Geo-environmental and socioeconomic determinants of poverty in China: an empirical analysis based on stratified poverty theory

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Received: 21 July 2022 / Accepted: 22 October 2022 / Published online: 4 November 2022
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Abstract
According to the stratified poverty theory, poverty includes individual (people) and regional (place) poverty. Understanding the interaction mechanism between individual poverty and regional poverty is crucial to achieving the UN goal of poverty eradication by 2030. However, at present, the relevant empirical research is still limited by the availability of data. To fill this important gap, based on the multi-source data of poverty census, geo-environmental and socio-economic data of China’s 1587 counties in 2013, we used exploratory spatial data analysis (ESDA) and spatial econometric models (spatial-lag and spatial-error model) to identify determinants of individual poverty and regional poverty in this county. Results show that the spatial distribution of the rural poor in China had strong spatial dependence (Global Moran’s $I = 0.574$). There was a high degree of spatial overlap between individual poverty and regional poverty. The poverty-causing factors were complex and varied across regions and individuals. Disease of family members was the leading factor driving rural areas in Northeast, Central, and Southwest China. Northeast China was mainly affected by the illness and lack of labor skills of family members. The complex terrain conditions were the determinants driving rural poverty in most areas of China. Improved transportation can greatly reduce rural poverty. Geographical isolation or lack of geographical capital caused by complex terrain conditions, backward transportation, and regional closure promoted regional poverty. In turn, regional poverty-causing factors further restricted the improvement of rural residents’ self-development ability and aggravated individual poverty. Our findings indicate that individual poverty and regional poverty have different poverty-causing mechanisms and poverty reduction priorities. Effective poverty reduction strategies require the coordinated promotion of individual and regional poverty reduction. The reduction of individual poverty should focus on enhancing the livelihood capital of the poor through differentiated policy intervention, while regional poverty alleviation should focus on creating a favorable development environment by increasing infrastructure investment and public service supply.

Keywords Poverty-causing factors · Stratified poverty theory · Regional poverty · Individual poverty · Spatial econometric model · China

Introduction
Poverty has always been a worldwide problem (Planta 2007; Liu et al. 2017; Li et al. 2019). Poverty eradication is an ideal that mankind has been pursuing unceasingly for a long time (Zhu and Peng 2022). The history of human development is the history of unremitting struggle against poverty. The 2015 Millennium Development Goals and the 2030 Sustainable Development Goals (SDGs) of the UN have always placed poverty eradication as their primary goal (UN 2015; Wang and Chen 2017). Through joint efforts, the global extremely poverty rate at US$2.15 a day (2017 PPP) decreased from 43.6% in 1981 to 8.4% in 2019, with an average annual decrease of 4.24%, and the number of...
people who live in extremely poverty dropped from 2114.46 million to 648 million (World Bank 2022). However, the sudden coronavirus disease 2019 (COVID-19) pandemic was estimated to push an additional 80 million to 115 million people into extreme poverty by 2020 alone, which has increased the extremely poor people in the world to more than 730 million people (World Bank 2021). The COVID-19 crisis has caused a debate about whether the SDG goals can be achieved on schedule (Naidoo and Fisher 2020; The Lancet Public Health 2020).

