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Impacts of poverty eradication on carbon neutrality in China

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Abstract

China is facing challenges to tackle the threat of climate change while reducing social inequality. Poverty eradication requires improvement in the living conditions of low-income households, which leads in turn to higher carbon footprints and may undermine the efforts of climate change mitigation. Previous studies have assessed the climate impacts of poverty eradication, but few have quantified how the additional carbon emissions of poverty eradication are shared at the subnational level in China and the impact on China's climate targets. We investigated the recent trend of carbon footprint inequality in China's provinces and estimated the climate burden of different poverty reduction schemes, measured by increased carbon emissions. The results indicate that poverty eradication will not impede the achievement of national climate targets, with an average annual household carbon footprint increase of 0.1%–1.2%. However, the carbon emissions growth in less developed provinces can be 4.0%, five times that in wealthy regions. Less developed regions suffer a greater climate burden because of poverty eradication, which may offset carbon reduction efforts. Therefore, interregional collaboration is needed to coordinate inequality reduction with

investments in low-carbon trajectories in all provinces.

Keywords: Carbon emissions, poverty eradication, carbon neutrality, inequality

1. Introduction

The dual challenge of curbing carbon emissions and improving the living standards of the poor is urgent and is at the core of global efforts to ensure resilient and inclusive development. Low-carbon growth in developing countries is critical for the global fight against climate change because economic growth has yet to be decoupled from carbon emissions. As the single largest carbon dioxide emitter [1–3], China is facing challenges in combating climate change and reducing carbon emissions. To facilitate domestic progress in decarbonization and boost resilient economic growth, China pledged to continuously curb its carbon emissions and reach carbon neutrality. China has a long way to go to reach carbon neutrality and is still striving to reach peak carbon emissions as committed.

In addition, reducing inequality and raising income for the poorest is a pressing challenge for China. Inequality harms the quality of economic development. The problem of income inequality coincides with other social problems, such as health inequality [4], opportunity inequality [5] and happiness inequality [6]. Persistent efforts are required to reduce inequality to achieve the Sustainable Development Goals (SDGs). In the developing world, income poverty has fallen dramatically since the millennium, driven especially by China's poverty eradication efforts. Over the past few decades, economic reform has brought great prosperity to many across the nation and lifted millions of people out of extreme poverty [7]. However, rapid economic growth has been accompanied by substantially rising inequality because not all populations benefited equally [8]. China has made significant efforts in poverty eradication, mainly targeting extreme poverty in rural areas [9]. With the eradication of extreme poverty, continuously reducing inequality by narrowing the urban–rural gap and regional development disparities is essential to mitigate relative poverty in China. Persistent efforts to improve the living conditions and income of the poor are required to guarantee resilient and sustainable economic development.

Poverty eradication creates extra burdens for climate change mitigation because the improvement of life conditions causes more emissions but there is little headroom in carbon budget for future carbon emissions under the 1.5 °C target. The empirical evidence shows that carbon footprints, which measure carbon emissions induced by consumption, increase in tandem with economic growth and accompanying rise in consumption [10–12]. Individual lifestyles tend to become more carbon-intensive as levels of affluence grow [12,13]. Therefore, the improvement in living standards brought by poverty eradication inevitably leads to additional carbon emissions. The conflict between climate change mitigation and poverty eradication becomes intense because of the large population in poverty. With robust economic growth over the past decades, the compatible poverty line for China is higher than the international Extreme Poverty Line. To better reduce inequality, future poverty eradication efforts should be focused on people living in relative inequality by adopting higher poverty lines. In addition, the impacts of climate change are unequal, with the poor contributing less to climate change but being more vulnerable to its impact. In the long term, as climate impacts will pose more far-reaching threats to the poor, more efforts in poverty eradication are needed. Higher poverty lines should be adopted to reduce the inequality that occurs with unequal income increases and unfair climate impacts. Considering the vast population in China, reducing inequality and alleviating poverty requires increasing the income and consumption of the poor and has the potential to cause tremendous carbon emissions. The additional emissions may offset global efforts in climate change mitigation. Therefore, it is necessary to quantify the impact of reducing poverty on climate targets in China in order to derive timely policy interventions to avert excessive climate burdens.

However, the impact of poverty eradication on climate targets remains to be quantitatively assessed at the subnational level considering the disparities in poverty distribution. Previous studies have suggested that eradicating extreme poverty will not affect global carbon reduction, and the additional carbon emissions represent approximately 2% of the global total [11,14]. Nonetheless, the global-level result is not universally applicable, especially for less developed regions. First, great disparity exists in social inequality at the provincial level [15,16]. Subnational heterogeneity indicates that more efforts are needed to address inequality in poor regions, especially as these regions will generally experience greater climate burdens. As global assessments would miss important information on how climate burdens are shared among regions, there has been an increased need to understand the impacts of poverty eradication on the achievement of climate targets at the subnational level to facilitate effective and efficient allocation of climate responsibility. Second, the carbon footprint increases will be larger when more ambitious poverty alleviation goals are adopted. Studies have shown that adjusting the poverty line from the Extreme Poverty Line to the lower-middle-income-country poverty line requires an almost tenfold increase in global climate mitigation efforts to reach the net zero goal [14]. In addition, global carbon emission will be much larger if poverty is eradicated below the upper-middle-income-country poverty line [11]. Third, high-carbon economic growth mode and large populations lead to uncertainties in carbon emission increases [11]. China's population is the largest in the world, with a quarter of the people living under the upper-middle-income-country poverty line in 2019 [17]. Assisting more than 300 million people at a higher poverty line is challenging and may have a considerable impact on national carbon emissions. The disparities in life conditions within the country and the large scales of both the poor populations and carbon emissions make it critical to quantitatively estimate the additional carbon emissions of poverty alleviation in different provinces in China. Such an estimate will promote understanding of how the climate burdens of poverty eradication are shared among regions.

To illustrate how the impact of poverty eradication on climate change mitigation is shared in regions that differ in their level of development, this paper quantifies the climate burden (measured by additional carbon emissions to the baseline level) of poverty reduction across subnational China. First, we assess carbon footprint inequality in China using the multiregional input–output (MRIO) model and a carbon footprint Gini (*CF-Gini*) coefficient. A *CF-Gini* value of zero represents perfect equality and a value of one indicates perfect inequality. Investigation of the recent trend of carbon footprint inequality in China is urgently needed, considering rising global carbon footprint inequality [14,18]. Second, we estimate the increased carbon footprint due to poverty reduction in four scenarios and the impact on the achievement of the carbon neutrality goal of China at the subnational level. Different poverty eradication schemes are designed to target various forms of poverty in the four scenarios. We delineate the recent trends in household carbon footprint inequality from 2007–2017 and quantify the impact of income inequality reduction on achieving climate targets at the subnational level. This study provides policy implications on the conjunction of combatting climate change and poverty in regions with differentiated development patterns.

