Humanities & Social Sciences Communications

ARTICLE

https://doi.org/10.1057/s41599-024-02631-3 OPEN

The effects of China's poverty eradication program on sustainability and inequality

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Poverty eradication is the first goal on the United Nations' list of 17 Sustainable Development Goals (SDGs). However, the relationships between poverty eradication and the other SDGs remain unclear, and thus current knowledge is insufficient to support the synergized achievement of the SDGs. China eliminated extreme poverty in 2021, and thus in this study, we analyzed the variations in sustainability and equality related to the environment and the provision of public services in China during the poverty eradication program from 2010 to 2020. We combined statistical data, point of interest data, and environmental monitoring and remote sensing data to evaluate progress in China's 832 poverty-stricken counties. The results showed that the mean values of environmental and public service sustainability indicators improved from 2010 to 2020. In addition, the mean Theil index value decreased from 0.46 to 0.35 during this period, implying a reduction in inequality. Inequality between poverty-stricken and non-poverty-stricken areas accounted for 9.3% of overall inequality among the counties in 2010, and this had decreased to 7.7% in 2020. However, unbalanced regional investment resulted in increased gaps between poverty-stricken and non-poverty-stricken counties in relation to education and health care. Overall, 15% of the population and 54.8% of the land area in poverty-stricken counties experienced both a loss of their advantage in terms of environmental quality compared with non-poverty-stricken counties and greater lags in the provision of public services. Linear estimation showed that investment in poverty-stricken counties should be increased by 226.2 and 72.0% in relation to education and health care, respectively, to eliminate these inequalities.

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Introduction

Humanity continues to exploit Earth's systems in search of ongoing economic and social development, leading to global environmental changes in the Anthropocene epoch (Lewis and Maslin, 2015). However, unbalanced development has resulted in hundreds of millions of people still living in extreme poverty, while a few individuals have amassed enormous wealth (Bruckner et al. 2022). This tremendous inequality exists not only in relation to material possessions, but also in terms of access to clean air and water, healthy ecosystems, and public services (Bluhm et al. 2022; Rammelt et al. 2023; Yang et al. 2023; Zhao et al. 2022b). To tackle this problem, the United Nations established 17 Sustainable Development Goals (SDGs) in 2015 (UN, 2015). SDG 1 is to 'End poverty in all its forms everywhere.' In addition to poverty eradication, the SDGs aim to end hunger, ensure good health and the provision of education, clean water, public services, and thriving ecosystems, and reduce inequality both among and within countries. Achieving one goal, such as poverty eradication, involves interactions with other goals (Wu et al. 2022), and there can even be tradeoffs among the SDGs (Fu et al. 2019). Thus, research is required on how and why the various SDGs interact in relation to poverty eradication, the provision of public services, and the environment.

Previous studies have explored China's progress in relation to poverty alleviation. Following the cultural revolution, China implemented a series of 'reform and opening up' policies in 1978 with the aim of boosting economic growth (Lu et al. 2019). The rapidly rising population and increasing industrialization and urbanization resulted in rapid economic growth and the removal from poverty of hundreds of millions of people. However, this was accompanied by environmental degradation and a series of natural disasters (Lu et al. 2019; Bryan et al. 2018). Also, during China's urbanization and economic development, the provision of public services in the relatively underdeveloped western regions has been comparatively inadequate compared to the more developed eastern regions (Zhao et al. 2022b). Regional imbalances in the development of public services hinder the sustainable development of the whole country and exacerbate the inequity between poverty and non-poverty areas.

In the late 1990s, in an effort to reverse the environmental degradation, China implemented an integrated portfolio of large-scale ecological restoration programs, such as Grain for Green, Natural Forest Conservation, and Grassland Ecological Protection (Bryan et al. 2018). A large amount of government investment contributes to the success of various programs in terms of ecological restoration and the sustainability of rural land systems (Bryan et al. 2018; Ouyang et al. 2016). In an effort to simultaneously promote ecological restoration and poverty alleviation, these programs offered large subsidies to people who transformed their steep farmland into forest, and were subsequently disadvantaged by logging and grazing bans (Liu et al. 2008). The sustainable effects of subsidies on poverty alleviation were limited because the subsidies were considered to place a budgetary burden on some local governments, and might result in a return to poverty of rural people when they ended, especially people who did not have off-farm jobs (Bryan et al. 2018). The subsidies also have limited effects on enhancing public services such as education in poverty areas (Miao and Li, 2023).

In 2010, there were still 165.7 million people in China living in extreme poverty. After decades of urbanization and economic growth, the people in extreme poverty were generally those living in the plateau or mountainous areas, which featured a harsh environment and inferior transportation, and thus presented a significant challenge in terms of eradicating poverty. Thus, the Chinese government enacted a new ten-year outline (2011–2020) for poverty alleviation in China's rural areas. In the meantime, targeted poverty alleviation were launched from 2013 (Guo et al. 2022). Also the National Rural Revitalization Administration drew up and published a list of 832 poverty-stricken counties in 2014 for monitoring and supervising the process of poverty alleviation (see detailed information in the data source section). The new ten-year outline and targeted poverty alleviation both emphasized the importance of investment in the agricultural and forestry industries, construction of green energy facilities, and improved infrastructure in the areas of roads, water, housing, electricity, education, and health care (FAO, 2011).

In 2021, China announced that it had eliminated extreme poverty throughout the country, which is a significant contribution toward the global achievement of the SDGs. Nowadays, after the announcement of poverty eradication, it is necessary to evaluate whether progress in eradicating poverty has been accompanied by improved sustainability and reduced inequality or if the opposite has occurred. And how can government investment be optimized to promote sustainability and equity?

Previous studies have focused on variations in sustainability during China's drive to eradicate poverty from 2010 to 2020. Using provincial statistical data, some previous studies have analyzed China's progress toward all 17 SDGs (Xu et al. 2020). In this study, because we focused on China's 832 poverty-stricken counties, a county-level indicator system using multiple data sources was introduced to quantify sustainability related to the environment and the provision of public services. Furthermore, this study is the first to analyze the variations in inequality in relation to both the environment and public services between the poverty-stricken counties and non-poverty-stricken counties during the poverty eradication program. The Theil index is widely used to evaluate regional inequality (Akita, 2003; Xian and Chen, 2022) because unlike the Gini index, it can be used to evaluate both total inequality throughout an entire region and inequalities within each sub-region, as well as inequality between various sub-regions (Sanders et al. 2023; Xian and Chen, 2022). However, the Theil index belongs to the generalized entropy index system (Xian and Chen, 2022). Thus, we also introduced a gap index to measure the specific gaps between the poverty-stricken and non-poverty-stricken counties. Then, we developed a hypothetical framework to analyze how multidimensional government investments affected multiple dimensions of sustainability and inequality. Thus, this is an empirical study of how the poverty eradication program interacted with the other SDGs and inequality. The results of this study provide valuable information for policymakers around the world aiming to optimize the effects of government investments designed to combat poverty in a more sustainable and equitable way.

In this study, we focused on China's 832 poverty-stricken counties. On the basis of 17 items of data, including statistical data, point of interest data, and environmental monitoring and remote sensing data, we have constructed nine sustainable development indicators in terms of the ecological and environmental status and provision of public services. We applied the Theil index and established a gap indicator to quantify inequality between poverty-stricken counties and non-poverty-stricken counties, in relation to the nine sustainable development indicators. The variations in sustainability and inequality from 2010 to 2020 were analyzed. The future variations were also estimated under a 'business-as-usual' scenario. We found a general increase in sustainability and decrease in inequality in terms of the ecological and environmental status and provision of public services. However, the gaps enlarged between poverty-stricken and non-poverty-stricken counties in relation to higher education and high-quality health care. We compared the multidimensional government investments in poverty-stricken and non-poverty-stricken counties and found that unbalanced regional investment might result in the enlarged gaps in relation to education and health care. At last, we estimated the optimal government investment necessary to eliminate inequality.

Materials and methods

Sustainability indicators. Following the Global Indicator Framework for SDGs (UN, 2015), 17 metrics were selected to reflect the variations in sustainability of China's poverty-stricken counties during the poverty eradication program from 2010 to 2020. Instead of analyzing annually, we chose the years 2010 and 2020 to compare changes in sustainability and inequality indicators before and after the most recent decade of poverty alleviation projects. We assume that most sustainability and inequality indicators exhibit linear variations, and we conducted a preliminary analysis to support our assumption (Fig. S1).

The 17 metrics were aggregated into nine sustainability indicators, including clean air, clean surface water, climate change, ecological resources, basic education, higher education, basic health care, high-quality health care, and housing and transportation (see Table 1). These indicators encompassed the two broad areas: ecological and environmental factors, as well as the provision of public services. These indicators were selected after referring to various SDGs, including SDG3 on good health and well-being, SDG4 on quality education, SDG6 on clean water and sanitation, SDG7 on affordable clean energy, SDG11 on sustainable cities and communities, SDG13 on climate action, and SDG15 on life on the land (see Table S1).