To eradicate poverty, understanding where the poor live and why they are poor is essential for the effective allocation of anti-poverty funds and targeted policy interventions (Steele et al. 2017). The poverty census is the most direct and effective way to understand the distribution of poverty (including poor people and poor areas) and the causes of poverty. Furthermore, refined poverty mapping is an important instrument for effective anti-poverty decision-making, because it can identify the spatial distribution of poor people, understand the causes of poverty, and assist in subsequent targeted policy interventions (Bigman et al. 2000; Davis 2003; Elbers et al. 2007; Séguin et al. 2012; Pokhriyal and Jacques 2017; Steele et al. 2017; Zhou and Liu 2022). Census data is the most reliable source of data for poverty mapping, but it has the problems of high cost, long cycle, and low efficiency (Minot and Baulch 2005; Niu et al. 2020). With the advancement of technology, multi-source big data have been used to assist poverty mapping, such as night lights (Jean et al. 2016; Andreano et al. 2021; Xu et al. 2021), remote sensing images (Elvidge et al. 2009), mobile phones (Pokhriyal and Jacques 2017), and livelihood assets (Erenstein et al. 2010). Poverty mapping based on multi-source data has been widely used in anti-poverty practices in regions such as Africa (Jean et al. 2016), Southeast Asia (Erenstein et al. 2010; Olivia et al. 2011; Xu et al. 2021), and Latin American and Caribbean (Andreano et al. 2021). Focus on the spatial scale of this theme has gone from global (Elvidge et al. 2009; Zhou and Liu 2022) to sub-national (Alejandro et al. 2015), county (Liu et al. 2017; Wang and Qi 2021), district (Minot and Baulch 2005; Erenstein et al. 2010), village (Wang et al., 2018), and even household level (Blumenstock et al. 2015). These studies have provided important support for the formulation of global and national anti-poverty policies. The poverty mapping based on the accumulation of census data cannot only identify the spatial aggregation characteristics of poor people, but also reflect the geo-environmental constraints behind regional poverty (Swinton et al. 2003; Dasgupta et al. 2005; Barbier 2010; Rizk and Slimane 2018; Khan 2019; Nabi et al. 2020).

The geo-environment influences the development of human society and economy by influencing production activities and processes (Wang et al. 2018; Ge et al. 2021). The geo-environment can have a significant or even decisive impact on poverty (Xu et al. 2019; Zhou et al. 2020; Ge et al. 2021; Zhou and Liu 2022). The poor are often identified in areas with unfavorable geo-environment, such as remote geographical location (Wang et al. 2020), backward transportation (Benevenuto and Caulfield 2019), fragile ecology (Raleigh 2011; Chen et al. 2021), and frequent disasters (Sawada and Takasaki 2017; Winsemius et al. 2018). Geo-environmental constraints affect livelihood capital, restrict the exchange of production factors inside and outside the region, and thus make people vulnerable to poverty (Bebbington 1999; Liu and Xu 2016; Zhou and Liu 2022). Poverty and environmental degradation are often considered as an interactive process (Duraiappah 1998; Ravnborg 2003; Zhou et al. 2020). Poverty is both the cause and the result of environmental degradation. The poor are often forced to overuse natural resources to survive, and environmental degradation further impoverishes them, which makes it fall into the vicious circle of poverty-environmental degradation-more poverty (Agudelo et al. 2003; Brenner et al. 2010).

China was once a developing country with the most prominent poverty problem in the world (Zhou et al. 2019). The complex geo-environment and the past urban-biased development policy have led to a large number of poor people gathering in rural areas. The constraints of geo-environment caused by complex terrain conditions, unfavorable geographical locations, insufficient natural resource endowments, fragile ecosystem and frequent natural disasters are important factors for the long-term existence of rural poor people gathering in its central and western regions (Liu and Xu 2016; Liu et al. 2017; Zhou et al. 2020). Natural conditions, especially complex terrain are the main determinants of poverty in China (Liu and Xu, 2016; Zhou and Xiong 2018; Zhou et al. 2020). Poverty and eco-environment degradation affect each other, especially in the southwest of the country (Chen et al. 2021; Ge et al. 2021; Liu et al. 2021). Geographic capital affects farmers’ production activities and livelihood capital, thus restricting the increase of income (Jalan and Ravallio 2002). Environmental variables are also considered as important indicators of effective poverty targeting (Olivia et al. 2011). These studies have promoted a deep understanding of the formation mechanism of regional poverty in China. Poverty includes regional poverty and individual poverty, which affect each other (Powell et al. 2001; Zhou and Liu 2022). Due to the limitation of available data, few studies have considered the determinants of regional poverty and individual poverty together. Accurate identification and targeting of anti-poverty objects are the basis for poverty eradication (Baker and Grosh 1994; Bigman et al. 2000). Fortunately, to eradicate poverty, through comprehensive bottom-up and top-down identification, by the end of 2013, China has identified 128,000 poor
villages and more than 80 million rural poor people based on current poverty line standard set by a constant price of CNY 2300 per capita net income in 2010 (Liu et al. 2017; Zhou et al. 2018; SCIO 2021). This is the first large-scale poverty census in China and even human history, realizing the transformation of anti-poverty targets from the previous poor counties or areas to poor villages and poor households (Liao and Fei 2019; Liu et al. 2020). It has played a vital role in China’s subsequent smooth promotion of targeted poverty alleviation policies and the realization of poverty eradication goals by the end of 2020 (SCIO 2021). This large-scale poverty survey provides useful data support for us to further understand China’s regional poverty and individual poverty. Therefore, the goal of this study was to characterize the spatial distribution of the rural poor in China and investigate the formation mechanism of rural impoverishment. To this end, based on available multi-source data of poverty census, geo-environmental and socio-economic data of 1587 counties in China, this study used exploratory spatial data analysis (ESDA) and spatial econometric models (SEMs) to map the spatial distribution of rural poverty in China at the end of 2013 and identify the determinants of rural poverty. Our findings would provide valuable information for the optimization of anti-poverty policies and paths in China and other developing countries in the world to achieve the SDGs.

