nature climate change
SUPPLEMENTARY INFORMATION
DOI: 10.1038/NCLIMATE3165

In the format provided by the authors and unedited.

Unequal household carbon footprints in China

Dominik Wiedenhofer[a,*], Dabo Guan[b,*], Zhu Liu[c], Jing Meng[d], Ning Zhang[e], Yi-Ming Wei[f,*]

a. *Institute of Social Ecology (SEC), IFF- Vienna, Alpen-Adria University Klagenfurt, Austria*

b. *School of International Development, University of East Anglia, Norwich, NR4 7JT, UK;*

c. *Kennedy School of Government, Harvard University, Cambridge, MA 02138, US.*

d. *School of Environmental Sciences, University of East Anglia, Norwich, NR4 7JT, UK;*

e. *College of Economics, Jinan University, Guangzhou, 510632, China.*

f. *Center for Energy and Environmental Policy Research, Beijing Institute of Technology, Beijing 100081, China.*

* *Corresponding email:* Dominik.wiedenhofer@aau.at; dabo.guan@uea.ac.uk; wei@bit.edu.cn

Keywords: climate justice; carbon footprint; inequality; sustainable consumption; multi-regional input-output analysis;

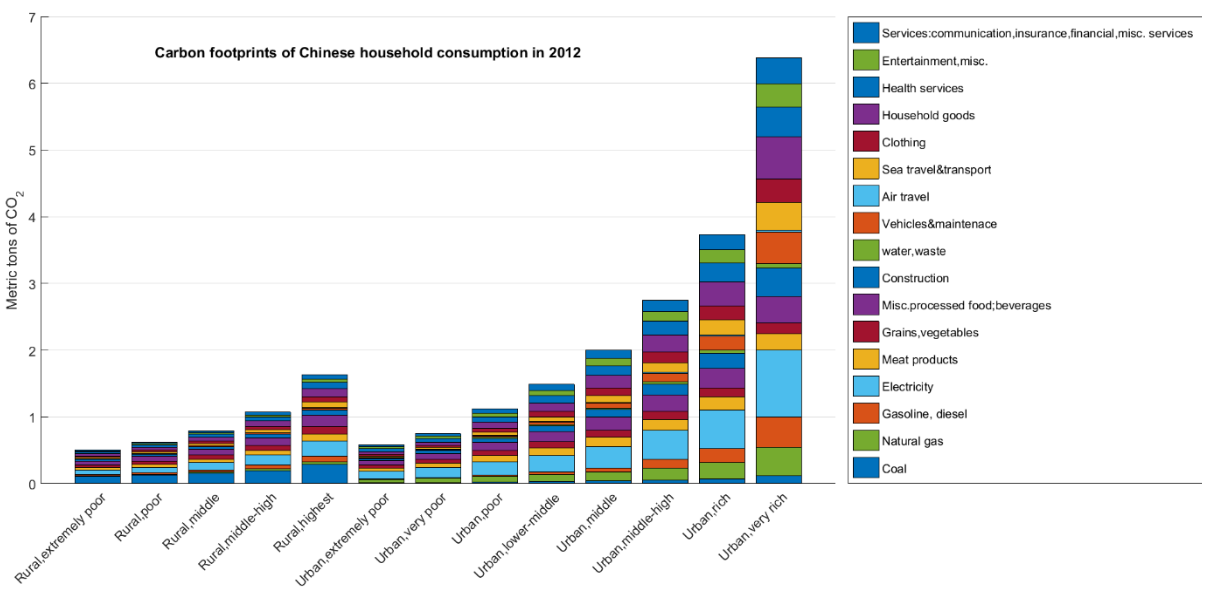

Figure S1: Detailed carbon footprints of Chinese household consumption per capita, for 13 income groups in 2012