Sustainability scores for each of these metrics were calculated using formulas (1) and (2) (Zhao et al. 2022b; Xu et al. 2020). Negative metrics were calculated using formula (1), including particulate matter, ammoniacal nitrogen, CO_2 emissions per capita, and percentage of households living in adobe houses (see Table 1). The use of negative metrics means that the greater the value, the greater the negative impact on sustainability. The other metrics were all positive, and were calculated using formula (2). All metrics were calculated at the county level. Then, the scores for the metrics relating to a specific sustainability indicator were averaged for each county to obtain an overall score for that specific sustainability indicator:

$$S_{ij} = \frac{\max(x_i) - x_{ij}}{\max(x_i) - \min(x_i)} \quad (1)$$

$$S_{ij} = \frac{x_{ij} - \min(x_i)}{\max(x_i) - \min(x_i)} \quad (2)$$

where S_{ij} is the sustainability score for metric i in year j, x_{ij} is the original value of metric i in year j, and $\max(x_i)$ and $\min(x_i)$ are the upper and lower bounds for the best and worst performances, respectively, in relation to metric i (Xu et al. 2020). The upper bound reflects the best performance toward achieving sustainability, while the lower bound reflects the worst performance. The values of S_{ij} ranged from 0 to 1, with values closer to 1 indicating that the county was closer to achieving sustainability. See the Supplementary Information and Table S1 for detailed information on the selection of the metrics and the upper and lower bounds.

Inequality indicators. We applied the Theil index and established a gap indicator to quantify inequality. One-stage Theil inequality decomposition analysis was used to quantify environmental and ecological inequality and inequality in public services both between poverty-stricken counties and non-poverty-stricken counties, and within counties (Akita, 2003; Duro and Padilla, 2006). The detailed calculation methods are as follows:

$$T_p = \sum_i \sum_j \left(\frac{Y_{ij}}{Y}\right) \ln\left(\frac{\frac{Y_{ij}}{Y}}{\frac{N_{ij}}{N}}\right) \quad (3)$$

$$T_{pi} = \sum_j \left(\frac{Y_{ij}}{Y_i}\right) \ln\left(\frac{\frac{Y_{ij}}{Y_i}}{\frac{N_{ij}}{N_i}}\right) \quad (4)$$

$$T_{WR} = \sum_i \left(\frac{Y_i}{Y}\right) T_{pi} \quad (5)$$

$$T_{BR} = \sum_i \left(\frac{Y_i}{Y}\right) \ln\left(\frac{\frac{Y_i}{Y}}{\frac{N_i}{N}}\right) = T_p - T_{WR} \quad (6)$$

where T_p is the Theil index value and Y_{ij} is the sustainability metric of county i in region j (see Table 1). We divided China into two regions: poverty-stricken and non-poverty-stricken regions. Y is the total value of the sustainability metric for all counties, N_{ij} is the population of county i in region j, N is the total population of all counties, T_{pi} is the Theil index value for region i, which measures inequality among the counties in region i, that is, the poverty-stricken counties and the non-poverty-stricken counties. Y_i is the total value of the sustainability metric of all counties in region i, N_i is the total population of all counties in region i, T_{WR} is the intra-region Theil index value, which measures the average inequality in terms of the sustainability metric between the poverty-stricken counties and non-poverty-stricken counties, and T_{BR} is the between-region Theil index value, which measures inequality between the poverty-stricken region and the non-poverty-stricken region.

In addition to the Theil index, we established a gap indicator to measure the gaps between poverty-stricken counties and non-poverty-stricken counties in terms of ecological and environmental status and provision of public services. The gap indicators were mainly based on the same metrics as the sustainability indicators and calculated as follows:

$$Gap_{ij} = k \times \frac{x_{ij} - mean\left(x_{inj}\right)}{mean\left(x_{inj}\right)} \quad (7)$$

where Gap_{ij} is the gap score for metric i in year j, x_{ij} is the original value of metric i in year j, $mean(x_{inj})$ is the average value of metric i for all non-poverty-stricken counties in year j, and k is a parameter that takes a value of –1 when the metric is negative and a value of 1 when the metric is positive. The classification of positive and negative metrics is based on the sustainability indicators.

The closer to zero the value of Gap_{ij}, the less the inequality between the mean of the poverty-stricken counties and the mean of the non-poverty-stricken counties. A negative value for Gap_{ij} means that the average performance of the poverty-stricken counties is worse than that of the non-poverty-stricken counties in relation to a specific metric, and a positive value for Gap_{ij} means that the average performance of the poverty-stricken counties is better than that of the non-poverty-stricken counties in relation to a specific metric.

The Theil index values and gap indicators were mainly calculated based on the same metrics as the sustainability indicators. However, only 'percentage of households using purified tap water' and 'proportion of natural villages with electricity' were used in the calculation of the inequality indicator for housing and transportation because the other metrics were not recorded in China's statistical yearbooks for the non-poverty-stricken counties (see Table 1).

Table 1 Indicators and performance in relation to various aspects of sustainable development and inequality.

Indicator	Metrics and unit	Poverty-stricken counties		Non-poverty counties	
		Mean value of 2010	Mean value of 2020	Mean value of 2010	Mean value of 2020
Ecological & environmental					
Clean air	Atmospheric particulate matter ($PM_{2.5}$, $\mu g/m^3$)	40.6	22.9	58.8	30.1
Clean surface water	Ammonia nitrogen in surface water (NH_3-N, mg/L)	1.2	0.1	1.2	0.2
Climate change	CO_2 emission per capita (Ton CO_2 per capita)	4.7	6.0	8.7	10.1
Ecological resources	Net primary production of terrestrial ecosystem (g C /m^2)	506.6	544.5	420.5	458.7
Public services					
Basic education	Primary educational buildings and facilities (Amounts per million persons)	102.2	175.4	171.2	261.0
	Vocational educational buildings and facilities (Amounts per million persons)	9.7	7.1	35.0	15.3
Higher education	Higher educational buildings and facilities (Amounts per million persons)	3.8	2.5	13.8	27.9
Basic health	Rural clinics and anti-epidemic stations (Amounts per million persons)	48.0	276.0	74.3	385.4
	Drug stores (Amounts per million persons)	50.7	487.8	163.4	1003.5
High-quality health	General hospital buildings and facilities (Amounts per million persons)	49.0	92.6	61.4	196.3
Housing and transportation	Percentage of households living in adobe houses (%)	7.7	1.4	null	null
	Percentage of households using purified tap water (%)	34.3	58.6	71.5	96.9
	Percentage of households using firewood for cooking (%)	57.7	36.6	null	null
	Proportion of natural villages with electricity (%)	98.0	100.0	100	100
	Proportion of natural villages with Internet (%)	43.7	95.1	null	null
	Proportion of natural villages connected to the highway (%)	66.2	100.0	null	null
	Proportion of natural villages connected to the public bus (%)	49.7	75.4	null	null

'null' indicates that these metrics were not recorded in the statistical yearbooks, and thus were not included in this study.

Future variations in sustainability and inequality indicators. Ongoing variations in sustainability and inequality (gap indicators) under a 'business-as-usual' scenario were projected for each county for one decade. All of the metrics used in the calculation of the sustainability and inequality indicators were used in these projections. The comprehensive consideration of policy optimization and its impacts in an accurate prediction exceeds the scope of this paper. The purpose of the 'business-as-usual' scenario is to demonstrate what will happen to sustainability and inequality indicators in the next 20 years if optimal policies or programs are not implemented (Winkler et al. 2011). Although the SDGs are announced to be achieved in 2030, progress towards attaining them is already lagging behind prior to the COVID-19 pandemic and was further delayed by it (Naidoo and Fisher, 2020; Zhao et al. 2022a). So, the scenario was projected to 2040. We hypothesized that all metrics in the poverty-stricken counties would vary over the next two decades in the same ratios as those found for the period from 2010 to 2020. The ratios for each metric in the poverty-stricken counties from 2010 to 2020 were calculated as follows:

$$V_i = \frac{mean\left(x_{ik}\right)}{mean\left(x_{ij}\right)} \tag{8}$$

where V_i is the variation ratio of metric x_i, $mean(x_{ik})$ is the mean value of metric x_i at the end of the period (2020) and $mean(x_{ij})$ is the mean value of metric x_i at the start of the period (2010).

The metrics for 2030 and 2040 were calculated as follows:

$$Px_{im} = V_i \times x_{il} \tag{9}$$

where Px_{im} is the projected value of metric x_i at the end of period m, V_i is the variation ratio of metric x_i, and x_{il} is the value of metric x_i at the start of period l.

The county-level sustainability and gap indicators were calculated based on the projected metrics using formulas (1), (2), and (7). The upper and lower bounds of the sustainability indicators were set as constants over the next two decades. The mean values of the metrics of non-poverty-stricken counties over the next two decades were also calculated using formulas (8) and (9). The inequality indicators were calculated based on the projected metrics of the poverty-stricken counties and the projected mean values of the non-poverty-stricken counties.