**Theoretical framework**

According to the target of poverty targeting or poverty reduction, poverty can be divided into individual poverty and regional poverty. The formation mechanism and poverty reduction priorities of the two are different, and scientific poverty reduction needs to be coordinated. This cognition can be raised to the stratified poverty theory (SPT). Individual poverty has a cumulative amplification effect (Zhou and Liu 2022). Regional poverty can be seen as the external manifestation of individual poverty and the result of regional man-nature relationship imbalance (Liu et al. 2017). Regional poverty and individual poverty interact, but their formation mechanisms are different (Fig. 1). Individual poverty is mainly caused by the lack or deprivation of farmers’ livelihood capital or the lack of endogenous development motivation. Its driving forces include the shortage of natural, financial, physical, human and social capital. The shortage of financial capital includes the lack of development funds, low income, or unstable income sources. The shortage of material capital mainly includes poor housing and unsafe sanitation facilities. The lack of human capital is caused by poor health, lack of labor force, low education level and serious education burden. The shortage of social capital is mainly due to social isolation, blocked information transmission, and social security system caused by complex geo-environment. The main poverty-causing factors of regional poverty include insufficient natural resource endowments, complex terrain conditions, unfavorable local conditions (such as remote location and backward transport infrastructure), frequent natural disasters, and fragile ecosystem (Zhou and Liu 2022). Lack of labor leads to limited sources of income, and unhealthy health can affect employment or even unemployment (Oostendorp 2017). Poor living conditions expose family members to unhealthy conditions and increase the risk of various diseases (Kibirige 1997). The high cost of education spending also limits spending on other economic activities, leading to poverty (Zhang 2014). At the same time, high education expenditure can also affect the education level of the next generation, resulting in the intergenerational transmission of poverty (Bird 2013). Social security such as the minimum living security system is an effective way to prevent the elderly from being elected into poverty, especially for the rural elderly who do not have any pension and are in poor health (Engelhardt and Gruber 2004).

**Insufficient natural resource endowments, especially land resources, restricts the residents in the region from engaging in agricultural production activities and hinders the growth of their productive income (Zhou et al. 2019). Remote location and inconvenient transportation restrict the flow of population, capital and information within and between regions, resulting in geographic isolation (Blank 2005). Unfavorable geographic location is closely related to the level of social and economic development in a region and is the root cause of regional poverty and individual poverty in the region (Barbier and Hochard 2019). Conversely, poverty-stricken areas have backward economic development, unreasonable economic structure, backward infrastructure,
low level of education and limited government financial expenditure capacity. Residents in poverty-stricken areas suffer from poor health, lack of employment opportunities, lack of land resources, and insufficient investment in regional infrastructure. Individual poverty is a manifestation of the lack of self-development motivation or development capacity of poor groups. Regional poverty reflects the backward socio-economic level and regional development capacity (Rodríguez-Pose and Hardy 2015). Both individual poverty and regional poverty have multi-dimensional characteristics, and the multi-dimensionality of poverty determines its complexity, indicating that poverty reduction cannot be achieved only by a single traditional intervention method (Zhou and Liu 2022).

