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Heterogeneity of consumption-based carbon emissions and driving forces in Indian states

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ABSTRACT

As the second most populous country in the world, India is on the way to rapid industrialization and urbanization, possibly becoming the next carbon giant. With its vast territory and high regional heterogeneity in terms of development stages and population, state-level consumption-based emissions patterns and driving forces are critical but unfortunately, remain far from completed. In this paper, we first applied a multi-regional input-output model to ascertain heterogeneity in consumption-based emissions and track carbon flows in the inter-state supply chain, using our newly constructed Indian multi-state input-output table for 2015, based on Flegg location quotient method. We found that household consumption dominated consumption-based emissions at state levels, accounting for 60–78% of total consumption-based emissions, while investment-led emissions were relatively higher in developed regions the in developing regions. More than 30% of consumption-based emissions in developed states were imported from less developed states with higher carbon intensity, indicating a large spillover effect. In India's low carbon transition, policymakers should not only focus on a local mitigation policy in developed states, but on carbon leakage from the developing states, given the significant heterogeneity in industrial distribution and population. Inter-state cooperation is recommended, with developed states subsidizing the mitigation in the developing states, which also entails a lower marginal cost to low carbon transition.

1. Introduction

India, responsible for 7% of global CO_2 emissions in 2018, is the third largest energy consumer and CO_2 emitter in the world [1]. Since 2010, India's emissions increased from 1750.56 Mt to 2621.29 Mt in 2018, and were responsible for 21.5% of the global emission increment over the same period [2]. This sharp increase of CO_2 emissions in India is mainly driven by economic growth, and in particular by the rapid industrialization of some developed states [3, 4]. Such performance suggests that India will be the next carbon giant. On the one hand, as home to 1.3 billion people, only 32% of India's population lives in urban areas, which means that it is likely to see the world's largest shift towards urbanization (with an estimate of a 50% urbanization level by 2050) [5]. On the other hand, India is the seventh largest country in terms of GDP, having an average annual growth rate of 7.0% GDP [6] but emits 1.9t CO_2 per capita a year, eight times lower than that of the United States and four times lower than that of China (as a comparable developing country) [7]. The potential for industrialization, and the catch-up effect in CO_2 per capita, will see resource-intensive and labor-intensive productions prevail in India, under the transition from service-oriented to industry-oriented and relaxed environmental standards [8]. Therefore, India's emissions will increase rapidly and continuously over the next few years, and see the country become one of the main contributors to global emissions [9].

To facilitate a low carbon transition, India launched its Intended Nationally Determined Contributions (INDC) with a pledge of reducing the emission intensity of its GDP by 33–35% from its 2005 level by 2030 [10]. India has also implemented a National Action Plan on Climate Change (NAPCC), which identifies eight "National Missions" to fulfill its INDC commitments [11]. In addition, State Action Plans on Climate Change (SAPCC) for all states in India set a series of targets to lower carbon intensity through regional efforts to achieve coherence between the

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strategies and actions at national and subnational level [12]. Due to its vast territory, diverse socioeconomic backgrounds and resource endowments, there is huge heterogeneity between Indian states. For example, less developed central and eastern states, such as former "BIMAROU" states,[1] including Bihar, Madhya Pradesh, Rajasthan, Odisha and Uttar Pradesh, are characterized by a weaker economy and lower socioeconomic status, but with sufficient natural mineral resources and cheap labor [13]. In order to comprehensively formulate regional mitigation policies, a pilot research project for feasibility and efficacy of interstate emission trading should be implemented, offering insights into the regional disparities discussed above [14, 15].

Previous studies have already investigated subnational production-based emissions and emphasized its policy implications for regional mitigation [16–18]. However, progress against emissions targets could also be evaluated through the use of consumption-based emission inventories that reallocate emissions from states where products are produced, to states where products are ultimately consumed [19, 20]. Such consumption-based accounting of CO_2 emissions may better reflect the responsibility for paying the costs of emission mitigation [21, 22]. Regarding research on consumption-based emissions for India, most studies focus on the national level, resulting in highly aggregated data and absence of regional variations [23, 24]. For a large country like India, addressing spatial aggregation issues and considering regional heterogeneities, will help clarify root drivers and allocate emission reduction responsibility to regions. Previous studies have already proposed a multi-regional input-output model for regional emission studies and have explained the pattern of emission flows in other countries with vast areas of territory [25, 26]. To the best of our knowledge, India's consumption-based emissions at a state level have not been quantified, leaving open the question of how to mitigate emissions from a regional and consumption-based perspective.

Here, our study focuses on the heterogeneity in consumption-based accounting of CO_2 (from combustion of fossil fuels) at state level in India and tracks CO_2 emission flows within India, by constructing a state-level multi-regional input output model (MRIO). Due to the lack of a MRIO table, the Flegg location quotient method and gravity model are applied to compile an Indian MRIO table in 2015, which includes 32 states and 50 sectors. The contribution of this paper is twofold: first, consumption-based emission inventories at state level are estimated for the first time; and second, we track CO_2 emission flow among states in India and establish the pattern of outsourcing of CO_2 emissions. Our findings demonstrate that household consumption in affluent states dominate the total consumption-based emissions in India. The pattern of outsourcing of CO_2 emissions within India suggests that another contribution these affluent states could make is to introduce cleaner technologies into less developed states via some financial mechanism, such as an interregional clean development mechanism. Our findings and suggestions are also made for the improvement of regional energy efficiency and management of energy use, due to the connection between energy use and CO_2 emission.

The paper is organized as following: After the introduction section, we give a brief review of the existing literature. Then, we briefly introduce the accounting framework of consumption-based emissions in India and the underlying data. In the results section, we provide a descriptive overview on consumption-based emissions among 23 regions (including 3 union territories, 2 aggregated regions and 18 states) in India, illustrating ranking and composition of consumption-based emissions. We then rank emission flows within India and identify which states are key net emission exporters and importers. After the results section, we discuss the domestic and international policy implication of our results. Lastly, we conclude this study and state the uncertainties and limitations.

[1] Note: Rajasthan and Odisha no longer belong to BIMAROU after 2018.

1.1. Literature review

As the Indian climate issue has become an increasing concern for 1.5 °C global mitigation target, a considerable body of research has investigated the potential trajectories to achieving low carbon development and emission mitigation policies [27]. In the existing literature, most research has focused on production-based emission management. Some scholars focus on specific industries, such as the iron and steel industry [28], the electricity generation industry [29], the cement industry [30, 31]. William et al. have initialed a forward projection of output from iron and cement industries and estimated the energy and CO_2 emissions savings, based on a bottom-up conservation supply curve methodology [31]. Some researchers also focus on production-based driven factors of CO_2 emissions. Rapid economic growth in India has been the dominating driving force contributing to the increase in carbon emissions, while energy intensity has been the main factor reducing carbon emissions [7, 32]. Meanwhile, research on demand-side management has gradually emerged. Some papers have quantified national indirect emissions and complete emissions [24, 33], and have identified dynamic or global drivers from a consumption-based perspective [34-36]. For example, Wang et al. have found that since 2008, final demand has been the major driving force behind the increase in carbon emissions transfers from capital formation to household consumption [34]. Few studies have investigated regional analysis to illustrate the specific policy implications. Jemyung et al. have quantified regional carbon footprints of households, and highlight the need to differentiate individual responsibilities for climate management [37]. However, previous studies have not clarified the root drivers, taken into account regional heterogeneities in the industry chain, which is the problem addressed in this paper.

