Unequal household carbon footprints in China

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Households' carbon footprints are unequally distributed among the rich and poor due to differences in the scale and patterns of consumption. We present distributional focused carbon footprints for Chinese households and use a carbon-footprint-Gini coefficient to quantify inequalities. We find that in 2012 the urban very rich, comprising 5% of population, induced 19% of the total carbon footprint from household consumption in China, with 6.4 tCO$_2$/cap. The average Chinese household footprint remains comparatively low (1.7 tCO$_2$/cap), while those of the rural population and urban poor, comprising 58% of population, are 0.5–1.6 tCO$_2$/cap. Between 2007 and 2012 the total footprint from households increased by 19%, with 75% of the increase due to growing consumption of the urban middle class and the rich. This suggests that a transformation of Chinese lifestyles away from the current trajectory of carbon-intensive consumption patterns requires policy interventions to improve living standards and encourage sustainable consumption.

The growing climate crisis[1] shows that becoming wealthy, while enabling a clean-up of the local environment[2], drives economic activity and subsequently carbon emissions, often in distant places[1,3,4]. The concept of a carbon footprint is increasingly used in the public debate on responsibility and mitigation of climate change to describe the direct and indirect carbon emissions of consumption along the international supply chain[5–8]. To achieve absolute reductions of emissions fairly, proposals grounded in climate justice have been put forward to target high-emitting individuals across all countries[9–11] while ensuring minimum levels required for a human development[11]. In 2013 a growing global upper class of top 10% consuming households already contributed 40–51% of global emissions from fossil fuels and other sources with their footprints, a third of them in emerging economies such as China[10]. At the same time the global poor (lower 50% of global income distribution) are driving 10–13% of global greenhouse gas emissions[10]. Improved methods[12], as employed in this study, provide important information for policymakers to explicitly consider the interactions and trade-offs between measures targeting inequality, poverty, climate mitigation, and towards sustainable lifestyles for the emerging middle class and rich households.

China, which recently announced a stronger focus on bolstering domestic consumption over its current export orientation, is steadily moving towards carbon- and resource-intensive consumer lifestyles, tracking the way of high-income countries[1,5,8,13,14]. The sheer scale of the Chinese economy means that the future global climate is strongly determined there[1,14,15]. Since the 1980s, a rapid reduction of the proportion of people living below the poverty line of 1.9 US dollar (2011 purchasing power parities) income per day has been achieved, from 88% in 1981 to 11% in 2014[16]. At the same time income inequality grew substantially to a Gini Index of 0.55 in 2010, leading to a stop of official reporting on the Gini coefficient for incomes[17], an established indicator on income distributions. A clear urban–rural divide of energy consumption can be observed in China, where rural households often use traditional and locally polluting energy carriers, such as straw, wood or coal, while electricity and natural gas

is slowly penetrating these areas[18,19]. In urban areas, modern energy carriers such as electricity, natural gas and LPG are dominant, and mobility is the main driver of direct household energy use[18,19]. Annually, approximately 20 million people move from rural to urban areas, and future population growth is projected to be concentrated in cities, which entails large new infrastructure and housing requirements[5]. Especially in urban areas, a sizeable middle class and a small segment of households with high incomes has emerged[5,8,20], while large swaths of rural China and migrant workers coming to cities still largely remain in poverty[21]. Increasing consumption in urbanizing China has been identified as an important driver of household carbon footprints over the past 20 years, due to the growing urban population and incomes, while decreasing carbon intensity of the Chinese economy only weakly dampens these trends[5,8,22]. These growing disparities in incomes and carbon footprints are driven by government investment policies favouring coastal and urban areas[17]. But in a globally carbon-constrained future with the urgent need for absolute reductions of annual emissions[1,23], relying on economic growth to lift all boats while also decreasing inequality and improving human development can become very challenging. Clearly, decarbonizing the energy system via production-focused efficiency measures and energy-pricing reforms is essential[3,24,25]. But developing carbon-free lifestyles beyond the current trajectory of increasing carbon footprints while becoming wealthy will require more substantial debates on the limits of green consumerism and the potential towards sustainable consumption[11,20,26–28].