2. Methods

We applied environmentally extended input–output analysis to estimate the household carbon footprint of ten urban and rural income groups in 30 provinces in China. *CF-Gini* coefficients were calculated to delineate the carbon footprint inequality changes from 2007 to 2017. Then, carbon intensity, population and economic growth rate under the carbon neutrality pathway were adopted to forecast the household carbon footprint, and four scenarios for poverty eradication were simulated to assess the impact of reducing income inequality on achieving climate targets.

2.1 Linking China's multiregional input–output table with the global table

We adopted the 2017 MRIO table for China's 42 sectors and 30 regions (26 provinces and four province-level municipalities) [19]. The MRIO table was built via a gravity model based on a single regional input–output table for China. The final demand in the table was divided into five categories: urban household consumption, rural household consumption, government, fixed capital formation and changes in inventories. The 2007 and 2012 China input–output tables are from previously published work and describe economic linkages among 30 sectors in 30 regions [10].

The China input–output tables were connected with global input–output tables by EXIOBASE to calculate the carbon emissions embodied in imports. The EXIOBASE MRIO tables describe international trade between 168 sectors in 44 major countries and 5 regions in the world [20]. The sectors in the two types of input–output tables are matched for the connection. All MRIO tables are deflated to 2017 prices to eliminate the impact of price inflation in different sectors. Imports and exports in China's MRIO tables are disaggregated into different countries according to China's import and export sources provided in the EXIOBASE MRIO tables. The connected global MRIO table delineates economic linkages among 30 sectors in 30 Chinese provinces as well as 48 countries or regions in the world.

2.2 Environmentally extended input–output analysis

Originally developed by Wassily Leontief in the 1930s, input–output analysis is effective for delineating the economic linkage among industries by quantifying the input and output flows [21]. By simply adding a column to describe the resource or emission intensity of each sector, the framework can be expanded to a broader field, including carbon emissions and other environmental topics. This is the widely applied environmental input–output analysis (EIOA). The fundamental theory of input–output analysis is shown:

$$\boldsymbol{X} = (\boldsymbol{I}\text{-}\boldsymbol{A})^{-1}\boldsymbol{F}, \quad (1)$$

$$\boldsymbol{X} = \begin{bmatrix} \boldsymbol{X}^1 \\ \boldsymbol{X}^2 \\ \vdots \\ \boldsymbol{X}^n \end{bmatrix}, \quad \boldsymbol{A} = \begin{bmatrix} \boldsymbol{A}^{11} & \boldsymbol{A}^{12} & \cdots & \boldsymbol{A}^{1n} \\ \boldsymbol{A}^{21} & \boldsymbol{A}^{22} & \cdots & \boldsymbol{A}^{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \boldsymbol{A}^{n1} & \boldsymbol{A}^{n2} & \cdots & \boldsymbol{A}^{nn} \end{bmatrix}, \quad \boldsymbol{F} = \begin{bmatrix} \boldsymbol{F}^{11} & \boldsymbol{F}^{12} & \cdots & \boldsymbol{F}^{1m} \\ \boldsymbol{F}^{21} & \boldsymbol{F}^{22} & \cdots & \boldsymbol{F}^{2m} \\ \vdots & \vdots & \ddots & \vdots \\ \boldsymbol{F}^{n1} & \boldsymbol{F}^{n2} & \cdots & \boldsymbol{F}^{nm} \end{bmatrix}, \quad (2)$$

where $\boldsymbol{X}^s = (x_i^s)$ is the vector of the total output, x_i^s is the total output of sector i in region s, $\boldsymbol{I}$ is the identical matrix and $(\boldsymbol{I}-\boldsymbol{A})^{-1}$ is the Leontief inverse matrix. The matrix $\boldsymbol{A}^{rs} = (a_{ij}^{rs})$ is the technical coefficient matrix, and $a_{ij}^{rs} = z_{ij}^{rs}/x_j^s$, in which z_{ij}^{rs} is the monetary input of sector j in region s from sector i in region r. In the final demand matrix, $\boldsymbol{F}^{rs} = (f_i^{rs})$, f_i^{rs} is the final demand of region s for the products of sector i from region r.

With the carbon emission intensity of each sector, the indirect carbon emissions can be calculated via

$$\boldsymbol{C} = \boldsymbol{E}\ (\boldsymbol{I}\text{-}\ \boldsymbol{A})^{-1}\boldsymbol{F}, \quad (3)$$

where $\boldsymbol{C}$ is the matrix of the total indirect carbon emissions and $\boldsymbol{E}$ is a vector of the carbon emission intensity of all sectors in all regions, which is measured by carbon emissions per unit of economic output. Emissions induced by fossil fuel combustion and cement production are included in this study. Carbon emissions of each sector in China's MRIO table were adopted from the CEADS database [22,23], which contains carbon emission inventories of 47 sectors in each Chinese province. The carbon intensity of each sector in other regions was adopted from the EXIOBASE satellite accounts. $\boldsymbol{F}$ is the final demand matrix. The household indirect carbon emissions can be calculated accordingly as follows:

$$\boldsymbol{C}_{\mathrm{h}} = \boldsymbol{E}\ (\boldsymbol{I}\text{-}\ \boldsymbol{A})^{-1}\boldsymbol{H}, \quad (4)$$

where $\boldsymbol{C}_{\mathrm{h}}$ is the household indirect carbon emissions and $\boldsymbol{H}$ is the rural and urban household consumption in each region. The household carbon footprint estimated by the MRIO model, $\boldsymbol{C}_{\mathrm{h}}$, is then aggregated into eight categories of consumption: food, clothing, residence, household facilities, transport, education, health care, and others [24]. In this study, the impact of poverty eradication on the achievement of carbon neutrality is elucidated by the impact of poverty eradication on household carbon footprint. In this term, carbon emissions embodied in exports, government expenditure, capital formation and inventory changes are not considered.