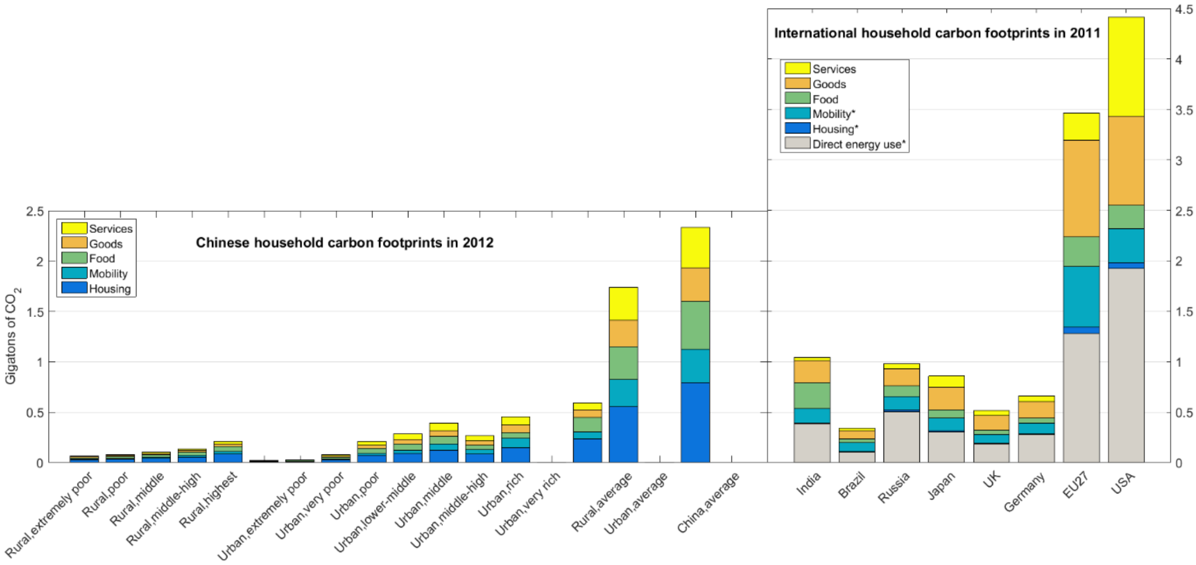

Figure S2: Absolute carbon footprints of Chinese and international household consumption in 2012/2011

Table S1: Consumption-Based Carbon-Gini coefficients of Chinese household consumption across 13 income groups

		Housing	Mobility	Food	Goods	Services	Total CF	Expenditure
National	2012	0.35	0.53	0.28	0.44	0.46	0.39	0.41
	2007	0.38	0.56	0.32	0.50	0.51	0.43	0.45
Urban	2012	0.32	0.48	0.20	0.35	0.33	0.33	0.33
	2007	0.31	0.49	0.20	0.36	0.34	0.33	0.32
Rural	2012	0.23	0.29	0.20	0.25	0.24	0.23	0.23
	2007	0.22	0.31	0.17	0.27	0.27	0.23	0.23