Herein we present the unequal distribution of carbon footprints between Chinese households along national and international supply chains for 13 income groups (5 rural and 8 urban). We quantify inequality between urban–rural and 13 income groups with a carbon-footprint-Gini coefficient (CF-Gini), for the latest available years (2012 and 2007). Gini coefficients are used to quantify inequality[10,17,29] and were applied to production-based territorial emissions[29], cumulative historical territorial emissions[30], interregional assessments of household footprints[7], urban Chinese carbon footprints[20], and estimates of household carbon footprints

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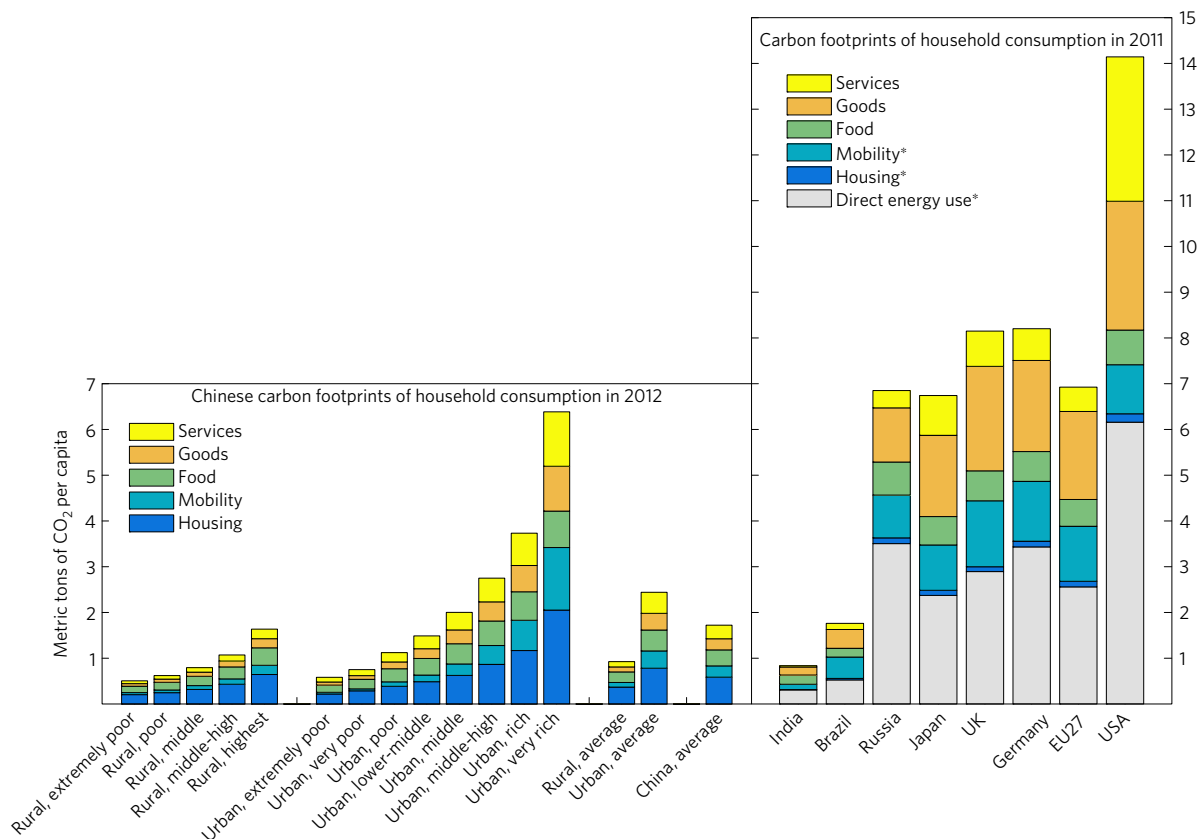
Figure 1 | Carbon footprints of Chinese and international household consumption in 2012 and 2011, respectively, from fossil fuels and cement production. *Due to data constraints the emissions from direct energy use of international households could not be allocated to the respective indirect emissions from mobility and housing. For Chinese households mobility and housing includes direct and indirect emissions.

across countries[10,12]. For income inequality and carbon footprints an inverse relationship was found[31–36]. We utilize a detailed Chinese Input-Output Table with the latest, substantially revised Chinese emissions statistics[37,38] and a Multi-Regional Input-Output Model (GTAP 9 database) for all other countries. Emissions data sets cover carbon emissions from fossil fuels and cement production.

