Earth's Future

RESEARCH ARTICLE
10.1029/2018EF001059

Key Points:
- Tibet displays unique emission patterns with China's highest ratio of consumption- to production-based emissions
- Virtual flow of Tibet's emissions is enabled by Qinghai-Tibet railway and should be enhanced under Belt and Road Initiative
- Tibet has high carbon footprint but low life expectancy, and a more sustainable pathway should be guided

Supporting Information:
- Supporting Information S1

Correspondence to:
D. Guan,
dabo.guan@uea.ac.uk

Citation:
Ou, J., Meng, J., Zheng, H., Mi, Z., Shan, Y., & Guan, D. (2019). Frequent interactions of Tibet's CO_2 emissions with those of other regions in China. *Earth's Future*, *7*, 491–502. https://doi.org/10.1029/2018EF001059

Received 26 SEP 2018
Accepted 23 MAR 2019
Accepted article online 28 MAR 2019
Published online 30 APR 2019

Frequent interactions of Tibet's CO_2 emissions with those of other regions in China

Jiamin Ou[1], Jing Meng[2], Heran Zheng[1], Zhifu Mi[2,3], Yuli Shan[1], and Dabo Guan[1,4,3]

[1]Water Security Research Centre, School of International Development, University of East Anglia, Norwich, UK, [2]The Bartlett School of Construction and Project Management, University College London, London, UK, [3]School of Management and Economics, Beijing Institute of Technology, Beijing, China, [4]Department of Earth System Science, Tsinghua University, Beijing, China

Abstract Tibet is usually missing from China's emission accounts, especially from those of consumption-based emissions. In this study, we developed a multiregional input-output table for 31 provinces in China and examined the production- and consumption-based characteristics of Tibet's CO_2 emissions in 2012. Results show that the consumption-based CO_2 emissions in Tibet (18.8 Mt, similar to Guinea's emissions in 2015) were three times as high as the production-based estimate (6.2 Mt). Tibet displays unique emission patterns with the highest ratio of consumption- to production-based emissions in China, which are more similar with the east developed provinces rather than its counterparts in west China. More than half of Tibet's consumption-based emissions are supported by Qinghai, Hebei, Sichuan, and others, enabled by the Qinghai-Tibet railway that connected Tibet to China's national railway system. High carbon footprint but low life expectancy is found in Tibet, suggesting the emerging need of a more sustainable consumption pathway under the intensifying interregional connections by Belt and Road Initiative.

Plain Language Summary Located in the most western part of China and the world's highest plateau known as Qinghai-Tibet Plateau, Tibet, plays a unique role in the global ecosystem and climate. Nevertheless, we did not know much about the emissions from human activities in this region. Under China's fast development of western provinces and Tibet's engagement in the Belt and Road Initiative, knowledge of anthropogenic emissions and the dynamics of emissions demands and economic sectors are crucial. This study quantified the emissions happening in Tibet as well as those caused by Tibet's demand but outsourced to other regions. We found that the demands of Tibet and the resulting emissions are largely supported by other regions in China. Emissions virtually transport from west to east due to the frequent interprovincial trade enabled by the Qinghai-Tibet railway. It is also found that Tibet has the third highest carbon footprint (carbon emissions per capita) in China but low life expectancy. It indicates that the current consumption of Tibet is neither climate friendly nor good for human welfare. Attention should be drawn on a more sustainable consumption pathway of Tibet, especially under the context of intensifying regional interactions.

1. Introduction

Located in the most western part of China, the Tibet Autonomous Region (hereafter referred to as Tibet) is the nation's second largest province in terms of area. However, Tibet has long been a missing piece of China's national and provincial emission accounts for various reasons. First, activity data are not regularly collected in this province. While Tibet has a consistent record of some fundamental data, such as population, land use, and gross domestic product (GDP), its energy statistics system has not yet been established, hindering the estimation of both greenhouse gas and air pollutant emissions. Second, due to its remote location and the fragile environment of the Qinghai-Tibet plateau, the population in this region is sparse, and its industry is less developed. Consequently, Tibet accounts for only 0.14% and 0.24% of China's GDP and population (data in 2015; National Bureau of Statistics of China, 2016), respectively. The omission of Tibet in China's emission accounts is therefore considered acceptable compared to the inherent uncertainty of emission inventories (Guan et al., 2012; Weber et al., 2007; Zheng et al., 2018).

However, the knowledge gap in Tibet's emission accounts needs to be filled for Tibet's future development and its significance as China's important carbon sink and natural resources conserver. With its high forest coverage (14% of its total area), large proportion of primary forest, and low anthropogenic disturbance, Tibet has the highest forest stocks in China (The State Council Information Office of China, 2015) and serves as an important carbon sink affecting the global carbon cycle (Sun et al., 2016). In addition, Tibet is located on the Qinghai-Tibet plateau, the world's highest geographical unit. This region plays a critical role in ecosystem and species conservation. Tibet's unique ecological conditions and role as a global carbon sink are partly the result of lower human disturbance. The challenge of balancing human development and natural environment protection has become urgent in recent years. From 2005 to 2015, Tibet had an annual GDP growth of more than 10%, even during the slowdown of China's economy after 2011 (National Bureau of Statistics of China, 2016). Studies on the pollution in Tibet are still sparse but have revealed some alarming signs of contaminants in the soil (F. Zhang et al., 2010), water (K. Zhang et al., 2016), air (Cao et al., 2009; Hindman and Upadhyay 2002), and biota (Pan et al., 2014). As one of the less economically developed provinces in China, Tibet is expected to experience fast development under the support of the central government and the influence of other provinces in the coming years. This rapid development has been especially true after Tibet was connected to the national railway network through the Qinghai-Tibet railway in 2007 and its involvement in China's Belt and Road Initiative. Despite of its possibly small quantity in total emission load, knowledge of emission sources in this region is still indispensable for China's Southwest development and the balance of economic development and nature conservation in Tibet.

There are generally two approaches to understanding an area's emissions. One is a production- or territory-based estimation, which calculates the emissions from local activities within the defined area (Shan et al., 2016). Another approach is consumption-based estimation, which measures the emissions related to the demand of a given province, including those emitted locally and outsourced to other regions (Meng et al., 2016, 2018; Mi et al., 2017; Zhao et al., 2015). While production-based approach is widely used due to its simplicity and clarity, consumption-based estimation complements the production-based method by providing vital information concerning the demand behind the emissions and their interactions with those of other regions (Peters, 2008; Peters & Hertwich, 2008). For Tibet, its emission is poorly understood, especially from the consumption side. A few of existing studies touched the production-based emissions of mercury (Huang et al., 2017), volatile organic compounds (VOCs; Li et al., 2017), and CO_2 (Shan et al., 2017). The sources within this climate-sensitive region and the demands driving the emission activities remain largely unknown.

In this study, multiregional input-output (MRIO) analysis was applied to develop a consumption-based CO_2 emission account for Tibet based on the established production-based inventory. The sector-based contributions, demand-driven emissions, and their interactions with those of other provinces in China through inter-provincial trade were investigated. This study provides the first knowledge of Tibet's emissions from the consumption side, which contributes to a more complete emission account of China and provides important implications for the sustainable development of Tibet.