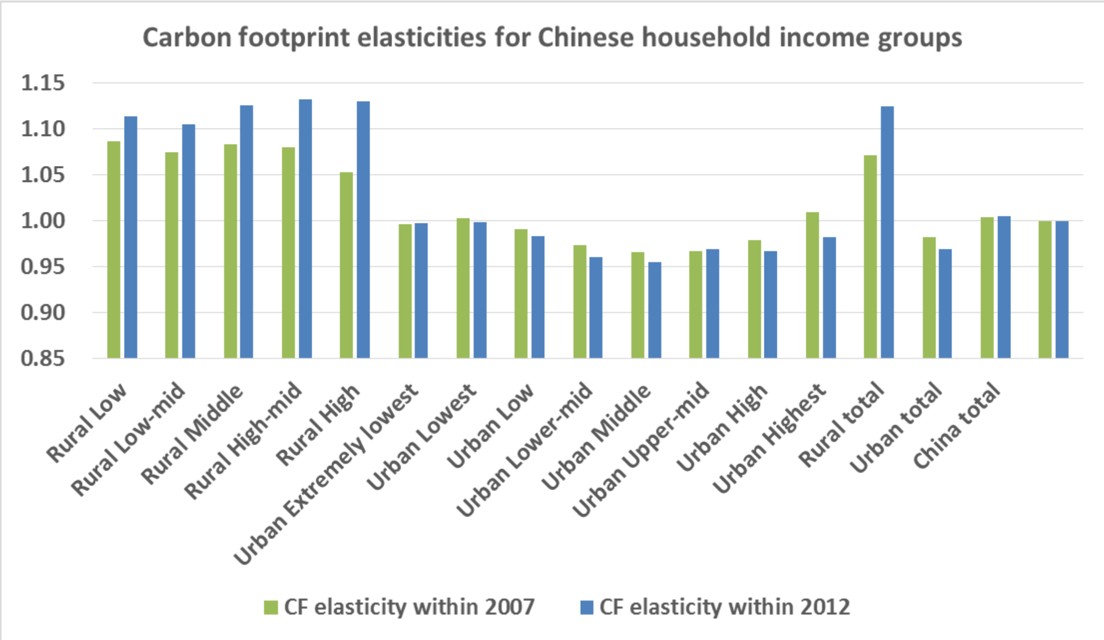

Figure S3: Carbon footprint elasticities for 2007 and 2012. CF elasticities were calculated using the basic income elasticity approach, where the relative change of each income groups' CF/cap from the average CF/cap is divided by the relative change of each income groups' expenditure/cap from the average exp/cap in 2012

Table S2: Main results for Chinese household carbon footprints in 2012 and 2007. CF elasticities were calculated using the basic income elasticity approach, where the relative change of each income groups' CF/cap from the average CF/cap is divided by the relative change of each income groups' expenditure/cap from the average exp/cap in 2012.

		2012					**2007**				
		CF cap (tCO2)	Total CF (Mt CO2)	Expenditure ($2012MER)	CF elasticity of expenditure	Population (Million people)	CF cap (tCO2)	Total CF (Mt CO2)	Expenditure ($2007MER)	CF elasticity of expenditure	Population (Million people)
	China, total	1.72	2,332	1,908	1.00	1,354	1.48	1,954	951	1.00	1,321
	Urban, total	2.44	1,738	2,803	0.97	712	2.41	1,429	1,583	0.98	594
	Rural, total	0.93	594	916	1.12	642	0.72	525	435	1.01	728
Urban China	Very rich	6.39	455	7,237	0.98	71	6.29	374	4,026	0.98	59
Urban China	Rich	3.73	266	4,298	0.97	71	3.70	220	2,439	0.97	59
Urban China	Middle-high	2.75	392	3,159	0.97	142	2.71	322	1,814	0.97	119
Urban China	Middle	2.00	285	2,334	0.95	142	1.99	236	1,330	0.97	119
Urban China	Lower-middle	1.49	212	1,725	0.96	142	1.47	175	978	0.99	119
Urban China	Poor	1.12	80	1,270	0.98	71	1.09	65	710	1.00	59
Urban China	Very poor	0.75	27	838	1.00	36	0.71	21	460	1.00	30
Urban China	Extremely poor	0.58	21	650	1.00	36	0.57	17	367	1.05	30
Rural China	Highest	1.64	210	1,611	1.13	128	1.27	185	780	1.05	146
Rural China	middle-high	1.07	138	1,054	1.13	128	0.80	117	479	1.08	146
Rural China	middle	0.79	102	785	1.13	128	0.63	92	378	1.08	146
Rural China	Poor	0.62	80	625	1.10	128	0.50	73	302	1.07	146
Rural China	Extremely poor	0.51	65	506	1.11	128	0.40	58	236	1.09	146

(1) Method and Data

In this study environmentally extended input-output analysis (EE-IO) was used to estimate emissions, energy or resource use linked with the production and supply of final demand and household consumption. The IO approach conceptually is similar to the consumer lifestyle approach[1,2], insofar as all direct and indirect emissions associated with a specific lifestyle or consumption pattern are quantified[3]. The strength of the IO method lies in the complete and systematic coverage of the entire upstream supply chain and especially of all indirect linkages between industrial sectors. For details of the methods and extensive mathematical treatments we have to refer elsewhere[4–6] and only summarize and focus on the specifics of this study.
Firstly, data on Chinese household expenditure from 2007 and 2012 by income groups for the entire population were used to discern the consumption patterns of 5 rural and 8 urban income groups. In contrast to most other studies which aggregated the IO tables to fit the expenditure data or time series of IO tables, we mapped this expenditure data to the detailed national input-output tables for 2007 and 2012, in order to preserve as much resolution as possible, which has been shown to substantially improve accuracy of results[7–9]. This data until 2007 has been used in the literature before to estimate the development and trajectories of Chinese household footprints[10–13], investigations of urban vs. rural household carbon footprints[2], over time[14],[15] or for specific cities[16]. For this study we disaggregated household consumption into 13 different income groups (8 urban and 5 rural), using the *China Urban Life and Price Yearbook*[17], which reports 8 urban and 5 rural income groups. The Yearbooks list average incomes and consumption expenditure patterns for each group, yielding the sum of total household final use reported in the Chinese IOT. The data discerns 8 major classes of expenditure items and 58 sector specific items, which is different than the 135 sectors of the IOT. We then disaggregated the 58 specific items unto the 135 sectors based on their according products.
Direct energy use and emissions of the 13 income groups were estimated via urban and rural energy prices derived from the Input-Output Tables and the separate reporting of total urban and rural household energy consumption in the Chinese energy statistics.
Because Chinese industry and consumers indirectly and directly demand imports we furthermore used a so-called multi-regional input-output model[18–20] derived from the most recent GTAP database[21,22] (v8 for 2007 and v9 for 2011). This model covers the majority of the world economy including all international supply chain linkages. With this we go beyond

