Environmental Research Letters

LETTER • OPEN ACCESS

Regional determinants of China's consumption-based emissions in the economic transition

To cite this article: Heran Zheng *et al* 2020 *Environ. Res. Lett.* **15** 074001

Environmental Research Letters

CrossMark

OPEN ACCESS

RECEIVED
7 November 2019

REVISED
20 February 2020

ACCEPTED FOR PUBLICATION
24 February 2020

PUBLISHED
18 June 2020

LETTER

Regional determinants of China's consumption-based emissions in the economic transition

Heran Zheng[1], Zengkai Zhang[2,10], Wendong Wei[3], Malin Song[4], Erik Dietzenbacher[5], Xingyu Wang[6], Jing Meng[7,10], Yuli Shan[8], Jiamin Ou[1] and Dabo Guan[9,10]

1 Water Security Research Centre, School of International Development, University of East Anglia, Norwich, NR4 7TJ, United Kingdom
2 College of Management and Economics, Tianjin University, Tianjin, 300072, People's Republic of China
3 School of International and Public Affairs, Shanghai Jiao Tong University, Shanghai, 200030, People's Republic of China
4 School of Statistics and Applied Mathematics, Anhui University of Finance and Economics, Bengbu, 233030, People's Republic of China
5 Faculty of Economics and Business, University of Groningen, Groningen, 9747 AG, The Netherlands
6 School of International Trade and Economics, University of International Business and Economics, Beijing, 100029, People's Republic of China
7 The Bartlett School of Construction and Project Management, University College London, WC1H 0QB, London, United Kingdom
8 Energy and Sustainability Research Institute Groningen, University of Groningen, Groningen, 9747 AG, The Netherlands
9 Department of Earth System Science, Ministry of Education Key Laboratory for Earth System Modelling, Tsinghua University, Beijing, 100084, People's Republic of China
10 Authors to whom any correspondence should be addressed.

E-mail: zengkaizhang@tju.edu.cn, jing.j.meng@ucl.ac.uk and guandabo@tsinghua.edu.cn

Keywords: peak, economic transition, China, consumption-based emissions, 2015

Abstract

China has entered the economic transition in the post-financial crisis era, with unprecedented new features that significantly lead to a decline in its carbon emissions. However, regional disparity implies different trajectories in regional decarbonisation. Here, we construct multi-regional input–output tables (MRIO) for 2012 and 2015 and quantitatively evaluate the regional disparity in decarbonisation and the driving forces during 2012–2015. We found China's consumption-based emissions peaked in 2013, largely driven by a peak in consumption-based emissions from developing regions. Declined intensity and industrial structures are determinants due to the economic transition. The rise of the Southwest and Central regions of China have become a new feature, driving up emissions embodied in trade and have reinforced the pattern of carbon flows in the post-financial crisis period. Export-related emissions have bounced up after years of decline, attributed to soaring export volume and export structure in the Southeast and North of the country. The disparity in developing regions has become the new feature in shaping China's economy and decarbonisation.

1. Introduction

Since the global financial crisis of 2008, China has experienced a massive economic transformation, which has seen a switch from the old growth model relying on strong investment and energy-intensive manufacturing, into a new phase of socioeconomic development which is formulated as 'New Normal' (Mi *et al* 2017, Mi *et al* 2017). A key feature of the new economic growth model is high quality but lower growth, with a restructuring of the economy into high domestic consumption and promoting value-added manufacture and services (Grubb *et al* 2015, Hilton and Kerr 2017, Mi *et al* 2018). Over the period 2007–2017, China's annual GDP growth has fallen from 14.2% to 6.9%, while the consumption contribution to GDP growth increased from 45% to 58.8%. Accordingly, GDP growth—due to investment—declined from 44% to 32% over the same period (National Bureau of Statistics 2018). In 2015, the contribution of tertiary sectors to GDP rose over 50% for the first time, marking the tipping point of economic structure under the new normal (Hilton and Kerr 2017).

As the largest carbon emitter in the world, the shift in the economic growth pattern with a focus on green development significantly affects China's decarbonisation trajectory and its International intended national determined contribution (INDC) (Jackson *et al* 2015, Guan *et al* 2018, Zheng *et al* 2018). Previous studies realised the implication of China's economic transition on the decarbonisation initiative and concluded that China's decarbonisation initiatives are able to benefit from the transition, via industrial structure adjustment, cleaning up the energy mix, improving energy efficiency, and the elimination of outdated capacity in key sectors etc (Green and Stern, 2016, Zhang *et al* 2016, Mi *et al* 2018). With these determinants, China's production-based emissions peaked at 9.53 gigaton (Gt) in 2013, while China's consumption-based emissions growth has significantly slowed down in the post crisis era, from more than 20% of growth rate in the pre-crisis period to 15% of growth during 2010–2012 (Mi *et al* 2017).

However, the consequence of economic transition on emissions declines varies across regions, due to the huge regional disparity in China. Several studies have evaluated the effects of the transition at regional level. For example, Mi *et al* found that the change of China's regional economic structure has seen a reversed role of less developed regions shifting from net carbon exporter into net importer in the post-crisis era, (Mi *et al* 2017). Pan *et al* highlighted that increasing carbon transfer between central regions and coastal regions is induced by the change in technology-intensive manufacturing (Pan *et al* 2018). Zheng *et al* measured seven socioeconomic drivers in China's emissions and found different regional development patterns lead to different decarbonisation paths (Zheng *et al* 2019). It is of interest to assess whether or not the new pattern led to a decline in China's consumption-based emissions in the economic transition, and how the regional determinants contribute. However, most of the studies focus on the pattern changes in consumption-based emissions before 2012.

Here, we quantified regional contributions in the change of China's consumption-based emissions and export-related emissions during 2012–2015, with a focus on how the new pattern evolved in the new normal. Specifically, we adopt the latest socioeconomic data to construct the multi-regional input–output (MRIO) model for 2012 and 2015, covering China's 31 provinces (except Hongkong, Macao, and Taiwan) with 42 sectors. We employed environmentally extended input–output analysis (EEIOA) to estimate consumption-based emissions and export-related emissions over the period from 2012 to 2015. We then used the structural decomposition analysis model (SDA) to quantitatively evaluate the socioeconomic driving factors behind the change in consumption-based emissions, and export-related emissions.

2. Method

2.1. MRIO table construction

The MRIO model is an essential tool in understanding the regional supply chain and identifying regional heterogeneity (Dietzenbacher *et al* 2013, Zheng *et al* 2019). Provincial single region IO (SRIO) tables are basic for the MRIO table construction, and they are normally published by provincial official agencies. In the provincial SRIO tables in 2015, however, not all provinces construct them, hence the conventional method which is based on provincial SRIO tables to construct provincial MRIO tables is not applicable for the 2015 MRIO table construction (Mi *et al* 2018). Therefore, we adopt a novel approach to construct the 2015 SRIO table, which is based on the entropy theory, before following the conventional way to construct the MRIO table. Currently, the MRIO table of 2015 constructed in this paper contains the least data to reflect the regional and sectorial links across the China, while the 2017 provincial SRIO tables are not currently available.

We start the MRIO construction from the estimate of domestic supply and demand for each sector. For the products of sector i, domestic supply S_j^i refers to commodities produced in province j supplied to all provinces in China where domestic supply is equal to output subtracting export. Mathematically, it is calculated as:

$$S_j^i = Output_j^i - Ex_j^i, \tag{1}$$

where $Output_j^i$ is the output of commodity i in province j; Ex_j^i is the export of commodity i in province j.

Domestic demand D_j^i indicates commodity required by province j, however, domestic demand has to be estimated that for sector i, we assume the same technical coefficient and the proportion of intermediate demands in total demands between 2012 and 2015. We first estimate intermediate demand by using technical coefficient multiplying output, and then divided by the proportion of intermediate demands, after which the preliminary total demand is scaled by the national demand.

$$D_j^i = \left(\left(\frac{(A_{2012j}^i \times Output_j^i)}{\left(\frac{Z_{2012j}^i}{TD_{2012j}^i}\right)}\right) \Bigg/ \sum\left(\frac{(A_{2012j}^i \times Output_j^i)}{\left(\frac{Z_{2012j}^i}{TD_{2012j}^i}\right)}\right) \times ND_{2015}{}^i - IM_j^i\right), \tag{2}$$

where A_{2012j}^i is the technical coefficient for sector i of province j in 2012; Z_{2012j}^i and TD_{2012j}^i are intermediate

Figure 1. The matrix of supply and demand.

demand and total demand for sector i of province j in 2012, respectively. $ND_{2015}{}^{i}$ is the national demand for sector i in 2015; IM_j^i is the import for sector i of province j. It is noted that if the 2015 SRIO table for province j is available, A^i_{2012j}, Z^i_{2012j}, TD^i_{2012j} can be derived directly from the 2015 SRIO table. In short, MRIO construction for 2015 is based on sectorial output, value-added, foreign trade data, 2015 national level SRIO table and 2012 provincial level SRIO tables.