Direct carbon emissions can also be obtained from CEADS database [22,23]. Carbon emissions associated with direct household energy consumption of coal and gas are allocated to “residence”, and carbon emissions associated with oil consumption are allocated to “transport”. Urban and rural household carbon footprint at the national level is then calculated by adding up household direct and indirect carbon emissions. Subsequently, national household carbon footprint by sector is allocated to each income group according to its purchasing power. Here purchasing power of each income group is measured by population multiplied by expenditure per capita [25]. As the number of households in each income group is constant (a quintile for each), we obtained the average household size of each income group to calculate the population from provincial statistical yearbooks.

2.3 Gini coefficient

Proposed by the Italian statistician and socialist Corrado Gini, the Gini coefficient is a useful statistic to measure inequality of income and wealth [26]. Scaling from zero to one, a small Gini coefficient indicates a relative equal distribution of income or wealth among people, and a large Gini coefficient indicates few people own most of the income or wealth whereas other people have little. By replacing the income-related indicators with carbon-footprint-related indicators, Eq. (5) is the calculation of the *CF-Gini* coefficient in this study [10]:

$$CF - Gini = \sum_{i=1}^{k} Pop_i CF_i + 2\sum_{i=1}^{k} Pop_i (1 - T\_CF_i) - 1, \quad (5)$$

where Pop_i is the ratio of population in income group i to total population in the province or China, CF_i is the ratio of carbon footprint in income group i to the total carbon footprint in the province or China; T_CF_i is the cumulative proportion of carbon footprint in group i, and i denotes the number of income group in the province or China (i = 1, 2, ···, 10 for provincial *CF-Gini*, or i = 1, 2, ···, 300 for national *CF-Gini*).

2.4 Long-term pathway of the household carbon footprint

The household carbon footprint in China is predicted by determining the pathway of population and expenditure of each income group, as well as carbon intensity and technological coefficients in the MRIO model, as shown in Eq. (6).

$$C_{h,t} = E_t L_0 H_t = E_t L_0 HS_t HV_t P_t, \quad (6)$$

where $\boldsymbol{C}_{h,t}$ denotes the household carbon footprint in year t. Sectoral carbon intensity, denoted by $\boldsymbol{E}_t$, is estimated by referring to the "strengthened policy" scenario according to the long-term pathway to reach the 1.5° target [29]. Here, we refer to the 1.5° pathway and the SSP2 pathway in the literature to determine the parameters [27–29], which are consistent with the requirement to reach the carbon peak and carbon neutrality goals in China (see Figs. S1 and S2 online for national and provincial results).We adjust the mid-century target in the original pathway according to China's carbon neutrality commitment. The decline rate of carbon intensity is differentiated in each province because the provinces have different levels of decarbonization capacities. The national carbon intensity decline rate is multiplied by a factor given by the quotient of the provincial carbon intensity reduction target and national carbon intensity reduction target in the 13th Five-Year Plan [30] for each province. We assume homogeneous carbon intensity reduction rates of the economic sectors because we do not change the Leontief inverse matrix $\boldsymbol{L}_0$.

$\boldsymbol{H}_t$ represents household consumption in year t of ten income groups in 30 provinces and is further decomposed into three factors, namely, household expenditure pattern $\boldsymbol{HS}_t$, household expenditure volume $\boldsymbol{HV}_t$, and population $\boldsymbol{P}_t$. Household expenditure volume $\boldsymbol{HV}_t$ is assumed to grow from the 2017 level with the assumption that the total expenditure of the rich groups grows faster than that of the poor groups. Here, the unit of $\boldsymbol{HV}_t$ is Yuan per capita. The Gross Domestic Product (GDP) growth rate under SSP2 is used as a proxy for the income and expenditure growth rate [28]. For example, the annual expenditure growth rate of the richest income groups will follow the GDP growth rate of the richest provinces in China, regardless of whether they are urban or rural and regardless of their location. The GDP growth rate is adjusted to ensure that the national total GDP is consistent with the projections in the 1.5° scenario. Population $\boldsymbol{P}_t$ is estimated according to the population growth and urbanization of each province under SSP2, and the proportion of each income group to the total urban/rural population in its province is assumed to remain unchanged as of 2017 [27].

Household expenditure pattern $\boldsymbol{HS}_t$ is projected according to the elasticity of each expenditure category, which is estimated:

$$\log\left(\boldsymbol{H}_{r,j}\right) = a + b\log(\boldsymbol{H}_r), \tag{7}$$

where in the log-log regression, $\boldsymbol{H}_{r,j}$ and $\boldsymbol{H}_r$ are household consumption. r is the regional index and j is the expenditure category index, representing the 30 provinces and eight expenditure categories, respectively. Here, we used household expenditure per capita in region r as $\boldsymbol{H}_r$. Therefore, b should be interpreted as the amount of expenditure change in category j when total household expenditure changes by one unit. For each province, we used household expenditure data of the ten income groups in 2007, 2012 and 2017 with the expenditure data deflated to 2017 prices according to consumer price index. The three-year dataset is aggregated and treated as cross-section data. The regression result of each expenditure category in each province is shown in Tables S1–S4 (online).

According to future household expenditure volume $\boldsymbol{HV}_t$, the future expenditure in each category, $\boldsymbol{HV}_{j,t}$, can be calculated by elasticity of demand as

$$\log(HV_{j,t}) = a + b\log(HV_t), \tag{8}$$

Household expenditure pattern $\boldsymbol{HS}_t$ is calculated based on the projected $\boldsymbol{HV}_{j,t}$ as

$$HS_t = HV_{j,t} ./ \sum_j HV_{j,t}. \tag{9}$$

With household expenditure pattern $\boldsymbol{HS}_t$ and household expenditure volume $\boldsymbol{HV}_t$, the distribution of household total expenditure among different expenditure categories can be determined. Such adjustment is conducted to ensure that the sum of all expenditure categories is equal to total household expenditure volume $\boldsymbol{HV}_t$.