Analysis of the connections between government investment and sustainability. Investments in forest and grassland restoration would simultaneously increase the income of the rural population and improve the ecosystem services related to air purification, water purification, and net primary production. Investment in rural clean energy facilities would simultaneously reduce the energy costs of the rural population and diminish CO_2 emissions and air pollution. Investment in education, health, transportation, and housing security are also necessary for the promotion of sustainability. Thus, we hypothesized that the government should invest more in all of the abovementioned dimensions in an effort to promote sustainability beyond poverty eradication in poorer regions.

Data on government investment, the poverty-stricken population, and GDP at the provincial level were collected from China's statistical yearbooks. Annual investment from 2010 to 2020 in forest and grassland restoration and infrastructure construction related to public services was analyzed, including livelihood projects related to forestry, forestry industry development, ecological construction and protection, rural solar facilities, small rural hydropower facilities, biogas facilities, housing security, public transportation, and education and health care. To test our hypothesis, the annual and cumulative investment in poverty-stricken and non-poverty-stricken counties were compared. Moreover, Pearson correlation analysis was undertaken in relation to the different investments and the proportion of the population living in extreme poverty, the proportion of poverty-stricken counties in a province, and GDP.

Calculation of the investment adjustment required to reduce future gaps. We hypothesized that the shares of government investment in poverty-stricken counties and non-poverty-stricken counties related to improvement in the provision of public services and ecological restoration would affect the level of inequality during the poverty eradication program. Investment scenarios were established to simulate ways to increase investment aimed at reducing and eventually eliminating inequality.

Firstly, the fields in which investment should be increased to reduce inequality were determined based on the projected inequality indicators. The projected negative and declining inequality indicators were treated as the keys to reducing inequality, and thus were selected for the simulation.

Secondly, we assumed that investment in poverty-stricken counties would reach at least the same level as that in non-poverty-stricken counties in an effort to prevent a continuing increase in inequality. In scenario 1, the mean increase in investment in the poverty-stricken counties necessary to prevent an increase in inequality was calculated as follows:

$$\Delta INV_i = INV_{ink} - INV_{ik} \tag{10}$$

where ΔINV_i is the increased investment needed to reduce inequality and INV_{ink} and INV_{ik} are the investments in metric x_i in non-poverty-stricken counties and poverty-stricken counties, respectively, at time k, which is 2020 in this study.

The intricate relationships between investment, sustainability, and inequality can be partially analyzed through linear regression analysis (Chen and Bian, 2023; Selçuklu et al. 2022). We assumed that the relationship between the increase in investment and the metrics related to inequality was linear. In scenario 2, the mean increase in investment in poverty-stricken counties necessary to eliminate inequality during the next decade was simulated as follows:

$$\Delta INV_i = \left\{mean\left(x_{ink}\right) - mean\left(x_{ik}\right)\right\} \times \frac{Annual\ invest\left(x_{icjk}\right)}{mean\left(x_{ick}\right) - mean\left(x_{icj}\right)} \tag{11}$$

where $mean(x_{in})$–$mean(x_i)$ represents the gap between non-poverty-stricken counties and poverty-stricken counties in the mean level of metric x_i at time k. $Annual\ invest(x_{icjk})$ is the average annual national investment in metric x_i at times j and k, which are 2010 and 2020 in this study, and $mean(x_{icj})$ and $mean(x_{ick})$ are the mean national values of metric x_i at times j and k, respectively. All investments were expressed in US$ per capita.

Data sources

Statistical data. The percentage of households living in adobe houses, using purified tap water, and using firewood for cooking, and the percentage of villages with electricity, Internet, highway connections, and public bus services were all obtained from China's statistical yearbooks and rural poverty monitoring reports.

County-level population data were obtained from the National County Statistical Yearbook of China. Data on investment in forest and grassland restoration, construction of green energy facilities, housing security, transportation, education, and health care in poverty-stricken and non-poverty-stricken areas were collected at the provincial level from China's statistical yearbooks.

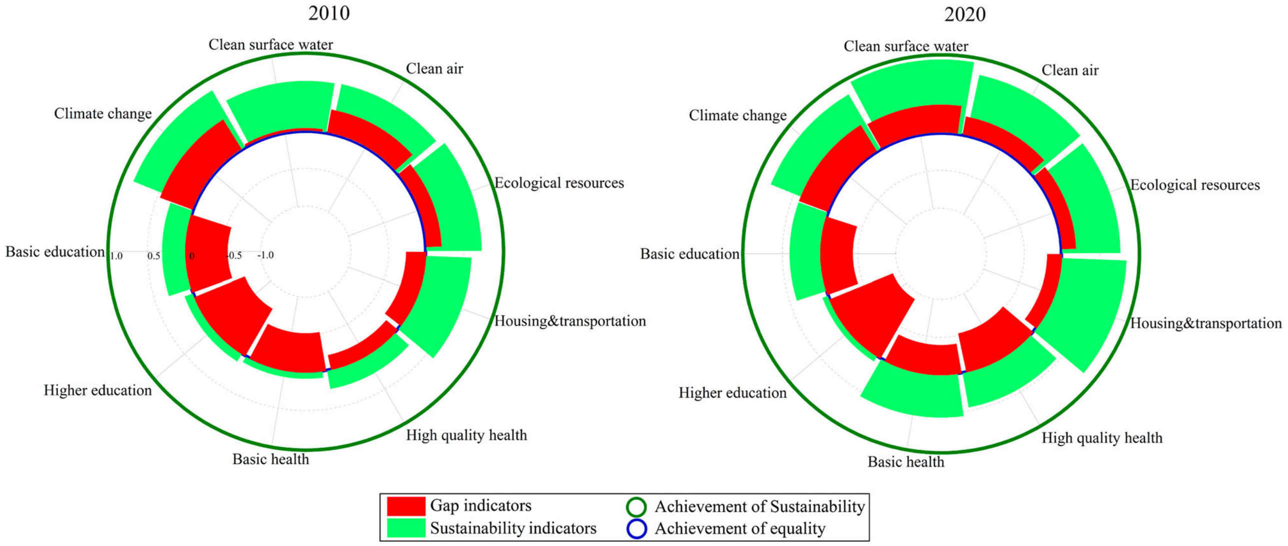

Fig. 1 Average multiple sustainability and gap indicator scores for 2010 and 2020. The sustainability and gap indicator values ranged from 0 to 1, with sustainability indicator values closer to 1 indicating greater sustainability and gap indicator values closer to 0 indicating greater equality. The more positive the gap indicator values, the more advantages the poverty-stricken counties had compared with the non-poverty-stricken counties, while negative gap indicator values indicated that the poverty-stricken counties lagged the non-poverty-stricken counties.

The list of poverty-stricken counties was obtained from the National Rural Revitalization Administration. Detailed information on the data sources, processing methods, and codes can be found in the supplementary files, Figs S3–S6, and Tables S3 and S4.

Point of interest data. The amounts of buildings and facilities for primary education, vocational education, higher education, rural clinics and anti-epidemic stations, drug stores, and general hospitals were calculated from the Points of Interest database obtained from the Resource and Environment Science and Data Center. The original data were points maps showing the name, type, and location of the various facilities and buildings. The amounts of each type of building or facility were summed for all counties using the spatial join function of ArcGIS 10 (ESRI Inc.), and the amounts for each county were divided by the population to obtain the amounts per million persons.

Environment monitoring data. The environmental monitoring data includes the atmospheric particulate matter, CO_2 emissions and amount of ammoniacal nitrogen in surface water.

Data on atmospheric particulate matter were obtained from the Tracking Air Pollution in China database (Geng et al. 2021; Xiao et al., 2021a, 2021b; Xiao et al. 2022). The original data were pixel data (ug/m^3) with a resolution of 1 km over the entire country. The average values for all counties in 2010 and 2020 were calculated using ArcGIS 10 (ESRI Inc.).

County-level CO_2 emissions were obtained from the Carbon Emission Accounts & Datasets (CEADs) database (Chen et al. 2020). The original data were total annual CO_2 emissions at the county level from 1997 to 2017. We selected emissions data for 2010 and 2017 to reflect the variations in CO_2 emissions during the poverty eradication program. We did not obtain data on CO_2 emissions in 2020 because these might have been reduced as a result of the COVID-19 pandemic (Le Quere et al. 2021), and thus might not have accurately reflected the effects of poverty eradication on CO_2 emissions. Total CO_2 emissions in each county were divided by the total population of the county in the corresponding year to calculate CO_2 emissions per capita. The original CEADs database did not include the emissions of Tibet, for which we estimated county-level CO_2 emissions based on the GDP of the county and CO_2 emissions per GDP for each relative year. See the Methods section in the in the supplementary files for detailed information.