The poverty reduction mechanisms of individual poverty and regional poverty are different (Zhou and Liu 2022). Alleviating or eliminating individual poverty focuses on improving the livelihood capital of farmers and enhancing their endogenous development motivation through the intervention of targeted and differentiated policies or measures, involving housing, family education, drinking water, and health (Zhou et al. 2020). Alleviating or eliminating regional poverty focuses on creating a favorable development environment through transportation infrastructure and public service investment, government investment promotion, preferential policy support, etc., so as to enhance the regional sustainable development capacity and promote social and economic development (Zhou et al. 2021). It is necessary to take unconventional measures, such as relocation, for specific areas that cannot be intervened by conventional anti-poverty policies or measures (Zhou et al. 2019). Effective anti-poverty strategies require coordinated promotion of regional poverty and individual poverty reduction.

Data and methods

Data

The data used in this study include poverty census, geo-environmental and socio-economic data. The 1587 counties in central and western China were included, which involves 20.24 million poor households (63.56 million population) in 2013 (Fig. 2). To explore the determinants of rural poverty at different economic level and natural conditions, we divided China into eastern, central, western and northeastern, and southern and northern regions (NBS 2020). The poverty-related data included information on the number of poor people, the incidence of poverty, and the main causes of poverty among the poor, which came from county-level statistical bulletins from 1587 counties in China in 2014. The poor population was identified by local government departments according to the unified poverty line standard of the country. These people were identified as poor people, whose per-capita annual income was less than 2300 yuan (at 2010 constant price), or they were worried about food...
and clothing, or their housing security, medical security, and education security were not guaranteed. In particular, since the poverty population identified in the poverty census at the end of 2013 was mainly distributed in 22 provinces of the country, the subsequent anti-poverty policies were mainly aimed at these regions, and the eastern region only included Hebei and Hainan provinces with poor people.

Geo-environmental data include digital elevation model (DEM), land use, climatic conditions, which are provided by the Resource and Environment Science and Data Center (RESDC) of Chinese Academy of Sciences (CAS). Socio-economic data included total population, saving deposits, fixed-asset investments, and gross domestic product (GDP), which were collected from the China County Statistical Yearbook and provincial statistical yearbooks. These data were available from the big data research platform of China’s economic and social data (https://data.cnki.net/).

**Methods**

**Exploratory spatial data analysis**

Everything is interdependent or interrelated in space (Tobler 1970). The problem of poverty is also spatially dependent. Exploratory spatial data analysis (ESDA) is an important instrument for spatial analysis. Global spatial autocorrelation can measure the overall spatial correlation and spatial difference between regions. The Global Moran’s $I$ index is a measure of global spatial autocorrelation, which has been extensively used to identify whether there is a linear association of a variable with itself in space (Sunderlin et al. 2008). The calculation formula of Global Moran’s $I$ index is as follows:

$$
\text{Global Moran’s } I = \frac{\sum_{i}^{n} \sum_{j=1}^{n} w_{ij} (x_i - \bar{x})(x_j - \bar{x})}{S^2 \sum_{i}^{n} \sum_{j \neq i}^{n} w_{ij}}
$$

where $x_i$ and $x_j$ are the values of the variable $x$ (such as poor population scale or poverty incidence) for county-$i$ and the neighboring county-$j$, respectively; $\bar{x}$ and $S^2$ represent the average and variance of $x$ that indices over all observations (districts) $n$, respectively. The spatial weight matrix $w_{ij}$ that we used to reflect spatial proximity can be defined as a first-order queen contiguity matrix, where $w_{ij} = 1$ if two observations, i.e., $i$ and $j$, share a common border; otherwise, $w_{ij} = 0$. Global Moran’s $I$ ranges between $-1$ and $+1$. A positive value denotes that clusters are groups with similar values (either high or low), while a negative one indicates spatial agglomeration of dissimilar values (for example, locations with low values are enclosed by neighbors with high values). Particularly, a spatial pattern of randomness leads to a Moran’s $I$ close to 0.