2.5 Scenario analysis of poverty eradication

Four scenarios (S1–S4) are designed to estimate the impact of reducing poverty on China's achievement of climate targets. In S1, we assume that people living below the upper-middle-income-country poverty line ($6.85 per day, 2017PPP) are lifted out of poverty by 2035, and people below the high-income poverty line ($24.36 per day, 2017PPP) [31,32] are lifted out of poverty by the end of the prediction period. In S2, we adopt the Societal Poverty Line [31], which measures relative poverty under half the median expenditure plus $1.15 a day. The Societal Poverty Line is updated yearly, and an equal number of people will be gradually lifted out each year until the end of the prediction period. S3 lifts the poorer four rural groups in each province to the higher rural groups and lifts the poorest urban group to the higher group right above in each province by the end of the prediction period. S4 aims to eliminate the gaps between urban and rural areas by gradually increasing the expenditure of rural residents to the level of urban residents in each group. Hereafter, the poverty lines in S1 is referred as static poverty standards because it remains constant, and the poverty lines/standards in other scenarios are referred as dynamic poverty standards because they are updated yearly. Details of the scenarios can be found in Supplementary materials (online).

2.6 Data availability

China's MRIO tables were constructed in previous studies [10,19]. Carbon emissions data of China are from Carbon Emission Accounts and Datasets [22,23] (CEADS, https://www.ceads.net/). The global MRIO tables are accessible online via the EXIOBASE3 database [20] (https://www.exiobase.eu/). The projected carbon emissions, economic and population data of the carbon neutrality pathway in the baseline scenario are accessible via Refs. [27–29]. Household expenditure and the average household size of each income group are obtained from the provincial statistics yearbooks. The 30 regions are divided into eight regions for regional-level analysis (Table S5 online) [33,34].

3. Results

3.1 The growth of the per capita carbon footprint slowed down

In 2017, the household carbon footprint contributed to 37% of China's national carbon footprint. Compared with 2012, the proportion of the household carbon footprint to the total had grown due to increased income and increased consumption in China. This was accompanied by a decline in the contribution of fixed capital formation and inventory changes to the total national carbon footprint, from 62% to 56%. Overall, the household carbon footprint increased by 42% from 2007 to 2012 and 15% from 2012 to 2017. In addition, the results show that the household carbon footprint was 1.6, 2.2 and 2.4 t CO_2 per capita in 2007, 2012, and 2017, respectively, indicating that the increasing trend of the carbon footprint per capita in China has slowed down (Fig. 1a). It can also be seen from the carbon footprint changes of each income group (Fig. 1b) that the household carbon footprint in most provinces remained unchanged in 2017 or even decreased. Hubei is an example that managed to maintain a relatively low household carbon footprint per capita while people's consumption increased. In 2017, the average carbon footprint of household consumption was 1.5 t per capita, increasing by 18% from the 2007 level and declining by 27% from the 2012 level. However, consumption was considerably increased in Hubei Province, rising by 55% and 185% compared with the 2012 and 2007 levels, respectively. Moreover, there was a continuous decline in the urban household carbon footprint per capita in Hubei, indicating that the lifestyle of rich people was greening and undergoing decarbonization. Hubei's success in limiting carbon emissions while lifting living standards was due to changes to the energy mix and the resulting decrease in carbon intensity. Hydropower and thermal power are the main sources of Hubei's electricity consumption. With the establishment of renewable power generation, the proportion of thermal power to total power generation decreased from 65% in 2007 to 54% in 2017.

Fig. 1. Household carbon footprint and carbon footprint inequality of 30 provinces in 2007–2017. (a) Household carbon footprint per capita of 30 provinces. Bars show provincial GDP per capita in 2017, and symbols show household carbon footprint per capita in 2007, 2012, and 2007. Provinces are sorted by descending household carbon footprint per capita in 2017 from left to right. (b) Household carbon footprint per capita of 10 income groups and *CF-Gini* coefficients at the national and provincial levels. The provinces are ordered by descending GDP per capita from left to right.

The richest regions, e.g., Beijing and Shanghai, contribute greatly to the national household carbon footprint because of the carbon-intensive lifestyle in these regions. In 2017, the household carbon footprints of Beijing and Shanghai were 4.8 and 5.1 t per capita, presenting increases of 36% and 31% compared with 2012, respectively. Carbon footprints of the richest income groups in both cities were 8.9 and 10.3 t in 2017, which were among the highest in

China. Previous studies show that climate change mitigation performance is distinguished in these regions, but this is partly due to energy outsourcing by importing electricity from surrounding provinces and by shifting climate pressure to the energy-producing provinces [34]. With the assistance of consumption-based accounting, the estimated household carbon footprint indicates the carbon emissions caused by the final demand in these rich regions. On the other hand, the Northwest provinces, which are usually the energy production bases of China and provide energy for other regions, are faced with the most pressure on climate change mitigation. In 2017, the per capita carbon footprint of household consumption in Nei Mongol reached 5.0 t, which was higher than the level in Beijing. However, consumption per capita in Nei Mongol (19.6 thousand Yuan per year) was only 55% of consumption in Beijing (35.4 thousand Yuan per year) in 2017, indicating that carbon intensity is very high in Nei Mongol; this is related to the reliance of the province on thermal power generation. In 2017, 35% of the electricity production was exported to neighbouring provinces, and thermal power accounted for 85% of the total.

3.2 Provincial gaps have widened

Adopting the *CF-Gini* coefficient, we measured household carbon footprint inequality from 2007 to 2017. Basically, carbon footprint inequality declined slightly in China at the national level, but the gap between the provinces and within urban/rural areas grew (Fig. S3 online). The *CF-Gini* coefficient dropped from 0.36 in 2012 to 0.35 in 2017. The top 10% of earners in China contributed 21% of the national household carbon footprint, which was represents a decrease from 23% in 2012.

China's achievement in carbon footprint inequality reduction from 2012 to 2017 was mainly due to the reduced *CF-Gini* coefficients in less-developed provinces. In the previous period from 2007 to 2012, carbon footprint inequality measured by the *CF-Gini* coefficient was lower in developed regions (Fig. 1b), because economic development in affluent regions is accompanied by higher share of low-carbon-consumption items [10]. For example, the *CF-Gini* coefficient of Beijing was only 0.19 in 2012, which was the lowest among all provinces. This trend has changed due to the profound advancement of inequality reduction in less-developed regions from 2012 to 2017. For example, the *CF-Gini* coefficient of Jilin Province was 0.35 in 2012 and declined significantly to 0.19 in 2017. Provinces such as Jilin, Qinghai and Hebei are among the bottom one-third group regarding economic development but experienced vast improvement in reducing carbon footprint inequality. The reduction of inequality in Hebei and Jilin was mainly attributed to the improvement of rural life conditions. For example, total household expenditure of rural residents increased by 80.7% to 112.5% in Jilin from 2012 to 2017, while the urban household increased expenditure only by 12.2% to 27.1%. The imbalanced development of rural and urban areas in these provinces was much mitigated in that period. Except for reducing rural-urban gap, Qinghai also managed to reduce inequality by poverty uplifts both in urban and rural areas. The rich groups in urban and rural areas increased their expenditure by 46.1% and 60.3% from 2012 to 2017, while the poor groups increased expenditure by 102.7% and 128.0%, respectively. The improved life condition of the poorest groups significantly released the carbon footprint inequality and income inequality in Qinghai.

