) in the U.S. and found that the latter is 2.6 % lower comparing to our analysis. This supports the reliability of our results, where the difference mainly comes from the difference in production-based GHG emissions and the calculation of direct GHG emissions which is documented in Tukker, Wood and Schmidt (2020). More details about the comparison of production-based GHG emissions between different data sources that supports the robustness of the results can be found in SI.

The 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. The challenges found from this study would motivate exploration of alternative strategies for more effective subnational climate mitigation actions.

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 leadership 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 et al., 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 association 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 et al., 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 in the northeastern United States, 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).

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 of boosting 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 (Peters et al., 2011; Aichele and Felbermayr, 2015; 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 fingerprint, 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 non-members 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 signatory 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 (Branger and Quirion, 2014; Sato and Dechezlepretre, 2015; Naegele and Zaklan, 2019). 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 are redirected to domestic consumption because of a border tax (Jakob and Marschinski, 2013), as non-Alliance states are likely to consume more carbon-intensive products because of price signals. 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 the adverse effects of one-sided interventions, one potential solution is to include 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 guidance of 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 to are mostly based on their territorial emissions. Some states initiated to include upstream emissions from electricity sectors which could be a leap step to address 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 in states' energy profile, it is still much less than the amount of emissions embodied in products between states (as seen in Supplementary discussion). Therefore, we suggest that subnational targets include embodied emissions from all products participating in the supply chain.

To be able to capture the effect of the embodied emissions 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).

5. Conclusions

Our study 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. We 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.

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. Our results also suggest that subnational actors should be mindful of potential carbon leakage through trade and relocations as a result of territory-centered climate policies.

We discussed the challenges, based on our 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, we 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. We suggest that subnational targets should include embodied emissions from all products participating in the whole supply chain.

CRediT authorship contribution statement

Kaihui Song: Conceptualization, Methodology, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Giovanni Baiocchi:** Conceptualization, Methodology, Investigation, Supervision, Writing – original draft, Writing – review & editing. **Kuishuang Feng:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Klaus Hubacek:** Conceptualization, Writing – original draft, Writing – review & editing. **Laixiang Sun:** Conceptualization, Writing – original draft, Writing – review & editing. **Daoping Wang:** Writing – original draft, Writing – review & editing. **Dabo Guan:** Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

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

Acknowledgments

University of Maryland College of Behavioral and Social Science (BSOS) Dean's Research Initiative 2953980 (KS).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloenvcha.2022.102596. Emission flows data are available online at

GitHub - kaihuis/GEC_US_statelevel_ghg_emisions

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