existing studies on Chinese household footprints, which rely on the so-called domestic technology assumption to approximate emissions from imports[2,14,15,23].

The total carbon footprint of Chinese household consumption $\mathbf{q_{hh}}$ then consists of the domestic indirect emissions $\mathbf{q_{dom}}$, the international upstream emissions $\mathbf{q_{mrio}}$ and the emissions from direct energy use of households $\mathbf{q_{direct}}$.

$$q_{hh} = \mathrm{q}_{\mathrm{direct}} + q_{dom} + q_{mrio} \qquad \text{Eq.1.}$$

(2) Estimating the domestic direct and indirect carbon footprints of Chinese household consumption $\mathrm{q}_{\mathrm{direct}}$ *and* q_{dom}

The latest input-output data for 2012 and 2007 is available from the Chinese National Bureau of Statistics[24]. The input-output tables were used in full detail of 135 sectors, going beyond existing studies which use more aggregated IO tables (8-40 sectors) due to for example a focus on time series analysis and the constraint of backwards compatibility of input-output tables[2,14,15,25,26]. CO2 from fossil fuels energy use data has been compiled from the latest revised data [27], which is up to 10% lower than the official Chinese Energy Statistical Yearbook [28]. This data covers 18 types of fuel, heat and electricity consumption in physical units, at a 45 sectors disaggregation. We used a mapping of the emissions dataset to the 135 input-output sectoral resolution developed in previous work[10]. Transformation losses were allocated to the respective energy user, for example losses in electricity generation to the electricity sector and therefore indirectly to the respective households consuming electricity. The Chinese input-output tables contain two idiosyncrasies: Firstly, the tables contains a vector "others", which is part of Chinese total output **x**. On an aggregate level this "others" item is <0.2% of GDP, but on a sectoral level it can range from -4.5% to +8% of total output. According to the Chinese National Bureau of Statistics[24] it primarily represents differences in reported data, particularly due to trade. Therefore, similarly as Minx et al.[10], we treat this item as an error term, representing differences in data sources. We exclude this term from further analysis and treat total output **x** as the sum of the matrix of industrial intermediate use **Z** and final demand **y**, minus "others". This new total output **x** is then used to arrive at the national inter-industry direct requirements matrix **A**, which represents the production recipe of the Chinese economy, where ^ represents diagonalization of a vector.

$$A = Z * \hat{x}^{-1}$$ Eq.1.

Secondly Chinese IO tables are compiled based on a non-competitive imports assumption[29], which means that imports **m** are reported as an aggregate column of total imports per sector *i*, with no additional information available to distinguish the proportions for intermediate use and final demand, nor the import structure of the 135 sectors. This is not a new problem in input-output analysis and following previous work[6,10,30] we calculate so-called importshares **s** for each sector *i* , where **ex** are all exports of each sector *i (Eq. 2).*

$$s_i = (m_i)/(x_i + m_i - ex_i)$$ Eq.2.

These importshares $\mathbf{s_i}$ allow us to separate the domestic production technology $\mathbf{A_d}$ from the direct requirements matrix **A**.

$$A = A_{dom} + A_m$$ Eq.3.

$$A_{dom} = diag(s_i) * A$$ Eq.4.

The same procedures apply for the separation of household final demand **y_hh** into a domestically supplied $\mathbf{y\_hh_{dom}}$ and directly imported fraction $\mathbf{y\_hh_m}$:

$$y\_hh = y\_hh_{dom} + y\_hh_m$$ Eq.6.

$$y\_hh_{dom} = diag(s_i) * y\_hh$$ Eq.7.

$$y\_hh_m = (1 - diag(s_i)) * y\_hh$$ Eq.8.