From a production-based territorial perspective, Chinese carbon emissions are 6.7 tons of per capita in 2013[37]. However, from a consumption-based perspective, the majority of Chinese emissions are related to capital investments (48%) and exports (20%) as main drivers[3,22], while households induce only 17% of the national footprint in 2012. We find that the average Chinese household footprint is only 1.7 tCO_2/cap in 2012, more than double the Indian average (0.9 tCO_2/cap), similar to the Brazilian average (1.5 tCO_2/cap), but one quarter of that in the EU27 (6.7 tCO_2/cap) and one sixth of that in the USA (10.4 tCO_2/cap) (Fig. 1 and Table 1). However, due to high income inequality in China[17], 5.3% of the Chinese population, the very rich urban dwellers, have carbon footprints of consumption at 6.4 tCO_2/cap, nearly four times of the average Chinese. The three richest urban groups, 21% of Chinese population, induce 48% of the total Chinese household carbon footprint. At the same time rural China and the urban poor, 58% of the population, induce only 31% of the total household footprint, all below the national average of 1.7 tCO_2/cap. The total household carbon footprint of 1,354 million Chinese is estimated at 2,332 Million tons of CO_2. In comparison, the total footprint of 1,247 million Indians is only half (1,152 $MtCO_2$), while 500 million Europeans, 37% the population size of China, have 1.4 times the total footprint (EU27: 3,347 $MtCO_2$) and 312 million US-Americans, 23% the population of China, also have 1.4 times the total carbon footprint (3,262 $MtCO_2$) (Table 1).

Urban residents, 53% of the Chinese population, induce 75% of the national household carbon footprint in 2012. Their average per capita footprint is 2.4 tCO_2 (Table 1). The top 5.3% very rich urban Chinese spend 7,237 US$ per year and have a per capita footprint of 6.4 tCO_2—which is very similar to the national averages of OECD countries, that is, Japan (6.6 tCO_2 with 27,692 US$), Russia (5.9 tCO_2 and 7,585 US$), the EU27 average (6.7 tCO_2 and 21,082 US$) and Germany (7.6 tCO_2 with 20,374 US$) (Fig. 1 and Table 1). This richest urban group comprises approximately 71 million people, or 5.3% of the entire Chinese population, inducing 19% of the total household carbon footprint in 2012 (Table 1). The total footprint of that richest group amounts to 455 $MtCO_2$, 1.6 times the entire Brazilian household footprint (290 $MtCO_2$). The second group, the urban rich, 5.3% of total Chinese population, spends approximately 4,298 US$ per capita and has an average footprint of 3.7 tCO_2. The urban middle class, divided into three income groups, spends 1,725–3,159 US$ and has a per capita footprint of 1.5–2.8 tCO_2. In total, the two urban rich groups and middle class together induce 69% of the national Chinese household carbon footprint. At the same time the urban poor, divided into three groups, totalling 10.5% of Chinese population, spend only 650–1,270 US$ and have footprints of 0.6–1.1 tCO_2/cap. This means their carbon footprints are below the Chinese (1.7 tCO_2) and Brazilian average (1.5 tCO_2) but similar to the Indian average (0.9 tCO_2), and in the same range as Chinese rural households. The extremely poor in urban areas have a footprint of only 0.5 tCO_2/cap.

Consumption of Chinese rural households, 47% of the population, induces 25% of the national household carbon footprint in 2012 (Table 1). The average rural carbon footprint is 0.9 tCO_2/cap— one-quarter of the urban average. Further decomposing the rural population into five income groups yields footprints of

Table 1 | Household carbon footprints from fossil fuels combustion and cement production, population size and final demand across income groups in China for 2012 and 2007 and for international comparisons for 2011.