With domestic supply and demand, we employ the cross-entropy model (CE) to estimate the inter-regional outflow and inflow for each sector. The CE model is based on the principle of minimal cross-entropy (also known as Kullback–Leibler divergence) which is applied to find the distribution that is closest to the prior information and satisfy the given constraint (McDougall 1999, Fernandez Vazquez *et al* 2015). The CE model is meant to preserve the minimal entropy distance between the estimated distribution and prior distribution, by satisfying the conditions. The CE model is equivalent to the widely known RAS. The principle of CE is similar to the maximising entropy model. Actually, the maximising entropy model is a special case for the minimising CE model, where the elements in prior distribution are evenly distributed (elements are equal) in the maximising entropy model (Golan *et al* 1996). Canning and Wang 2005 suggest using the minimising CE model to optimise an initial interregional trade flow matrix in order to introduce more effective information to improve the outcomes. For each sector, domestic supply and demand can be divided into self-supply, supply to other provinces, self-demand and demand from other provinces (figure 1).

In our case, we derive the detailed supply and demand (self-supply, supply to other provinces, self-demand and demand from other provinces) from the 2012 SRIO table as priori information, and setting estimated supply and demand above as constraint. Mathematically, it can be shown as:

$$\min C(P\|Q) = \sum_i \sum_j p_{ij} \cdot \ln\left(\frac{p_{ij}}{q_{ij}}\right) \tag{3}$$

s.t.

$$\sum_i \sum_j (p_{ij}^{Sd} + p_{ij}^{So}) = 1;$$

$$\sum_i \sum_j (p_{ij}^{Dd} + p_{ij}^{Do}) = 1;$$

$$\sum_j p_i^{So} \times S_i = \sum_j p_i^{Do} \times D_i;$$

$$(p_{ij}^{Sd} + p_{ij}^{So}) \times S_i = CCol_{ij};$$

$$(p_{ij}^{Dd} + p_{ij}^{Do}) \times D_i = CRow_{ij},$$

where p_{ij} is the distribution of supply and demand for 2015, which is to be estimated in the CE model; q_{ij} is the priori distribution of supply and demand for 2012. S_i and D_i are aggregated domestic supply and demand for sector i. $CCol_{ij}$ and $CRow_{ij}$ indicate estimated supply and demand for sector i in province j. After modelling, we are able to know the self-supply, supply to other provinces, self-demand and demand from other provinces for each sector in 2015, which we further estimate a provincial SRIO table based on the estimated detailed supply and demand data, and generalised RAS model (Biproportional Techniques for matrix balancing) (Junius and Oosterhaven 2003, Lenzen *et al* 2007). Specifically, we first estimate the preliminary intermediate demand Z^{ik}_{2015j} by using the technical coefficient for 2012 multiplying output for 2015, and preliminary final demand F^{if}_{2015j} by assuming an identical structure in 2012 is the same as it in 2015, and then multiplying the aggregated final demand, which is equal to GDP minus net export.

$$Z^{ik}_{2015j} = A^{ik}_{2012j} \times Output^k_j, \tag{4}$$

Table 1. Primary data used in the model.

Variable	Source	Description	Equation
$Output_j^i$	Provincial Statistical Yearbook for 2015	Output for industry *i* in province *j*	1
Ex_j^i	China Customs Database for 2015	Export for industry *i* in province *j*	1
Z_{2012j}^i	Provincial IO table for 2012	Intermediate demands for industry *i* and province *j* in 2012	2
TD_{2012j}^i	Provincial IO table for 2012	Total demands for industry *i* and province *j* in 2012	2
$ND_{2015}{}^i$	National IO table for 2015	Total demands for industry *i* in 2015	2
IM_j^i	China Customs Database for 2015	Import for industry *i* in province *j*	2
$D^{\gamma s}$	National Railway Statistical Data for 2015	National Railway Distance from region r to region s	7
T_i^{rs}	National Railway Statistical Data for 2015	National Railway Statistical Data by industry *i* from region r to region s	7

$$F_{2015j}^{if} = S_{2012j}^{if} \times \left(\sum_i VA_j^i - Ex_j^i - SO_j^i + IM_j^i + DO_j^i \right), \tag{5}$$

where A_{2012j}^{ik} refers to the technical coefficient for 2012 for sector i to k in province j; $Output_j^k$ is the 2015 output for sector k in province j; S_{2012j}^{if} is the final demand structure for sector i of categories f in province j. There are five categories in final demand: Urban household consumption, rural household consumption, government consumption, capital formation, and the change of inventory. The generalised RAS model is further used to optimise the matrix:

$$\min C(P\|Q) = \sum_i \sum_j |q_{ij}| \cdot p_{ij} \cdot \ln\left(\frac{p_{ij}}{e}\right) \tag{6}$$

s.t.

$$\sum_j q_{ij} \cdot p_{ij} = Output_j - \mathrm{VA}_j;$$

$$\sum_i q_{ij} \cdot p_{ij} = Output_i - net\ export_i,$$

where q_{ij} refers to priori matrix which is the matrix $Z_{2015} + F_{2015}$; p_{ij} is equal to X_{ij}/q_{ij} where X_{ij} is the distribution matrix for 2015; e is the Natural logarithm (Lenzen *et al* 2007). The model results are able to yield the balanced SRIO table for each province.

To estimate interregional trade flow, we use the gravity model which is the most adopted trade estimate method in MRIO construction for over 40 years, including the 2012 MRIO table (Mi *et al* 2018). It assumes the trade between two regions is the function of supply and demand and the impedance in costs. The standard gravity model is as follows:

$$T_i^{rs} = G^{\alpha} \frac{(E_i{}^{ro})^{\beta_1} \times (M_i{}^{os})^{\beta_2}}{(D^{\gamma s})^{\gamma}}, \tag{7}$$

where T_i^{rs} is trade flow for commodity i between region r and region s; $E_i{}^{ro}$ and $M_i{}^{os}$ are total supply of the exporter and the total demand of the importer, respectively. $D^{\gamma s}$ is the distance between two regions, which is the proxy for transportation cost. We use railways as an interregional commodity from the 2015 Collection of National Railway Statistical Data as sample data for the shippable commodity, while for the non-shippable commodity we assume they are evenly distributed based on the supply and demand, except for electricity which we use the interregional electricity transmission matrix of 2015 as sample data (China Electric Power Yearbook Committe 2016). The initial trade flow estimates do not meet the row and column constraints which are total outflow and inflow derived from the provincial SRIO table. We apply RAS (bi-proportional techniques (Lahr and de Mesnard 2004)) to balance the trade matrices to make them satisfy the constraint. The MRIO table can be made by linking provincial SRIO tables with adjusted trade matrices, where we are assuming the identical inflow proportion in the supply. The details can be found in Zheng *et al* 2019. All the primary data are summarised in the table 1.

2.2. Linking into GTAP-MRIO database

China's imports are from different countries with a different production structure, and different technology and carbon intensity. Previous studies adopted the assumption of a production structure and technology identical to China's domestic structure, which could generate considerable uncertainty (Meng *et al* 2016). To capture the heterogeneity, we link China's MRIO table into a GTAP-MRIO table, which is based on the GTAP (Global Trade and Analysis Project). As GTAP-MRIO tables are available for 2011 and 2014, we connect the 2015 MRIO table into the 2014 GTAP-MRIO table, and the 2012 MRIO table into the 2011 GTAP-MRIO table. Since trade data are always conflicting between two databases, we make China's MRIO table as standard and use trade data from the GTAP-MRIO table to adapt to the China MRIO table. We follow previous studies to assume that provincial import structure by countries is identical with the national import structure. Details can be found in (Feng *et al* 2013). The nested China-GTAP-MRIO table is initially unbalanced, with the RAS method applied to optimise the MRIO table. RAS technique is well applied in input–output table optimisation, which is able to preserve the initial matrix as much as possible while making the adjusted matrix follow the pre-set constraints (Lahr and de Mesnard, 2004). It is noted that China's MRIO would totally replace the matrix of China in the GTAP, and therefore, the China MRIO would not be adjusted when RAS is applied. In short, we use other countries' data in the GTAP to adapt the China MRIO to retain the authenticity.