2. Methods and Data

To study the consumption-based emissions of Tibet and the interactions of these emissions with those of other regions in China, an MRIO table for 31 regions (27 provinces and 4 cities, hereafter referred to as 31 provinces) is constructed. Then, input-output analysis is applied to estimate the consumption-based emissions based upon the production-based inventory. The data used in this study are generally derived from the Chinese official statistics (Ministry of Transport of China, 2013; National Bureau of Statistics of China, 2013; National Statistics Bureau of China, 2013; Tibet Bureau of Statistics, 2013) and previous studies on production-based CO_2 emissions in Tibet (Shan et al., 2017) and other provinces in China (Shan et al., 2016, 2017). The detailed methods and data sources are described below.

2.1. MRIO Table

The MRIO table for 31 provinces is compiled based on the input-output tables (IOTs) for 31 provinces, which are released by the National Statistics Bureau of China. (National Statistics Bureau of China, 2013). These IOTs include 42 economic sectors and five final demands, namely, rural household consumption, urban household consumption, government consumption, fixed capital formation, and inventory change. Exports and imports are also reported and divided into international and domestic amounts.

The above IOTs depict the sectoral inputs and outputs in monetary terms for a given region. However, their interactions with other regions are unknown. To simulate interregional flows, a gravity model is adopted. The standard gravity model expresses the interregional flow as a function of the total regional outflows, total regional inflows, transfer cost, and distance, as shown in equation (1).

$$y_i^{rs} = e^{\beta 0} \frac{\left(x_i^{rO}\right)^{\beta 1} \left(x_i^{Os}\right)^{\beta 2}}{\left(d^{rs}\right)^{\beta 3}} \tag{1}$$

where y_i^{rs} is the trade flows of sector i from region r to s; $e^{\beta 0}$ is the constant proportionality factor; x_i^{rO} is the total outflows of sector i from region r to s; d is the distance between region r and s, which is approximated by the distances between capitals; β_1 and β_2 are weighting coefficients assigned to the masses of origin and destination, respectively; and β_3 is the distance decay parameter. Taking the logarithm of both sides, equation (1) can be expressed as follows:

$$\ln\left(y_i^{rs}\right) = \beta_0 + \beta_1 \ln\left(x_i^{rO}\right) + \beta_2 \ln\left(x_i^{Os}\right) - \beta_3 \ln\left(d^{rs}\right) + \varepsilon \tag{2}$$

Considering the dimensions of the matrix, equation (3) is constructed.

$$\mathbf{Y} = \beta_0 \mathbf{L}_0 + \beta_1 \mathbf{X}_1 + \beta_2 \mathbf{X}_2 - \beta_3 \mathbf{X}_3 + \varepsilon \tag{3}$$

where $\boldsymbol{Y}$ is an $\boldsymbol{N} \times 1$ matrix of the logarithm of the trade flows of product i between regions; $\boldsymbol{L_0}$ is an $\boldsymbol{N} \times 1$ matrix with all elements equal to 1; $\boldsymbol{X_1}$ and $\boldsymbol{X_2}$ are the logarithms of the total outflows from origin regions and total inflows to destination regions, respectively; and $\boldsymbol{X_3}$ is the logarithm of the distance between two regions. Equation (3) is solved by multiple regression.

Based upon the above standard gravity model, two ratios, namely, the impact coefficients and impact exponent, are introduced to reflect varying interregional competition and cooperation relationships for different sectors (Mi et al., 2017). Details on the calculations of these two ratios can be found in the supporting information. The modified trade flow is written as follows:

$$Y' = \hat{Y} / \left(c_i^{gh}\right)^{\theta i} \tag{4}$$

where Y' is the modified trade flow and $\widehat{Y}$ is the trade flow obtained from the standard gravity model. Due to data availability, 42 sectors in the IOTs are aggregated into 30 sectors before the gravity model is applied. The concordance of sectors can be found in Table S1 in the supporting information.

With the above adjusted gravity model, an initial trade flow matrix that describes the flows between every pair of economic sectors for 31 provinces in monetary terms is constructed. Such an initial trade flow matrix does not match the double sum constraints; that is, the total output and input of a specific sector do not match. Therefore, an RAS (Biproportional Matrix Adjustment) approach was adopted to adjust the initial trade flow matrix to ensure agreement with the sum constraints (Jackson & Murray, 2004; Miller & Blair, 2009). The error terms of the adjusted flow matrix were generally within 5%.

2.2. Input-Output Analysis for Consumption-Based Emissions

The interregional and intersectoral flows in the MRIO table enable the estimation going from production-based emission to consumption-based emission. In consumption-based accounting, emissions are allocated to the consuming sectors, regions, and final demands, instead of the sectors and regions that directly emit the emissions. Such an estimation is built on the framework of an MRIO table. For an economy with M regions ($M = 31$ in this study) and N industries ($N = 30$ in this study) in each region, $z_{ij}^{rs}(r, s = 1, 2, ..., 31)$ represents the intermediate product sold from industry i in country r to industry j in country s, y_i^{rs} represents the finished goods sold from industry i in country r to final consumers in country s, and x_i^r represents the total output of industry i in country r.

$$x_i^r = \sum_{s=1}^{31}\sum_{j=1}^{30} z_{ij}^{rs} + \sum_{s=1}^{31} y_i^{rs} \tag{5}$$

A technical coefficient $a_{ij}^{rs} = z_{ij}^{rs}/x_j^s$ is defined as the input from sector i in region r needed to produce one unit of output from sector j in region s. Equation (5) can therefore be formulated as follows:

$$\mathbf{X} = \mathbf{AX} + \mathbf{Y} \tag{6}$$

where $\mathbf{X}$, $\mathbf{A}$, and $\mathbf{Y}$ are the matrices of x_i^r, a_{ij}^{rs} and y_i^{rs}, respectively.

Then, a vector of direct emission intensity, h, is introduced to describe the sector-specific CO_2 emissions per unit of economic output as follows:

$$h = E'/X' \tag{7}$$

where E' and X' are the vectors of production-based CO_2 emissions and total output in monetary terms for 30 industries and 31 regions.

The CO_2 emissions associated with the final consumption in region r can be calculated as follows:

$$F_r = \widehat{h}(I-A)^{-1}\gamma^r \tag{8}$$

where $\widehat{h}$ is the diagonal matrix of h, I is the identity matrix, and γ^r is the final demand vector of region r.

Specifically, the interaction of emission flows between every pair of regions, that is, the emissions transferred from region r to region s, can be calculated as follows:

$$F^{sr} = \widehat{h}^s(I-A)^{-1}\gamma^r \tag{9}$$

When $r = s$, F^{rr} represents the emissions related to the final consumption of products produced locally, and when $r \neq s$, F^{sr} denotes the emissions released in region s related to cross-regional final products that are consumed in region r.