Data on the amount of ammoniacal nitrogen in surface water were obtained from weekly reports on water quality in key sections of China's major river basins. The original data included information on the amount of ammoniacal nitrogen in surface water and the geographical coordinates of the monitoring points. There were 100 monitoring points in 2010 and 1992 monitoring points in 2020. The monitoring point data were interpolated into a pixel map with 1 km resolution using the cokriging interpolation method in ArcGIS 10 (ESRI Inc.), and average values were calculated for all counties in 2010 and 2020.

Remote sensing data. Data on net primary production from terrestrial ecosystems were obtained from the Moderate Resolution Imaging Spectroradiometer (MOD17A3). The original data were at pixel level with 500 m resolution, and average values were calculated for all counties in 2010 and 2020.

Results

Multiple increased sustainability and partially increased inequality. During the poverty eradication program from 2010 to 2020, the average sustainability score of the poverty-stricken counties increased from 0.48 to 0.64. However, the ecological and environmental aspects of sustainability scored higher than the public services aspect, which showed a relatively low increase over the decade (see Table 1). Specifically, the ecological and environmental aspects of sustainability improved by 15.2%, from 0.74 to 0.85, while the public services aspect improved by 74.9%, from 0.27 to 0.47 (see Fig. 1). Most sustainability indicators improved in the poverty-stricken counties, although two indicators declined: the indicator for climate change decreased by 4.2%, from 0.892 to 0.855, while that for higher education decreased by 34.2%, from 0.112 to 0.074 (see Fig. 1). The reduction in the climate change sustainability indicators is due to the fact that China has not yet reached a peak in carbon emissions, which have continued to increase during the past decade of economic development and poverty alleviation.

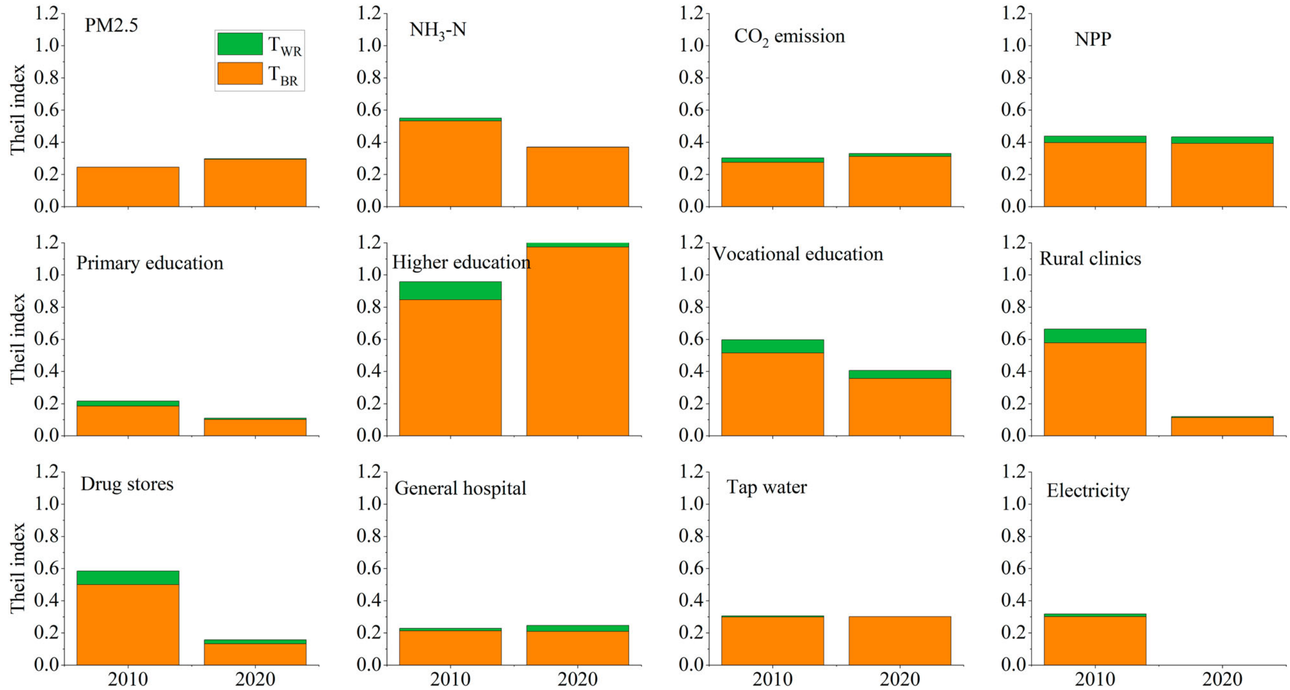

Fig. 2 Variations in inequality during the poverty eradication program. T_{BR} represents the Theil index between-region component, showing the inequality between poverty-stricken and non-poverty-stricken counties, while T_{WR} represents the Theil index within-region component, showing the inequality among counties. The higher the Theil index values, the greater the inequality. $PM_{2.5}$, NH_3-N, CO_2 emissions, NPP, Primary education, Higher education, Vocational education, Rural clinics, Tap water and Electricity represent atmospheric particulate matter, ammoniacal nitrogen in surface water, CO_2 emissions per capita, net primary production from terrestrial ecosystems, primary educational buildings and facilities, higher educational buildings and facilities, vocational educational buildings and facilities, rural clinics and anti-epidemic stations, general hospital buildings and facilities, percentage of households using purified tap water (%), and proportion of villages with electricity (%), respectively (see Table 1).

The variations in the inequality indicators were more complex than those in the sustainability indicators. The mean Theil index value decreased from 0.46 to 0.35 from 2010 to 2020, demonstrating a general reduction in inequality during the poverty eradication program. T_{WR} was 0.51 and 0.40 for poverty-stricken and non-poverty-stricken counties, respectively, in 2010, and 0.38 and 0.31, respectively, in 2020, implying that inequality within poverty-stricken counties was generally greater than that within non-poverty-stricken counties in both 2010 and 2020. T_{BR} was 0.043 and 0.027 in 2010 and 2020, respectively, indicating that inequality between poverty-stricken and non-poverty-stricken areas only accounted for 9.3 and 7.7% of the total inequality among the counties in 2010 and 2020, respectively. T_{WR} and T_{BR} both increased for higher education from 2010 to 2020, indicating that inequality increased both between poverty-stricken and non-poverty-stricken areas and within the counties (see Fig. 2).

In addition to the variations in inequality, the gaps between the poverty-stricken and non-poverty-stricken counties changed in different ways. Generally, during the poverty eradication program from 2010 to 2020, the advantages of poverty-stricken counties over non-poverty-stricken counties in terms of ecological and environmental status increased, with the average inequality indicator scores increasing from 0.28 to 0.32. Meanwhile, the gap between poverty-stricken counties and non-poverty-stricken counties in terms of the provision of public services also increased, with the average inequality indicator scores decreasing from −0.46 to −0.49 (see Fig. 1).

These metrics contributed to the variations in sustainability and inequality in different ways. First, there were gaps between the poverty-stricken counties and the non-poverty-stricken counties in terms of the amounts of both primary and vocational educational buildings and facilities. From 2010 to 2020, the amounts of primary educational buildings and facilities per million persons increased in both poverty-stricken and non-poverty-stricken counties, although the rate of increase was higher in poverty-stricken counties. Meanwhile, the amounts of vocational educational buildings and facilities per million persons decreased in both poverty-stricken and non-poverty-stricken counties, although the rate of decrease was lower in poverty-stricken counties. These changes contributed to an overall decrease in inequality in terms of basic education. The amount of higher educational buildings and facilities per million persons decreased in the poverty-stricken counties, while it more than doubled in the non-poverty-stricken counties, resulting in a decrease in sustainability and an increase in inequality.

The environmental and social costs of poverty eradication. The poverty-stricken counties were categorized into four types based on variations in the sustainability and gap indicators related to ecological and environmental status, and provision of public services (see Fig. 3). The four types represented the relative cost to the counties of poverty eradication.