2. Methodology and data sources

2.1. Accounting scope

A clear definition of the scope of emission accounting could avoid double-counting in emission estimates. The International Council of Local Environmental Initiatives initialed 3 scopes of emission boundaries [38]. Scope 1 includes direct emissions from fossil fuels combustion within territory boundaries. Scope 2 includes emissions from consumption of imported electricity from upstream power plants. Scope 3 includes the indirect emission from upstream productions, that is, emissions embodied in trade [39].

In this study, carbon emissions were calculated using two approaches: production-based emissions (Scope 1, Sectoral Approach) and consumption-based emissions (Scope 3, Regional Input-output Model) [40]. Production-based carbon emissions in this study only refer to energy-related emissions from the combustion of fossil fuels, excluding emissions from industry processes or agriculture production. In addition, this study only considered CO_2 emissions without other non-CO_2 greenhouse gasses (CH_4, NO_2), because of lack of regional emission factors. Based on the production-based emission inventories, we applied the MRIO model to calculate consumption-based emissions.

2.2. Flegg location quotient method to compile the MRIO

An input-output table (IOT) based on extensive surveying by statistical institutions is considered better than a non-survey-based IO table [41, 42]. Many practitioners are also critical of applying some non-survey methods for simulating IO tables [43, 44]. Some hybrid methods are favoured, requiring fewer primary data but retaining significant accuracy. However, hybrid approaches are still costly in some developing countries because of the imperfection of statistical systems [45]. Therefore, given the limited data resources in sub-national IO tables in India, we used the Location Quotient (LQ) method, a non-survey method, to compile the MRIO table for India's 32 states.

In the standard LQ method, regional input coefficients are specified as a piecewise function of national input coefficients and LQ. Mathematically, it is expressed as:

$$a_{ij}^{rr} = \begin{cases} a_{ij}^{n}, & LQ_{ij}^{r} > 1 \\ a_{ij}^{n} \times LQ_{ij}^{r}, & LQ_{ij}^{r} \le 1 \end{cases} \quad (1)$$

Where a_{ij}^{rr} is intraregional input coefficients; a_{ij}^{n} is national input coefficients; LQ_{ij}^{r} is the proportion of regional requirements of input i purchased from within region r. a_{ij}^{n} can be obtained directly from the national IO table. LQ_{ij}^{r} can be derived from the steps in supporting information (SI).

Further, intraregional intermediate transactions, z_{ij}^{rr}, can be obtained from $a_{ij}^{rr}x_j^r$. In addition, interregional intermediate transactions, z_{ij}^{rs} ($s \neq r$), should also be estimated. The total amount of interregional intermediate transactions ($\sum_{s,r;s\neq r} z_{ij}^{rs}$) should be consistent with the residual of the national total amount of intermediate transactions that have not been allocated to intraregional transaction. The residual can be expressed as:

$$residual_{ij} = z_{ij} - \sum_{r} z_{ij}^{rr} \quad (2)$$

Obviously, the residual is non-negative because the intraregional input coefficients are bounded by national input coefficients. The residual then needs to be distributed among the interregional transactions with b_{ij}^{rs}. Here, b_{ij}^{rs} refers to a proxy (or an initial estimate) of interregional transactions or an initial estimate. d^{rs} indicates the distance between region r and region s.

$$b_{ij}^{rs} = \begin{cases} \frac{x_i^r x_j^s}{d^{rs}}, & for\ s \neq r \\ 0, & for\ s = r \end{cases} \quad (3)$$

Then, consistent estimations are constructed with the help of a key parameter of g_{ij}^{rs}, scaling the b_{ij}^{rs}, so that they sum to unity:

$$g_{ij}^{rs} = \frac{b_{ij}^{rs}}{\sum_{r,s} b_{ij}^{rs}} \quad (4)$$

Therefore, the interregional intermediate transaction estimates can be simply proportional to the size of the sending sector and the receiving sector.

$$z_{ij}^{rs} = g_{ij}^{rs} \times residual_{ij} \quad (5)$$

Initial estimates of final demand, imports and export of each region are shown in supporting information (SI). These estimates based on sectoral value added, output, sample survey datasets, and etc., do not meet the “double sum constraints”, in which the row and column totals match the known values in national IOT [46]. The minimum entropy approach is used to adjust the initial estimates to ensure agreement with the summed constraints. The procedure of minimizing the squared distances tends to preserve the structure of the initial estimates as much as possible with a minimum number of necessary changes to restore the row and column sums to the known values.

$$\min S = \sum_{i,j,s,r} \frac{\left(z_{ij}^{sr} - \bar{z}_{ij}^{sr}\right)^2}{w_{ij}^{sr} z_{ij}^{sr}} + \sum_{i,r} \frac{\left(x_i^r - \bar{x}_i^r\right)^2}{x_i^r} + \sum_{i,r} \frac{\left(v_i^r - \bar{v}_i^r\right)^2}{v_i^r} + \sum_{i,r,h} \frac{\left(y_{ih}^r - \bar{y}_{ih}^r\right)^2}{y_{ih}^r} + \sum_{i,r} \frac{\left(m_i^r - \bar{m}_i^r\right)^2}{m_i^r} + \sum_{i,r} \frac{\left(e_i^r - \bar{e}_i^r\right)^2}{e_i^r} \quad (6)$$

S.t.

$$\sum_{i,s} z_{ij}^{sr} + m_j^r + v_j^r = x_i^r \quad (7)$$

$$\sum_{j,r} z_{ij}^{sr} + \sum_{h} y_{ih}^r + e_i^r = x_i^r \quad (8)$$

2.3. Consumption-based accounting of CO_2 emissions

The multiregional input output model is the accepted tool employed to account for consumption-based emissions, which illustrates the interregion and inter-industry relationships along supply chains and interregional trades [47]. Specifically, consumption-based CO_2 emissions can comprehensively present emissions directly and indirectly embodied in the final consumption [48]. In this study, consumption-based emissions in certain regions includes emissions from local production and emissions embodied in domestic imports, excluding emissions embodied in international imports.