2.3. Environmental extended input–output model

To calculate the consumption-based emissions, we employ the Environmental extended input–output model (EEIO) (Serrano *et al* 2016, Meng *et al* 2018), which can be expressed as:

$$C = \boldsymbol{E}(\mathbf{I} - \mathbf{A})^{-1}F, \tag{8}$$

where $\mathbf{A}$ is the technical coefficient which is calculated as $A^{rs} = (z_{ij}^{rs}/x_j^s)$; $\boldsymbol{F}$ is the total final demand by sector. All of these parameters are derived from the MRIO table. $\boldsymbol{E}$ is the carbon inventory for all sectors in all regions for the target year. Carbon inventories for 2012 and 2015 are constructed by Shan *et al* 2018 and can be accessed from the China Carbon Emissions Dataset (http://ceads.net/). Due to the lack of MRIO tables for 2013 and 2014, consumption-based emissions for 2013 and 2014 are estimated as follows:

$$C_{2013} = \frac{2}{3}E_{2013}\boldsymbol{L}_{2012}(\boldsymbol{FS}_{2012}\boldsymbol{FV}_{2013}) + \frac{1}{3}E_{2013}\boldsymbol{L}_{2015}(\boldsymbol{FS}_{2015}\boldsymbol{FV}_{2013}), \tag{9}$$

$$C_{2014} = \frac{1}{3}E_{2014}\boldsymbol{L}_{2012}(\boldsymbol{FS}_{2012}\boldsymbol{FV}_{2014}) + \frac{2}{3}E_{2014}\boldsymbol{L}_{2015}(\mathbf{FS}_{2015}\boldsymbol{FV}_{2014}), \tag{10}$$

where $\boldsymbol{FS}_t$ refers to the structure of final demands for the year t, and $\boldsymbol{FV}_t$ refers to the total final demand for the year t, $\boldsymbol{L}_t$ is the Leontief inverse which is equal to $(\mathbf{I} - A_t)^{-1}$. Total demand for 2013 and 2014 is able to be derived from the China Statistics Yearbook, but there remains a lack of detailed information. Therefore, the structures of final demands are estimated by the structure for 2012 and 2015 with different weights. A similar approach can be found in Mi *et al* 2018.

2.4. Structural decomposition analysis (SDA)

Structural decomposition analysis has been widely used in identify socioeconomic drivers of changes in environmental issues, especially in carbon emissions (Mi *et al* 2017). In our study, as our focus is on the impacts of new normal on the carbon flow pattern, we decompose the consumption-based emissions into five factors: carbon intensity (E), production structure (L), consumption structure (Ys), consumption per capita (Yc), and population (P). It can be expressed as:

$$\begin{aligned}
\Delta CO_2 &= CO_{2t} - CO_{2t-1}\\
&= E_t \cdot L_t \cdot Ys_t \cdot Yc_t \cdot P_t - E_{t-1} \cdot L_{t-1} \cdot Ys_{t-1} \cdot Yc_{t-1} \cdot P_{t-1}\\
&= \Delta E \cdot L_t \cdot Ys_t \cdot Yc_t \cdot P_t\\
&+ E_{t-1} \cdot \Delta L \cdot Ys_t \cdot Yc_t \cdot P_t\\
&+ E_{t-1} \cdot L_{t-1} \cdot \Delta Ys \cdot Yc_t \cdot P_t\\
&+ E_{t-1} \cdot L_{t-1} \cdot Ys_{t-1} \cdot \Delta Yc \cdot P_t\\
&+ E_{t-1} \cdot L_{t-1} \cdot Ys_{t-1} \cdot Yc_{t-1} \cdot \Delta P,
\end{aligned} \tag{11}$$

where Δ denotes the change in a factor. Each of five factors in equation (11) represents the contributions to carbon emission changes induced by one force while other factors are kept constant. The five factors have $5\,! = 120$ equivalent decomposition forms, but this approach is too time consuming for the modelling. Instead, we use the average of two polar decompositions (Dietzenbacher and Los 1998). In emissions embodied in exports, we combine the population and export per capita together into export volume, because our focus is on China's exports, rather than the effects from the growth in population in other countries. Therefore, four factors are considered into SDA in emissions embodied in export: carbon intensity (E), production structure (L), export structure (Es), export volume (EV).

3. Results

3.1. Peaked consumption-based emissions for China

China's consumption-based emissions have grown rapidly over the last decade, from 3308 Mt in 2007 to a peak of 8331 Mt in 2013, after which the emissions then declined by 2.9 % in 2014 and rose slightly by 0.6% in 2015, respectively, reaching 8110 Mt in 2015 (figure 2(a)). As emissions induced by consumption can be emitted from the boundary where the consumption happened, consumption-based emissions consist of two parts: emissions embodied in domestic products and emissions embodied in imports, where the former takes the dominant proportion with more than 90% of the total consumption-based emissions. Both components followed the same trajectory and peaked in 2013, with 7796 Mt for emissions embodied in domestic products and 512 Mt for emissions embodied in imports. There is a fluctuation for domestic emissions from 2014 to 2015, with a rise by 0.7%, after a decline of 3.0% from 7796 in 2013, while import-related emissions constantly declined to 495 Mt in 2015. In import-related emissions, less developed countries accounted for more than 60% of the import-related emissions over the period from 2012 to 2015.

Huge regional heterogeneity in China makes different regions have variant roles in the peaking of consumption-based emissions (figure 2(b)). To facilitate the results and discussion, we aggregate 31 provinces and cities into eight regions. Figure 2(b) highlights the change in consumption-based emissions from 2012 to 2015 for each region. Among eight regions, East Coast, Southwest, and West show the peak in consumption-

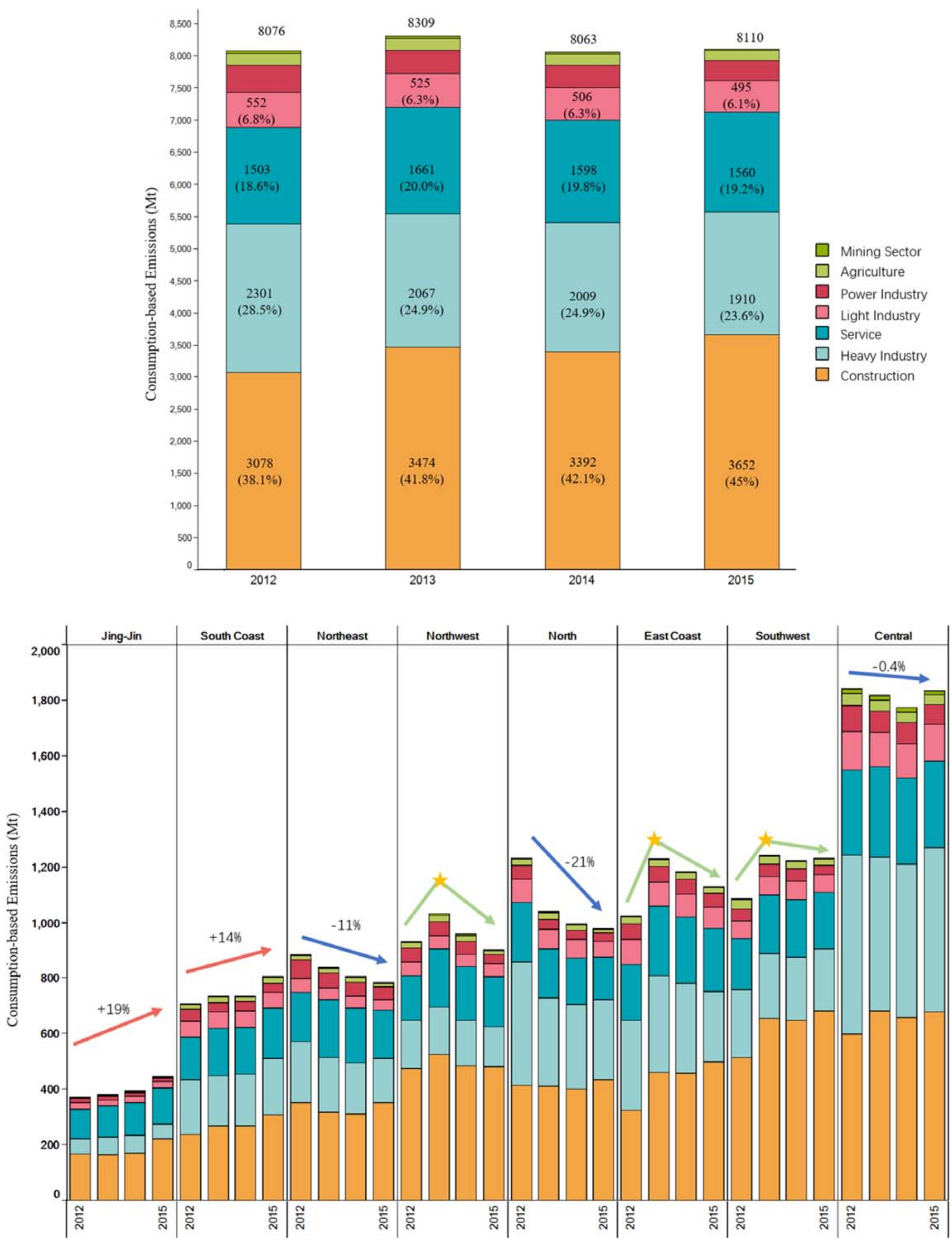

Figure 2. (a) Change in national consumption-based emissions between 2012 and 2015 by sectors; (b) Change in regional consumption-based emissions between 2012 and 2015 by sectors.