Local indicators of spatial association (LISA), as one of ESDA, were also used to identify the counties where there were local patterns of spatial association for rural poverty (Anselin 1995; Ruiz et al. 2013). Local Moran’s $I$ can be measured as follows:

$$
\text{Local Moran’s } I = \frac{(x_i - \bar{x})}{S^2} \sum_{j=1}^{n} w_{ij}(x_j - \bar{x})
$$

where the definition of each variable is the same as that of global Moran’s $I$. Applied to this context, a LISA cluster map was drawn to present significant spatial clusters and outliers based on local Moran’s $I$ statistic of different thresholds of Pseudo-$p$ values. Four types of cluster were mapped: High-High, locations with high values surrounded by neighbors with high values; Low-Low, locations with low values surrounded by neighbors with low values; High-Low, locations with high values surrounded by neighbors with low values; Low-High, locations with low values surrounded by neighbors with high values. Again, the high and low values are defined with respect to the mean of their neighbors.

**Spatial econometric models**

We used the ordinary least-squares (OLS) regression model and spatial autoregressive (SAR) model to identify the determinants of poverty (Okwi et al. 2007). The OLS model can be expressed as follows:

$$
y_i = \beta_0 + \beta_1 x_i + \epsilon_i \tag{1}
$$

where $y_i$ is a vector of the dependent variable (poverty incidence); $x_i$ is a matrix of independent variables (causes for poverty of farmers, and geo-environmental and socio-economic factors in a county); $\beta_0$, $\beta_1$ is a vector of constants; $\beta_i$ is a vector of coefficients, and $\epsilon_i$ is a vector of random errors.

The estimated variable statistics are shown in Table 1.

Without considering spatial autocorrelation, OLS regression model has been restricted in analyzing spatial association. Omitting this association is likely to result in assumptions being biased. As a position-based statistical regression approach, SAR model can not only address spatial dependence inherent but also reduce spatial error in geographic phenomena through including a supplementary explanatory variable (Anselin 2016; Gao et al. 2020). In the case of spatial dependence, the dependent variable $Y$ at a given location may be affected by dependent variables in neighboring regions. Such a phenomenon can be detected by using spatial-lag model (SLM). The SLM model can be expressed as follows:

$$
Y = \beta_0 + \beta X + \rho WY + \epsilon, \epsilon \sim (0, \delta^2 I_n) \tag{2}
$$
where $Y$ is the dependent variable; $X$ is a matrix of selected independent variables; $\beta_0$ denotes a constant; $\beta$ denotes the matrix of coefficients; $W$ is the spatial weight matrix, which is determined by inverse distance weight matrix. $\rho$ is the coefficient of spatial lag $W Y$; $\epsilon$ represents the spatially independent error, and $\sigma^2$ represents the variance of $\epsilon$; $I_n$ denotes Moran’s $I$ because the clustering of the residuals is examined by using the Moran’s $I$ statistic.

Spatial-error model (SEM), as one of SAR models, is used to deal with the spatial dependence caused by ignoring variables or measuring errors through error terms (Okwi et al. 2007). The SEM can be expressed as follows:

$$Y = \beta_0 + \beta X + \mu, \mu = (\epsilon - \lambda W)^{-1} \epsilon \tag{3}$$

where $Y$, $X$, $\beta_0$, $\beta$, $W$ are the same definitions as those of SLM. $\mu$ is the spatially dependent error, and $\epsilon$ is the spatially independent error. $\epsilon$ denotes a unit vector, and $\lambda$ denotes the coefficient of spatial error. Usually, a Lagrange multiplier test can be used to choose the appropriate model in practice by conducting statistical significance of the coefficients. When spatial autocorrelation exists, the significant result of the test appears. The higher Lagrange multiplier test value, the better the model performed.