Now the Leontief inverse **L** can be calculated, which represents the direct and indirect economic activity required to supply a given quantity of final demand for each sector *i*.

$$L = (I - A)^{-1}$$ Eq.9.

Similarly the total domestic production multipliers $\mathbf{L_d}$ are derived.

$$L_{dom} = (I - L_{dom})^{-1}$$ Eq.10.

As a next step we normalize the data on total emissions **T** per sector, by aggregating the new total output **x** to the sectoral classification used in the energy and emissions data and then derived emissions intensities per sector **F,** where **P** represents the mapping of the emissions data classification back to the 135 input-output sectors. This mapping and procedure has been developed in a previous study of the authors[10]. This procedure rests on the assumption that sectors in the 135 classification which are lumped together in the emissions data classification can be assigned the same emissions multiplier (CO2 / $).

$$F = T * (\widehat{P * x})^{-1} * P \quad \text{Eq.12.}$$

Following standard procedures we then apply the Leontief inverse, yielding the usual input-output identity which allows us to estimate the domestic emissions $\mathbf{q}_{dom}$, which were required to satisfy a specific level of final demand for domestic production $\mathbf{y\_hh}_{dom}$.

$$q_{dom} = F * (I - A_d)^{-1} * y\_hh_{dom} \quad \text{Eq.13.}$$

Emissions from direct energy use $\mathbf{q}_{direct}$, including electricity, gasoline, natural gas and coal have been allocated based on the rural and urban energy prices in the Chinese input-output table for deliveries to households of the sectors ‘coal mining and processing’, ‘gas production and supply’, ‘electricity generation’ and ‘petroleum and nuclear fuel refining’ of each income group.

(3) Estimating international indirect carbon footprints of Chinese household consumption q_{mrio}

To account for the embodied CO_2 emissions in imports $\mathbf{q}_{\mathbf{mrio}}$ ether the so-called domestic technology assumption is used in existing studies on China, which simplifies by assuming that imports were produced similarly as domestic output or the embodied carbon in imports are not estimated[2,14,15,25]. This is often done due to the very large data requirements of a more exact multi-regional approach, but misses important international inter-industry feedbacks and emission transfers[20,31].

We use the most recent version of the GTAP database as basis for such an MRIO, the construction and compilation of which has been described before[19,32]. In total the GTAP model covers 57 sectors for 129 regions in 2007 and 140 regions in 2011. For the international emissions data we include $CO2$ emissions from fossil fuels combustion, cement production and gas flaring by sector, corrected for the latest revisions of Chinese emissions[27]. Following standard input-output procedures the international production structure and carbon footprints $\mathbf{q_{mrio}}$ can be calculated via the direct and indirect economic activity required to satisfy final demand $\mathbf{y_{mrio}}$.

$$q_{mrio} = F_{mrio}(I - A_{mrio})^{-1} * y_{mrio} \quad \text{Eq.15.}$$

The international carbon footprint of Chinese households $\mathbf{q_{mrio}}$ consists of three components: Firstly the Chinese and international emissions embodied in imports which are directly consumed by households $\mathbf{q_{mrio,y}}$. Secondly, the emissions embodied in imports which are used as intermediate inputs into Chinese domestic production of goods and services ultimately consumed by Chinese household demand $\mathbf{q_{mrio,Z}}$. And thirdly, all emissions from China, going into international intermediate use, being re-imported as Chinese intermediate use and then ending up in Chinese domestic final demand. This third, probably very small component cannot be fully captured with our combination of the national IOT and the MRIO at the moment, without double-counting issues. Therefore we define the international carbon footprint of Chinese households as (Eq 16):

$$q_{mrio} = q_{mrio,y} + q_{mrio,Z} \quad \text{Eq.16.}$$

Because the GTAP-MRIO covers all origins and destinations of deliveries, a vector of total Chinese household final demand $y_{mrio=China}$ can be extracted in which domestically supplied household final demand is discerned from internationally supplied Chinese household demand. Because the more detailed national IOT was used to estimate the domestic portion of the entire carbon footprint (see section above), we are only interested in the international upstream emissions of domestic production. Therefore a two-step procedure had to be applied. Firstly, we remove Chinese territorial emissions from the GTAP emissions inventory $F_{mrio,China=0}$. By setting all international direct deliveries to Chinese households to zero a vector is derived $y_{MRIO=China,domestic}$ which only contains the domestically delivered final consumption of Chinese households, but still covering all international supply chains. This vector is then multiplied by the adjusted emissions-extended MRIO Leontief inverse, arriving at $q_{mrio,Z}$ which covers the international upstream emissions of domestic production for domestic consumption.