based emissions in 2013. Northeast, North and Central have constant declines in their consumption-based emissions over the period, in which North had the largest declines from 1232 Mt to 978 Mt. In contrast, only Jing-Jin and South Coast show a rise in the emissions, with an increase of 73 Mt and 97 Mt. However, emissions embodied in local products and trade play different roles in the peak of different regions. As the main component in consumption-based emissions, emissions embodied in local products of Jing-Jin, East Coast, Southwest, Northeast, and Northwest peaked in 2013, which largely contributes to the peak of total consumption-based emissions. Notably, all the regions, whether rise or decline of consumption-based emissions, both show the declined emissions driven by local demands. Correspondingly, it indicates that all regions outsourced more emissions embodied in domestic trade over the period. Emissions embodied in trade shows the increase for all regions except North and Northeast from 2012 to

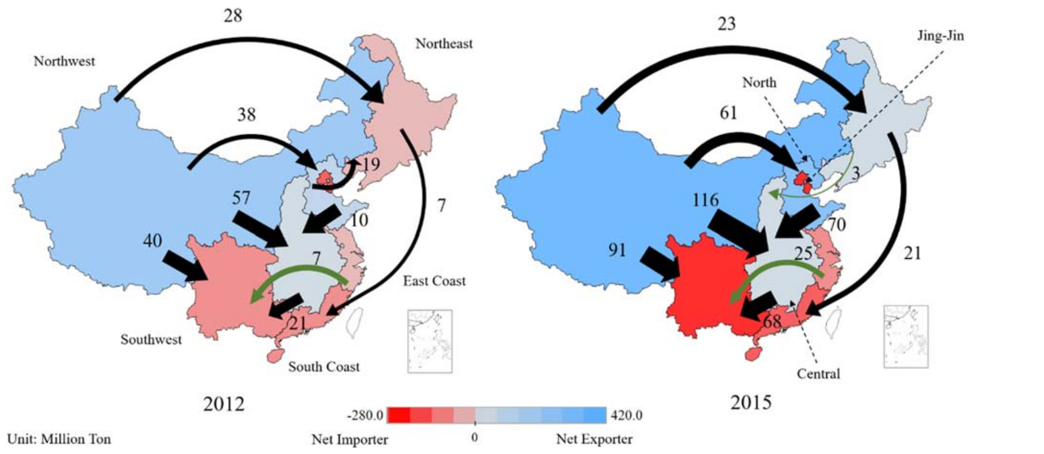

Figure 3. Change in net interregional carbon flows between 2012 and 2015.

2015, particularly in Southwest and Central where the trade-related emissions rose by 164 Mt and 151 Mt respectively. From a sectorial perspective, most of the declines in consumption-based emissions after 2013 was from heavy industry and tertiary sectors. With the exception of Southeast Coast and Central regions, all other regions have a decline in the emission embodied in heavy industry, in which East Coast and Northeast contributed the most, with the decline of 97 Mt and 34 Mt respectively. In tertiary sectors, Northeast and Northwest are the main contributors with a decline of 34 Mt and 29 Mt respectively. In contrast, this decline is partially offset by the rise of emissions embodied in construction which increases by 178 Mt from 3474 Mt to 3652 Mt during 2013–2015, most of which are from affluent regions. Jing-Jin, East Coast and Southeast Coast saw the emissions embodied in construction increase by 58 Mt, 41 Mt, and 39 Mt respectively.

Figure 3 highlights the outsourced emissions embodied in domestic trade within China. The rising of the Southwest and the Central figures frames the interregional carbon flows over the period. As the less developed inner region in China, Southwest and Centre had the role of producers to support affluent Coastal regions. Previous studies found the reversed regional carbon flow pattern from developed coastal regions into developing inner regions after the financial crisis, with Southwest switching from net emissions exporter into net emission importer (Mi *et al* 2017), which is in line with our study. During 2012–2015, the pattern has been reinforced with the rapid growth of consumption-based emissions, most of which are from inflow. Inflow-related emissions for the Southwest and the Central regions increased from 390 Mt to 548 Mt and from 594 Mt to 724 Mt respectively. The rise of the Southwest has become a regional highlight in China's economic transition, where the huge demands in the regions are largely strategically induced by Belt and Road Initiative and the industrial upgrade. Massive investments in infrastructure lead to the significant demands for carbon-intensive products, such as steel and cement, which are mainly supplied from the Northwest and the Central. This is the underlying reason of the increasing carbon embodied in inflow from the Northwest and the Central. Although the Central region is still at the stage of net emissions exporter, its role is set to gradually change, with several subtle but significant signs. During the period, net emissions export for the Central region declined from 40 Mt to 20 Mt, with emissions embodied in inflows from Northwest significantly increased (40 Mt to 91 Mt), and reversed flows from the net emission export into the net emission import from Northeast. One of reasons is associated with regional policies to promote economic development in Central areas, especially the industry upgrade in China where the low value-added industries are re-locating from the coastal regions. Therefore, it is expected the Central region would be about to turn into a net importer in the recent future.

On the other hand, other less developed regions like Northwest and North have larger emissions in the net export, with the emissions surging from 268 Mt to 422 Mt for Northwest and 82 Mt to 287 Mt for North. More than 50% of the growth in net emissions are from Southwest and the Central. In addition, Northeast is found as showing a reversal from net emissions importer in 2012 to net emissions exporter in 2015, from 31 Mt net import emissions to 39 Mt net export emissions, largely because of Southwest and the Central, whose net flow rose from 4 Mt to 21 Mt for the net exports in Southwest and from 12 Mt in net imports to 3 Mt in net export in the Central.

3.2. Socioeconomic driving force in the economic transition

Despite the lack of an MRIO table for the peaking year, the trend of driving forces over the period from 2012 to 2015 should be consistent. Among all the factors, a change in intensity is the major socioeconomic driving factor in the decline in China's consumption-based emissions, with a reduction of 804 Mt of emissions

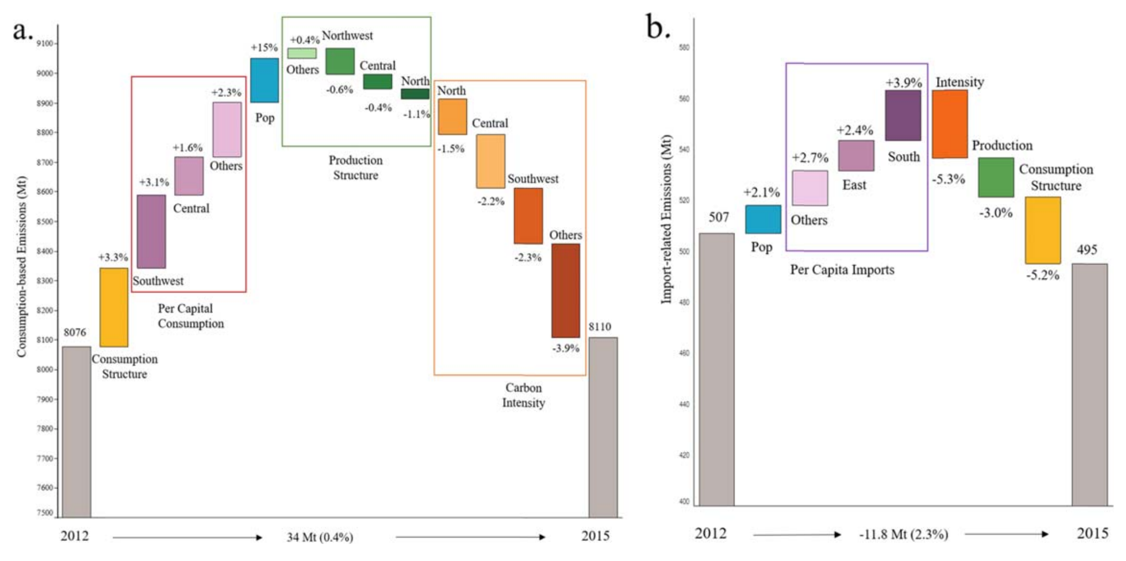

Figure 4. (a) Socioeconomic driving forces in the change of consumption-based emissions during 2012–2015; (b) Socioeconomic driving forces in the change of import-related emissions during 2012–2015.