2.3. Data Sources

The single-region IOTs for 31 provinces in China are from the National Statistics Bureau (National Bureau of Statistics of China, 2012) for the year 2012. MRIO table is developed based on the well-established methods (Mi et al., 2017; see supporting information). The production-based CO_2 emission inventories for Tibet and other provinces in China developed by Shan et al. (2016), and Shan et al. (2017) are adopted. These inventories are compiled with a consistent methodology and data sources using the energy consumption data from China's Energy Statistical Yearbooks and the best available local emission coefficients (Liu et al., 2015; Mi et al., 2016). All the emission data can be freely downloaded from the China Emission Accounts and Datasets website (http://www.ceads.net/). The flows of cargo between Tibet and other regions in China are mainly derived from the China Railway Yearbook (The Ministry of Railway, China, 2013) and China Transport Statistical Yearbook (Ministry of Transport of China, 2013). Sectoral trade is approximated by the available data on Qinghai. The sectoral GDPs of China and the Tibet Statistical Yearbooks are also used in the analysis (National Bureau of Statistics of China, 2016; Tibet Bureau of Statistics, 2013).

3. Results and Discussions

3.1. Emissions of Two Boundaries

While production-based accounting calculates emissions within a territory, consumption-based estimations cross territorial boundaries and track the emissions embodied in the regional supply chain induced by the demands of the study area (Chen et al., 2013; Meng et al., 2016; Mi et al., 2016). In this study, we found that consumption-based emissions of Tibet were much greater than the production-based emissions and that emissions occurring in other regions accounted for a large proportion of Tibet's consumption-based emissions.

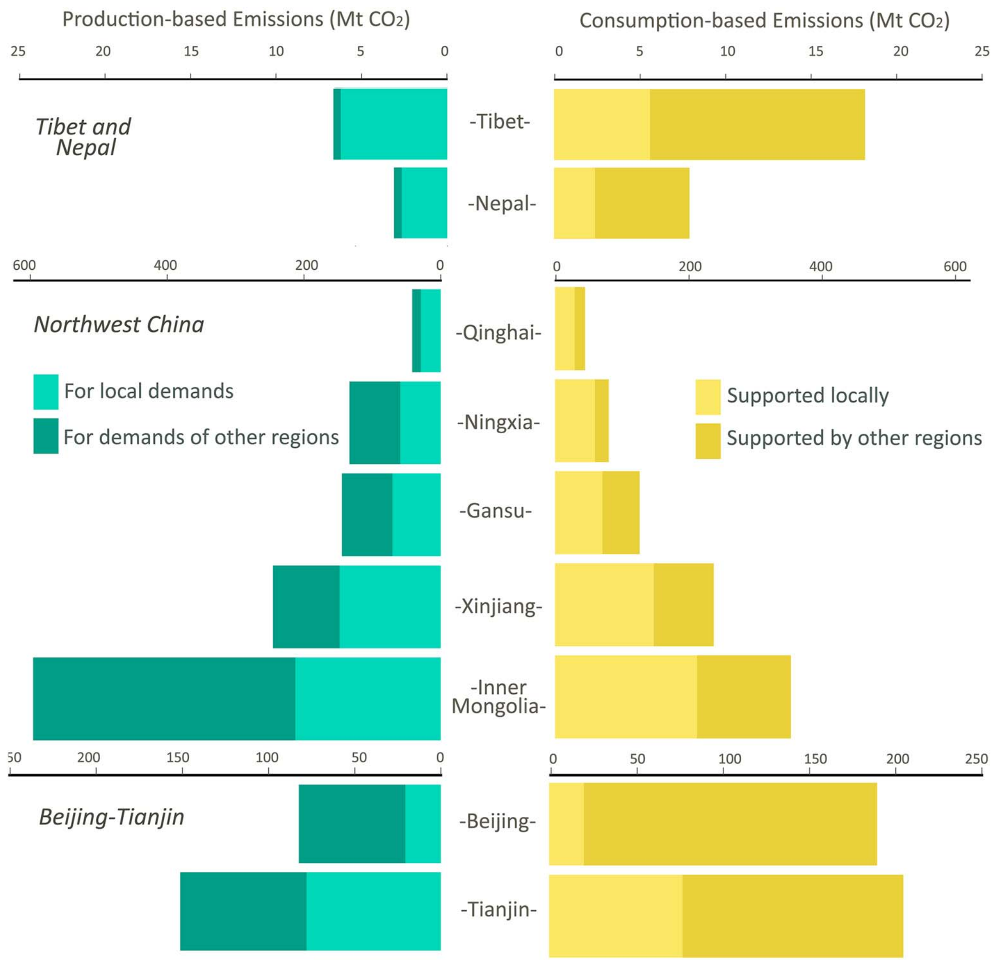

Figure 1. Composition of production- and consumption-based CO_2 emissions.

In 2012, the production-based emissions of Tibet were estimated to be 6.2 Mt of CO_2, accounting for 0.07% of China's total CO_2 budget. From the consumption-based perspective, Tibet's CO_2 emissions increased three folds, reaching 18.8 Mt (0.2% of the national total), which is equal to the emissions of Guinea in 2015 (20.75 Mt; Emissions Database for Global Atmospheric Research, 2017). Consequently, the consumption-based emission intensity of Tibet was much greater than the production-based intensity. The production-based emission intensity was 0.41 $tCO_2/10^4$ RMB in 2012, ranking 23rd among the 31 provinces studied here. In contrast, the consumption-based emission intensity was 1.56 $tCO_2/10^4$ RMB in 2012, ranking fourteenth among the 31 provinces.

The pattern of Tibet's consumption-based emissions was more similar with those of the more developed regions than those of its counterparts in western China. Figure 1 compares the production- and consumption-based emissions of Tibet, provinces in western China, developed regions in east China and Tibet's neighbor, Nepal. The production- and consumption-based estimates share one common emission component: the emissions emitted locally to satisfy local demand. The differences between these estimates are thus caused by the gap between local emissions induced by the exported emissions (in dark green in the left-hand side of Figure 1) and imported emissions (in dark yellow in the right-hand side of in Figure 1). In China, substantial CO_2 emissions are driven by the demands of the more developed provinces along the east coast. In addition, the emissions related to the goods and services consumed in these regions are imported from less developed provinces in central and western China (Mi et al., 2017). As a result, the consumption-based emissions of developed regions are generally much higher than their territory-based emissions. As an example, the territory-based emissions of Beijing were 79.4 Mt of CO_2 in 2012, but its