In the MRIO model, the total output of each industry in each region, $\mathbf{x}$, stimulated by a vector of final demand, $\mathbf{y}$, is given by

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} \quad (9)$$

Where $(\mathbf{I} - \mathbf{A})^{-1}$ is the Leontief inverse (matrix of total requirements), with L_{ij}^{rs} indicating the total output of industry i in region r that is stimulated by a unit of demand of j in region s; where $\mathbf{A}$ is the direct requirement matrix, with a_{ij}^{rs} indicating the amount of direct inputs from industry i in region r required to generate one unit output of j in region s; where $\mathbf{y}$ is the final demand matrix with y_i^{rs} indicating the final demand for goods of industry i in region s from region r; where $\mathbf{x}$ is the total output matrix with x_i^r indicating the total output of industry i in region r. Using familiar matrix notation and dropping the subscripts, we have the following:

$$\mathbf{A} = \begin{bmatrix} \mathbf{A}^{11} & \mathbf{A}^{12} & \cdots & \mathbf{A}^{1n} \\ \mathbf{A}^{21} & \mathbf{A}^{22} & & \mathbf{A}^{2n} \\ \vdots & & \ddots & \vdots \\ \mathbf{A}^{n1} & \mathbf{A}^{n2} & \cdots & \mathbf{A}^{nn} \end{bmatrix};\ \mathbf{y} = \begin{bmatrix} \mathbf{y}^{11} & \mathbf{y}^{12} & \cdots & \mathbf{y}^{1n} \\ \mathbf{y}^{21} & \mathbf{y}^{22} & & \mathbf{y}^{2n} \\ \vdots & & \ddots & \vdots \\ \mathbf{y}^{n1} & \mathbf{y}^{n2} & \cdots & \mathbf{y}^{nn} \end{bmatrix};\ \mathbf{x} = \begin{bmatrix} \mathbf{x}^{1} \\ \mathbf{x}^{2} \\ \vdots \\ \mathbf{x}^{n} \end{bmatrix}.$$

To calculate the embodied emissions in the goods and services, we extend the MRIO model with environmental extension by defining direct emission intensity, which indicates CO_2 emissions per unit of economic output for all industries and regions. Mathematically, it is expressed as: $k_i^r = e_i^r / x_i^r$, where e_i^r indicates the CO_2 emission emitted from industry i in region r. Therefore, total consumption-based emissions embodied in goods and services used for final demand can be estimated by:

$$CO_2^r = \mathbf{k}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}^r \quad (10)$$

where $\mathbf{k}$ is a vector of emission intensity for all industries in all regions; $\mathbf{y}^r$ is the final demand including four categories for region r from all regions.

In turn, the total embodied emissions in exports from region r to region s can be estimated by:

$$\mathbf{Exp}^{rs} = \widehat{\mathbf{k}^r}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}^s \quad (11)$$

where $\mathbf{k}^r$ represents the direct emission intensity for region r but zero for all other regions; similarly, $\mathbf{y}^s$ indicates the final demand including four categories for region s from all regions. $\widehat{\mathbf{k}^r}$ is the diagonal matrix of $\mathbf{k}^r$.

2.4. Data sources

The production-based carbon emissions from fossil fuels (e.g. coal, petroleum and gas) for regions in India came from the GHG Platform of India (GHGPI), which is the most comprehensive GHG (greenhouse gas) emission datasets at a state level in India (see Table 1 and Table 2). These emission data included 35 regions and 22 sectors (*SI Table S2*). The Multi-Regional Input-Output Table (MRIOT) used in this paper was compiled based on 2015 Indian Supply-Use Table (SUT) at a national level. The MRIOT contains 32 regions and 50 economic industries for each region. In addition, imports from other countries appeared as a single row vector on the input side in MRIOT, and the intermediate transaction matrix and final use only included goods and services produced domestically. Hence, we mainly discuss the consumption-based emissions supported by domestic production, excluding imported emissions from other countries. To facilitate discussion, several states with lower population density and GDP (see *SI Table S1*), were clustered into geographic regions (i.e. Himachal Pradesh, Jammu and Kashmir. Uttarakhand are aggregated into North region, and Assam, Sikkim and Tripura are aggregated into Northeast region). Basic data for compilation of the MRIOT came from CEIC datasets, Annual Survey of Industry (ASI) datasets and

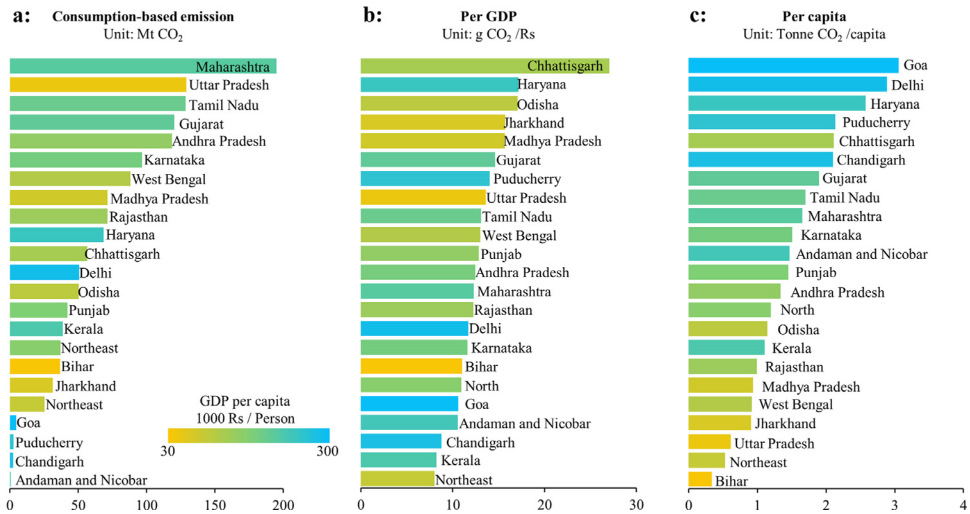

Fig. 1. a shows the ranking of state-level consumption-based emissions. **b** shows the ranking of state-level consumption-based emissions intensity per GDP. **c** shows the ranking of state-level consumption-based emissions intensity per capita. For all bar chart, length of bar indicates its size according to the x-coordinate, and color of bars corresponds to state GDP per capita from the least developed states in yellow to the most developed states in blue.

the Ministry of Statistics and Programme Implementation (MoSPI). Detailed information about how we compiled the MRIOT can be found in the Supporting Information (SI).

3. Results

3.1. The heterogeneous distribution of consumption-based emissions for India in 2015

In 2015, India emitted 1766 Mt CO_2 from the burning of fossil fuels, accounting for 6% of global emissions. 83% of emissions were consumed by domestic final demand and the remaining 17%, driven by export to other countries. Fig. 1 ranks consumption-based emissions in 2015 for all 23 regions in India. Some states where services and light industries are substantially developed, display high consumption-based emissions. For example, the highest consumption-based CO_2 emissions of 195.1 Mt was in Maharashtra, (accounting for 13.5% of the total), which is mainly due to the state having the largest GDP in India (accounting for 14% of national GDP). More than 70% of its GDP is attributed to services and light industries. Similarly, 96.7 Mt emission in Karnataka and 128.7 Mt emission in Tamil Nadu also are associated with high levels of total GDP. By contrast, some states such as Madhya Pradesh, Chhattisgarh and Odisha, have lower consumption-based emissions, which is associated with being less populous and having lower per capita GDP. The economy in these states is heavily dependent on coal use and energy intensive activities such as energy industry, heavy industry or materials manufacturing, with the result that consumption-based emissions are significantly lower than production-based ones. However, when standardized by socioeconomic factors (GDP and population), the ranking changes drastically (see Fig. 1). Uttar Pradesh, as the second largest consumption-based emissions consumer, has a middle level of emission intensity by GDP and a lower level of emission intensity per capita. This is because Uttar Pradesh is the most populous state and has lower GDP per capita. In other words, the consumption-based carbon intensity (emissions per unit of GDP) is greatest in less developed states in central and east areas. By contrast, the high GDP and more developed states in the west, south and union territories, tend to be the least carbon intensive. For example, Odisha, whose value-added iron and steel accounted for 18% of its GDP, had the highest consumption-based emission intensity, 27.04 g CO_2 per Rs, which is more than double the consumption-based emission intensity of Maharashtra. Conversely, per capita consumption-based carbon emissions in developed states and union territories such as Goa, Delhi, Haryana and Puducherry, are more than three times that of Odisha, Madhya Pradesh, and Jharkhand. Affluent states with a GDP per capita of around 200,000 Rs or more such as Goa and Delhi, have consumption-based emissions per capita of around 3 tonnes. In contrast, Jharkhand, an eastern state with a GDP per capita of just around 60,000 Rs, has consumption-based emissions per capita of around 1 tonne.