and 9.96% of emissions in 2012 (figure 4(a)). Changes in production structure led to a decline of 137 Mt of emissions, accounting for 1.69% of emissions in 2012. Notably, the share of intensity in the consumption-based emissions decline is significantly larger in comparison with the period 2010–2012 (+1.3%) (Mi *et al* 2017), which indicates that China's efforts in promoting clean technology and energy transition in the new normal still makes significant impacts in China's decarbonisation (Shan *et al* 2015).

From the regional perspective, changes in production structure and intensity in developing regions were of importance in the declines of consumption-based emissions, especially for Central region where the changes in production structure and intensity led to the fall of 33 Mt and 179Mt respectively. Southwest and North were leading in emissions reduction from changes in intensity, with declines of 189 Mt and 121 Mt. This is associated with China's policy to clean its energy mix, including encouraging renewable energy development in the Southwest, fostering cleaner coal technology and reducing coal consumption, especially in the North (Hu *et al* 2016, Engels 2018, Wang *et al* 2018).

On the other hand, per capita consumption is still the main component to drive up emissions, with 6.9% if other factors remain constant. However, the consumption structure plays another role in driving up emissions, which is reversed from the role over the period 2010–2012 (Mi *et al* 2017). The reversal is mainly due to the increased demands in construction where final demands for construction increased by 4% over the period. Although the direct carbon intensity in construction is relatively tiny, its indirect carbon intensity can be very large, because of the large amounts of carbon-intensive products required for construction, such as steel, cement, and electricity.

Increasing per capita consumption in Southwest and Central contributed almost half of the growth of per capita consumption. A key reason why Southwest and Central were leading in emissions growth is associated with China's regional development strategy in economic transition, which prioritises the industry transfer from coastal regions to inner regions, particularly in Southwest and Central (Zheng *et al* 2019). In 2015, most of the provinces in Southwest and Central - especially Chongqing, Hubei, and Guizhou - were the fastest provinces in GDP growth, with an increase by 32% and 26% in comparison with a 25% national growth rate over the period.

In contrast to socioeconomic driving forces of total consumption-based emissions, consumption structure contributes to the decline of emissions, which is largely due to less energy intensive imports from developed countries (figure 4(b)). For example, consumption structure for the imports from Japan, South Korea, the US, and EU 28 sees a decline of 16.3 Mt of import-related emissions, accounting for 63% of declined emissions induced by consumption structure for imports. On the other hand, consumption structure for imports from less developed countries in Central Asia, Africa and South Asia drives up emissions, which indicates China would outsource more energy intensive products from these less developed countries. Per capita import is the main driving force, especially for affluent regions, like East Coast and South Coast.

Figure 5 shows disaggregation for the effects of production structure and intensity on emissions from local, domestic trade, and import. Declines in consumption-based emission by lower carbon production structure and intensity was largely from emissions embodied in local products, except in Northeast. Lower intensity for products and services in domestic

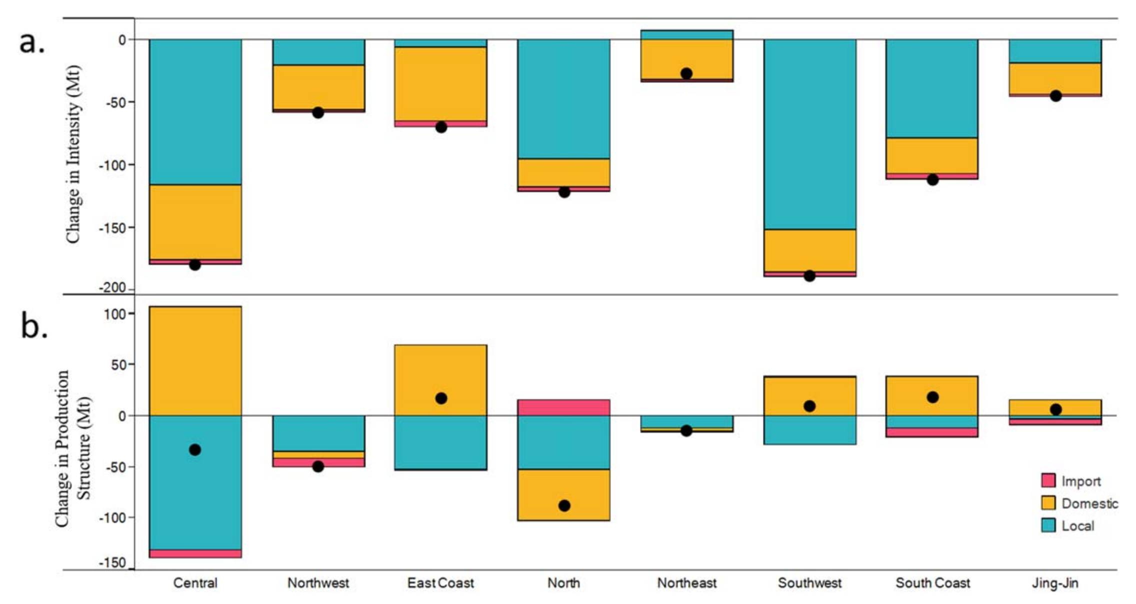

Figure 5. Disaggregation of production structure and intensity by source.

trade reinforced the declines in consumption-based emission, especially for Northwest, East Coast, Jing-Jin, and Northeast where changes in carbon intensity from domestic trade become the main contributor in reducing consumption-based emissions. In developed and rapidly developing regions, however, the declines induced by local production structure are offset by changes in production structure for domestic trade, which reflects high carbon-intensive products domestically imported from other regions. It might be explained by the fact that industries in the regions were transforming into high value-added industries that require more outsourced primary but carbon intensive ingredients, such as fossil fuel.

3.3. Bounce-up export related emissions

Previous studies predicted China's export-related emissions would decline after the financial crisis with estimated export data or extrapolation (Zhifu *et al* 2018, Huang *et al* 2019). However, we found that Carbon emissions embodied in export bounced up with an increase from 1557 Mt to 1576 Mt over the period 2012–2015. Figure 6(b) indicates the contributions of socioeconomic driven forces for each region. The rise of export-related emissions was mainly driven by the trade volume which leads to 107 Mt of growth in China's export-related emissions, with other factors remaining constant. It is related to increased export volume over the period, where the gross value of Chinese exports increased almost 8% from 2012 to 2015. Among other factors, lower intensity in production led to a significant decline in carbon emissions, with 126 Mt of declines in total. In line with domestic emissions, production structure for exports turned out to be less carbon intensive, declining 38 Mt emissions embodied in exports. It is notable that export structure was estimated to be turned from the emissions contributors into the reducer after the financial crisis in the previous studies (Zhifu *et al* 2018). However, we found that export structure reverted back to the emissions driving up factor during the period from 2012 to 2015, which induces 75 Mt of the export-related emissions growth.

At the regional level, growth in export-related emissions mainly came from South Coast and North (figure 6(a)), with 46 Mt and 23 Mt of the growth over the period. However, the growth of export-related emissions for South Coast is induced by increasing trade volume while export structure is the largest reason behind the emission rising in North. In contrast, the growth of emissions is largely offset by the decline of export-related emissions from Northwest, with a decline of 72 Mt emissions. In Northwest, all factors contribute to the declines, though decreased trade volume is the main reason. East Coast is the largest emission exporter, accounting for one third of total emissions embodied in export, but its export-related emissions declined from 547 to 538 Mt, in which the production structure drove down emissions. In contrast, as the second largest exporter, export-related emissions from South Coast increased by 14% from 318 to 364 Mt, due to increasing trade volume, carbonised production structure and export structure, but offset by the intensity reduction. Notably, export structure in all regions drove up the emissions except Northwest, which was associated with China's trade trend that the country is in transition from exporter for labour-intensive products into value-added intensive products, such as machines and electronic devices. In 2015, China's export of heavy industry products (e.g. machinery and equipment) accounted for 57% of total exports.