Table 1 shows the statistical results of the variables. Among all the 1587 sample counties, in 2013, the average poverty incidence was 14.0%, with a standard deviation of 11.0%. The maximum and minimum values were 0.1% in Dongsheng District of Inner Mongolia, and 89.5% in Golmud city of Qinghai, respectively, indicating striking regional variations. The topography of these counties was complex, with an average elevation of 1130 m. The average proportion of the area with slopes above 25° within the county was 9.7%, with a maximum value of 75.10%. The per capita arable land area of poor households was less than 0.01 ha. The road density in the study area was 0.38 km/km², lower than the national average of 0.46 km/km² in the same period. The average of per capita deposit was CNY 13,618, with the standard deviation being CNY 10,022. Compared with deposit, the average per capita
investment and per capita GDP for the sample counties were relatively higher, with a mean value of CNY 13,618 and CNY 21,047, respectively.

Results

Spatial distribution of rural poverty in China

At the end of 2013, China launched a nationwide large-scale rural poverty census and identified 128,000 poor villages, 29.48 million poor households, and 89.62 million poor people through bottom-up poverty targeting. Figure 3 shows the geographic distribution of the rural poor and poverty incidence in China at the county level. The results show that by the end of 2013, the rural poor in China were mainly distributed in the remote mountainous areas at the junction of the central and western regions (Fig. 3a). Global Moran’s I value of the poor was 0.574 (Z = 34.232, P < 0.01), indicating the distribution of the poor had a high spatial autocorrelation. Further local autocorrelation analysis identified 6 spatial clusters of rural poor population distribution, namely, Liupan Mountains (A), Qinba Mountains (B), Wuling Mountains (E), Wumeng Mountains (D), Dabie Mountains (C) and the rocky desertification areas of Yunnan, Guangxi and Guizhou provinces (F) (Fig. 3b). This result means the existence of spatial poverty trap.

Poverty incidence is an important indicator that is often used to measure the degree or level of poverty. Here, a significant positive global Moran’s I for poverty incidence was detected (Moran’s I = 0.593; Z = 36.310, P < 0.01). LISA

Fig. 3 Spatial distribution of rural poverty in China in 2013. Three shades of colors from shallow to deep represent significance at 95%, 99%, and 99.9%, respectively, in b and d. In b, A, B, C, D, E, F are respectively Liupan Mountains (A), Qinba Mountains (B), Dabie Mountains (C), Wuming Mountains (D), Wuling Mountains (E), and the rocky destruction areas of Yunnan, Guangxi and Guizhou (F). In d, G, H and I represents Loess Plateau (H), Qinghai-Tibet Plateau (G), Yunnan-Guizhou Plateau, respectively.
map of poverty incidence also further demonstrates that the distribution of the rural poor in China had obvious spatial heterogeneity. Agglomeration areas with high incidence of poverty were mainly located in the Loess Plateau (H), Qinghai-Tibet Plateau (G), Yunnan-Guizhou Plateau (I), and southwestern Xinjiang (Fig. 3c). The Northeast Plain, the North China Plain, and the middle and lower reaches of the Yangtze River were the main clusters of low poverty incidence in China (Fig. 3d).

Poverty-causing factors

The poverty census can not only identify where the poor population is located, but also understand their causes of poverty, laying a solid foundation for the subsequent adoption of differentiated assistance measures and dynamic management of the poor population due to poverty reasons. The causes of poverty among the poor households in rural China were complex and diverse, with obvious regional differences (Fig. 4). Most of the poor households had multiple poverty-causing factors. Illness and lack of funds, labor and technology were identified as the main reasons for poverty among Chinese rural residents. At the end of 2013, among the more than 23 million poor households in China, 42.52%, 36.06%, 26.31%, 25.60%, 11.81%, 10.58%, 7.37%, 4.13%, 3.5%, and 4.9% were poor farmers due to disease, lack of funds, lack of land, lack of technology, physical disability, insufficient endogenous power development, children’s schooling, natural disasters, and backward transportation, respectively. The causes of regional poverty also show obvious spatial differentiation characteristics. For example, poverty of more than 70% of rural households in Northeast China was caused by diseases. The poverty of 55.43% of farmers in the eastern and 48.65% of the farmers in the central region was also caused by the illness of family members. The problem of poverty in the western region due to lack of funds and lack of technology was prominent.