	Population (million people, in 2012)	Household expenditure per capita (2011/12 US$ MER)	CF elasticity of consumption (2012)	CF cap (tCO$_2$, in 2012)	Total CF (MtCO$_2$, in 2012)	Shares in total CF (%; in 2012)	Total CF 2007 (MtCO$_2$)
China, total	1,354 (100%)	1,908	1.00	1.7	2,332	100	1,954
Urban China, total	712 (53%)	2,803	0.97	2.4	1,738	75	1,429
Very rich	71 (5.3%)	7,237	0.98	6.4	455	19	374
Rich	71 (5.3%)	4,298	0.97	3.7	266	11	220
Middle-high	142 (10.5%)	3,159	0.97	2.8	392	17	322
Middle	142 (10.5%)	2,334	0.95	2.0	285	12	236
Lower-middle	142 (10.5%)	1,725	0.96	1.5	212	9	175
Poor	71 (5.3%)	1,270	0.98	1.1	80	3	65
Very poor	36 (2.6%)	838	1.00	0.8	27	1	21
Extremely poor	36 (2.6%)	650	1.00	0.6	21	1	17
Rural China, total	642 (47%)	916	1.12	0.9	594	25	525
Highest	128 (9.5%)	1,611	1.13	1.6	210	9	185
Middle-high	128 (9.5%)	1,054	1.13	1.1	138	6	117
Middle	128 (9.5%)	785	1.13	0.8	102	4	92
Poor	128 (9.5%)	625	1.10	0.6	80	3	73
Extremely poor	128 (9.5%)	506	1.11	0.5	65	3	58
India	1,247	939		0.9	1,152		
Brazil	193	7,707		1.5	290		
Russia	143	6,585		5.9	845		
Japan	127	27,692		6.6	843		
UK	63	26,479		5.7	361		
Germany	80	26,169		6.4	511		
EU27	500	21,082		6.7	3,347		
USA	312	34,853		10.4	3,262		

Carbon footprint (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 (for details see Methods and Supplementary Information; US$ at 2011/2012 market exchange rates (MER)) (all numbers were rounded).

0.5–1.6 tCO$_2$/cap. Even the richest rural households, 9.5% of the Chinese population, spend only 1,611 US$ per capita and have a footprint of 1.6 tCO$_2$/cap, which is similar to the urban lower-middle class (1.5 tCO$_2$/cap). The rural middle and middle-high classes have footprints of 0.8–1.1 tCO$_2$/cap, spending 785–1,054 US$ per capita. The two poorest rural groups, 19% of the entire Chinese population, have footprints of 0.5–0.6 tCO$_2$, which together is only 6% of the total national household carbon footprint, and less than the Indian average footprint.

Between 2007 and 2012, the total Chinese household carbon footprint increased by 19% or 378 MtCO$_2$, with 82% of these increases due urban consumption (Table 1). The urban 'very rich', 5.3% of population, took 21% of the total increase, almost the increase for all of rural China, with 47% of the population (80 versus 70 MtCO$_2$). Per capita footprints in urban areas increased on average by 2% from a relatively higher level, while those in rural areas increased by 28%. The poor in urban and rural areas, together 29.5% of population, increased their footprint by 16%, but induced only 10% of the increase in total household footprint. The two richest urban and one rural richest groups together, 20% of population, increased their footprints by 20%, thereby taking 40% of the total increase. The urban middle class induced 41% of the total increase.

Interestingly, for the carbon-footprint elasticities of consumption we find slightly elastic relationships for the middle class and richer urban income groups (0.97–0.98), while for the urban poor and rural groups we find proportional to inelastic relationships (1–1.13) (Table 1). For the urban very rich, a 1% increase in expenditure would lead to +0.98% in carbon footprints, while +1% increase of expenditures of the rural poor would lead to +1.11%. This

means that coming out of poverty is relatively carbon-intensive, due to low-quality commercial energy such as coal, first purchases of appliances and so forth. Richer households tend to use growing incomes for higher-quality commercial energy (electricity, LPG, natural gas), and especially more goods and services, which are relatively less carbon-intensive. When comparing elasticities for 2007 and 2012, interestingly rural households become slightly more carbon-intensive, while for urban households the carbon-footprint elasticity decreased (see Supplementary Information). These patterns replicate across countries[7,8,19,39], where generally with rising affluence the marginal carbon intensity of consumption decreases, but larger overall expenditure still means higher total carbon footprints than less affluent households.