$$q_{mrio,Z} = F_{mrio,China=0}(I - A_{mrio})^{-1} * y_{MRIO=China,domestic} \quad \text{Eq. 17.}$$

For the second part we define a vector $y_{China,international}$ where all domestically supplied Chinese monetary final household demand is set to zero, leaving all international imports in place. Because this time we are also interested in the Chinese inter-industry deliveries and subsequently all embodied emissions from China to international intermediate demand, we multiply by the full emissions-extended MRIO Leontief inverse, arriving at $q_{mrio,y}$.

$$q_{mrio,y} = F_{mrio}(I - A_{mrio})^{-1} * y_{MRIO=China,international} \quad \text{Eq. 18.}$$

This term now contains the emissions embodied in those imports which are directly consumed by Chinese households and which accrued during international and Chinese inter-industry intermediate deliveries.

Adding both terms to q_{mrio} (Eq. 16) now covers the total international carbon footprint of all Chinese households, which we still need to allocate to the respective income groups. For this purpose we utilise the information on the amounts of imported final demand y_hh_m derived from the national Chinese IOT in Eq. 8 – 10. This vector y_hh_m can now be calculated for all 13 income groups *n* (Eq. 10) and after conversion from the original 135 sectors to the 57 GTAP-MRIO sectors, using two concordances **P_iot_gtap** (see next section), we arrive at a matrix $y_{mrio,m,n}$ of imported *m* final demand *y* by income group *n* in the 57 MRIO classification. Then the shares *S* of each income group *n* in total imports *m* for each of the 57 sectors are calculated (Eq.19) and by multiplying each income group's share with q_{mrio}, a complete allocation of international carbon footprints to the respective income group is achieved.

$$S_{n,m,mrio} = \frac{y_{mrio,m,n}}{\sum_n y_{mrio,m,n}} * \text{P\_iot\_gtap} \quad \text{Eq.19.}$$

(4) Translating between the national Chinese IOT and the global MRIO: concordances, classifications and sectoral splits

To translate information from the Chinese IOT with 135 sectors to the GTAP-MRIO with 57 sectors for 129 and 140 countries, it was necessary to reconstruct two concordances, following the procedures by Prof. Liu Yu[22], who contributes the Chinese IOTs to the GTAP project (Table 1-3). The first concordance translates the 135 Chinese sectors into 45 sectors[22] (Table 1). The second contains the mapping of these 45 sectors to the 57 GTAP sectors[22] (Table 2). Several of the GTAP sectors are more disaggregated then the original Chinese IOT data, such as crops (1 vs 8 groups), livestock (1 vs 4 groups) and meat products (1 vs 2). The GTAP team used splitting procedures based on detailed trade data, for which we refer to the documentation of the GTAP database[21]. In order to retrieve these splits ex-post, shares in the total output of these sectors in the GTAP model were used. The concordances are available from the first author upon request.

(5) Limitations of Method and Data

The input-output method in general is based on several important assumptions: Firstly, the constancy of prices in the sectoral and demand relationships is a generally applied and accepted part of the methodology[33]. Secondly, input-output analysis makes a so-called proportionality assumption, asserting that changes in final demand are met by proportional adjustments of total industrial output, based on empirical sectoral interdependencies estimated from the input-output data. Thirdly, when extending the IO model environmentally, for example with CO_2 emissions per sector and final demand, both assumptions also apply. This means that the amount of CO_2 is treated as being strictly proportional to the (sectoral or total) outputs and price structures along the production recipes and therefore any changes or fractions of final demand translate into proportional shares of total output and CO_2 emissions, based on above mentioned empirical sectoral interlinkages and feedbacks. More detailed discussions of the limitations of the input-output methodology can be found here[6].
Linking Chinese input-output tables with a multi-regional input-output model also introduces several issues. Greatest care has been applied in reproducing the transformation procedures and concordances laid out by Prof. Liu Yu[22], who originally provided the Chinese IO tables for the GTAP database. But on the treatment of the “other” column, which is a statistical remainder of conflicting data in the Chinese input-output tables, the authors of this study diverge and follow Minx et al.[10], who treat this column as uncertainty and error column, rather than integrating it into the overall Chinese input-output structure[22]. Furthermore the GTAP team used detailed trade price indices and trade data to link up the individual country tables and establish sectoral interlinkages, while for this study only shares of total outputs and importshares[6,10] were used to estimate domestic and imported demand. For further systematic

and detailed treatment of uncertainties in multi-regional input-output models we refer the interested reader to the literature[8,9,26,29,31,34–38].