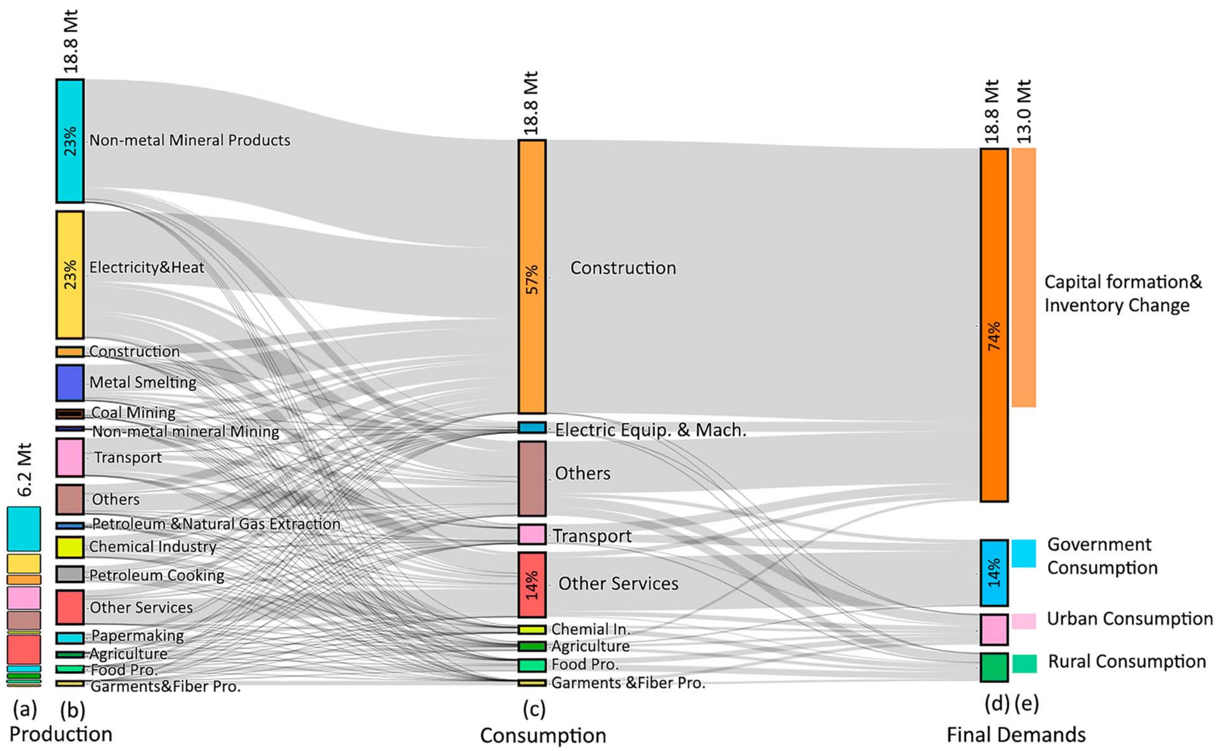

Figure 2. Emission flows from production to consumption and final demands. (a) CO_2 emissions from local production activities in Tibet—6.2 Mt (production-based emissions), which is not sufficient to support Tibet's demands; (b) CO_2 emissions from production activities in Tibet and other regions in China that support Tibet's demands—18.8 Mt; (c) Consumption-based sectoral CO_2 emissions totaling 18.8 Mt; (d) CO_2 emissions by final demand—18.8 Mt; and (e) CO_2 emissions supported by production in other regions by final demand—13.0 Mt.

consumption-based emissions were 196.6 Mt, 2.5 times greater than the territory-based value. In sharp contrast, the territory-based emissions of the less developed western provinces tended to exceed the consumption-based emissions. For example, the consumption-based emissions of Inner Mongolia and Ningxia were 334.9 and 87.2 Mt in 2012, respectively, each equal to 60% of the territory-based emissions. Indeed, approximately 66% and 54% of the emissions in Inner Mongolia and Ningxia, respectively, were emitted during the production of goods and services that were ultimately consumed in other regions.

On contrast, the consumption-based emission of Tibet far exceeded its production-based account. Of the 18.8 Mt of consumption-based emissions in Tibet, 69% were exported to other regions rather than emitted locally. This pattern distinguishes Tibet from other western provinces in China that are generally emission importers supporting the consumption and exports in the richer eastern regions. In fact, the ratio of consumption- based to territory-based emissions in Tibet (3.0) was the highest among the 31 provinces studied here, including greatly developed areas such as Beijing (2.5), Tianjin (1.5), and Guangdong (1.3). The neighbor of Tibet, Nepal, has very similar characteristics; the consumption-based emissions in Nepal were 2.8 times greater than the production-based emissions. These regions are both located near the Himalayas and have limited natural resources and fragile environments that make mass industrial production difficult. Such low self-sufficiency results in high dependencies on other regions.

3.2. Sector-Based Contributions and Driven Demands

The discrepancies between sectoral contributions from production- and consumption-based estimation were also substantial. As shown in Figure 2a, the production-based CO_2 emissions in Tibet were mainly attributed to nonmetal mineral products (29%), other services (19%), transport (15%), and electricity and heat production (12%). Other services accounted for the second largest level of production-based emissions. This result is due to the high share of tertiary industry in Tibet, which accounted for 54% of its GDP in 2012, ranking the third highest in China after Beijing (76%) and Shanghai (60%; National Bureau of Statistics of China, 2013).

The local production activities and production activities in other regions in China (Figure 2b) collectively supported the consumption in Tibet (Figure 2c). From the consumption-based perspective, a large amount of emissions from nonmetal mineral products, electricity and heat production, and metal smelting and processing were due to the demand for construction. Construction accounted for 57% of the consumption-based emissions followed by other services (14%) and transport (4%). Food processing, garments and fiber products, agriculture, the chemical industry, and electric equipment and machinery each contributed 2% to the total consumption-based emissions. Though the contribution of construction to consumption-based emissions is generally higher than its contribution to production-based emissions (Huo et al., 2014; Mi et al., 2016; Ou et al., 2017), the share of emissions from construction in Tibet was still astonishingly high.

The consumptions of different sectors are associated with different final demands (Figure 2d), namely, rural consumption, urban consumption, government consumption, capital formation, and inventory change. The consumptions of construction and electric equipment and machinery were predominantly driven by capital formation and inventory change. As a result, 74% of the consumption-based emissions were related to the demands of capital formation and inventory change. The second highest demand was government consumption, which accounted for 14% of the total consumption-based emissions. Approximately 84% and 42% of the emissions from other services and transport were related to the government's demand, respectively. Urban and rural consumption each accounted for 6% of the total emissions through the demands of food processing, garments and fiber products, and agriculture. Among these final demands, 74%, 44%, 56%, and 72% of the demands of capital formation and inventory change, government consumption, urban consumption, and rural consumption, respectively, were supported by production in other provinces, as shown in Figure 2e.

3.3. Inflowing Provinces

Tibet was interconnected with most provinces in China through interprovincial trade. Figure 3 illustrates the CO_2 emissions related to Tibet's demands, that is, embodied emissions in import to Tibet. In particular, flows of CO_2 emissions were significant for the provinces adjacent to Tibet, for example, Qinghai, Sichuan, and Gansu. Qinghai, Tibet's neighbor to the east, was the region with the largest support of Tibet's demands and consumption-based emissions (20%, 3.8 Mt). Approximately 0.9 and 0.6 Mt CO_2 emissions were embodied in the interprovincial trade from Sichuan and Gansu to Tibet, respectively. Net emission flows from other regions to Tibet were also observed, especially from regions in the north, such as Hebei (1.9 Mt) and Inner Mongolia (0.8 Mt). Some minor flows also originated from the Yangtze River (Shanghai, Zhejiang, and Jiangsu) and the Pearl River Delta (Guangdong), which are China's most economically developed areas. These results make Tibet stand out from its western counterparts, which are usually net emission exporters supporting the developed coastal areas; that is, CO_2 emissions flowed from west to east (Mi et al., 2016).