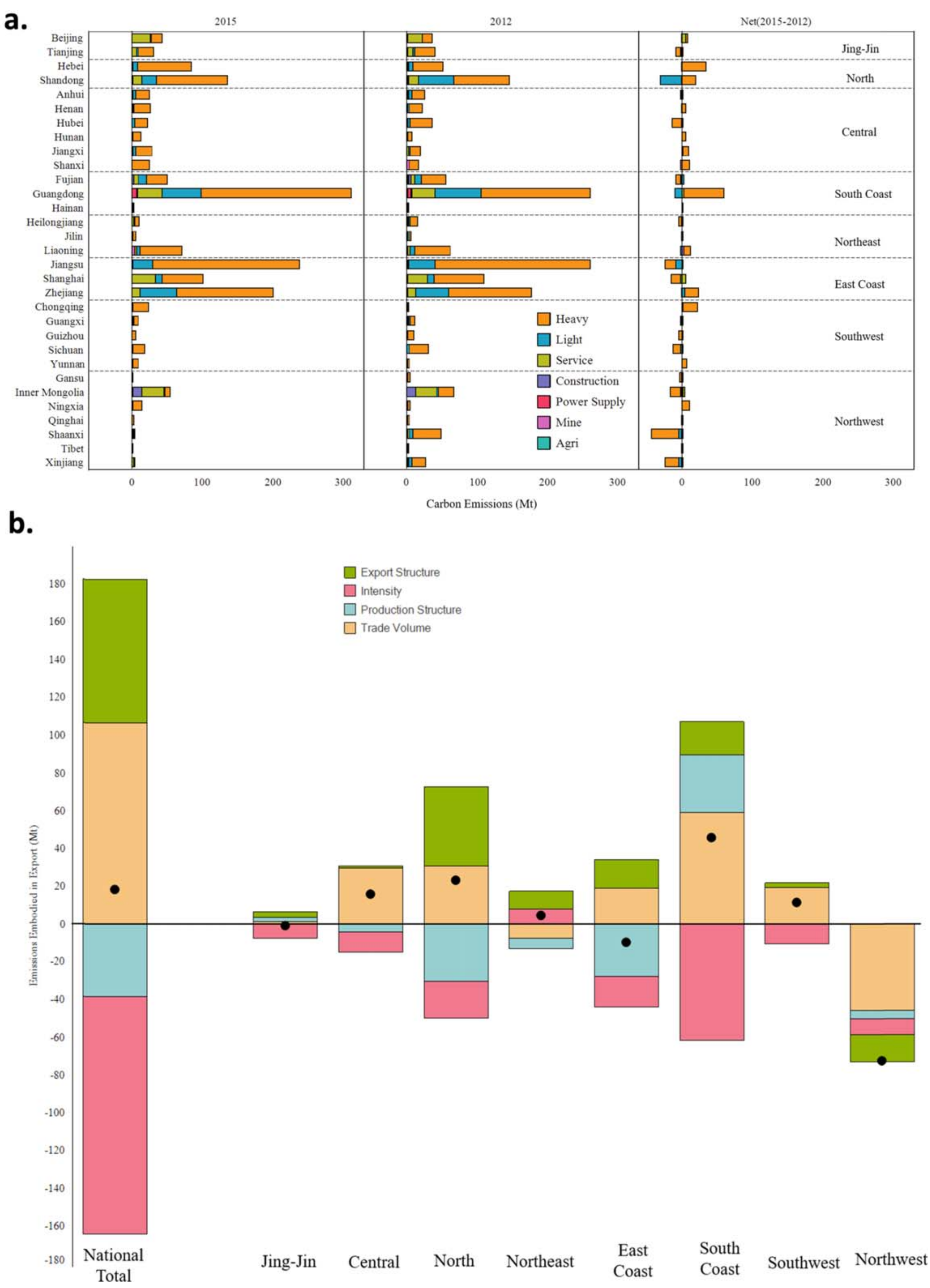

Figure 6. (a) Comparison in emissions embodied in export between 2012 and 2015; (b) Socioeconomic driving factors behind the change.

4. Discussion

As the world's top emitter, peaking consumption-based emission is a milestone for China and the tipping point for China's decarbonisation. Regional contributions varied due to the regional disparity, in which the disparity between developing regions led to the trend. Northeast, North, and Central have peaked in their consumption-based emissions before 2012, while Northwest and Southwest saw the highest emissions in 2013. Among five socioeconomic driven forces decomposed by SDA, change in intensity and production structure are the biggest contributor in the decline of consumption-based emissions, which were both rooted in China's economic model transition in the post-financial crisis, especially in developing regions

(Mi *et al* 2017). In the last few decades, China's rapid development adopted the growth model which emphasised the high investment in heavy industry such as steel, cement production and infrastructures (Green and Stern 2016). Despite the merits of the rapid economic progress, the growth model led to serious consequences in all socioeconomic aspects, such as air pollution, low energy efficiency, regional inequality and widespread excess capacity in steel, cement, and energy sectors (Sheehan *et al* 2014, Zheng *et al* 2014, Green and Stern 2016).

To respond to the challenges, economic transition policies prioritise the elimination of outdated and excessive capacity in key sectors, promoting high value-added manufactory, and shifting energy mix into less coal consumption (Mi *et al* 2016, Ou *et al* 2019, Zheng *et al* 2019). Although detailed polices were officially launched in the 13th five-year plan (2016–2020), many efforts have been made during 2012–2015. For example, China has eliminated outdated capacity, such as 21.1 GW in coal-fired power generation capacity, 520 Mt in coal production, and 126 Mt in iron and steel processing (Guan *et al* 2018). In the 13th five-year period, clear targets in elimination of outdated and excessive capacity have been applied in key sectors, for example, reducing capacity of raw steel production by 100 Mt to 150 Mt in total and of raw coal production by 800 Mt per year (Ministry of Industry and Information Technology 2016, National Development and Reform Commission 2016).

At regional level, however, the huge heterogeneity in the socioeconomic conditions indicates the different pathway and foci may be chosen in different regions. For the eastern and south regions, given that their developed economy largely relies on supply from the less developed regions, mitigation on the supply chain could be prioritised. From 2012 to 2015, it shows the growth in net carbon inflows indicating the more outsourced carbon generated in the western regions to supply their economy. The pattern has been observed in many studies where the developed economy usually outsources more emissions from the less developed economy (Feng *et al* 2014, Fang *et al* 2019). It is not a surprise for the continual increasing in consumption-based emissions in Jing-Jin region and South region, given the increasing consumption and population. However, eastern coastal regions show the decline of consumption-based emissions after 2013, which possibly attributes to industrial relocation. For example, the industrial value-added from the eastern region is increasingly less weighted in the nationally aggregated, dropping from 62.71% to 54.93% from 2004 to 2017. Since 2013, the emissions from local production consistently declined from 550 Mt to 442 Mt, while the outsource emissions increased from 678 Mt to 685 Mt and domestically outsourced emissions increased from 551 to 579 Mt. Traditional energy-intensive but low value-added industries are transferred from eastern regions to the central and western regions, which leads to positive contributions of domestic production structure to emissions, as shown in figure 5 (Xin-gang and Fan 2019).

In economic transition, southwest and central regions become the key growth points with increasing demands and infrastructure investment. This is largely induced by the Belt and Road Initiative and industrial upgrade, where the Southwest is regarded as the front markets connecting with the south Asia countries. In addition, the industrial upgrade for Southwest prioritises high-tech industries and tertiary sectors in the regional development strategy. High-tech industries, such as car manufacturing and the telecommunications and electronic industries, are rapidly developed in these regions and have gradually become the backbone industries. For example, the telecommunications industry in Guizhou contributes to 27% of provincial GDP, and its growth rate has been the leading one in China since 2013, with approximately more than 20% growth per year. In addition, large infrastructure investments induced by the Belt and Road Initiative promote massive scale urbanisation, which significantly increased the demands for carbon-intensive products throughout the supply chain. In Chongqing, Yunnan, and Guizhou, the growth rates of the retail industry, accommodation and catering, and the financial industry are leading among Chinese provinces. In contrast, China's traditional heavy manufacturing hub, such as North and Northeast, follows the mitigation pathway in eliminating the outdated technology factories and reducing carbon intensity by using cleaner energy types (Feng and Wang 2019, Zheng *et al* 2019). As the energy and heavy industrial products supplier, reducing production-based emissions from the key industries is the priority for local authorities. Since 2012, a series of economic policies to phase out excessive production capacity and halt the new coal plant construction have been implemented. For example, small-sized coal producers often with outdated technology have been eliminated and by 2015, coal production from medium and large producers accounted for 80% of the total supply in comparison with 58% in 2010. Energy supply provinces in North, Northeast, and West regions are key in the policy implementation.