3.2. The heterogeneous drivers of consumption-based emissions in India

Consumption-based emissions can be supported by domestic productions and imported goods and services (shown in Fig. 2a), which explains where the emissions come from. Consumption-based emissions can also be triggered by different drivers, such as four categories of final demand (shown in Fig. 2b) and different sectoral final demand (shown in Fig. 2c), which demonstrate the heterogeneity of drivers in Indian states. In 23 states or regions of India, with the exception of Odisha and Chhattisgarh, more than 50% of consumption-based emissions were attributed to imports from external regions, which indicates that in 2015, consumption relied heavily on foreign products as opposed to local products. The above results are consistent with previous studies which state that approximately 40–80% of emissions in Japan were attributed to imports [49]. For example, Delhi (94%), the top state in terms of shares of imported emissions, corresponded with its overwhelming consumption-based emissions that were three-fold its production-based emissions. Chhattisgarh and Odisha, by contrast, accounted for the minimum percentages of imported emissions, reaching a low level of 40–50%, because they are typical production-based emission producers. From the perspective of categories of final demand, household consumption induced the largest share of consumption-based emission, followed by fixed capital formation. The results are consistent with previous researches on consumption-based emissions in India at the nation-level [33]. More than 60% of consumption-based emissions in each state were triggered by households, especially in Chhattisgarh (78%) and in Odisha (75%). Emissions induced by capital formation accounted for a larger proportion of total consumption-based emission in more affluent states, such as the top three consumers of Tamil Nadu, with 33%, Maharashtra and Uttar Pradesh, with 27%, than less developed states of Odisha and Chhattisgarh, with 18%, and Madhya Pradesh, with 22%. An underlying explanation is that industrial sectors in less developed states with high emission intensity, consumed more but invested less in new high-tech growth and urbanization. In contrast, development models in more developed states, including rapid economic growth associated with rapid urbanization, push investment in transportation infrastructure and construction, which accounted for 70% of total capital formation in India. From the perspective of the consumption-based emissions of different sectors, services, transport, energy industry and construction are the main contributors. Fig. 2c shows regional disparities between

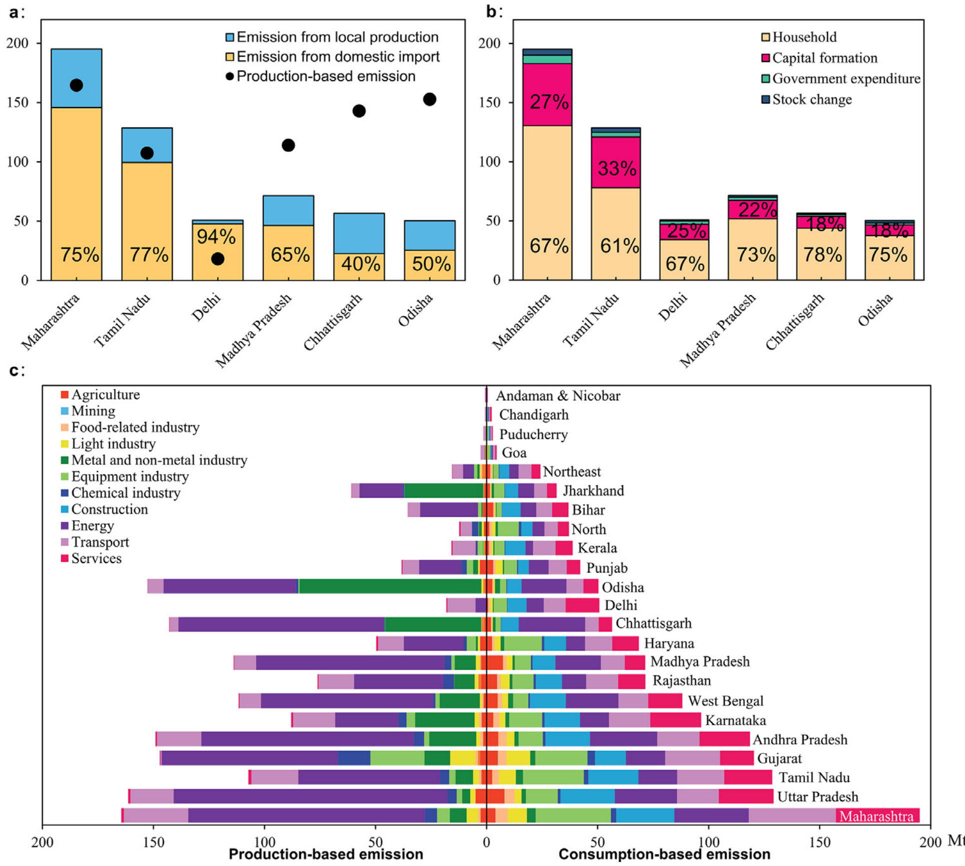

Fig. 2. Composition of consumption-based emission by states, all divided into emissions from local production and emission from domestic imports (a), 11 sectors (c) and four final demand categories (b) (Unit: Mt CO_2).

Table 1
List of abbreviation.

Abbreviation	Item
GDP	Gross domestic product
INDC	Intended Nationally Determined Contributions
NAPCC	National Action Plan on Climate Change
SAPCC	State Action Plan on Climate Change
BIMAROU	Bihar, Madhya Pradesh, Rajasthan, Odisha and Uttar Pradesh
MRIO	Multi-regional input output
MRIOT	Multi-regional input output table
IO	Input output
IOT	Input output table
CCS	Carbon capture and storage
CDM	Clean development mechanism
LQ	Location Quotient
FLQ	Flegg Location Quotient
GHGPI	Greenhouse gas Platform of India
GHG	Greenhouse gas
SUT	Supply -Use Table
ASI	Annual Industry Survey
MoSPI	Ministry of Statistics and Programme Implementation
CEIC	China entrepreneur Investment Club

sectoral consumption-based emissions. Energy industry accounted for a large share of consumption-based emissions in heavy-industry intensive states, while services and equipment industry are the main drivers of consumption-based emissions in developed states. For instance, energy industry accounted for 53% and 17% of total emissions in Chhattisgarh and Maharashtra, respectively, while services and equipment industry accounted for 15% and 37% of total emissions in these two states.