Despite the decreased carbon footprint inequality in most provinces, the carbon footprint inequality only slightly declined from 2012 to 2017 at the national level. Compared with the significantly reduced *CF-Gini* coefficient from 2007 to 2012, decreasing from 0.43 to 0.36, the *CF-Gini* coefficient was 0.35 in 2017, representing an insignificant decrease, indicating that efforts in reducing carbon footprint inequality in China ran into bottlenecks in consistent reduction off carbon footprint inequality among different income groups. It is also worth noting that in 2007 and 2012, there were several provinces in which the carbon footprint inequality was greater than the national level, while in 2017, the *CF-Gini* coefficients of all provinces were lower than the national line (Fig. 1b). This indicates that in each province, carbon footprint inequality between the ten urban and rural income groups was significantly mitigated from 2012 to 2017. Nonetheless, at the national level, carbon footprint inequality among the 30 provinces remained high, revealing that imbalanced regional development exerts a considerable impact on household carbon footprint and thus leads to national carbon footprint inequality. For example, the *CF-Gini* coefficient of Shandong, a wealthy province in North China, decreased from 0.32 in 2012 to 0.28 in 2017, and the *CF-Gini* coefficient of Guizhou, a poor province in the Southwest, was declined considerably from 0.37 in 2012 to 0.26 in 2017. Although Guizhou managed to reduce carbon footprint inequality, the gap between the two provinces was actually enlarged. The carbon footprint per capita rose considerably from 2.4 to 3.5 t in Shandong from 2012 to 2017, while in Guizhou, the increase was only from 1.9 to 2.2 t per capita (Fig. 2). For less-developed provinces, it is crucial to not only narrow the gaps between income groups to achieve sustainable development but also promote the purchasing power of consumers to boost economic progress.

Fig. 2. Household carbon footprint per capita of ten income groups in 30 provinces in 2007, 2012 and 2017. The colour of the bars corresponds to the household expenditure per capita, from the wealthiest groups in red to the poorest groups in blue (see scale).

3.3 Poverty eradication does not jeopardize the achievement of national climate targets

In light of the growing gaps between provinces and within rural/urban areas, continuous efforts to reduce inequality are necessary, and accordingly, we forecasted the household carbon footprint and designed four scenarios to quantify the subnational impact of reducing poverty eradication based on China's carbon emissions pathway. The total household carbon footprint will peak at 3.7 Gt in 2025 driven by increasing urbanization rates and expenditure of urban residents, according to the 1.5° pathway (baseline scenario without any poverty eradication measures, Fig. 3a). At the end of the prediction period, the household carbon footprint is projected to be 0.3 Gt. In addition, the household carbon footprint per capita is estimated to peak at 2.6 t in 2021 (Fig. 3b). Together with the plateaued population since

2026, these two factors drive the peak of the total household carbon footprint in China. From 2028 to 2060, the population in China will gradually decrease from 1.45 billion to 1.25 billion, and the per capita carbon footprint will decrease to 0.2 t. The rising household carbon footprint is mainly due to the urban populations. The average carbon footprint of urban residents in China was 3.2 t per capita in 2017 and will peak at 3.4 t per capita in 2026, while the per capita carbon footprint of rural residents will peak at only 1.7 t in 2026. The volume of the rural household carbon footprint shows a continuous downward trend because of urbanization and the decreasing rural population. As estimated, the urbanization rate will rise by 0.24 from 2017 to 2060 and reach 0.85. This leads to a rising proportion of the urban carbon footprint to the total, from 0.77 in 2017 to 0.92 in 2060. The results highlight the carbon footprint inequality between rural and urban areas in China and show the necessity of addressing the high carbon intensity of the urban lifestyles. It is also important to ensure a fair rural–urban transition of the less wealthy group to guarantee the accessibility of vital energy resources and other necessary resources.

National results show that eradicating poverty does not affect the overall achievement of carbon emissions peak and carbon neutrality targets. An average increase in household carbon footprint will be 0.1%–1.2% annually in all the four scenarios. The most ambitious goal of narrowing the gap between rural and urban areas and finally reaching balanced urban–rural development in S4 leads to carbon footprint increases of less than 2.5% annually at the national level (Fig. 3a, c). In S4, household expenditure due to poverty alleviation will cumulatively rise by 54.5 trillion Yuan (2017 price) by 2060, accounting for 64.8% of GDP in 2017, and the additional carbon footprint will be 1.1 Gt from 2017 to 2060 (Fig. 3d). S3 is also ambitious in addressing poverty, narrowing the gaps inside the rural groups and urban groups. Poverty eradication in S3 will cause an annual increase in the carbon footprint by up to 1.9% at the national level (0.8 Gt in total). We applied further analysis by simulating earlier or later achievement of carbon neutrality in China and the results show the robustness of the findings (see in Supplementary materials and Fig. S4 online).

Comparisons between different scenarios show that dynamic poverty standards are more effective than static standards. By adopting dynamic standards of Societal Poverty Lines, S2 can better reveal poverty with economic development compared with static standards of international poverty lines in S1, although both are less ambitious than the province-specific standards (S3 and S4). The carbon footprint increments in S1 are the lowest among the four scenarios, indicating that poverty eradication according to the international poverty lines involves less burden (Fig. 3d). The increase in the annual household carbon footprint is less than 1% in S1, with a total of 0.07 Gt carbon emission increments and 1.9 trillion Yuan increases in household expenditure until 2060. In contrast, household expenditure rises by 13.8 trillion Yuan in S2, with an additional 0.2 Gt carbon emissions induced. It is worth noting that the increased expenditure in S2 is less than that in S1 at early stages due to the lower poverty line and fewer people identified as living in poverty. However, adopting the international poverty lines in S1 causes reduced carbon footprint increments compared to that in S2 after 2024. As the expenditure of each group is assumed to grow with economic development, the gap between the expenditure of the identified poor people in S1 and the static poverty lines narrows over time. Therefore, static standards fail to identify poverty in the long term. However, the Societal Poverty Lines in this study are dynamic and updated per year with the growth in expenditure. With the assumption that the expenditure of the higher income groups increases faster than that of the lower income groups, inequality also increases without poverty alleviation efforts. The dynamic standards in S2 could consequently better identify the people living in poverty and reduce the inequality occurring with unbalanced economic growth.