The sustainability indicators of 753 (90.6%) of the 831 poverty-stricken counties (two poverty-stricken counties were combined into a single county in 2018; for details, see the ‘Data source for the list of poverty-stricken counties’ in the Supplementary Information) increased in terms of both ecological and environmental status and provision of public services, implying sustainable development (see Fig. 3a). These sustainably developing poverty-stricken counties represented 96.5% of the population and 73.2% of the land area of all poverty-stricken counties. Meanwhile, 60 poverty-stricken counties representing 2.7% of the population and 19.7% of the land area of all poverty-stricken counties

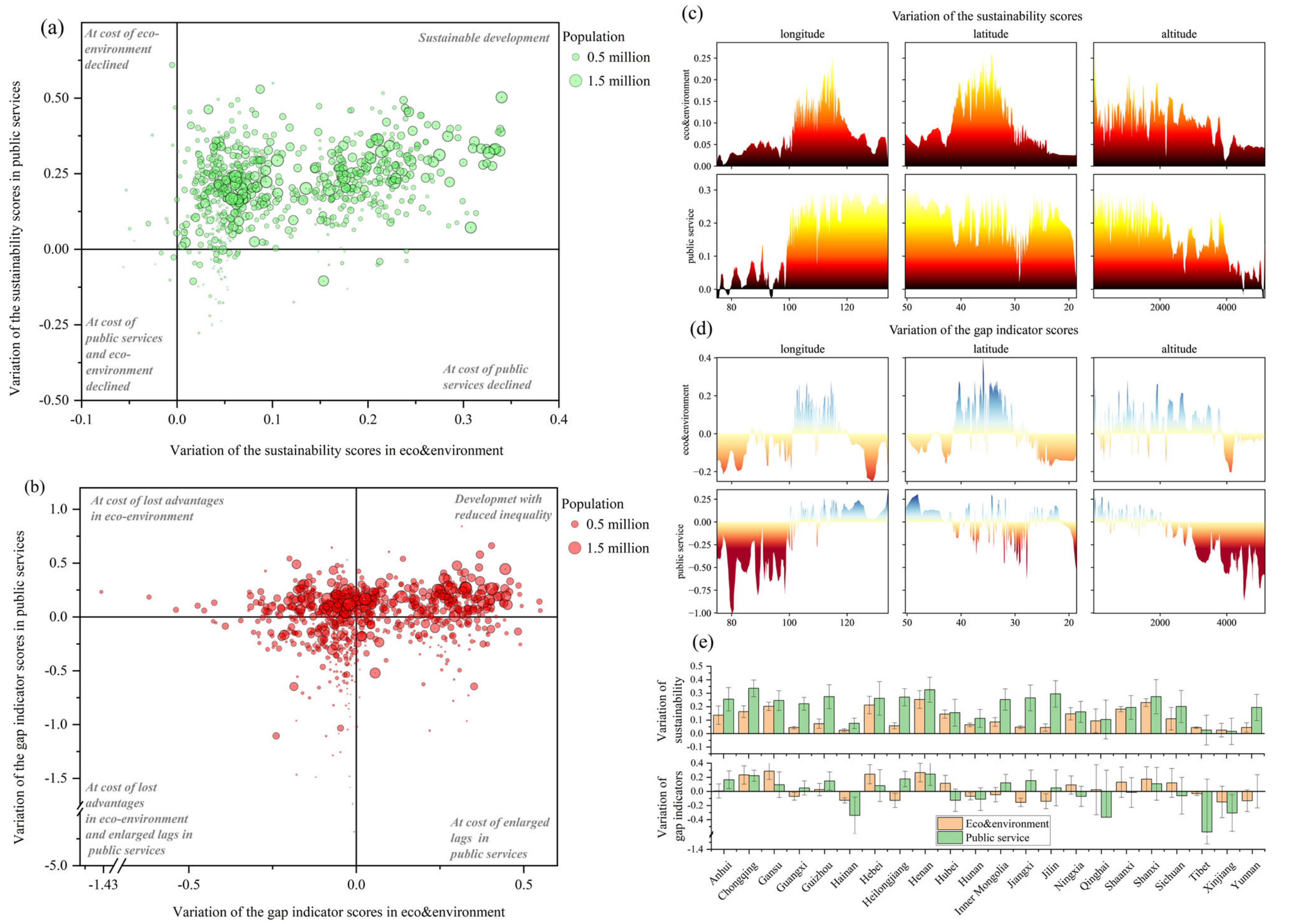

Fig. 3 Environmental and social costs in poverty-stricken counties during the poverty eradication program from 2010 to 2020. The counties' performances in terms of sustainability were divided into four groups based on their sustainability indicator scores related to their ecological and environmental status and provision of public services. Each scatter point represents a poverty-stricken county, with the circle around the point indicating the total population of the county in 2020. The methods used to divide the inequality indicators were the same as those used for the sustainability indicators. Ideally, counties should be located in the top right corner, indicating that they were developing with increased sustainability (see **a**) and reduced inequality (see **b**) during the poverty eradication program from 2010 to 2020. The top left corner means that the poverty-stricken counties were developing with reduced ecological and environmental sustainability (see **a**) and lost their advantage in terms of ecological and environmental status compared with the non-poverty-stricken counties (see **b**). The bottom right corner means that the poverty-stricken counties were developing with reduced sustainability in relation to public services (see **a**) and increased lags in the provision of public services compared with the non-poverty-stricken counties (see **b**). The bottom left corner means that the poverty-stricken counties were developing with reduced sustainability in terms of both ecological and environmental status and the provision of public services (see **a**), and simultaneously lost their advantages in terms of ecological and environmental status and experienced increased lags in the provision of public services compared with the non-poverty-stricken counties (see **b**). The variations of sustainability scores (see **c**) and gap indicators scores (see **d**) along the longitudinal, latitudinal and altitude gradients, and at provincial level (see **e**).

experienced a decrease in sustainability of public services, reflecting a decline in the provision of public services during the poverty eradication program from 2010 to 2020. In addition, 13 poverty-stricken counties experienced a decline in their ecological and environmental status, while five poverty-stricken counties experienced declines in both ecological and environmental status and the provision of public services. The counties that experienced a decline in ecological and environmental status and/or the provision of public services were mainly located in western China (see Fig. 4a).

The number of counties experiencing a reduction in inequality was much smaller than the number of counties experiencing improved sustainability. The gap indicators of 275 (33.1%) of the 831 poverty-stricken counties that experienced an increase in inequality, in terms of both ecological and environmental status and provision of public services, represented 42.8% of the population and 15.2% of the land area of all poverty-stricken counties. These 275 poverty-stricken counties either maintained or enhanced their advantage in terms of ecological and environmental quality, while the lags in the provision of public services were reduced compared with the non-poverty-stricken counties (see Fig. 3b). In addition, 208 poverty-stricken counties representing 30.9% of the population and 21.1% of the land area of all poverty-stricken counties experienced a reduction in their advantage in terms of ecological and environmental status compared with non-poverty-stricken counties from 2010 to 2020, while 121 poverty-stricken counties representing 11.3% of the population and 9.0% of the land area of all poverty-stricken counties experienced an increased lag in the provision of public services, and 227 poverty-stricken counties representing 15% of the population and 54.8% of the land area of all poverty-stricken counties experienced both a reduced advantage in terms of ecological and environmental status compared with non-poverty-stricken counties and an increased lag in the provision of public

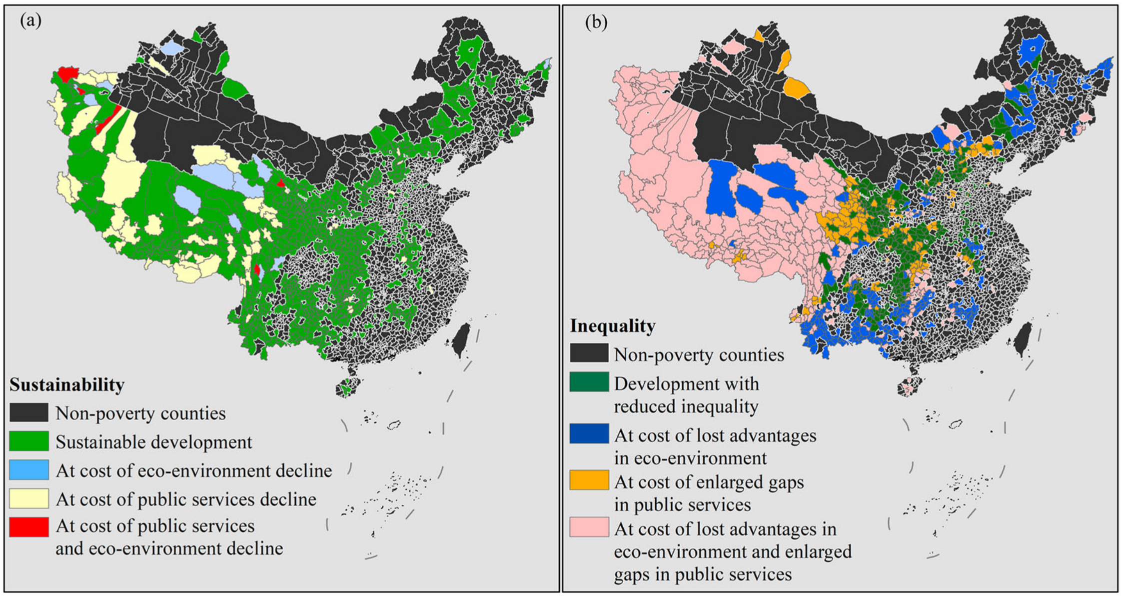

Fig. 4 Spatial patterns of development related to sustainability and inequality in the poverty-stricken counties during the poverty eradication program from 2010 to 2020. Spatial patterns of development related to sustainability (see **a**) and inequality (see **b**). The classification methods used in relation to the results shown in Figure were the same as those used to obtain the results shown in Fig. 3.

services (see Fig. 3b). The counties experiencing increased inequality were mainly located in southwestern China (see Fig. 4b). The results suggest that poverty eradication comes at the cost of diminishing ecological advantages in certain poverty-stricken counties, while the persisting challenges in education and health care remain unaddressed. This is primarily attributed to the comparatively higher levels of improvement in relation to atmospheric and water environment, education, and medical services observed in non-poverty-stricken counties, as indicated by sustainability indicators.