Some studies have noted that CO_2 emission flows began to reverse in 2012 (Mi et al., 2017). Some provinces in southwest China (e.g., Sichuan, Chongqing, Guizhou, and Guangxi) have shifted from being net emission exporters to net emission importers. However, the provinces in northwest China (including Xinjiang, Qinghai, Inner Mongolia, Gansu, Shaanxi, and Ningxia) are still net emission exporters. The aftermath of the global financial crisis and China's supply- and demand-side reforms might be the reasons leading to this change. Tibet borders provinces in both southwest and northwest China and is not included in previous studies. In this study, the consumption-based emission patterns of Tibet were more similar with those in southwest China. The consumption characteristics of Tibet in this study are additional evidence of the ongoing reversal in emission flows within China.

Such frequent interaction between Tibet and other provinces in China has been enabled by the development of the Qinghai-Tibet railway in recent years. As shown in Figure 3, the density of the national railway network becomes sparser from the east to west. After 2006, Tibet was connected to the national railway network through the Qinghai-Tibet railway stretching from Lhasa in Tibet to Golmud in Qinghai. Prior to this time, only road and air transportation were available. Air transport was expensive and limited in volume. Road transport was unreliable due to the harsh geographical conditions and weather such as frequent mud and rock slides. More stable and cheaper transportation was available after the Qinghhai-Tibet Railway was put into use, which reduced the freight rate from 0.27 (road transport) to 0.12 RMB per ton (price in 2007 RMB). The volume of railway freight surged from 24.9 Mt in 2006 to 40.2 Mt tons in 2012, and this transportation method is responsible for 75% of the goods transported to/from Tibet.

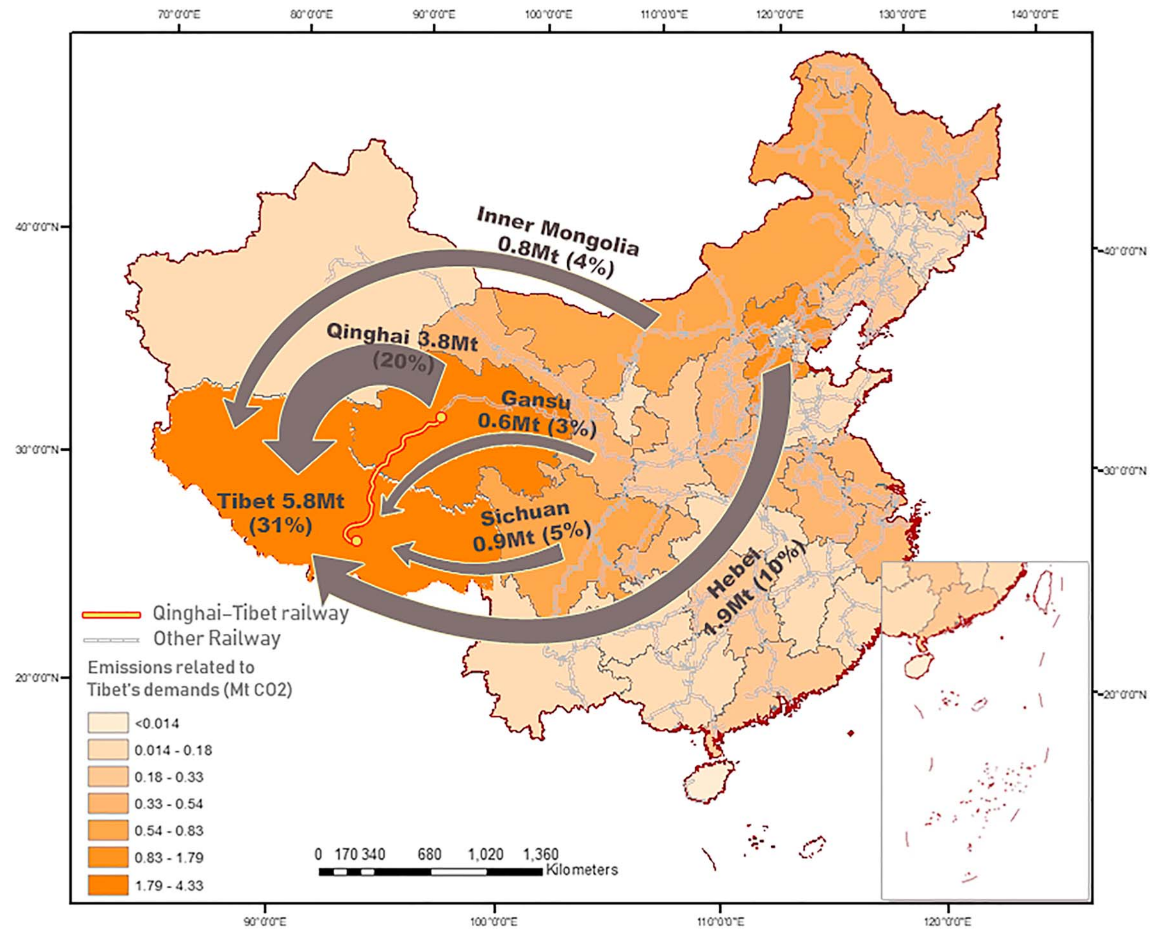

Figure 3. CO_2 emissions related to Tibet's demands. Percentage represents the contribution of the inflowing province to the consumption-based emission of Tibet.

3.4. Inflowing Production Activities

Tibet's economy is mainly supported by agriculture, animal husbandry, forestry, and services. Such an economic structure results in high dependences on a wide range of industrial products, especially those from heavy industries such as cement, iron, steel, machinery, and equipment. Specifically, nonmetal mineral products, iron and steel, general and special equipment and machinery, metal products, chemical products, processed food, garments and fiber products, and paper products from other regions in China accounted for 71% of imported goods to Tibet. The supply of such products has inevitably led to more intense production activity in other provinces, especially in the regions that support Tibet the most, including Qinghai, Hebei, Inner Mongolia, Gansu, and Sichuan. The production activities related to Tibet's demands were generally in energy intensive sectors. As shown in Figure 4, the sectors associated with Tibet's demands were the most diversified in Qinghai and included nonmetal mineral products, electricity production, metal pressing and smelting, and the chemical industry. The emissions from these four sectors increased by 1.7, 1.0, 0.6, and 0.5 Mt, respectively. The emissions outsourced to Hebei were mainly related to nonmetal mineral products (0.5 Mt), electricity production (0.5 Mt), and metal pressing and smelting (0.5 Mt). For Inner Mongolia, Gansu, and Sichuan, electricity production and nonmetal mineral products were the dominant sectors. Electricity production made up an important proportion of outsourced production activities, but Tibet did not directly import electricity from other regions. Instead, it was induced by the increased electricity demand from other production activities such as equipment and machinery manufacturing, food processing, and other products when they were produced locally and exported to Tibet afterward.