When looking at the contribution of each income group's consumption pattern to the total Chinese footprint, it becomes evident that the urban rich and middle class are driving the categories mobility, goods, and services, while footprints from food and housing are less unequal (Fig. 2). For example, 78% of the total footprint of mobility, 74% for goods and 75% for services is due to the urban middle class and the two rich groups, although these income groups constitute only 42% of the population. At the same time the urban and rural poor together, which also amount to 29.5% population, induce only 7% of the mobility-related emissions and 10% of the total Chinese carbon footprints from goods as well as from services.

Finally, we quantify inequality between carbon footprints of Chinese income groups using Lorenz curves and carbon-footprint-Gini Indices. In a Lorenz curve the cumulative share of population is plotted against their cumulative footprints, where the Gini Index then quantifies the area under that curve. We find that CF-Gini
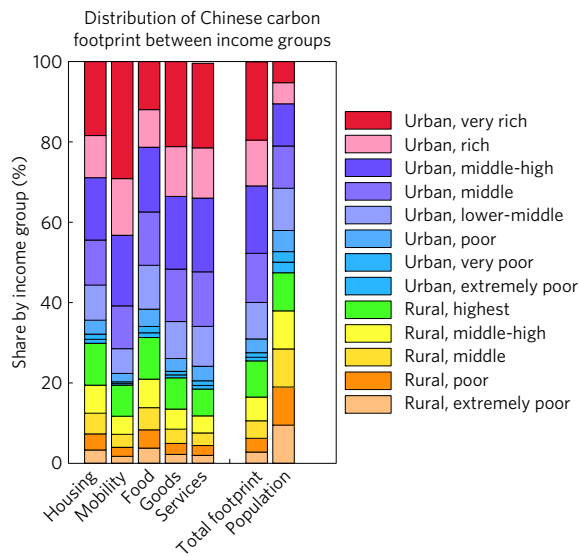
Figure 2 | Relative distribution of household carbon footprints from fossil fuels and cement, income and population size among 13 income groups in 2012.

distributed among the Chinese population. Between 2007 and 2012, national inequality decreased slightly across all categories (Fig. 3b), except for rural food and housing-related carbon footprints, which is also the major contributor to increasing per capita footprints in rural areas (Fig. 3). While urban inequality did not change significantly (Fig. 3b,c), rural inequality increased (Fig. 3b,d).

To encourage economic growth, China's government has enacted policies focusing on increased domestic consumption as a substitute for its declining growth in investment and exports, while also announcing an absolute emissions peak for 2030. Recently, Chinese emissions growth did slow down[37], largely driven by a stabilization of coal use[13,38]. Substantial policy efforts in carbon taxation, feed-in tariffs for renewables, and accelerated deployment of renewables and nuclear have been modelled to achieve this stabilization of Chinese emissions at modest costs until 2030[25], while most of these current Chinese climate policies consider regional inequality only by using differentiated goals between provinces. However, at the same time it is clear that stabilizing the climate at 1.5–2 °C will require unprecedented absolute global reductions of emissions over the next two to three decades[1,15].