Spatially, people who are poor due to diseases were mainly distributed in Heilongjiang, Jilin, Hebei, Anhui, Jiangxi, Henan, and Sichuan provinces. In most counties in these provinces, people who were poor due to illness accounted for more than 45% of their poor population (Fig. 5a). In most areas of western and southwestern China, the proportion of people impoverished by illness was relatively small. The reason for the poor health of the poor in northeast and central China may be related to the higher degree of aging among the poor in these areas. Poverty due to family members with disabilities was also one of the main causes of poverty in rural China. Such poor families were mainly distributed in Jiangxi and Anhui provinces (Fig. 5b). The heavy burden of education was also one of the main reasons for the poverty of rural residents in China. The proportion of rural residents being poor due to education in some counties in Guangxi, Guizhou, Hunan and Hubei provinces was also relatively high (Fig. 5c).

Lack of labor, funds and technology were the common causes of poverty among rural residents in China. The poverty of rural residents in most counties in Guangxi, Guizhou, Hunan, Gansu, Sichuan, Shaanxi and Shanxi provinces was mainly due to lack of funds. Especially in some counties such as central Qinghai, western Sichuan and central Tibet, the poverty of more than 60% of rural residents was mainly due to lack of funds (Fig. 5d). The main reason for the poverty of rural residents in Yunnan-Guizhou Plateau and Qinghai-Tibet Plateau was due to labor shortage (Fig. 5e). Lack of labor was responsible for poverty among rural residents in the Yunnan-Guizhou Plateau, Qinghai-Tibet Plateau, Loess Plateau, and Xinjiang, where more than 40% of the rural

Fig. 4 Causes of poverty among poor households in China and its eastern, central, western, and northeastern regions in 2013. The total number of poverty-stricken households was 23.7 million, and the poverty of rural households can have multiple causes.
poor groups attributed their poverty to lack of labor (Fig. 5f). It is worth noting that the poverty of rural residents in China’s Yunnan-Guizhou Plateau, Loess Plateau and Qinghai-Tibet Plateau was driven by multiple factors such as lack of land, lack of funds, lack of labor, and illnesses of family members. The main reason for the poverty of rural residents in Northeast China, North China and the middle and lower reaches of the Yangtze River was due to illness.

**Geo-environmental and socio-economic determinants for poverty**

Table 2 provides the estimated results for regional poverty at the national level (using spatial-lag model) based on the diagnostics for spatial dependence. Three spatial regression models were undertaken using the county-level poverty incidence as the dependent variable and 15 explanatory indicators as independent variables for poverty estimation. As the parameters of diagnostic tests were all statistically significant ($p = 0.00$), SAR model was considered more efficient by ruling out the nuisance caused by spatial autocorrelation presented by comparison with OLS regression model. Since robust Lagrange Multiplier (lag) exhibited a stronger level of significance than robust LM (error), the spatial lag model was suitable for national-level estimation.

Estimated results for the whole China indicate that among the selected explanatory variables, 8 of the 15 variables were statistically significant at a significance level of 0.05 and above. Poverty incidence was statistically significantly and positively correlated with terrain complexity but negatively correlated with per capita arable land area, road density and economic development level (Table 3). The proportion of areas with slopes above 25° in the county had a stronger impact on the incidence of poverty, showing that for every 1% increase in the proportion of the area above 25°, the incidence of poverty would increase by 0.13%. For every increase of 0.067 ha of arable land per capita, the incidence of poverty would drop by 0.41%. Keeping other variables constant, every 1 km/km² increase in road density would reduce the incidence of poverty by 6.08%. Interestingly, per capita GDP had a significant negative impact on poverty incidence, but its impact was relatively small. Although fixed asset investment had a negative impact on the incidence of poverty, the impact was also statistically insignificant. The heavy burden of education, insufficient funds, and lack of labor skills were identified as the main factors that exacerbated rural poverty. Strangely, we found that the disability of family members helps to reduce poverty level. This may be

| Table 2 | Diagnostics for spatial dependence |
|---------|----------------------------------|
| Test methods          | Value  | Probability |
| Lagrange multiplier (lag) | 870.176 | 0.000      |
| Robust LM (lag)         | 763.930 | 0.000      |
| Lagrange multiplier (error) | 171.421 | 0.000      |
| Robust LM (error)       | 65.175 | 0.000      |

Fig. 5 The main cause of poverty among rural residents in China in 2013
related to China’s relatively perfect social security system for disabled families, which can obtain more transfer income.