We also examine the influence of geographical factors on sustainability and inequality indicators in poverty-stricken counties. In general, the Tibetan Plateau, characterized by high elevation in southwest China, and Xinjiang in northwest China, have not exhibited comparable advancements in sustainability in terms of both ecological and environmental status and provision of public services as observed in the poverty-stricken counties of eastern and central China. (Fig. 3c). The changes of gap indicator score indicate that the advantages of these regions in terms of ecological and environmental status are weakening, while the gaps in terms of public services are widening (Fig. 3d). The findings are substantiated by the analysis conducted at the provincial level. The poverty-stricken counties in Tibet, Xinjiang, and Qinghai provinces exhibit a comparatively weaker progress in terms of sustainability indicators improving when compared to other provinces; meanwhile, the gaps in public services has witnessed the significant enlargement (Fig. 3e).

Future projections. Our results confirm that there was improved sustainability across multiple dimensions and partially increased inequality during the poverty eradication program from 2010 to 2020. Likely future variations in the sustainability and inequality indicators were analyzed using ‘business-as-usual’ projections.

The sustainability indicators related to clean air, clean surface water, and ecological resources should continue to increase from 2020 to 2040 (see Fig. 5). Meanwhile, the inequality indicators should remain positive, implying constant improvements in the poverty-stricken counties compared with the non-poverty-stricken counties in terms of these indicators. In addition, the sustainability indicators related to basic education, basic health, housing, and transportation should also continue to increase from 2020 to 2040 (see Fig. 5). Meanwhile, the inequality indicators should remain negative, but gradually approach zero, implying that the lags between the poverty-stricken counties and the non-poverty-stricken counties in relation to these indicators will gradually be reduced. The sustainability and inequality indicators related to climate change should slightly decrease, implying a continued increase in CO_2 emissions and a gradual convergence between poverty-stricken and non-poverty-stricken counties in terms of CO_2 emissions per capita.

The sustainability indicator related to high-quality health care should increase, while the inequality indicator should remain negative and continue to decrease. This variation implies a slower rate of improvement in high-quality health care in poverty-stricken counties than in non-poverty-stricken counties, leading to an increased gap between poverty-stricken counties and non-poverty-stricken counties. The sustainability indicator related to higher education should decrease, while the inequality indicator should remain negative and continue to decrease. This variation implies a gradually deteriorating situation in the poverty-stricken counties and an increased gap between poverty-stricken and non-poverty-stricken counties in relation to higher education.

Optimization of government investment. It is worth noting that several aspects of sustainability improved during the poverty eradication program from 2010 to 2020. In addition to providing direct subsidies to people in poverty, the Chinese government invested in forest and grassland restoration, as well as the construction of infrastructure in an effort to improve various aspects of sustainability in the poverty-stricken counties. Pearson correlation analysis demonstrated that government investment in ecological construction and protection, solar energy facilities, small hydropower facilities, biogas facilities, and housing security and transportation were significantly positively correlated with the proportion of the population living in extreme poverty and the proportion of the poverty-stricken counties in the province (see Table 2). Furthermore, a stepwise linear regression was applied and produced similar results (See Table S2).

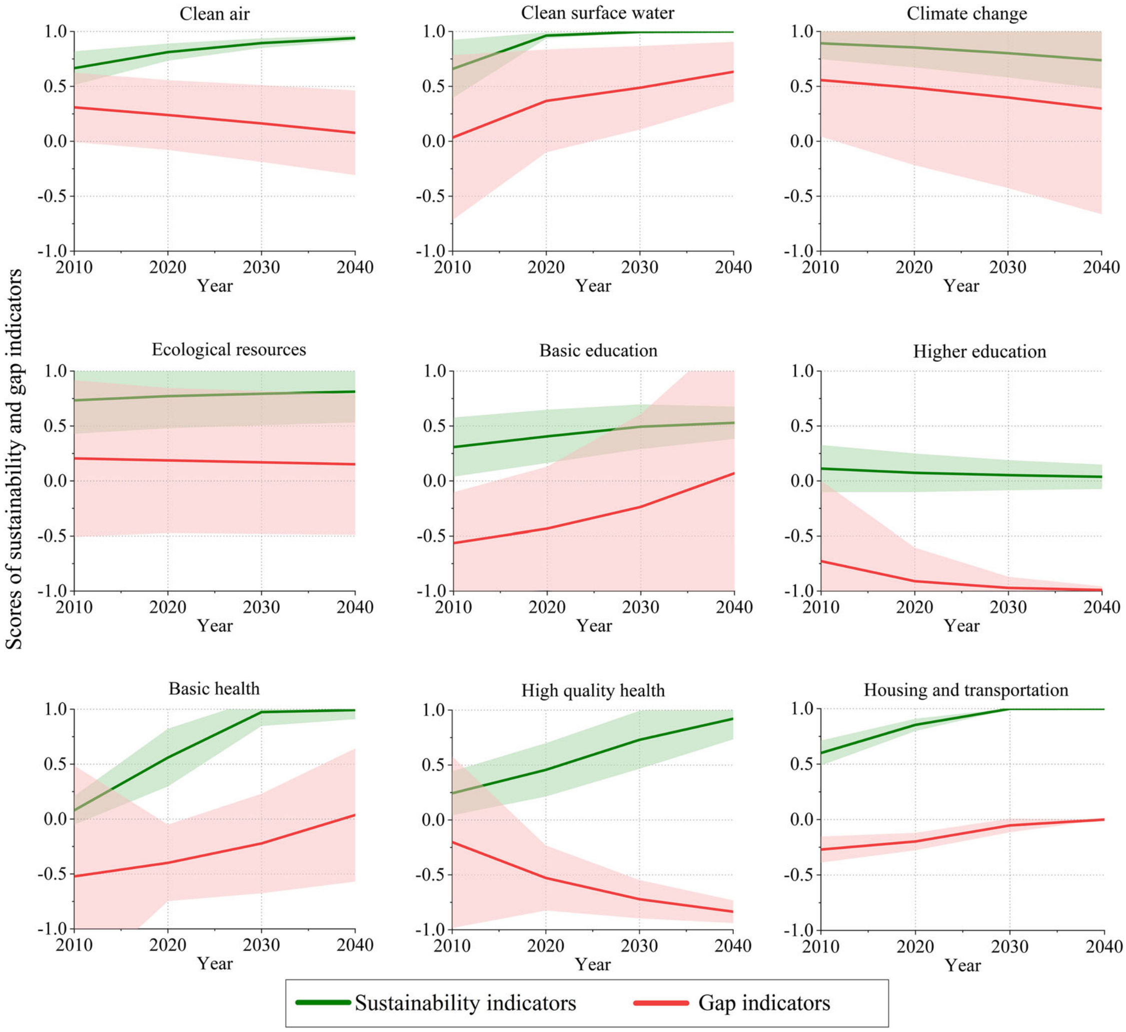

Fig. 5 Historical trends (2010–2020) and projected trends (2020–2040) in the performance of poverty-stricken counties in terms of the sustainability and inequality indicators. The solid lines represent the average values of the indicators, while the shaded areas represent the standard deviations.

Table 2 Correlations between government investment and poverty.

Pearson coefficient		Proportion of the population living in extreme poverty	Proportion of the poverty-stricken counties of the province	GDP
Governmental investment on (US$ per capita)	Solar energy facility	0.318	0.487**	−0.250
	Biogas facility	0.502**	0.379*	−0.529**
	Small rural hydropower	0.787**	0.828**	−0.506**
	Ecological construction and protection	0.287	0.367*	−0.041
	Forestry industry development	0.115	−0.060	−0.200
	Livelihood projects of forestry	0.099	0.126	−0.264
	Educational expenditure	0.079	0.215	0.442*
	Health expenditure	0.187	0.357*	0.293
	Transportation expenditure	0.462**	0.628**	−0.112
	Housing security expenditure	0.456**	0.641**	−0.149

Government investment in various items comprised total investment from 2010 to 2020 at the provincial level; the proportion of the population living in extreme poverty was taken as the average value for the province from 2010 to 2020; the classification of poverty-stricken counties in each province was based on the results presented in Fig. 3; GDP represented the average GDP at the provincial level from 2010 to 2020.
*$P < 0.05$, **$P < 0.01$.