The household expenditure survey data used in this study discerns 8 major classes of expenditure items and 58 sector specific items, which is different than the 135 sectors of the IOT. Disaggregation of these 58 specific items unto the 135 sectors based on their according products is preferable to aggregation of the IO table in terms of uncertainty and errors introduced[39]. Still, this procedure means that variations in consumption patterns between income groups might be underestimated. Furthermore such macro-economic survey data probably does not capture the full consumption patterns of the richest Chinese households (the 1%). For this, more sophisticated and detailed approaches on household expenditures are necessary.

References:

1. Bin, S. & Dowlatabadi, H. Consumer lifestyle approach to US energy use and the related CO2 emissions. *Energy Policy* **33,** 197–208 (2005).
2. Feng, Z.-H., Zou, L.-L. & Wei, Y.-M. The impact of household consumption on energy use and CO2 emissions in China. *Energy* **36,** 656–670 (2011).
3. Kok, R., Benders, R. M. J. & Moll, H. C. Measuring the environmental load of household consumption using some methods based on input-output energy analysis: A comparison of methods and a discussion of results. *Energy Policy* **34,** 2744–2761 (2006).
4. Leontief, W. & Ford, D. Environmental Repercussions and the Economic Structure: An Input-Output Approach. *The Review of Economics and Statistics* **52,** 262–271 (1970).
5. Lenzen, M. A Generalized Input–Output Multiplier Calculus for Australia. *Economic Systems Research* **13,** 65–92 (2001).
6. Miller, R. E. & Blair, P. D. *Input-output analysis : foundations and extensions*. (Cambridge University Press, 2009).
7. Lenzen, M. AGGREGATION VERSUS DISAGGREGATION IN INPUT–OUTPUT ANALYSIS OF THE ENVIRONMENT. *Economic Systems Research* **23,** 73–89 (2011).
8. Su, B., Huang, H. C., Ang, B. W. & Zhou, P. Input–output analysis of CO2 emissions embodied in trade: The effects of sector aggregation. *Energy Economics* **32,** 166–175 (2010).

9. Steen-Olsen, K., Owen, A., Hertwich, E. G. & Lenzen, M. EFFECTS OF SECTOR AGGREGATION ON CO_2 MULTIPLIERS IN MULTIREGIONAL INPUT–OUTPUT ANALYSES. *Economic Systems Research* 1–19 (2014). doi:10.1080/09535314.2014.934325

10. Minx, J. C. *et al.* A 'Carbonizing Dragon': China's Fast Growing CO2 Emissions Revisited. *Environ. Sci. Technol.* **45,** 9144–9153 (2011).

11. Guan, D., Hubacek, K., Weber, C. L., Peters, G. P. & Reiner, D. M. The drivers of Chinese CO2 emissions from 1980 to 2030. *Global Environmental Change* **18,** 626–634 (2008).

12. Hubacek, K., Guan, D., Barrett, J. & Wiedmann, T. Environmental implications of urbanization and lifestyle change in China: Ecological and Water Footprints. *Journal of Cleaner Production* **17,** 1241–1248 (2009).

13. Hubacek, K., Guan, D. & Barua, A. Changing lifestyles and consumption patterns in developing countries: A scenario analysis for China and India. *Futures* **39,** 1084–1096 (2007).

14. Liu, L.-C., Wu, G., Wang, J.-N. & Wei, Y.-M. China's carbon emissions from urban and rural households during 1992–2007. *Journal of Cleaner Production* **19,** 1754–1762 (2011).

15. Zhang, Y. IMPACT OF URBAN AND RURAL HOUSEHOLD CONSUMPTION ON CARBON EMISSIONS IN CHINA. *Economic Systems Research* **25,** 287–299 (2013).

16. Feng, K., Hubacek, K., Sun, L. & Liu, Z. Consumption-based CO2 accounting of China's megacities: The case of Beijing, Tianjin, Shanghai and Chongqing. *Ecological Indicators* **47,** 26–31 (2014).