3.3. Spillover effects from inter-state emission flows across India

Table 3A, shows the largest gross emission flows within India, reflecting the patterns of CO_2 outsourcing. Maharashtra and Tamil Nadu are the most populous and affluent regions in India, accounting for nine of the top 10 emission inflows (seven inflows to Maharashtra, two inflows to Tamil). Former "BIMAROU" states with lower socioeconomic status, accounted for six of the top 10 emission outflows. For example, 40% of consumption-based emission in Maharashtra are imported from Gujarat (13%), Madhya Pradesh (7%), Chhattisgarh (6%), Odisha (7%) and Uttar Pradesh (7%).

Table 3B and D show emission flows induced by fixed capital formation and household consumption, respectively. Similar to gross emission inflows, Maharashtra is also the major destination of the largest emission inflows triggered by household consumption. People living in locations with the largest inflows have much higher per capita household consumption than people living in other states that export emission intensive goods to more affluent regions. This indicates that the higher levels of household consumption in developed states are supported by carbon intensive production in less developed, heavy industry-oriented regions. In keeping with rapid growth, more developed regions, such as Maharashtra and Tamil Nadu, invest a larger share of GDP (27–33%) to promote urbanization than less developed states (only 18–22%) in east and central areas of India, resulting in a higher level of per capita fixed capital formation. However, the largest emission inflows embodied in capital formation normally originate from less developed states, such as Odisha and Chhattisgarh, to those developed states. This is mainly caused by the difference in industrial structure and endowments of natural resources. For example, the central and eastern regions have the highest reserves of metal and non-metal minerals and a lower position in the supply chains.

In addition, our results show that states with higher emission intensity of production tend to be net emission exporters. ***Table 3****C*, shows that the largest net inflows originate from high intensity states to low intensity states (comparisons of sectoral intensity are shown in *SI Table S4*). Per GDP emission intensity consists of energy intensity (energy

Table 2
Data sources of key socioeconomic information at a state level.

Items (by states)	Data sources
Value added of agriculture and services-2015 year	CEIC datasets
Output of agriculture-2015 year	Ministry of Statistics and Programme Implementation
Output/Value added/capital formation/stock change of industries-2015 year	Annual Survey of Industry
Population/Area-2015 year	Office of Registrar General of India, Ministry of Home Affairs
Monthly per capita consumer expenditure-2015 year	National Sample Survey Organization
Revenue Expenditure-2015 year	Reserve Bank of India

Table 3
The largest interstate emission flows embodied in trade, household and capital formation.

A. Emission flows embodied in trade	(Net emission embodied in trade) Origin	Destination	***B.*** Emission flows embodied in capital formation	(Capital formation per capita) Origin	Destination
24.9	Gu (−2.2)	Ma (47.9)	6.5	Od (15.5)	TN (53.5)
18.9	Ma (47.9)	Gu (−2.2)	6.4	Gu (37.4)	Ma (40.0)
14.4	AP (−14.9)	Ma (47.9)	5.9	Od (15.5)	Ma (40.0)
14.3	AP ((−14.9)	TN (34.9)	5.0	AP (26.1)	Ma (40.0)
13.3	UP (−16.1)	Ma (47.9)	4.7	Ch (24.0)	Ma (40.0)
13.0	MP (−31.4)	Ma (47.9)	4.3	Od (15.5)	AP (26.1)
12.9	Od (−75.5)	Ma (47.9)	4.2	Od (15.5)	UP (14.4)
12.4	Ch (−71.4)	Ma (47.9)	4.2	AP (26.1)	Ma (40.0)
12.4	Od (−75.5)	TN (34.9)	4.2	Ka (41.5)	Ma (40.0)
11.4	Ka (18.3)	Ma (47.9)	4.2	Ka (41.5)	TN (53.5)
C. Net emission flows embodied in trade	(Emission intensity per GDP) Origin	Destination	***D.*** Emission flows embodied in household	(Household consumption per capita) Origin	Destination
11.0	Od (51.7)	Ma (10.4)	16.8	Gu (91.2)	Ma (77.4)
10.8	Od (51.7)	TN (10.9)	14.3	Ma (77.4)	Gu (91.2)
10.4	Ch (68.4)	Ma (10.4)	9.3	AP (65.1)	Ma (77.4)
7.9	Ch (68.4)	TN (10.9)	9.0	UP (28.9)	Ma (77.4)
7.4	MP (25.0)	Ma (10.4)	8.8	MP (38.6)	Ma (77.4)
7.3	Ch (68.4)	UP (17.0)	8.5	AP (65.1)	TN (84.4)
6.2	Od (51.7)	UP (17.0)	7.6	Ma (77.4)	Ka (92.5)
6.2	Od (51.7)	WB (16.5)	7.3	TN (84.4)	Ma (77.4)
6.2	AP (15.6)	TN (10.9)	6.9	Ch (38.4)	Ma (77.4)
6.1	Ch (68.4)	AP (15.6)	6.8	UP (28.9)	Gu (91.2)

Note: Abbreviation: Gu-Gujarat, Ma-Maharashtra, AP-Andhra Pradesh, TN-Tamil Nadu, UP-Uttar Pradesh, Ch-Chhattisgarh, MP-Madhya Pradesh, Od-Odisha, Ka-Karnataka. Unit: Emission flows (Mt CO_2), Capital formation per capita (Rs/person), Household consumption per capita (Rs/person), Emission intensity per GDP (g CO_2/Rs).

consumption per GDP) and carbon intensity (CO_2 emission per energy consumption). In the case of energy intensity, developed states or union territories, such as Maharashtra and Delhi, entail a lower level of energy intensity than those of less developed states, due to advanced technology for production and greater shares of low-energy but high-value-added products in more developed regions. In another case of carbon intensity, states located in north or northeast India tend to consume a greater share of low-carbon energy sources (i.e. solar power, wind power and nuclear power, see *SI Table S3*) than states located in east and central parts of India, but rely heavily on heavy industry.

3.4. The heterogeneous drivers of emission flows across India

Fig. 3 shows, at the sectoral level, the imported emissions and exported emissions of each state or region. For some service-oriented states, the largest share of embodied emissions in imports can be attributed to the service sector. In addition, there is a relatively large amount of embodied emissions in the imports of light industry in these states (e.g. Maharashtra, Tamil Nadu, Delhi and Karnataka), followed by construction, transport and food-related industries. For some heavy industry-oriented states (e.g. Chhattisgarh, Odisha and Jharkhand), the largest share of embodied emission in exports can be attributed to construction, followed by light industry.