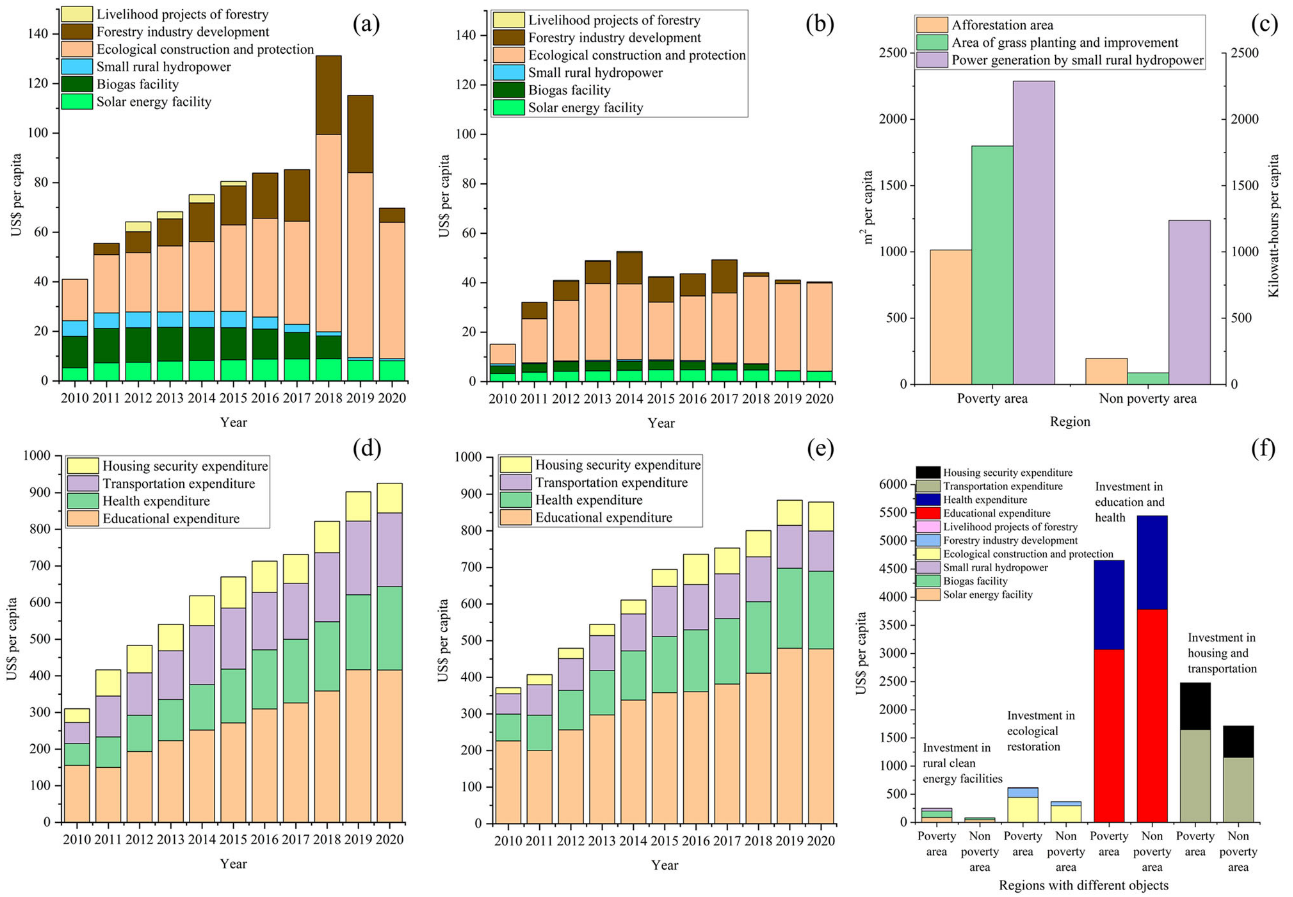

Fig. 6 Government investment aimed at eradicating poverty during the period 2010–2020. **a** mean annual government investment in ecological security and clean energy in poverty-stricken areas; **b** mean annual government investment in ecological security and clean energy in non-poverty-stricken areas; **c** cumulative area of ecological construction and protection and cumulative power generation by small rural hydropower facilities; **d** mean annual government investment in public services and infrastructure in poverty-stricken areas; **e** mean annual government investment in public services and infrastructure in non-poverty-stricken areas; **f** cumulative government investment in various facilities in different regions during the period 2010–2020.

Forest and grassland restoration investment included livelihood projects in relation to forestry, forestry industry development, and ecological construction and protection. Total investment per capita in forest and grassland restoration during the period 2010–2020 was 67.9% higher in the poverty-stricken counties than in the non-poverty-stricken counties (US$88.50 vs US$52.70) (see Fig. 6a, b, f). Investment in rural clean energy facilities included investment in solar energy facilities, small hydropower facilities, and biogas facilities. Total investment per capita in rural clean energy facilities during the period 2010–2020 was more than three times greater in the poverty-stricken counties than in the non-poverty-stricken counties (US$35.80 vs US$11.70) (see Fig. 6a, b, f). The increased investment in forest and grassland restoration, as well as clean energy facilities, resulted in a fivefold increase in the afforestation area, a 20-fold increase in the grass planting and improvement area, and almost double the power generation by small rural hydropower facilities in the poverty-stricken counties compared with the non-poverty-stricken counties during the period 2010–2020 (see Fig. 6c).

It should also be noted that there was some increase in inequality during the poverty eradication program from 2010 to 2020, and this is expected to continue over the next two decades, highlighting the need to optimize government investment. Investment in education was still significantly positively correlated with GDP from 2010 to 2020 (see Table 2). Based on the projected trends, we focused on the increased inequality in higher education and high-quality health care. Linear estimations of the optimal investment needed to prevent increasing inequality were applied to two scenarios. In scenario 1, investment in higher education and high-quality health care facilities such as colleges and general hospitals in the poverty-stricken counties should increase by 23.2 and 5.0%, respectively, during the period 2020–2030. Meanwhile, investment in the non-poverty-stricken counties should not increase. In scenario 2, investment in higher education and high-quality health care facilities should increase by 226.2 and 72.0%, respectively.

Discussion

Synergy of the poverty eradication and SDGs. The results of this study suggest that poverty eradication does not necessarily require a tradeoff with environmental protection (Lu et al. 2019; Li et al. 2021). The sustainability of clean air, clean surface water, and ecological resources all improved during the poverty eradication program from 2010 to 2020 in China's poverty-stricken counties. Meanwhile, sustainability in relation to climate change declined as a result of increased CO_2 emissions. These trends were generally in line with national trends, whereby economic development has resulted in a decrease in major pollutants since 2015, but an increase in CO_2 emissions (Lu et al. 2019). Globally, the eradication of poverty for more than one billion people would only result in an increase in CO_2 emissions of around 2% (Bruckner et al. 2022). However, the risk of a large increase in CO_2 emissions as a result of poverty eradication remains in some Chinese counties (Bruckner et al. 2022). In addition, inequality in relation to CO_2 emissions remains a serious problem, with rich people responsible for significantly more CO_2 emissions than poor people (Bruckner et al. 2022). This inequality might be reduced as economic growth continues, but it continues to be a major global challenge (Mi et al. 2020).

Our results also indicate that tradeoffs among various SDGs can also be avoided to some extent by optimized policies and government investment (Wu et al. 2022; Biermann et al. 2022). Government investment that is planned and implemented through either cross-ministry coordination or central government coordination is the key to avoiding tradeoffs among the SDGs (Xie et al. 2023). In China, various government departments are responsible for different sustainability outcomes (Xie et al. 2023). For example, the recovery of forest and grassland is the responsibility of the Ministry of Natural Resources, reductions in $PM_{2.5}$ are mainly the responsibility of the Ministry of Ecology and Environment, and increasing farmers' incomes is mainly the responsibility of the Ministry of Agriculture and Rural Affairs. Different government departments tend to favor their specific departmental interests. Thus, in an effort to coordinate the various departments, China established a lead poverty alleviation and development group headed by the vice-premier during the poverty eradication program.

Benefits of Poverty Alleviation Policy. The investment in infrastructure, new technologies, and support for rural industries in poverty alleviation policies have a more favorable impact on sustainable development compared to cash subsidies. Investments in ecological restoration projects and green energy facilities are commonly used to avoid poverty traps and alleviate poverty around the world (Olesen et al. 2021; Pan et al. 2022). For example, investment in ecological restoration can boost ecotourism (Gregr et al. 2020; Wang et al. 2019), while investment in grassland recovery and forage plantations can boost livestock husbandry (Pan et al. 2021). In addition, investment in the construction of solar cookers and solar-powered houses in poverty-stricken areas can significantly increase gender equality by reducing female labor intensity related to activities such as collecting firewood, as well as reducing energy costs and emissions of CO_2 and other pollutants (Ding et al. 2014; Liu et al. 2018). The effects of these investments might not be as immediate as those of the cash subsidies paid to people to alleviate poverty, but they boost multidimensional sustainability. In the past decade of poverty alleviation, the government has significantly augmented investments in infrastructure and implemented green energy technologies in poverty-stricken counties. Moreover, the government actively promotes the engagement of impoverished people in rural infrastructure construction projects, thereby offering employment opportunities as a means of poverty relief instead of cash subsidies. These measures have yielded commendable outcomes in terms of poverty alleviation and sustainable development in poverty-stricken counties.