Fig. 3. Projected household carbon footprint under 1.5° scenario and poverty eradication scenarios. (a) Total household carbon footprint. (b) Carbon footprint per capita. (c) Carbon footprint increases under four poverty eradication scenarios, compared with the baseline scenario. (d) Carbon footprint increases (area) and expenditure increases (lines) under four poverty eradication scenarios.

Narrowing gaps between urban and rural areas and ensuring the accessibility of necessary public services and employment for new urban residents will be the main challenges in addressing carbon footprint inequality in the future. Raising poverty eradication standards from S3 to S4 causes increased carbon emissions and expenditures, but the increases in carbon footprints are larger than the increases in expenditures, and the disparity grows over time. By the end of the prediction period, the additional carbon emissions in S4 are 1.31 times those in S3, while the additional expenditures in S4 are 1.19 times those in S3, indicating a disparity of 10%. The results indicate that the lifestyle transition inside rural areas and inside urban areas (S3) does not lead to as much increase in carbon intensity as the transition of rural residents towards an urban lifestyle. The higher carbon intensity of household consumption in S4 is because of the high-carbon lifestyle of urban residents. On the one hand, this indicates extra climate pressure in reducing the rural–urban gap than in reducing internal carbon footprint inequality in urban areas and in rural areas. As progress in urbanization will continue in the future, the high carbon intensity of the urban lifestyle should be addressed concurrently through infrastructure upgrades, transitions in the energy mixes, and low-carbon transitions in consumption behaviours. Cities must take responsibility and exert efforts in climate change mitigation. On the other hand, those who migrate from rural areas to urban areas may encounter difficulty in acquiring the additional resources to settle in urban areas, including access to social infrastructure, employment and housing. Living in urban areas requires more energy consumption, for example, a greater need for electricity and longer commutes in daily life, and therefore, new urban residents face a drastic increase in energy demand. With the urbanization rate projected to increase from 60% in 2017 to 90% in 2060, hundreds of millions of rural people will migrate to cities. Ensuring the accessibility of resources for new migrants will also create challenges in poverty eradication.

3.4 The climate burden of poverty eradication is inequitably large in less developed regions

Although the carbon footprint experiences a small increase at the national level, the provincial results show that reducing carbon footprint inequality causes an unevenly large climate burden in the less-developed provinces in China (Fig. 4 and Fig. S5 online). Increases in expenditure and carbon footprints resulting from poverty eradication are much higher in poor provinces, including Hebei, Gansu and Guizhou, than in wealthy regions, such as Beijing, Shanghai and Tianjin. The average increases in carbon footprints in S4 are approximately 1.5% annually compared with the baseline scenario. The increases in carbon emissions in S4 are similar to those in S3 in the wealthy provinces, indicating that reducing carbon footprint inequality within rural and urban areas causes a consonant level of climate burden with reducing carbon footprint inequality between rural and urban areas in wealthy regions. In contrast, in the poor provinces, annual increases in the carbon footprint in S4 are as large as 4% in Hebei and Gansu and are much higher than those in the other three scenarios. The extra climate and economic burden caused by poverty eradication in S4 in the poor provinces shows that the development of rural areas in these provinces lags far behind that of urban areas. Mitigating unbalanced urban–rural development should be prioritized by boosting the economic development of rural areas and improving the life conditions of rural residents in less-developed provinces.

Fig. 4. Relative carbon footprint increase associated with poverty eradication in provinces differentiated by economic development level. Note: Carbon footprint increase (left axis) and expenditure increase (colour) at the end of the prediction period are displayed. Size of the scatters denotes carbon footprint per capita in 2017.

The national unified poverty lines are insufficient to identify the groups living in poverty in wealthy regions, and poverty eradication goals should be compatible with the inequality incidence in the specific region. Beijing, Shanghai, Tianjin and Zhejiang are among the wealthiest regions in China; no poverty is identified in these provinces because the expenditure of all income groups in these provinces is above the poverty lines in S1 and S2 (Fig. 5). The poverty lines in S1 and S2 aim to identify poverty across all groups in the country and reduce carbon footprint inequality between these provinces. The urban and rural residents living in the wealthiest regions are all above the lines, while the additional expenditure and carbon emissions caused by poverty alleviation in S2 in the less-developed provinces in Southwest and Northwest China can be as high as those in S3. Apparently, the unbalanced development between coastal (South Coast and East Coast) and inland (Southwest and Northwest) regions urgently needs to be solved by improving the living conditions of poor people in inland regions, and developed regions need to take responsibility for assisting in the economic development of poor provinces. In addition, more ambitious targets should be set to reduce poverty due to the increased living costs in wealthy provinces. The overall expenditure in wealthy provinces is usually higher than that in other regions, and therefore, less attention is given to poverty alleviation in these provinces. However, poverty should not be neglected because of the higher living costs in these provinces. Data accuracy is another important issue. In addition to the high level of expenditure in wealthy provinces, data accuracy is another reason for the lack of poverty identification in these provinces in S1 and S2. As the population in each province is divided into ten groups in this study, it is difficult to reflect the real expenditure of the people living at the bottom and thus insufficient to identify these minority groups. In summary, elevating the standard of poverty alleviation is necessary, and more targeted investigation to identify those living in poverty is crucial.

Fig. 5. Relative carbon footprint increases in 30 provinces under the four poverty eradication scenarios, compared with the carbon footprint in baseline scenario in each province.