In terms of net emission flows between inflows (emissions embodied in imports) and outflows (emissions embodied in exports) of each region, the net emission exporters are highly centralized, with the top four exporters accounting for 80% of total net outflow in India, while the net emission importers are more decentralized. The largest net emission importers are dominated by the affluent states and highly urbanized union territories such as Delhi, Maharashtra and Tamil Nadu. Some less developed regions, such as those in the north (including Himachal Pradesh, Jammu and Kashmir, Uttarakhand) and northeast (including Assam, Sikkim and Tripura) also import large embodied emissions, produced elsewhere in India, with respective net imported emissions of 26.4 and 11.0 Mt. The underlying explanation is that there is a cleaner energy mix in those regions, where a large share of the electricity supply is borne by solar and wind power. In addition, lower levels of industrialization in those regions prompt more imports of high-tech industrial goods from external regions [50]. Normalizing net emission flows per unit of capita and per GDP, further highlights the imbalance of emission flows from less developed eastern regions to the developed south and west regions or highly- urbanized union territories. For example, per unit GDP carbon intensity of net emission exporters is greatest in Chhattisgarh (34.1 g CO_2 per Rs), Odisha (25.6 g per Rs), and Jharkhand (10.3 g per Rs), due to the prevalence of emission intensive products (i.e. iron and steel, non-metal minerals, electricity mainly supported by fossil fuel) exported from these states. Meanwhile, per unit capita carbon intensity of net emission importers is greatest in Delhi (1.94 Tonne CO_2 per capita), Chandigarh (1.50 Tonne per capita) and Goa (1.50 Tonne per capita) due to the higher per capita consumption in affluent regions.

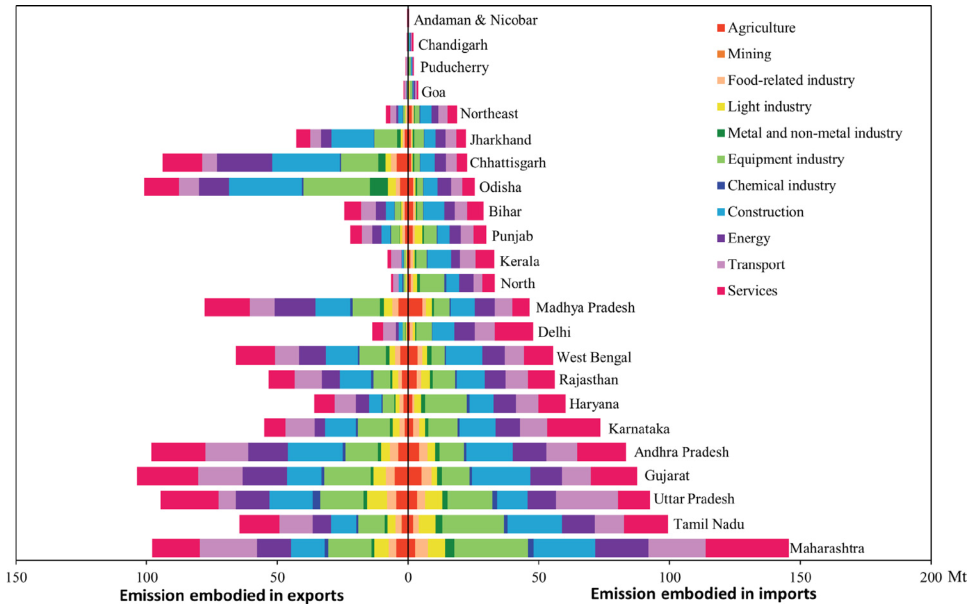

Fig. 3. Emission embodied in imports and exports by states, all divided into 11 sectors (Unit: Mt CO2).

4. Discussion

As potential giant emitter, India's climate actions to address climate change are critical to the 1.5 °C global mitigation target [51]. The largest challenge to seeking a cleaner pathway to industrialization or urbanization in India is that there is no successful previous model to follow, among either developed countries or industrialized emerging countries like China. Mitigation in a vast country like India cannot be achieved without considering the regional heterogeneity in industries and socioeconomic stages. Like most countries with vast territory, regional emission disparities in India also show that the most affluent regions dominate the total consumption-based emissions. For example, consumption-based CO_2 emissions in Maharashtra with the largest GDP in India, accounted for 13.5% of the national total. The overall economic growth rate of the state is expected to be at a compound annual growth rate of 7% until 2051, and is likely to remain the highest contributor, accounting for about 12.8% of national GDP by 2051 [12], which may correspond to its position as largest contributor to total emissions. High economic growth in the affluent states would undoubtedly increase their consumption-based emissions, especially carbon flows embodied in the supply chains from other under-developed states with higher carbon intensity. The spillover effects could undermine mitigation efforts, observed in other developing countries, and require the policymakers to shift the scale of mitigation more broadly with the participation of multi-states, especially for those inextricably connected in terms of supply chains.

Exploring the green growth way requires cooperation to balance economic growth and inequality reduction. In a carbon-constrained future, developed countries' efforts to become carbon neutral (e.g. capturing carbon and storing) [52], will save the carbon quota for industrialization for developing countries, such as India. Similarly, the carbon quota should be also allocated at the sub-national level between affluent and developed states such as Delhi, Goa and Maharashtra, and less developing states such as Odisha and Telangana. Therefore, these affluent states should also set ambitious targets of mitigation (e.g. carbon neutrality) to provide room for less developed states. Our study found that household consumption was the largest contributor to consumption-based emissions at state level. More than 60% of total emissions in 2015 were triggered by embodied emissions in households in each state, which are highly associated with transport, food processing and energy. A low-carbon lifestyle of wealthier households is critical. Considering the comparative advantages in wealthier areas, planting trees or carbon capture and storage (CCS) in wealthier areas is not a reasonable approach to achieving carbon neutrality. Connecting poor regions and rich regions through a carbon credit mechanism will provide opportunity for a carbon sink [53].

By contrast, capital formation, as the largest contributor to consumption-based emissions in most developing countries [54], only accounted for 20–30% of total regional consumption-based emissions in India. This reverse was mainly caused by India's large population but lower level of urban infrastructure expansion. However, with rapid industrialization since the financial crisis in 2008, India as the second largest populated country, also has the world's largest potential for urbanization, which will make capital formation dominant in India again. We also found that more urbanized states are characterized by a higher proportion of emissions embodied in capital formation, for example 33% in Tamil Nadu, 27% in Maharashtra but only 18% in Odisha and Chhattisgarh. In terms of percentage, in less developed states, the urban population is significantly lower than the national average. Therefore, theses states are in a unique position to chart out an urbanization path that learns from the mistakes or experiences of other more developed states. Given the climate change dimension, these states should go further by defining a climate-friendly urbanization path. For example, developing an energy efficient building and transport infrastructure in the primary stages of urbanization, could be a low-cost way to substantially reduce future energy use caused by the potential expansion of urbanization.