The outsourced sectors described above are generally the critical supporting sectors in secondary industry, but these sectors are not flourishing in Tibet due to the limitations of the local environment and natural

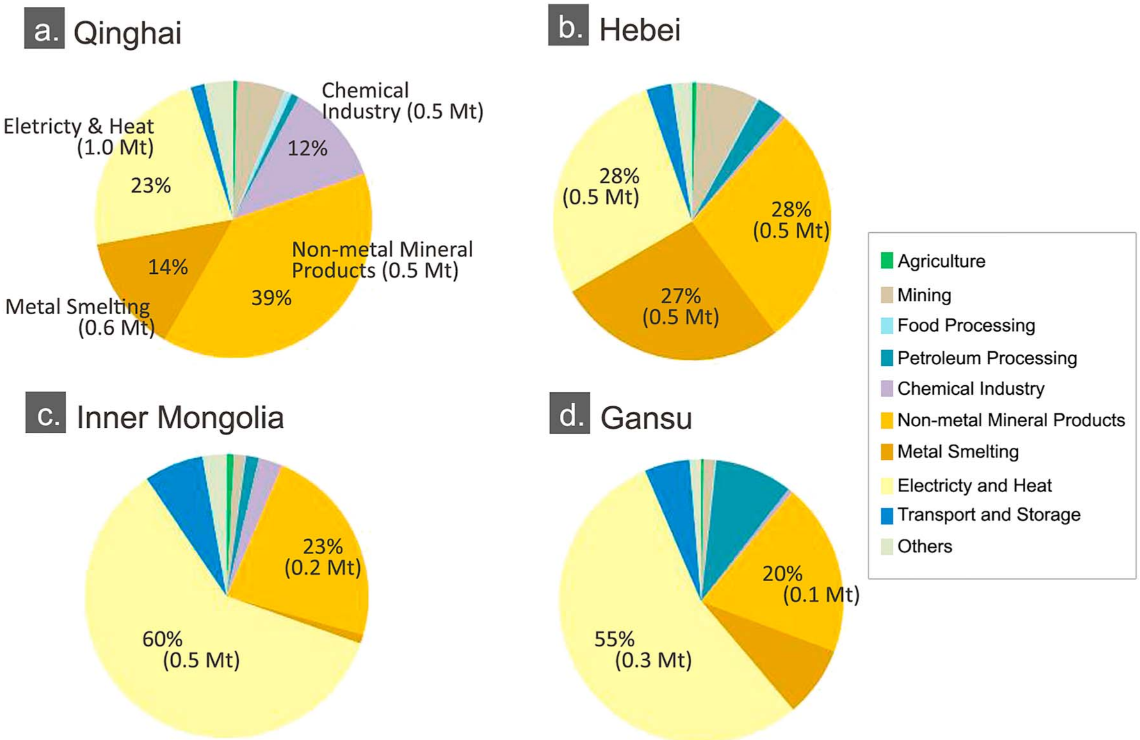

Figure 4. Production activity inflows from (a) Qinghai, (b) Hebei, (c) Inner Mongolia and (d) Gansu due to the demands of Tibet. The number next to each sector's name (e.g., 1.0 Mt) indicates the absolute CO_2 emissions, and the percentage represents the sectoral contribution to CO_2 emissions related to Tibet's demand in a given region.

resources. Tibet is a traditionally agriculture-based autonomous region. After the economic development of the past decade, tertiary industry is now the leading economic driver in this region and accounted for 54% of its GDP in 2012 (National Bureau of Statistics of China, 2013). Industry, including nonmental mineral products, metal processing, chemical industry, and others, accounted for only 8% of the annual GDP of Tibet.

4. Conclusions and Policy Implications

This study presents the first consumption-based estimation of Tibet's emissions. Though Tibet's emissions might be low compared to the total emissions of China (0.2% of the national total from the consumption perspective), such knowledge is indispensable in understanding the environmental issues in Tibet. Results also show that Tibet's emission patterns are unique. Compared to its counterparts in western China, Tibet's consumption-based emission patterns are more similar with those of developed regions in east China with relatively high proportion of emissions supported by other regions.

The ratio of consumption-based to production-based emissions of Tibet was the highest among the 31 Chinese provinces studied here. Nearly 70% of the consumption-based emissions of Tibet were emitted in other regions instead in Tibet itself. If these off-site emissions were to occur locally, Tibet's local emissions would triple, increasing from 6.2 to 18.8 Mt CO_2 in a year. Considering the less advanced manufacturing technology in Tibet, these emissions would climb to 22.3 Mt, 3.6 times greater than the current emissions. Such a relocation of emissions is not as relevant for greenhouse gases that are long-lived and have environmental impacts that are not sensitive to emission location, such as CO_2. However, for short-lived air pollutants and air toxics, such as sulfur dioxide, nitrogen oxides, VOCs, and heavy metals, the emission location greatly determines the harm to ecosystems and human health (Q. Zhang et al., 2017; Jiang et al., 2015; Lin et al., 2014). Given that air pollutants and CO_2 have large overlaps in their emissions sources from fossil fuel combustion (Cifuentes et al., 2001; Schmale et al., 2014; West et al., 2013), the consumption-based characteristics observed in this study are also applicable to air pollutants. If off-site emissions occurred locally in Tibet, the fragile environment would experience catastrophic damage. Further study on how the consumption patterns and virtual transport of emissions affect the local and national environment should be carried out.

As interregional interactions are expected to become more frequent under the development of western China, the design of a more sustainable consumption pathway for Tibet is crucial. The interregional interactions observed in this study are enabled by the transformation of the transportation system in the northwest China in recent years. The transportation infrastructure is expected to be steadily upgraded in the coming decade under China's plan to develop the northwest and the Belt and Road Initiative. Previous studies have defined two criteria for regions within "Goldemberg's Corner," namely, per capita carbon emissions (consumption-based perspective) of less than 1 t C/year and a life expectancy of over 70 years (Lamb et al., 2014; Steinberger et al., 2012; Steinberger & Roberts, 2010). Regions within Goldemberg's Corner represents a sustainable lifestyle with a good balance of environmental conservation and human welfare. Tibet exhibits the opposite trend with a high carbon footprint and a low life expectancy. The per capita carbon emissions in Tibet were 1.74 t C in 2012, and the average life expectancy was 67.8 years. The carbon footprint of Tibet ranked third highest among the 31 Chinese provinces studied here after Tianjin and Shanghai. However, the life expectancies of Tianjin and Shanghai were 75.4 and 72.3 years, respectively (see supporting information Figure S1). The geographical and meteorological constraints would be one reason for the lower life expectancy in Tibet. Thin oxygen, strong solar radiation, and frequent extreme weather are prone to shorten life expectancy. Underdeveloped medical care and other economic factors are also contributing. From the perspective of consumption, the high carbon footprint suggests more can be done to benefit both human welfare and environmental concerns. The high proportion of red meat in Tibet's dietary structure, for example, shortens human life expectancy and leads to high carbon and air pollutant emissions. Under the quickly developing transportation system, opportunities to change the consumption patterns are emerging with easier access of healthier and more environmentally friendly products. In addition, substantial consumption-based emissions are associated with construction, whose emission intensity is generally high. Tibet needs to diversify the local economy toward low carbon development in the long run.