Less developed provinces suffer more carbon emissions growth from reducing the urban–rural gap. Considerable increases in the carbon footprint occur by improving the living conditions of rural residents to those of urban residents in Southwest and Northwest China, including Guizhou, Guangxi, Gansu, Qinghai, etc. (Fig. 5). This can be seen via the large carbon footprint increase in S4 compared with the other scenarios in these provinces. For example, in Qinghai and Gansu, the additional carbon footprints in S2 and S3 are comparable, showing that reducing national carbon footprint inequality and addressing internal rural/urban inequality entail similar climate burdens. However, carbon footprint increases are almost doubled in S4 in these regions because of the large rural populations and the obvious gap between urban and rural residents. In contrast, poverty eradication in S3 and S4 in Guangdong and Jiangsu, as the richest areas in South Coast and East Coast China, causes a similar increase in carbon footprint. The results indicate that with the progress in urbanization and economic development in these wealthy regions, living conditions of both urban and rural residents are improved as the urban–rural gap narrows. However, internal carbon footprint inequality within rural/urban areas still exists and should be reduced. Nonetheless, in poor regions, large populations still remain in rural areas where life conditions need to be enhanced. The climate burden of poverty eradication to reduce the urban–rural gap in poor regions is more intensive than that in wealthy regions. To abate the additional carbon emissions of poverty eradication and achieve the dual goals of climate change mitigation and carbon footprint inequality reduction, green economic development and low-carbon transition should be fostered to create green jobs in poor regions [35].

Regional characterises indicate that cooperation can initiate sustainable development toward poverty eradication and carbon reduction. Development gaps between wealthy and poor provinces can be reduced through interregional cooperation through fiscal support, technical transfer and resourcing sharing. In addition to encouraging wealthy regions taking more responsibility, intraregional cooperation should also be boosted because neighbouring provinces share common geographical, cultural and poverty conditions [36]. For instance, Southwest China is endowed with abundant hydropower resources, with four Southwest provinces ranking among top five hydropower generator (Sichuan, Yunnan, Guizhou and Guangxi). The resource endowment enables Southwest region to keep household carbon footprint at relatively low level (1.1 to 2.2 t per capita) in the country. But they also suffer from poverty because of insufficient economic development. In the four provinces mentioned above, additional carbon footprint caused by poverty eradication accounts for 3.5% annually compared with baseline scenario. Intraregional cooperation between Southwest provinces can facilitate better exerting advantages of hydro resources to develop low-carbon industries, and regional infrastructure construction can better connect the provinces to boost collaborative growth along the supply chain. Analogously, Northwest provinces also share common characteristics in solar and wind resource endowment while the economic development is insufficient. In Northwest region, poverty eradication in S4 to reduce rural-urban gaps causes significantly more carbon footprints than in other scenario, indicating rural areas in the Northwest in under development. Intraregional cooperation should focus on increasing agricultural added value as well as creating green jobs by boosting solar- and wind-related industries.

4. Discussion

Our research reveals an overall decreasing trend of carbon footprint inequality in China from 2007 to 2017. However, the reduction in carbon footprint inequality slowed during 2012–2017 because of the widening development gap between regions. Four scenarios of poverty eradication show that poor regions suffer carbon emissions growth higher than the national average. The increase in household carbon footprints from 2007 to 2017 is also reported in Ref. [37]. The decrease trend in inequality has also been revealed in multidimensions in Ref. [37]. Carbon emissions inequality is found to decline slightly in recent years at both city- and county-level [38, 39]. Using survey data and without considering the different carbon emission intensities of the goods and services produced in different provinces, household carbon footprints are found to be highest in the wealthy provinces and carbon footprint inequality slightly increased from 2012 to 2018 [40]. As China has managed to diminish extreme poverty in 2020, carbon footprint inequality is supposed to be reduced because the life condition has been considerably improved for the poor. But the identified low-income population is about 4.7% of the total population in China, indicating that persistent efforts in poverty eradication is required [41]. The impact of poverty eradication is found to have little impact on total carbon emissions, which is also concluded in other studies [11, 14]. But more ambitious poverty eradication targets need to be coordinated with more efforts in carbon reduction to minimize the impacts on climate change [14].

The effect of inequality reduction reaches bottlenecks despite the obvious achievements resulting from the imbalanced development among the regions. First, the *CF-Gini* coefficients in all the provinces were less than the national carbon footprint inequality in 2017, elucidating that although internal inequality decreased in each province, the national carbon footprint inequality was merely mitigated due to the disparities in the household carbon footprint among different provinces. Second, the *CF-Gini* coefficients of several expenditure categories were higher among the rural groups and the urban groups than the national coefficient. Such inequality is because of the differing capacities for climate action; therefore, some provinces managed to decarbonize production, while other provinces even experienced higher carbon intensity. Consequently, although China has seen a continuous decrease in its national carbon intensity and reduced expenditure inequality, carbon footprint inequality among regions contributes greatly to national carbon footprint inequality.

Less developed regions bear more climate burdens in combating poverty, although efforts in climate change mitigation will not be offset by poverty reduction at the national level. Based on a baseline of 1.5° pathway and several poverty eradication scenarios, this study sheds light on the subtle impact of poverty eradication on the achievement of climate targets in China in the long run. Improving the poverty lines indicates targeting poverty in a larger population and requires much more effort in climate change mitigation. This result is reassuring with respect to the possibility of concurrently addressing climate problems and eradicating poverty. However, such a climate burden is unevenly distributed in less developed provinces because of the high poverty incidence as well as the high-carbon-intensity growth mode. In contrast, rich regions experience little pressure in addressing poverty or the associated carbon emissions. The disparity in climate burden can be as great as fivefold between rich and poor regions.

Less developed regions also suffer from an inability to decarbonize because of reliance on energy exports and carbon-intensive production, highlighting the necessity to tackle unbalanced development among regions via interregional cooperation and coordinated development. Although income inequality has been consistently reduced at the national level, the inequality of the carbon footprints associated with consumption increase has not been effectively reduced. The developed provinces were able to decarbonize their production process and energy generation and therefore manage to constrain the carbon footprint per capita. However, less-developed provinces, especially those relying on energy exports and carbon-intensive production, witnessed a growing carbon intensity of household consumption. The gap in household carbon footprints among the provinces is widening due to the inability of less-developed provinces to curtail carbon emissions. To close the gap, interregional cooperation is essential to ensure the accessibility of necessary decarbonization technologies for energy producers. Considering the insufficient capacity of these less-developed provinces to mitigate climate change and decarbonize their production, developed provinces should take responsibilities to collaborate with these provinces to jointly cope with carbon emission reduction.