Meanwhile, other technologies are worthy of investment in an effort to promote multidimensional sustainability. The construction of buildings using engineered timber could promote carbon sinks and infrastructure in poverty-stricken areas (Churkina et al. 2020), while the implementation of agrophotovoltaics could reduce CO_2 emissions and simultaneously provide energy and food (Schindele et al. 2020). Implementation of hydrogen production systems using wind and solar energy in poverty-stricken areas could promote economic development without producing additional air pollution and CO_2 emissions (Okunlola et al. 2022).

Achieving equity is challenging. Reducing inequality is part of the framework of the SDGs, and is incorporated in various goals, such as SDG4, 'Ensure inclusive and equitable quality education,' SDG 5, 'Achieve gender equality,' and SDG 10, 'Reduce inequality within and among countries' (UN, 2015). However, more general global inequality exists in terms of access to energy, water, food, and infrastructure, and this has been termed 'great inequality' (Rammelt et al. 2023). Various studies have identified energy inequality among different income groups (Oswald et al. 2020), inequality in relation to air quality among different racial communities (Bluhm et al. 2022), and inequality in relation to flood risks among different ethnic and racial groups (Sanders et al. 2023). Thus, in this study, we introduced various inequality indicators in an effort to reflect the inequality between poverty-stricken and non-poverty-stricken areas across multiple dimensions, including access to clean air and water, a thriving ecosystem, green energy, education, and health care. We also introduce Mean Log Deviation Index, which is more responsive to changes at the bottom tail, as a verification of the Thiel index (Maria Sarabia et al. 2017; Wedrowska and Muszynska, 2022). The results revealed similar variations in inequality as the findings obtained from the Thiel index (Fig. S2).

We did not expect China to achieve absolute equality within a single decade, and the results showed that the poverty-stricken counties, which are mainly located in the western and southern inland areas, were generally weaker in terms of provision of public services, but better in terms of ecological and environmental status than the non-poverty-stricken counties, especially those in the eastern coastal cities (Zhao et al. 2022b; Ouyang et al. 2016; Zhang et al. 2019). Therefore, we argue that the poverty eradication program was reasonably successful in reducing inequality. Specifically, the advantages of poverty-stricken counties in terms of ecological and environmental status were either maintained or slightly reduced, while the lags in the provision of public services were significantly reduced. However, numerous poverty-stricken counties experienced both the loss of their advantage in terms of environmental quality and an increased lag in the provision of public services. This increased inequality was most obvious in relation to higher education and high-quality health care.

Based on our analysis of the structure of government investment, per capita investment in education and health care during the period from 2010 to 2020 were the only areas in which investment in poverty-stricken counties was less than that in non-poverty-stricken counties, which might have caused the increased inequality. If this unbalanced investment continues, the gaps will increase. In addition, the effects of ecological restoration are restricted by the natural environment, for example, the revegetation of the Loess Plateau in China is restricted by the level of precipitation (Feng et al. 2016). Thus, even if investment in ecological restoration continues, its effectiveness might decrease.

China's poverty alleviation policies in the last decade have also strengthened investment in education and medical care in poor areas (FAO, 2011). However, investments in education have primarily focused on compulsory education, while investments in health care have mainly concentrated on basic medical security such as rural clinics. Based on the findings of this paper, the main gaps and sources of inequality lie in higher education and high-quality health care, which require increased future investment. It has been proven that investing in higher education would promote regional economic growth (Qi et al. 2022; Valero and Van Reenen, 2019). Therefore, increasing investment in higher education could be a win-win situation for reducing inequality and promoting subsequent economic development in poor areas. This highlights the need to increase investment in education and health care in the poverty-stricken areas in an effort to reduce national inequality. In addition, cross-ministry coordination or central government coordination is necessary to ensure balanced investment in public services across various local government areas.

Limitation. The results of the 'business-as-usual' scenario projection were utilized as baseline projections for future analysis and should not be conceived as 'prediction' (Lelieveld et al. 2015). These baselines generally illustrate the potential outcomes if no optimal programs or policies were implemented, serving as a reference case against alternative scenarios or a worst-case scenario (Lelieveld et al. 2015; Winkler et al. 2011). Relevant studies often employ 'business-as-usual' scenario projections to demonstrate future air pollution, carbon emissions or variations in sustainable development goals (González-Abraham et al. 2023; Lelieveld et al. 2015; Winkler et al. 2011). In this study, the results of 'business-as-usual' scenario showed the worst case that the gap between poverty-stricken counties and non-poverty-stricken counties on higher education and high-quality health care would be continue enlarged. The results also present a wake-up call for governments to optimize existing policies and investments. Based on the investment optimization simulation, the government should first increase per capita investment in education and health care for poverty-stricken counties to at least match that of non-poverty counties in order to prevent further widening of the gap. Then, the government can gradually increase per capita investment to narrow these gaps. This approach embodies the rationale behind optimizing governmental policies. However, a simulation based on the correlation between investment and inequality indicators might generate more precise results.

We analyzed the variations in sustainability and inequality indicators from 2010 to 2020. These results could reflect the overall effects of China's poverty eradication program on sustainability and inequality. However, conducting annual analyses of the dynamic variations in sustainability and inequality may provide more detailed information and help identify different dynamic impacts. (Wackernagel et al. 2021). In the projection section, the assumption of a linear relationship between government investment and sustainability was made, which may oversimplify the intricate nature of their association given the existence of non-linear relationships (Ari and Koc, 2020).

However, the future prospects regarding sustainability and inequality may not be as dire as the worst-case scenario suggests. In addition to implementing poverty eradication policies, the government has also introduced a range of measures aimed at fostering rural development and enhancing ecological conservation nationwide. The policies include the rural revitalization policy and goals of reaching national peak total CO_2 emissions before 2030 and achieving carbon neutrality before 2060. Following the implementation of poverty eradication policies, the carbon peak and neutrality policies would effectively counteract the upward trend in carbon emissions observed between 2010 and 2020, as indicated by the study (Liu et al. 2022). The air quality is expected to further improve as China's recent carbon reduction policies have been consistently aligned with measures aimed at enhancing air quality. (Qian et al. 2021; Shi et al. 2022). The gaps between poverty-stricken counties and non-poverty-stricken counties in terms of education and health care would also decrease due to the implementation of integrated urban-rural development through the rural revitalization strategy (Liu et al. 2020). The counties were categorized into poverty-stricken and non-poverty-stricken based on the official governmental list. However, even in the non-poverty counties or urban areas, there still exist individuals experiencing poverty(Sun et al. 2022). The variations in their sustainability can be captured through household survey data (Wang et al. 2023).

Conclusion

Assessments based on the integrated data reflected the variations of sustainability and inequality in multiple dimensions. During the poverty eradication program from 2010 to 2020 in China, there was an increase in sustainability in relation to the environment and the provision of public services, accompanied by a reduction in inequality. However, gaps between poverty-stricken and non-poverty-stricken counties were still enlarged, especially in relation to higher education and high-quality health care. The paper also shows that there is a strong correlation between the sectoral and regional bias of government investment and the incidence of inequality. To eliminate these inequalities, governmental investment in poverty-stricken counties should be highly increased relation to education and health care. The 'business-as-usual' scenario projection was limited in reflecting the reality of the next 20 years, but it represents the worst-case scenario. In future research, the inclusion of more comprehensive scenarios assessing the impacts of policies and investments would enhance government decision-making support.

Data availability

All of the data used in this study are publicly available and can be downloaded from the following links: (1) atmospheric particulate matter (http://tapdata.org.cn); (2) county-level CO_2 emissions (https://www.ceads.net); (3) ammonia nitrogen in surface water (http://www.cnemc.cn/sssj/szzdjczb); (4) net primary production from terrestrial ecosystems (https://modis.gsfc.nasa.gov/); (5) points of Interest database for education and health (https://www.resdc.cn/); (6) statistical data (www.stats.gov.cn); (7) list of poverty-stricken counties (https://nrra.gov.cn/; reference number 000019502-2014-00018). Detailed information regarding the data sources and processing methods are available in the supplementary material.

Received: 28 August 2023; Accepted: 5 January 2024;
Published online: 18 January 2024

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Acknowledgements

This work was supported by the National Natural Science Foundation of China (Grant No. 31971560). The authors thank the editor and reviewers for their helpful comments and suggestions on the manuscript.

Author contributions

PY designed the study and planned the analysis. PY, SK, ZZ and LY prepared the basic data. PY and SK did the data analysis. PY wrote the original draft. PY and SK wrote the Supplementary Information. WJ reviewed and edited the manuscript. All authors provided revisions to the manuscript, and approved the final manuscript.

Competing interests

The authors declare no competing interests.

Ethical approval

This paper does not contain any studies with human participants performed by any of the authors.

Informed consent

This paper does not contain any studies with human participants performed by any of the authors.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1057/s41599-024-02631-3.

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