The slight decreases in expenditure inequality between Chinese households, mostly due to a small catch-up of rural households, is triggered by governmental subsidies to rural households' general purchase and income tax free policies. But our findings suggest that coming out of poverty is fairly carbon-intensive due to a larger carbon-footprint elasticity of consumption of the poorer income groups, strongly driven by their dirtier direct energy mix. However, much more problematic are the growing carbon footprints of the urban middle class and the rich, which together induce 69% of
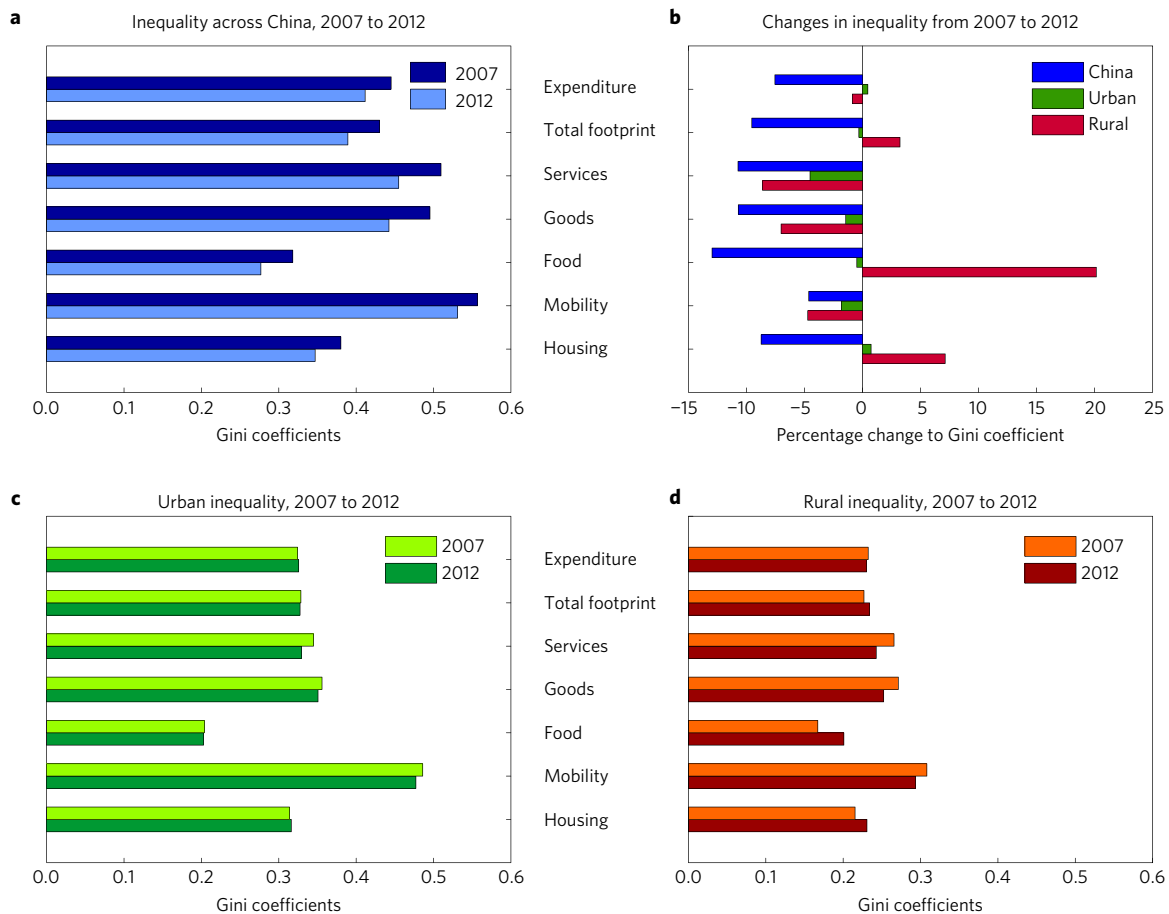
indices for total and goods footprints are similarly unequally distributed as household expenditure in 2012 (around 0.4) (Fig. 3a). We find higher inequality for carbon footprints of services (0.5) and mobility (0.6), while those for food and housing (0.3) are more equally

Figure 3 | Quantifying inequality. Carbon-footprint-Gini coefficients for 13 Chinese income groups in 2012 and 2007, for carbon emissions from fossil fuels and cement production.

the total Chinese household footprint and rapidly westernize their lifestyles. It has been suggested that income redistribution in urban China could reduce aggregate carbon footprints while improving living standards and income inequality[20]. From the results in Table 1 we can estimate that simply redistributing expenditure to achieve equality at 1,762$/cap, which is −8% lower than the current average expenditure, would result in a −1% decrease of total household footprints, due to differential CF elasticities. Therefore, social and redistributive policies need to be understood as interacting with climate and energy policy, as well as with efforts towards enabling sustainable lifestyles for all[17,20,31,36].