Interregional trade in India, triggered by comparative advantages and regional heterogeneity, brings economic benefits both for developed states (lower costs) and developing states (GDP growth). Meanwhile, the high carbon flows embodied in inter-state trade indicate the considerable spillover effects. To be more specific, household consumption in developed states such as Maharashtra and Tamil Nadu, were supported by outsourcing emissions to surrounding regions, while capital formation was mainly supported by emissions occurring in less developed states that are heavily reliant on heavy industry. The pattern of outsourcing of CO_2 shows the trade between developed states and developing states tend to be carbon-intensive and involve low value-added goods, such as metal and non-metal industry. In addition, we found that the net emission flows tended to originate from high intensity states with to low intensity states. The major mechanism for interregional trade to drive CO_2 emissions rests on differences of production-based emission intensity between importers and exporters [55]. Carbon-intensive manufacturing in less developed states, such as former "BIMAROU" states, entails drastically more emissions than making the same products in the most affluent states, using advanced technology; thus, interstate trade increases India's CO_2 emissions. We also found that net emission exporters are highly centralized and mainly located in the east. Restructuring the industrial sector among Indian states goes against existing comparative advantage. Therefore, there is a potential opportunity to decarbonize, by improving emission intensity in the main net exporters in India, in which more energy-efficient technologies can be installed. Such action will upgrade the industry chain and enhance the value added of products in developed states. Given that consumption in developed states is supported by carbon intensive production in less developed heavy industry-oriented regions, such low marginal cost approaches can be supported by the affluent regions' efforts to introduce accessible, high-technologies into less developed states in India. For example, an interregional clean development mechanism (CDM) will incentivise developed net importers with cleaner production processes to buy carbon emission permits [56], by investing in less developed net exporters to use advanced technologies and upgraded productions.

5. Conclusion

In the study, we used the Flegg location quotient method and gravity model to construct a multi-regional input-output table for India in 2015. Consumption-based CO_2 emissions at state level for India in 2015 were first measured to establish regional disparities and supplement regional mitigation policies. We found that the developed western region dominated India's carbon footprint. Household consumption dominated consumption-based emissions in all states, while investment-led emissions were relatively higher in developed regions than in the developing regions. Consumption-based emissions were significantly redistributed among Indian states via interstate supply chains. We found that states not only emitted CO_2 emissions within territory boundaries but also imposed emissions on other regions through interregional trade. Especially, carbon-intensive productions in eastern region are significantly triggered by demand in developed western region.

Mitigation policies should focus on the connection between developed and developing states. A low-carbon lifestyle of wealthier households in developed states and planting trees or carbon capture and storage in developed states, via a carbon credit mechanism (payment from developed states) will save the carbon quota for developing states. Seeking a climate-friendly urbanization path in developed states will not only reduce local carbon emissions, but also future energy use and carbon emissions caused by the potential expansion of urbanization in developing states. Introducing accessible, high-technologies from developed states via an interregional clean development mechanism will improve emission intensity in developing states and also bring about high value-added industries. Future work can link our multi-regional input-output table with global input-output table (for example Global Trade Analysis Project) to the relationship between Indian states and other countries. A time-series research, such as Structural decomposition analysis, is also proposed to explore dynamic drivers in different regions.

5.1. Limitation and uncertainty

This study faced a number of limitations and assumptions in the process of conducting the research. First, we only considered consumption-based emissions from domestic production in our study. The data of imported goods at a state level in MRIO were not officially available during the study period. However, India, as a "manufacturer" in global supply chains, was characterized by higher exports than imports. Consumption in India was mainly supported by domestic goods. Therefore, the uncertainty about a possible disconnect between India and the rest of the world, was limited. Second, our analysis focused on energy-related CO_2 emissions excluding other greenhouse gasses (for example, CH_4, NO_2, emissions from agriculture production, and emissions from industrial processes), such that we may undervalue the implication of agriculture on mitigation. Third, the interregional trade estimated in this study is based on the FLQ model and gravity model due to data availability, which inevitably leads to some uncertainty regarding interregional trade.

Data and code availability

Datasets for this research are available in: CEIC (CEIC is not accessible to public but accessible with licensing in the site) https://info.ceicdata.com/en-products-india-premium-database, MoSPI http://www.mospi.gov.in/publication/state-wise-and-item-wise-value-output-agriculture-forestry-and-fishing-2011–12–2017–18, GHGPI http://www.ghgplatform-india.org/economy-wide. India state MRIO data for 2015 can be found in China Emission Accounts and Datasets https://www.ceads.net/data/input_output_tables/ for free download. The MATLAB and GAMS codes are available in Table S6.

Author contributions

H.Z. and J.M. designed the study. Q.H. performed the analysis and prepared the manuscript. Q.H., H.Z., J.M. and interpreted the data. D.G. and J.L coordinated the project. All authors participated in writing the manuscript.

Declaration of Competing Interest

The authors declare no competing financial or nonfinancial interests.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.adapen.2021.100039.

References

[1] Wang Q, Zhou YL. Evolution and drivers of production-based carbon emissions in China and India: differences and similarities. J Clean Prod 2020:277.
[2] IEA Data services homepage. International Energy Agency; 2019.
[3] Wang Q, Su M, Li RR. Toward to economic growth without emission growth: the role of urbanization and industrialization in China and India. J Clean Prod 2018;205:499–511.
[4] Sridhar KS. Urbanization and Carbon Emissions in India and China. Environ Urban Asia 2018;9:113–26.
[5] United Nations Department of Economic and Social Affairs PD World urbanization prospects: the 2014 revision; 2014. Highlights.
[6] IMF World economic outlook database. International Monetary Fund; 2019.
[7] Ortega-Ruiz G, Mena-Nieto A, Garcia-Ramos JE. Is India on the right pathway to reduce CO2 emissions? Decomposing an enlarged Kaya identity using the LMDI method for the period 1990-2016. Sci Total Environ 2020:737.
[8] Pappas D, Chalvatzis KJ, Guan DB, Li X. Industrial Relocation and CO2 Emission Intensity: focus on the Potential Cross-Country Shift from China to India and SE Asia. Enrgy Proced 2017;142:2898–904.
[9] Parikh KS, Parikh JK, Ghosh PP. Can India grow and live within a 1.5 degree CO2 emissions budget? Energ Policy 2018;120:24–37.
[10] Ministry of Environment and Forests GoI. India's Initial National Communication to the United Nations Framework Convention on Climate Change. 2012.
[11] Chandel SS, Shrivastva R, Sharma V, Ramasamy P. Overview of the initiatives in renewable energy sector under the national action plan on climate change in India. Renew Sust Energ Rev 2016;54:866–73.
[12] TERI Assessing climate change vulnerability and adaptation strategies for maharashtra: maharashtra state adaptation action plan on climate change (MSAAPC). New Delhi: The Energy and Resources Institute; 2014. p.302