As the economic transition policies will be consistent and continue even more rigorously in the future, it is expected that lower intensity and a less carbon-intensive production structure is likely to be persistent in the long run, thereby with declined consumption-based emissions. As part of the economic transition target, regional developments—especially in the Southwest and the Central regions—should be noted, as industrial relocation from coastal regions might drive up the local emissions. Fortunately, the local production structure and intensity in SDA show the positives in decarbonisation, while increasing emissions embodied in domestic trade, which mainly came from

Northwest, have highlighted the spillover from outsourcing high carbon intensive materials from less advantaged regions. Given the supply chain from the Northwest and Central, it raises a potential opportunity in the coordination strategies across regions, where the net consumer regions are supposed to subsidise the cost of low carbon transition for the producer regions (e.g. upgrading cleaner technology), such as the linkage between the Southwest and the Northwest.

The recent declines in consumption-based emissions are rooted in China's changing production structure and the wide adoption of low carbon techniques, and is expected to be sustained with the continuous and consistent economic policy prioritising clean production. However, the uncertainty remains on China's emissions trajectory due to the long-term socioeconomic policies, where China's decreasing growth rate might make governments take action to stimulate the economy, such as with more infrastructures investment or promoting the consumption in the Belt and Road Initiative. The scenario is likely where the rise of emissions, led by growth in the consumption, offset the declines due to the change of production structure and intensity. The Southwest and Central region of China is likely to see the rise of emissions due to the socioeconomic growth under the context of the Belt and Road Initiative. Given the large scale hydropower development in the Southwest, penetration of renewable energy is increasing, where 79% of power supply in Sichuan province is from hydropower (Hu *et al* 2016). The potential clean energy output in the Southwest could largely reduce the domestic emissions for the local demands. However, the central region is in energy transition and still largely relies on traditional fossil fuel, which challenges the low carbon transition in the future. It might be too early to identify the long-term tipping point in consumption-based emissions, while the decline indicates a sign that the changing socioeconomic structure has profoundly affected the emission trajectory and plays an increasingly determined role in the future mitigation.

Improved energy efficiency and increased domestic consumption are two features in China's economic transition. These may lead to the concern of the rebound effect where the rise of emissions induced by the consumption could offset the mitigation triggered by improvement in energy efficiency. Based on the SDA results (figure 4(a)), the emissions reduction due to decreased carbon intensity is more than the emissions increase due to the increased consumption. It can be expected that increased consumption will continue with the economic growth in China, while the carbon intensity might reach a threshold which is difficult to reduce further. The decrease in carbon intensity largely relies on the clean technology and clean energy mix. Given coal is still the main energy type used in China, the potential for 'cleaning' the energy mix is still huge. The government has made great efforts in renewable energy development and replacement of coal combustion. According to the energy development plan (2016–2020), China set the target that the share of non-fossil fuel should reach 15% of the total energy consumption, with the share of natural gas increasing to more than 10% and the share of coal reducing to below 58%. In addition, more restricted emissions standards are introduced into the manufacturing sector to encourage the adoption of clean technology (Tang *et al* 2019). Therefore, it can be expected that the restriction policy in energy transition and technology penetration could be consistent in the future, and would not be offset by increasing consumption in the foreseeable future.

Given emissions embodied in domestic products account for more than 90% in China, peak consumption-based emission is largely compatible with the peak in China's territory emissions, which was estimated in 2013 with 9.5 Gt CO_2 (Guan *et al* 2018). However, import-related emissions have to be cautiously monitored in the future, as import-related emissions from Africa, Southeast Asia countries, and the Middle East is increasing, albeit gradually. It is worth noting the phenomenon of offshoring low-value but energy-intensive industries to other emerging markets in Southeast Asia in China's economic transition, due to the comparative advantage in emerging markets (Meng *et al* 2018). For example, during 2014–2018, Chinese steel firms have built 32 million ton of capacity in Indonesia and Malaysia, accounting for 40% of steel consumption by 10 Southeast Asia countries in 2016 (Financial Times 2018). It might result in China importing more such carbon-intensive products from less restricted climate policy countries while reducing its domestic production capacity, and therefore increasing its emissions embodied in imports (Branger and Quirion 2014, Meng *et al* 2018). Although all regions, except North, showed declined import-related emissions, more import-related emissions are expected in industrial regions, such as Northwest and Northeast, with more imports of primary commodities.

Increased export-related emissions reflected China's export recovery from the financial crisis, with the export volume doubled from 1.2 to 2.3 million USD. Export structure was found to be a factor in declining the emissions in the post-crisis period (Pan *et al* 2017, Zhifu *et al* 2018), but it reversed as a driving factor in the bounce-up of export-related emissions. This is largely associated with increasing share of carbon-intensive products. For example, shares of metal products (e.g. iron, steel, and machinery etc) and cement exports increased from 16% to 17.4%. It is notable that China's iron and steel exports in 2015 was a record high with 124 million ton, which was double the export in 2008. In contrast, the share of electronic devices (e.g. computers, mobile phones) which are less carbon-intensive, declined significantly from 22% to 20.9% during 2012–2015. The increasing trend of export is likely to persist, as a result of the increasing trade between China and developing countries and the Belt and

Road Initiative. The construction of infrastructure and manufacturing industries for other developing countries, especially those in the Belt and Road Initiative, will boost the considerable demands of low-value, energy intensive products, with China's export in such products likely to take a large share in supply (Zhang *et al* 2017).

Acknowledgments

This work was supported by the National Key R&D Program of China(2016YFA0602604), National Natural Science Foundation of China (41629501 and 71533005), Chinese Academy of Engineering (2017-ZD-15-07), UK Natural Environment Research Council (NE/N00714X/1 and NE/P019900/1), Economic and Social Research Council (ES/L016028/1), Royal Academy of Engineering (UK-CIAPP/425), British Academy (NAFR2180103,NAFR2180104), China Scholarship Council (no. 201606510016) and the Norwegian Research Council: 287690/F20.

Data availability statement

The data that support the findings of this study are available upon request from the authors. China provincial MRIO data for 2015 can be found in China Emission Accounts and Datasets www.ceads.net for free download.

Author contributions

HZ, and JM designed the study. HZ performed the analysis and prepared the manuscript. HZ, JM, DG, W-DW and Z-KZ interpreted data. DG coordinated and supervised the project. All authors (HZ, JM, Z-KZ, X-YW, ED, YS, MS, and JO) participated in writing the manuscript.

Declaration of interests

The authors declare no competing financial or non-financial interests.

ORCID iDs

Heran Zheng https://orcid.org/0000-0003-0818-7933
Yuli Shan https://orcid.org/0000-0002-5215-8657
Jiamin Ou https://orcid.org/0000-0001-5040-4941
Dabo Guan https://orcid.org/0000-0003-3773-3403

References

Branger F and Quirion P 2014 Climate policy and the 'carbon haven' effect *WIREs Clim. Change* **5** 53–71

Canning P and Wang Z 2005 A flexible mathematical programming model to estimate interregional input–output accounts *J. Reg. Sci.* **45** 539–63

China Electric Power Yearbook Committee 2016 *China Electric Power Yearbook 2016* (Beijing: China Electricity Press)

Dietzenbacher E and Los B 1998 Structural decomposition techniques: sense and sensitivity *Econ. Syst. Res.* **10** 307–24

Dietzenbacher E, Los B, Stehrer R, Timmer M and de Vries G 2013 The construction of world input–output tables in the wiod project *Econ. Syst. Res.* **25** 71–98

Engels A 2018 Understanding how China is championing climate change mitigation *Palgrave Commun.* **4** 101

Fang D, Chen B, Hubacek K, Ni R, Chen L, Feng K and Lin J 2019 Clean air for some: unintended spillover effects of regional air pollution policies *Sci. Adv.* **5** 4707

Feng C and Wang M 2019 The heterogeneity of China's pathways to economic growth, energy conservation and climate mitigation *J. Clean. Prod.* **228** 594–605