Due to the limited data source, a quantitative estimation on Tibet's consumption-based emission is unavailable. Nevertheless, it is expected that the uncertainty of Tibet's consumption-based carbon account would be much higher than China's national metrics. A recent study found that Chinese national data are one of the largest contributors to the uncertainty of global consumption-based carbon account with a coefficient of variation of 9.07% (Rodrigues et al., 2018). Another consensus is that consumption-based emission is associated with higher uncertainty than the production-based metrics since more data transformation are involved (Owen et al., 2014; Sato, 2014). According to the estimation by Shan et al. (2018), the uncertainties of China's provincial CO_2 emission were roughly (−15%, 25%) at a 97.5% confidence interval. Given the poorer data quality of activity level data and emission factors, the uncertainty of Tibet's consumption-based emission estimation would be higher than the above mentioned range. We urge more efforts to measure the uncertainty of consumption-based account to prioritize uncertainty reduction efforts.

The above results and discussion show the significance of consumption-based accounting in understanding a region's emission characteristics. Similar to production-based accounting, a regular update of consumption-based estimations, an extension to air pollutant emission account, and uncertainty analysis are recommended. Tibet is one of China's important gateways to South Asia under the Belt and Road Initiative. The consumption characteristics in Tibet might change profoundly in the near future. The MRIO table developed in this study can also be applied to study the virtual interregional interactions of air pollutants, water, and energy between Tibet and other regions in China.

Acknowledgments
This study was supported by National Key R&D Program of China (2016YFA0602604), National Natural Science Foundation of China (41629501, 71533005), Chinese Academy of Engineering (2017-ZD-15-07), the UK Natural Environment Research Council (NE/N00714X/1 and NE/P019900/1), the Economic and Social Research Council (ES/L016028/1), the Royal Academy of Engineering (UK-CIAPP/425), and British Academy (NAFR2180103 and NAFR2180104). The MRIO table and Tibet's emissions can be found in http://www.ceads.net/data/input-output-tables/.

References

Cao, X., Q, Y., Q, G., Chen, Y., Ding, K., Zhu, J., & Chen, L. (2009). Indoor air pollution from solid biomass fuels combustion in rural agricultural area of Tibet, China. *Indoor Air*, *19*, 198–205. https://doi.org/10.1111/j.1600-0668.2008.00579.x

Chen, G. Q., Guo, S., Shao, L., Li, J. S., & Chen, Z.-m. (2013). Three-scale input—Output modeling for urban economy: Carbon emission by Beijing 2007. *Communications in Nonlinear Science and Numerical Simulation*, *18*(9), 2493–2506. https://doi.org/10.1016/j.cnsns.2012.12.029

Cifuentes, L., Borja-Aburto, V. H., Gouveia, N., Thurston, G., & Davis, D. L. (2001). Climate change: Hidden health benefits of greenhouse gas mitigation. *Science*, *293*(5533), 1257–1259. https://doi.org/10.1126/science.1063357

Emissions Database for Global Atmospheric Research (2017). CO_2 time series 1990–2015 per region/country. Available via http://edgar.jrc.ec.europa.eu/overview.php?v=CO2ts1990-2015

Guan, D., Liu, Z., Geng, Y., Lindner, S., & Hubacek, K. (2012). The gigatonne gap in China's carbon dioxide inventories. *Nature Climate Change*, *2*(9). Nature Publishing Group, 672–675. https://doi.org/10.1038/nclimate1560

Hindman, E. E., & Upadhyay, B. P. (2002). Air pollution transport in the Himalayas of Nepal and Tibet during the 1995–1996 dry season. *Atmospheric Environment*, *36*, 727–739.

Huang, Y., Deng, M., Li, T., Japenga, J., Chen, Q., Yang, X., & He, Z. (2017). Anthropogenic mercury emissions from 1980 to 2012 in China. *Environmental Pollution*, *226*. Elsevier Ltd, 230–239. https://doi.org/10.1016/j.envpol.2017.03.059

Huo, H., Zhang, Q., Guan, D., Su, X., Zhao, H., & He, K. (2014). Examining air pollution in China using production- and consumption-based emissions accounting approaches. *Environmental Science and Technology*, *48*(24), 14,139–14,147. https://doi.org/10.1021/es503959t

Jackson, R., & Murray, A. (2004). Alternative input-output matrix updating formulations. *Economic Systems Research*, *16*(2), 135–148. https://doi.org/10.1080/0953531042000219268

Jiang, X., Zhang, Q., Zhao, H., Geng, G., Peng, L., Guan, D., et al. (2015). Revealing the hidden health costs embodied in Chinese exports. *Environmental Science & Technology*, *49*(7), 4381–4388. https://doi.org/10.1021/es506121s

Lamb, W. F., Steinberger, J. K., Bows-Larkin, A., Peters, G. P., Roberts, J. T., & Wood, F. R. (2014). Transitions in pathways of human development and carbon emissions. *Environmental Research*, *9*(1). https://doi.org/10.1088/1748-9326/9/1/014011

Li, H., He, Q., Song, Q., Chen, L., Song, Y., Wang, Y., et al. (2017). Diagnosing Tibetan pollutant sources via volatile organic compound observations. *Atmospheric Environment*, *166*. Elsevier Ltd, 244–254. https://doi.org/10.1016/j.atmosenv.2017.07.031

Lin, J., Pan, D., Davis, S. J., Zhang, Q., He, K., Wang, C., et al. (2014). China's international trade and air pollution in the United States. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(5), 1736–1741. https://doi.org/10.1073/pnas.1312860111

Liu, Z., Guan, D., Wei, W., Davis, S. J., Ciais, P., Bai, J., et al. (2015). Reduced carbon emission estimates from fossil fuel combustion and cement production in China. *Nature*, *524*(7565), 335–338. https://doi.org/10.1038/nature14677

Meng, J., Liu, J., Xu, Y., Guan, D., Liu, Z., Huang, Y., & Tao, S. (2016). Globalization and pollution: Tele-connecting local primary $PM_{2.5}$ emissions to global consumption. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Science*, *472*(2195). https://doi.org/10.1098/rspa.2016.0380

Meng, J., Mi, Z., Guan, D., Li, J., Tao, S., Li, Y., et al. (2018). The rise of South–South trade and its effect on global CO_2 emissions. *Nature Communications*, *9*(1), 1871. https://doi.org/10.1038/s41467-018-04337-y

Mi, Z., Meng, J., Guan, D., Shan, Y., Song, M., Wei, Y.-M., et al. (2017). Chinese CO_2 emission flows have reversed since the global financial crisis. *Nature Communications*, *8*(1), 1712. https://doi.org/10.1038/s41467-017-01820-w

Mi, Z., Zhang, Y., Guan, D., Shan, Y., Liu, Z., Cong, R., et al. (2016). Consumption-based emission accounting for Chinese cities. *Applied Energy*, *184*. Elsevier Ltd, 1073–1081. https://doi.org/10.1016/j.apenergy.2016.06.094

Miller, R. E., & Blair, P. D. (2009). *Input-output analysis: Foundations and extensions*, (Second ed.). Cambridge: Cambridge University Press.

Ministry of Transport, China (2013). *China transport statistical yearbook*. China Communications Press.

National Bureau of Statistics of China (2013). *China statistics yearbook*. Beijing, China: China Statistics Press.

National Bureau of Statistics of China (2016). *China statistics yearbook 2016*. Beijing, China: China Statistics Press.