There are several problems to be addressed in reducing poverty in emerging economies like China. First, reducing the carbon intensity of the urban lifestyle is important for mitigating carbon footprint inequality. The growing gaps between urban and rural areas require extensive efforts in lifting the conditions of rural populations. The rapid urbanization is a way to enhance the access to resources and energy for rural residents, but this leads to additional carbon emissions because of the high-carbon lifestyle in urban areas. The transition of low-carbon lifestyle of urban residents necessitates a holistic and coordinated approach via policy execution. The wealthy groups should take responsibility to reduce their carbon footprint by using energy efficient appliances and shift to low-carbon consumption patterns. In addition, transitions in energy mix and infrastructure upgrades to facilitate decarbonization and low-carbon consumption are crucial to decarbonization goals. This entails fostering sustainable urban planning, transit-oriented development (TOD), circular economies, and the promotion of low-carbon technologies, especially in wealthy eastern and central regions. Climate-friendly urban planning complements the decarbonization of urban economic activities. A compact and dense urban form helps to reduce per capita carbon footprint due to less demand for transport and improved energy efficiency. Nevertheless, the current urban planning has experienced rapid suburban expansion, resulting in extensive infrastructure investments and heightened commuting demand. In this regard, the concept of TOD should be well-designed in urban planning [42]. TOD is a type of urban development to cluster jobs, housing, services and amenities around public transport. Incorporating TOD principles into urban planning can greatly improve the effectiveness of public transport and subsequently reduce transport-related emissions, e.g., private-car-induce emissions. Furthermore, TOD contributes to increasing job availability and thereby reducing unemployment and mitigating income inequality. Circular economies present opportunities to reduce the carbon footprints of urban residents because of reduced production of new materials. This involves the usage of recycled material, expanding product life through repairing rather than replacing, and increasing material recycling [43]. Policies should be implemented to incentivize behaviours that benefit circularity. In the process of low-carbon urban lifestyle transition, technologies play important roles, for example, improving energy efficiency of electrical appliances and decarbonization of energy systems.

Second, ensuring the resilient transition of rural residents into new urban residents is important to protect vulnerable poor groups and pursue sustainable urbanization. Considering that urbanization will contribute to an increase in the household carbon footprint in emerging economies, narrowing the gap between urban and rural areas is important to reduce inequality. Regarding the differences in the carbon footprint of basic consumption between rural and urban populations, higher urban household carbon footprints indicate that rural residents must experience a drastic increase in energy demand and other lifestyle costs when moving into cities. It is very important to ensure the energy and resource accessibility of the new urban population from rural areas. On this subject, local policies and institutions play critical roles by precise poverty identification, green job creation and energy-efficiency technology updates in the western poor regions [44,45]. Regarding poverty eradication, local government should be capable of identifying people living in poverty, not only those in poor rural areas but also the relatively poor group in urban or wealthy areas. As indicated in this study, urban residents may suffer from increased living costs to sustain themselves. Local government should be aware of inequality in urban and wealthy regions by adopting higher poverty eradication standards to identify those in poverty. In addition, local government should foster resilient and sustainable poverty eradication through green job creation to improve the affordability of energy for impoverished households [46]. Policies to boost the development of low-carbon industries should be implemented to provide employment for the poor group. For example, the prosperity of the industrial chain of biomass energy production can concurrently bolster employment opportunities and facilitate energy transition. Moreover, maximizing local advantages of poor regions is focal to address the concern of additional emissions from poverty eradication. Those regions characterized by small population density but rich renewable resources can increase investments in renewable energy, such as hydropower in Southwest China and solar and wind power in Northwest China. Promotion of energy-efficient buildings and appliances can reduce energy demand for lightning, cooling and heating, etc. Local institutions should take efforts in providing financial assistance targeted low-income residents for energy-efficiency improvement technology to reduce energy costs.

Third, sustainable poverty eradication without causing an overburdening climate pressure requires broader capacity building in poor regions. The potential energy demand and carbon emissions may be different if the multidimensionality of inequality reduction is considered. Efforts are required not only to reduce income equality, but also to address disparities in healthcare and education. Ensuring adequate investments and public expenditure is vital to provide social services encompassing transport, culture, retirement, etc. In this regard, interregional cooperation is necessary for sustainable and low-carbon poverty eradication [47], based on information transparency, adequate fiscal support and a healthy competition system. Through interregional cooperation, there could be effective exchange of knowledge, experience, and resources [48]. In addition, long-term cooperation could promote capacity building and private investment. Therefore, interregional cooperation could facilitate efficient rebalance of economic benefits and natural resources for sustainable development [49]. It is essential to establish a platform for timely and transparent information exchange, recognition and use between provinces. The well-guaranteed transparency of information accessibility is the foundation for regional trusts and capacity building, while information barriers cause resistance to cooperation. Information transparency also enables effective and efficient communications between government, research institutions, and companies, and therefore, enables accurate resource allocation. In addition, ensuring fiscal budgets to fund the transformation of scientific and technological achievements is vital for technology transfer between regions and provinces. Government should also take efforts in boosting the development of technology licensing organizations and education in related fields. Importantly, the effective impacts of markets and companies on interregional cooperation should be enhanced. Eliminating the obstacles in the market, such as unfair competition, monopoly and local protection helps to establish healthy competition and improve efficiency.

We show that efforts should be made not only to assist carbon abatement and poverty reduction in China's poor regions but also in less-developed countries. Recently, there has been a growing consensus on the probability of the dual achievement of both climate change mitigation and poverty eradication, showing that carbon emissions arising from extreme poverty reduction do not jeopardize global climate targets. Although this makes sense at a broad level, for example, at the global or national level in China, we note that the excessive climate burden in poor regions is worth attention globally. The major disparity in the climate burden may be aggravated in less-developed countries, indicating that they encounter a more challenging situation in reducing the climate impact of poverty reduction. Extra carbon emissions by poverty eradication not only offset efforts in climate change mitigation but conceivably affect poor regions' ambition in carbon reduction, as they may prioritize economic development to fulfil the demands of people living in poverty. In addition, as the carbon emissions in developed countries have peaked and declined for years, curbing excessive carbon emissions in developing countries, especially poor countries, is critical for the global achievement of climate targets. Therefore, collaboration between regions and countries is important for combating both poverty and climate change.

Conflict of interest

The authors declare that they have no conflict of interest.

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Author contributions

Xinlu Sun calculated and analysed the data and drew the figures; Zhifu Mi designed and supervised the project. Xinlu Sun, Zhifu Mi, Huibin Du and D'Maris Coffman all contributed critically to manuscript drafting.

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