Feng K, Davis S J, Sun L, Li X, Guan D, Liu W, Liu Z and Hubacek K 2013 Outsourcing CO_2 within China *Proc. Natl Acad. Sci.* **110** 11654–9

Feng K, Hubacek K, Sun L and Liu Z 2014 Consumption-based CO_2 accounting of China's megacities: the case of Beijing, Tianjin, Shanghai and Chongqing *Ecol. Indicator* **47** 26–31

Fernandez Vazquez E, Hewings G J D and Ramos Carvajal C 2015 Adjustment of input–output tables from two initial matrices *Econ. Syst. Res.* **27** 345–61

Financial Times 2018 China steelmakers shift focus to south-east Asia (https://ft.com/content/dfa122b8-6f95-11e8-92d3-6c13e5c92914)

Golan A, Judge G and Karp L 1996 A maximum entropy approach to estimation and inference in dynamic models or counting fish in the sea using maximum entropy *J. Econ. Dyn. Control* **20** 559–82

Green F and Stern N 2016 China's changing economy: implications for its carbon dioxide emissions *Clim. Policy* **0** 1–15

Grubb M, Sha F, Spencer T, Hughes N, Zhang Z and Agnolucci P 2015 A review of Chinese CO_2 emission projections to 2030: the role of economic structure and policy *Clim. Policy* **15** S7–S39

Guan D, Meng J, Reiner D M, Zhang N, Shan Y, Mi Z, Shao S, Liu Z, Zhang Q and Davis S J 2018 Structural decline in China's CO_2 emissions through transitions in industry and energy systems *Nat. Geosci.* **11** 551–5

Hilton I and Kerr O 2017 The Paris agreement: China's 'new normal' role in international climate negotiations *Clim. Policy* **17** 48–58

Hu Y, Huang W, Wang J, Chen S and Zhang J 2016 Current status, challenges, and perspectives of Sichuan's renewable energy development in Southwest China *Renew. Sustain. Energy Rev.* **57** 1373–85

Huang R, Lenzen M and Malik A 2019 CO_2 emissions embodied in China's export *J. Int. Trade Econ. Dev.* **28** 919–34

Jackson R B, Canadell J G, Le Quéré C, Andrew R M, Korsbakken J I, Peters G P and Nakicenovic N 2015 Reaching peak emissions *Nat. Clim. Change* **338** 1–4

Junius T and Oosterhaven J 2003 The solution of updating or regionalizing a matrix with both positive and negative entries *Econ. Syst. Res.* **15** 87–96

Lahr M L and de Mesnard L 2004 Biproportional techniques in input–output analysis: table updating and structural analysis *Econ. Syst. Res.* **16** 115–34

Lenzen M, Wood R and Gallego B 2007 Some comments on the GRAS method *Econ. Syst. Res.* **19** 461–5

McDougall R A 1999 Entropy theory and RAS are friends *Center for Global Trade Analysis, Department of Agricultural Economics* Purdue University GTAP Working Papers

Meng J, Liu J, Xu Y, Guan D, Liu Z, Huang Y and Tao S 2016 Globalization and pollution:tele-connecting local primary PM2.5 emissions to global consumption *Proc. R. Soc.* A **472** 20160380

Meng J *et al* 2018 The rise of South–South trade and its effect on global CO_2 emissions *Nat. Commun.* **9** 1871

Mi Z, Meng J, Green F, Coffman D and Guan D 2018 China's 'exported carbon' peak: patterns, drivers, and implications *Geophys. Res. Lett.* **45** 4309–18

Mi Z, Meng J, Guan D, Shan Y, Liu Z, Wang Y, Feng K and Wei Y-M 2017 Pattern changes in determinants of Chinese emissions *Environ. Res. Lett.* **12** 074003

Mi Z, Meng J, Guan D, Shan Y, Song M, Wei Y-M, Liu Z and Hubacek K 2017 Chinese CO_2 emission flows have reversed since the global financial crisis *Nat. Commun.* **8** 1712

Mi Z, Meng J, Zheng H, Shan Y, Wei Y M and Guan D 2018 Data descriptor: a multi-regional input–output table mapping China's economic outputs and interdependencies in 2012 *Sci. Data* **5** 180155

Mi Z, Wei Y-M, Wang B, Meng J, Liu Z, Shan Y, Liu J and Guan D 2016 Socioeconomic impact assessment of China's CO_2 emissions peak prior to 2030 *J. Cleaner Prod.* **142** 2227–36 (http://linkinghub.elsevier.com/retrieve/pii/S0959652616318935)

Mi Z, Meng J, Green F, Coffman D and Dabo D 2018 China's 'exported carbon' peak: patterns, drivers, and implications *Geophys. Res. Lett.* **45** 4309–18

Mi Z, Zheng J, Meng J, Shan Y, Zheng H, Ou J, Guan D and Wei Y-M 2018 China's energy consumption in the new normal *Earth's Future* **6** 1007–16

Ministry of Industry and Information Technology 2016 Industry Upgrade Guideline for Iron and Steel Industry (2016–2020) (http://miit.gov.cn/n1146295/n1652858/n1652930/n3757016/c5353943/content.html) (in Chinese)

National Bureau of Statistics 2018 *China Statistics Yearbook 2018* (Beijing: China Statistical Press)

National Development and Reform Commission 2016 13th Five-Year Plan for Coal Industry (https://www.ndrc.gov.cn/xxgk/zcfb/ghwb/201612/W020190905497889672824.pdf) (in Chinese)

Ou J, Meng J, Shan Y, Zheng H, Mi Z and Guan D 2019 Initial declines in China's provincial energy consumption and their drivers *Joule* **3** 1163–8

Pan C, Peters G P, Andrew R M, Korsbakken J I, Li S, Zhou D and Zhou P 2017 Emissions embodied in global trade have plateaued due to structural changes in China *Earth's Future* **5** 934–46

Pan C, Peters G P, Andrew R M, Korsbakken J I, Li S, Zhou P and Zhou D 2018 Structural changes in provincial emission transfers within China *Environ. Sci. Technol.* **52** 12958–67

Serrano A, Guan D, Duarte R and Paavola J 2016 Virtual water flows in the EU27: a consumption-based approach *J. Ind. Ecol.* **20** 547–58

Shan Y, Guan D, Zheng H, Ou J, Li Y, Meng J, Mi Z, Liu Z and Zhang Q 2018 China CO_2 emission accounts 1997–2015 *Sci. Data* **5** 170201

Shan Y, Liu J, Liu Z, Xu X, Shao S, Wang P and Guan D 2015 New provincial CO_2 emission inventories in China based on apparent energy consumption data and updated emission factors *Appl. Energy* **184** 742–50

Sheehan P, Cheng E, English A and Sun F 2014 China's response to the air pollution shock *Nat. Clim. Change* **4** 306–9

Tang L *et al* 2019 Substantial emission reductions from Chinese power plants after the introduction of ultra-low emissions standards *Nat. Energy* **4** 929–38

Wang C, Engels A and Wang Z 2018 Overview of research on China's transition to low-carbon development: the role of cities, technologies, industries and the energy system *Renew. Sustain. Energy Rev.* **81** 1350–64

Xin-gang Z and Fan L 2019 Spatial distribution characteristics and convergence of China's regional energy intensity: an industrial transfer perspective *J. Clean. Prod.* **233** 903–17

Zhang N, Liu Z, Zheng X and Xue J 2017 Carbon footprint of China's belt and road *Science* **357** 1107

Zhang X, Karplus V J, Qi T, Zhang D and He J 2016 Carbon emissions in China: how far can new efforts bend the curve? *Energy Econ.* **54** 388–95

Zheng H, Meng J, Mi Z, Song M, Shan Y, Ou J and Guan D 2019 Linking city-level input–output table to urban energy footprint: construction framework and application *J. Ind. Ecol.* **23** 781–95

Zheng H, Shan Y, Mi Z, Meng J, Ou J, Schroeder H and Guan D 2018 How modifications of China's energy data affect carbon mitigation targets *Energy Policy* **116** 337–43

Zheng H, Wang X and Cao S 2014 The land finance model jeopardizes China's sustainable development *Habitat International* **44** 130–6

Zheng H, Zhang Z Z, Zhang Z Z, Li X, Shan Y, Song M, Mi Z, Meng J, Ou J and Guan D 2019 Mapping carbon and water networks in the north china urban agglomeration *One Earth* **1** 126–37

Zheng J, Mi Z, Coffman D, Milcheva S, Shan Y, Guan D and Wang S 2019 Regional development and carbon emissions in China *Energy Econ.* **81** 25–36