National Bureau of Statistics of China (2012). "Input-output tables for Beijing/Tianjin/Hebei/Shanxi/Inner Mongolia/Liaoning/Jilin/Heilongjiang/Shanghai/Jiangsu/Zhejiang/Anhui/Fujian/Jiangxi/Shandong/He nan/Hubei/Hunan/Guangdong/Guangxi/Hainan/Chongqing/Sichuan/G."

National Statistics Bureau of China (2013). Input-output tables for Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia, Liaoning, Jilin, Heilongjiang, Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Shandong, Henan, Hubei, Hunan, Guangdong, Guangxi, Hainan, Chongqing, Sichuan, Guizhou, Yunnan, Sh. China Stat. Press, Beijing, China.

Ou, J., Meng, J., Zheng, J., Mi, Z., Bian, Y., Yu, X., et al. (2017). Demand-driven air pollutant emissions for a fast-developing region in China. *Applied Energy*, *204*. The Authors, 131–142. https://doi.org/10.1016/j.apenergy.2017.06.112

Owen, A., Steen-olsen, K., Barrett, J., Wiedmann, T., & Lenzen, M. (2014). A structural decomposition approach to comparing MRIO databases. *Economic Systems Research*, *26*(3), 262–283. https://doi.org/10.1080/09535314.2014.935299

Pan, J., Gai, N., Tang, H., Chen, S., Chen, D., Lu, G., & Yang, Y. (2014). Organochlorine pesticides and polychlorinated biphenyls in grass, yak muscle , liver, and milk in Ruoergai high altitude Prairie, the eastern edge of Qinghai-Tibet Plateau. *Science of the Total Environment*, *491-492*. Elsevier B.V., 131–137. https://doi.org/10.1016/j.scitotenv.2014.03.074

Peters, G. P. (2008). From production-based to consumption-based national emission inventories. *Ecological Economics*, *65*(1), 13–23. https://doi.org/10.1016/j.ecolecon.2007.10.014

Peters, G. P., & Hertwich, E. G. (2008). Post-Kyoto greenhouse gas inventories: Production versus consumption. *Climatic Change*, *86*(1–2), 51–66. https://doi.org/10.1007/s10584-007-9280-1

Rodrigues, J. F. D., Moran, D., Wood, R., & Behrens, P. (2018). Uncertainty of consumption-based carbon accounts. *Environmental Science and Technology*, *52*(13), 7577–7586. https://doi.org/10.1021/acs.est.8b00632

Sato, M. (2014). Embodied carbon in trade: A survey of the empirical literature. *Journal of Economic Surveys*, *28*(5), 831–861. https://doi.org/10.1111/joes.12027

Schmale, J., Shindell, D., von Schneidemesser, E., Chabay, I., & Lawrence, M. (2014). Air pollution: Clean up our skies. *Nature*, *515*(7527), 335–337. https://doi.org/10.1038/515335a

Shan, Y., Guan, D., Zheng, H., Jiamin, O., Li, Y., Meng, J., & Mi, Z. (2018). China CO_2 emission accounts 1997–2015. *Scientific Data*, *5*(170201), 1–14.

Shan, Y., Liu, J., Liu, Z., Xu, X., Shao, S., Wang, P., & Guan, D. (2016). New provincial CO_2 emission inventories in China based on apparent energy consumption data and updated emission factors. *Applied Energy*, *184*. Elsevier Ltd, 742–750. https://doi.org/10.1016/j.apenergy.2016.03.073

Shan, Y., Zheng, H., Guan, D., Li, C., Mi, Z., Meng, J., et al. (2017). Energy consumption and CO_2 emissions in Tibet and its cities in 2014. *Earth's Future*, *5*(8), 854–864. https://doi.org/10.1002/2017EF000571

Steinberger, J. K., & Roberts, J. T. (2010). From constraint to sufficiency: The decoupling of energy and carbon from human needs, 1975–2005. *Ecological Economics*, *70*(2). Elsevier B.V), 425–433. https://doi.org/10.1016/j.ecolecon.2010.09.014

Steinberger, J. K., Roberts, J. T., Peters, G. P., & Baiocchi, G. (2012). Pathways of human development and carbon emissions embodied in trade. *Nature Climate Change*, *2*(2). Nature Publishing Group), 81–85. https://doi.org/10.1038/nclimate1371

Sun, X., Wang, G., Huang, M., Chang, R., & Ran, F. (2016). Forest biomass carbon stocks and variation in Tibet's carbon-dense forests from 2001 to 2050." Scientific Reports. *Nature Publishing Group*, *6*(1), 1–12. https://doi.org/10.1038/srep34687

The Ministry of Railway, P.R. China (2013). *China railway yearbook*. China Railway Publishing House.

The State Council Information Office of China (2015). Tibet's forest stock ranks top in China [Chinese document]. Available at http://www.scio.gov.cn/zhzc/8/1/document/1389206/1389206.htm

Tibet Bureau of Statistics (2013). Tibet statistics yearbook. In *China Statistics Press* (Chapter 2, 8 and 9). Beijing, China.

Weber, C. L., Guan, D., & Hubacek, K. (2007). China's growing CO_2 emissions—A race between increasing consumption and efficiency gains. *Environmental Science & Technology*, *41*(17), 5939–5944. https://doi.org/10.1021/es070108f

West, J. J., Smith, S. J., Silva, R. A., Naik, V., Zhang, Y., Adelman, Z., et al. (2013). Co-benefits of mitigating global greenhouse gas emissions for future air quality and human health. *Nature Climate Change*, *3*(10). Nature Publishing Group), 885–889. https://doi.org/10.1038/NCLIMATE2009

Zhang, F.-p., Li, C.-f., Tong, L.-g., Yue, L.-x., & Li, P. (2010). Response of microbial characteristics to heavy metal pollution of mining soils in central Tibet, China. *Applied Soil Ecology*, *45*(3). Elsevier B.V), 144–151. https://doi.org/10.1016/j.apsoil.2010.03.006

Zhang, K., Su, J., Xiong, X., Wu, X., Wu, C., & Liu, J. (2016). Microplastic pollution of lakeshore sediments from remote lakes in Tibet plateau, China. *Environmental Pollution*, *219*. Elsevier Ltd, 450–455. https://doi.org/10.1016/j.envpol.2016.05.048

Zhang, Q., Jiang, X., Tong, D., Davis, S. J., Zhao, H., Geng, G., et al. (2017). Transboundary health impacts of transported global air pollution and international trade. *Nature*, *543*(7647). Nature Publishing Group), 705–709. https://doi.org/10.1038/nature21712

Zhao, H. Y., Zhang, Q., Guan, D., Davis, S. J., Liu, Z., Huo, H., et al. (2015). Corrigendum to "Assessment of China's virtual air pollution transport embodied in trade by using a consumption-based emission inventory" published in Atmos. Chem. Phys., 15, 5443–5456, 2015. *Atmospheric Chemistry and Physics*, *15*(12), 5443–5456. https://doi.org/10.5194/acp-15-6815-2015

Zheng, H., Shan, Y., Mi, Z., Meng, J., Ou, J., Schroeder, H., & Guan, D. (2018). How modifications of China's energy data affect carbon mitigation targets. *Energy Policy*, *116*(February), 337–343. https://doi.org/10.1016/j.enpol.2018.02.031