While the Chinese government is making efforts to build regional inequalities into climate policies from production efficiency and technology level approaches (for example, rich coastal versus poorer inland areas), this study reveals that there are substantial inequalities within these regions and along income groups. The CF-Gini could be useful for developing sustainable consumption programmes for those income groups which dominate the footprints of certain consumption areas, or for guiding policy design in achieving poverty alleviation while reducing emissions and increasing energy efficiency. Direct emissions from heating with coal or natural gas at present amount to 11% of the total footprint and 21% of the rural footprint. Some practical policies are designed to alleviate poverty and reduce emission at the same time. For example, Beijing municipality government set up a subsidization plan to implement a 'coal replacement by clean energy programme' for every rural household in 400 villages surrounding Beijing. By end of 2017, appropriately 4 million tonnes of coal consumption for residential usage will be saved, which is equivalent to 7 million tonnes of CO_2 emissions and 210 thousand tonnes of SO_2. The emission reduction effort is the same as three years aggregated emission discharge by 66 thousand taxis in Beijing.

Usually, shifting consumer choices is seen as yielding substantial climate mitigation benefits, for example eating less (red) meat and more vegetarian diets, less to no fossil fuelled mobility, energy-efficient dwellings, and purchasing high(er)-quality long-lived goods[40,41]. Tapping these potentials requires substantial policy guidelines, careful policy designs and matching infrastructures. At present, direct mobility emissions from fuels make up only 3% of the total household footprint, most of it by the rich and urban middle class. But following 'on the road' American culture, there are increasingly demands for cheap 4×4 fleets by the Chinese middle class. Domestic car manufacturers are upgrading production lines to fulfil such demands. Beijing and Shanghai have implemented tailored policies to limit absolute gasoline fleets and encourage electric vehicle (EV) purchases with heavy subsidies. However, such policies ignore China's coal-dominant energy mix. China's gasoline vehicle replacement programme with EVs is not effective at present. In fact, evidence shows that the CO_2 emissions reduction in the petroleum sector is offset by the increase in CO_2 emissions in the electricity sector[42]. The EV programme can be effective only with significant changes in the Chinese energy mix towards renewables. Therefore, green consumerism alone (even with policy guidelines) cannot drive the entire production system towards sustainability, and more systemic approaches are necessary to achieve sustainable consumption and production[11,26,28]. More sustainable urban forms and spatial planning have been identified as important long-term factors towards facilitating low-carbon lifestyles, especially in growing cities which are currently expanding their infrastructures[5,6,43,44].

Overall the required long-term transformations towards a net-zero carbon society should be included into a national discourse about the currently dominant mode of ecological modernization, green growth and conspicuous consumer lifestyles[28]. The carbon-intensive lifestyles of the wealthy are being emulated, and serve as role models, while investments in infrastructure and cities are made. Based on the CF elasticities (Table 1), a hypothetical scenario of

an expenditure catch-up of all Chinese households to the average urban rich expenditure pattern (that is, mobility by cars and planes and living with an average 90 m² per household) can be estimated, resulting in a tripling of the total Chinese household carbon footprint. A catch-up only to the average urban middle class would translate into a 58% increase of the total footprint. But in a carbon-constrained post-Paris COP21 future, high wellbeing and human development needs to be achieved while rapidly reducing total emissions[1,13]. Reducing inequalities but preventing emission-intensive lifestyle westernization in populous developing countries can be a step forward to contribute global climate change mitigation. Cost-effectively using limited public and private funding for these societal goals will be crucial. Some countries have already achieved a high level of human development (HDI of >0.8) with an average carbon footprint of 1 ton per capita[45–47], highlighting that pathways to livable and potentially more sustainable societies exist.

Methods

Methods and any associated references are available in the online version of the paper.

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Author contributions

D.W. and D.G. designed the research, performed calculations and discussed the results. D.W. wrote the paper. D.G., Z.L., J.M., N.Z. and Y.-M.W. collected data and contributed to writing the paper.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints.
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Competing financial interests

The authors declare no competing financial interests.