[13] Ahmad S, Baiocchi G, Creutzig F. CO2 Emissions from Direct Energy Use of Urban Households in India. Environ Sci Technol 2015;49:11312–20.
[14] Meng J, Mi ZF, Guan DB, Li JS, Tao S, Li Y, et al. The rise of South-South trade and its effect on global CO2 emissions. Nat Commun 2018;9.
[15] Sun XD, Li JS, Qiao H, Zhang B. Energy implications of China's regional development: new insights from multi-regional input-output analysis. Appl Energ 2017;196:118–31.
[16] Wang Q, Yang X. New insight into aggressive Intended Nationally Determined Contributions in China - What lessons China should learn from Germany to reduce production-based carbon emission. J Clean Prod 2021:279.
[17] Harris S, Weinzettel J, Bigano A, Kallmen A. Low carbon cities in 2050? GHG emissions of European cities using production-based and consumption-based emission accounting methods. J Clean Prod 2020:248.
[18] Marland G, Hamal K, Jonas M. How Uncertain Are Estimates of CO2 Emissions ? J Ind Ecol 2009;13:4–7.
[19] Davis SJ, Caldeira K. Consumption-based accounting of CO2 emissions. P Natl Acad Sci USA 2010;107:5687–92.
[20] Barrett J, Peters G, Wiedmann T, Scott K, Lenzen M, Roelich K, et al. Consumption-based GHG emission accounting: a UK case study. Clim Policy 2013;13:451–70.
[21] Feng KS, Davis SJ, Sun LX, Li X, Guan DB, Liu WD, et al. Outsourcing CO2 within China. P Natl Acad Sci USA 2013;110:11654–9.
[22] M. L. Zheng HR, Zhang ZY, Zhang ZK, Li X, Shan YLS, Mi ZF, et al. Mapping Carbon and Water Networks in the North China Urban Agglomeration. One earth 2019;1:126–37.
[23] Li YZ, Su B, Dasgupta S. Structural path analysis of India's carbon emissions using input-output and social accounting matrix frameworks. Energ Econ 2018;76:457–69.
[24] Sun CW, Ding D, Yang M. Estimating the complete CO2 emissions and the carbon intensity in India: from the carbon transfer perspective. Energ Policy 2017;109:418–27.
[25] Su B, Ang BW. Input-output analysis of CO2 emissions embodied in trade: a multi-region model for China. Appl Energ 2014;114:377–84.
[26] Zheng HR, Zhang ZK, Wei WD, Song ML, Dietzenbacher E, Wang XY, et al. Regional determinants of China's consumption-based emissions in the economic transition. Environ Res Lett 2020:15.
[27] Bhat A, Mishra PP, Review D. The Kyoto Protocol and CO2 emission: is India still hibernating? Indian Growth 2018.
[28] Das A, Kandpal TC. Iron and steel manufacturing technologies in India: estimation of CO2 emission. Int J Energy Res 1997;21:1187–201.
[29] Garg A, Shukla PR, Kankal B, Mahapatra D. CO2 emission in India: trends and management at sectoral, sub-regional and plant levels. Carbon Manag 2017;8:111–23.
[30] Dhar S, Pathak M, Shukla PR. Transformation of India's steel and cement industry in a sustainable 1.5 degrees C world. Energ Policy 2020:137.
[31] Morrow WR, Hasanbeigi A, Sathaye J, Xu TF. Assessment of energy efficiency improvement and CO2 emission reduction potentials in India's cement and iron & steel industries. J Clean Prod 2014;65:131–41.
[32] Shahbaz M, Sharma R, Sinha A, Jiao ZL. Analyzing nonlinear impact of economic growth drivers on CO2 emissions: designing an SDG framework for India. Energ Policy 2021:148.
[33] Banerjee S. Conjugation of border and domestic carbon adjustment and implications under production and consumption-based accounting of India's National Emission Inventory: a recursive dynamic CGE analysis. Struct Change Econ Dyn 2021;57:68–86.
[34] Wang Z, Meng J, Guan D. Dynamic driving forces of India's emissions from production and consumption perspectives. Earth's Future 2020;8:e2020EF001485.
[35] Wang ZY, Meng J, Zheng HR, Shao S, Wang DP, Mi ZF, et al. Temporal change in India's imbalance of carbon emissions embodied in international trade. Appl Energ 2018;231:914–25.
[36] Zhu BZ, Su B, Li YZ. Input-output and structural decomposition analysis of India's carbon emissions and intensity, 2007/08-2013/14. Appl Energ 2018;230:1545–56.
[37] Lee J, Taherzadeh O, Kanemoto K. The scale and drivers of carbon footprints in households, cities and regions across India. Global Environ Chang 2021;Volume 66.
[38] Kennedy C, Steinberger J, Gasson B, Hansen Y, Hillman T, Havranek M, et al. Methodology for inventorying greenhouse gas emissions from global cities. Energ Policy 2010;38:4828–37.
[39] Dou XY, Deng Z, Sun TC, Ke PY, Zhu BQ, Shan YL, et al. Global and local carbon footprints of city of Hong Kong and Macao from 2000 to 2015. Resour Conserv Recy 2021:164.
[40] Wang XY, Zheng HR, Wang ZY, Shan YL, Meng J, Liang X, et al. Kazakhstan's CO2 emissions in the post-Kyoto Protocol era: production- and consumption-based analysis. J Environ Manage 2019:249.
[41] Bonfiglio A, Chelli F. Assessing the Behaviour of Non-Survey Methods for Constructing Regional Input-Output Tables through a Monte Carlo Simulation. Econ Syst Res 2008;20:243–58.
[42] Hermannsson K. Beyond Intermediates: the Role of Consumption and Commuting in the Construction of Local Input-Output Tables. Spat Econ Anal 2016;11:315–39.
[43] Jiang XM, Dietzenbacher E, Los B. Improved Estimation of Regional Input-Output Tables Using Cross-regional Methods. Reg Stud 2012;46:621–37.
[44] Zheng HR, Meng J, Mi ZF, Song ML, Shan YL, Ou JM, et al. Linking city-level input-output table to urban energy footprint: construction framework and application. J Ind Ecol 2019;23:781–95.
[45] Jahn M. Extending the FLQ formula: a location quotient-based interregional input-output framework. Reg Stud 2017;51:1518–29.
[46] Mi ZF, Meng J, Zheng HR, Shan YL, Wei YM, Guan DB. A multi-regional input-output table mapping China's economic outputs and interdependencies in 2012. Sci Data 2018;5.
[47] Mi ZF, Zhang YK, Guan DB, Shan YL, Liu Z, Cong RG, et al. Consumption-based emission accounting for Chinese cities. Appl Energ 2016;184:1073–81.
[48] Chen GQ, Wu XD, Guo JL, Meng J, Li CH. Global overview for energy use of the world economy: household-consumption-based accounting based on the world input-output database (WIOD). Energ Econ 2019;81:835–47.
[49] Hasegawa R, Kagawa S, Tsukui M. Carbon footprint analysis through constructing a multi-region input-output table: a case study of Japan. J Econ Struct 2015;4.
[50] Assam state action plan on climate change (2015-2020). Department of Environment and Forest; 2015.
[51] Vishwanathan SS, Garg A, Tiwari V, Shukla PR. India in 2 degrees C and well below 2 degrees C worlds: opportunities and challenges. Carbon Manag 2018;9:459–79.
[52] Mallapaty S. How China Could Be Carbon Neutral by Mid-Century. Nature 2020;586:482–3.
[53] Mathews JA. How carbon credits could drive the emergence of renewable energies. Energ Policy 2008;36:3633–9.
[54] Feng KS, Hubacek K, Sun LX, Liu Z. Consumption-based CO2 accounting of China's megacities: the case of Beijing, Tianjin, Shanghai and Chongqing. Ecol Indic 2014;47:26–31.
[55] Liu Z, Davis SJ, Feng K, Hubacek K, Liang S, Anadon LD, et al. Targeted opportunities to address the climate-trade dilemma in China. Nat Clim Change 2016;6:201 -+.
[56] Kim J, Park K. Effect of the Clean Development Mechanism on the deployment of renewable energy: less developed vs. well-developed financial markets. Energ Econ 2018;75:1–13.