17. NBS. *China Urban Life and Price Yearbook*. (National Bureau of Statistics, Statistical Press, 2008).

18. Peters, G. P., Andrew, R. & Lennox, J. Constructing an environmentally-extended Multi-Regional Input-Output Table using the GTAP database. *Economic Systems Research* **23,** 131–152 (2011).

19. Andrew, R. M. & Peters, G. P. A MULTI-REGION INPUT–OUTPUT TABLE BASED ON THE GLOBAL TRADE ANALYSIS PROJECT DATABASE (GTAP-MRIO). *Economic Systems Research* **25,** 99–121 (2013).

20. Wiedmann, T., Wilting, H. C., Lenzen, M., Lutter, S. & Palm, V. Quo Vadis MRIO? Methodological, data and institutional requirements for multi-region input–output analysis. *Ecological Economics* **70,** 1937–1945 (2011).

21. Narayanan, B., Dimaranan, B. & McDougall, R. *GTAP 8 Data Base Documentation - Chapter 2: Guide to the GTAP Data Base*. 20 (Center for Global Trade Analysis, Purdue University, 2012).

22. Yu, L. & Li, X. *GTAP 8 Data Base Documentation - Chapter 7:B: China*. 14 (Center for Global Trade Analysis, Purdue University, 2012).

23. Liu, L.-C. & Wu, G. Relating five bounded environmental problems to China's household consumption in 2011–2015. *Energy* **57,** 427–433 (2013).

24. NBS. *2007 Input-Output Table of China*. (National Bureau of Statistics, Statistical Press, 2009).

25. Golley, J. & Meng, X. Income inequality and carbon dioxide emissions: The case of Chinese urban households. *Energy Economics* **34,** 1864–1872 (2012).

26. Hawkins, J., Ma, C., Schilizzi, S. & Zhang, F. Promises and pitfalls in environmentally extended input–output analysis for China: A survey of the literature. *Energy Economics* doi:10.1016/j.eneco.2014.12.002

27. NBS. *Energy Statistical Yearbook of China*. (National Bureau of Statistics, Statistical Press, 2009).

28. Liu, Z. *et al.* Reduced carbon emission estimates from fossil fuel combustion and cement production in China. *Nature* **524,** 335–338 (2015).

29. Su, B. & Ang, B. W. Input–output analysis of CO2 emissions embodied in trade: Competitive versus non-competitive imports. *Energy Policy* **56,** 83–87 (2013).

30. Weber, C. L., Peters, G. P., Guan, D. & Hubacek, K. The contribution of Chinese exports to climate change. *Energy Policy* **36,** 3572–3577 (2008).

31. Su, B. & Ang, B. W. Multi-region input–output analysis of CO2 emissions embodied in trade: The feedback effects. *Ecological Economics* **71,** 42–53 (2011).

32. Narayanan, B., Aguiar, A. & McDougall, R. *Global Trade, Assistance, and Production: The GTAP 9 Data Base*. (Center for Global Trade Analysis, Purdue University, 2015).

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

34. Lenzen, M., Wood, R. & Wiedmann, T. Uncertainty Analysis for Multi-Regional Input-Output Mdoels - A Case Study of the UK's Carbon Footprint. *Economic Systems Research* **22,** 43–63 (2010).

35. Bouwmeester, M. & Oosterhaven, J. Specification and Aggregation Errors in Environmentally Extended Input–Output Models. *Environ Resource Econ* **56,** 307–335 (2013).

36. Inomata, S. & Owen, A. COMPARATIVE EVALUATION OF MRIO DATABASES. *Economic Systems Research* **26,** 239–244 (2014).

37. Wiedmann, T. & Barrett, J. POLICY-RELEVANT APPLICATIONS OF ENVIRONMENTALLY EXTENDED MRIO DATABASES – EXPERIENCES FROM THE UK. *Economic Systems Research* **25,** 143–156 (2013).

38. Lenzen, M., Pade, L.-L. & Munksgaard, J. CO2 Multipliers in Multi-region Input-Output Models. *Economic Systems Research* **16,** 391–412 (2004).

39. Lenzen, M. AGGREGATION VERSUS DISAGGREGATION IN INPUT–OUTPUT ANALYSIS OF THE ENVIRONMENT. *Economic Systems Research* **23,** 73–89 (2011).