Methods

We quantify the household carbon footprints of 13 Chinese income groups (5 rural and 8 urban) for 2012 and 2007, using a detailed Chinese Environmentally Extended Input-Output model (IOT)[48] and a global Multi-Regional Input-Output Model derived from the GTAP database (MRIO). The Chinese IOT has 135 sectors in producers' prices[49], and is extended by China's sectoral CO_2 emissions from fossil fuel combustion and cement production, each corrected for the latest published estimates on coal carbon contents and energy use, which significantly altered the previously available official data[38,50]. Household consumption patterns for eight urban and five rural income groups are derived by disaggregating the urban and rural household final demand vectors in the Chinese IOTs with data on the respective consumption structures from the China Urban Lifestyle and Price Yearbooks[50]. These list average incomes and consumption patterns per income group, discerning 8 major classes of expenditure items and 58 sector specific items, which were mapped to the 135 sectors of the Chinese IOTs. In particular, we convert all 58 consumption categories into percentage to total per capita consumption; we then produce a concordance matrix to map the 58 sector-specific items with 135 IOT sectors; finally, we disaggregate the urban household vector in IOT into 8 income groups. We repeat the same process and utilize income-grouped household expenditure data provided from Chinese Rural Statistics to disaggregate the rural household average consumption into 5 income groups.

All international upstream emissions were calculated via an MRIO derived from the GTAP database for 2011 (140 countries × 57 sectors) and 2007 (129 countries × 57 sectors)[51]. International emissions of fossil fuels and cement production by sector are derived from the GTAP emissions database and corrected with the latest revised Chinese emissions statistics[38,50]. This is important because households directly consume imports and the Chinese economy requires imported intermediate inputs to produce domestic final output, which constitutes an important international inter-industry feedback[52]. The limitations of this study are first, that non-CO_2 greenhouse gas emissions are not included due to lack of available sector level data for China. Second, Input-Output Analysis generally considers only the annual emissions (flows) within the same year, which means that cumulative emissions (stocks) required to build existing infrastructure and buildings are not accounted for—which can be seen as an issue especially for housing-related footprints, which are driven at present by electricity, natural gas and household appliances. More generally, this means that the consumption of capital is currently not endogenized in our model, as this is an ongoing issue for IO analysis in general (see Supplementary Information for a longer discussion on the methodological limitations). The concordances between the MRIO and the Chinese IOT are derived from the GTAP documentation (see Supplementary Information).

Carbon-footprint results for 135 Chinese and 57 international sectors were aggregated to five major categories of consumption: housing, mobility, food, goods and services (Supplementary Information). Emissions from direct household energy use of coal, natural gas and electricity are allocated to the category housing, while oil emissions are allocated to mobility[53]. Chinese national emission data is available online at China Emission Accounts and Datasets - CEADs (http://www.ceads.net). Due to data constraints in the GTAP-MRIO, direct energy use for non-Chinese households cannot be completely allocated, and thus was kept separate (see Fig. 1 and Supplementary Information).

The consumption-based carbon-footprint-Gini coefficient presented herein is based on the well-known Gini coefficient, which is derived from Lorenz curves, initially proposed by Lorenz in 1907 and widely used to measure inequality[7,10,17,29,30]. The original Lorenz curve plots population shares against income shares, where the area below that curve is defined as Gini coefficient, ranging from 0 to 1. A straight 45° line in the Lorenz curves would indicate perfect equality; similarly, a Gini coefficient of 0 indicates perfect equality, and 1 indicates perfect inequality. In this paper, we present a consumption-based carbon-footprint-Gini index across 13 income groups and their carbon footprints. Let us define the following variables for group n: C_i^n is the carbon footprint of group n for product i, Pop^n is the population size of income group n, and $p^n = (\text{Pop}^n / \sum_m \text{Pop}^n)$ is the population share of group n. $C^n = (C_i^n / \sum_m C_i^n)$ is then the share in total household carbon footprint of group n for product i. Define the area between the actual allocation curve and perfect equal allocation curve as X, the area below the actual allocation curve as Y. Then the Gini index is defined as $X/(X+Y)$. Supplementary Table 3 provides the population and carbon footprints of each group in 2007 and 2012.

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