Table 4 provides the estimated results of the leading factors of rural poverty in China’s six regions. Results show that the impact of farmers’ livelihood capital on rural poverty in China showed obvious regional differences. There was a statistically significant and positively correlation relationship between the disease of family members and the rural poverty level in the central, western, northeast, and southern regions. Heavy education burden had a significant positive impact on the poverty level in the central, western, and northern regions, but its impact on the eastern and northeastern regions was insignificant ($p = 0.1$). Insufficient development funds significantly promoted the impoverishment of the western, northern, and southern regions, and the impact was most obvious in the western region. The rural poverty in the western and northeastern regions had also been significantly affected by the lack of labor skills.

The geo-environmental and socioeconomic determinants of rural poverty in China varied across regions. Altitude had a significant positive impact on the incidence of poverty in the eastern, central, northeastern, northern and southern regions, while the impact on the western region was not statistically significant. The proportion of area with gradient

| Variable          | Coefficient | Std. Error | Z-value | Probability |
|-------------------|-------------|------------|---------|-------------|
| Sickness          | -3.82×10^-4 | 2.41×10^-4 | -1.58   | 0.114       |
| Disability        | -1.12×10^-3 | 4.15×10^-4 | -2.70   | 0.007       |
| Education         | 1.98×10^-3  | 4.08×10^-4 | 4.85    | 0.000       |
| Capital shortage  | 1.83×10^-3  | 2.57×10^-4 | 7.13    | 0.000       |
| Labor shortage    | 1.93×10^-4  | 3.69×10^-4 | 0.52    | 0.601       |
| Skills shortage   | 1.54×10^-3  | 3.05×10^-4 | 5.05    | 0.000       |
| Cropland          | -4.06×10^-3 | 1.26×10^-3 | -3.22   | 0.001       |
| Elevation         | 2.73×10^-6  | 3.67×10^-6 | 0.74    | 0.457       |
| Slope25           | 1.30×10^-3  | 2.08×10^-4 | 6.26    | 0.000       |
| Precipitation     | -8.07×10^-6 | 8.15×10^-6 | -0.99   | 0.322       |
| Temperature       | -8.77×10^-4 | 8.31×10^-4 | -1.06   | 0.291       |
| Road density      | -6.08×10^-2 | 9.67×10^-3 | -6.29   | 0.000       |
| Deposit           | 4.47×10^-7  | 2.76×10^-7 | 1.62    | 0.106       |
| Investment        | -1.87×10^-7 | 1.36×10^-7 | -1.37   | 0.171       |
| GDP               | -5.59×10^-7 | 1.44×10^-7 | -3.87   | 0.000       |
| Constant          | 1.37×10^-1  | 2.38×10^-2 | 5.79    | 0.000       |

The dependent variable is the incidence of poverty. The shaded part in the first seven lines represents the poverty causing factors at the household level, and the unshaded part in the back represents the poverty causing factors at the regional level. Sickness indicates the proportion of poverty due to illness of family members; disability indicates the proportion of poverty caused by disability of family members; education means the proportion of children who become poor due to heavy school burden; capital shortage indicates the proportion of poverty caused by insufficient development funds; labor shortage indicates the proportion of poverty caused by lack of labor force; skills shortage indicates the proportion of poverty caused by lack of labor skills; cropland is the per capita cropland area of the poor in a county. Road density represents the road density of a county. Elevation and slope25 represent the average elevation and the proportion of area with a slope greater than 25° in a county, respectively. Precipitation and temperature are the annual average temperature and precipitation in a county during the period 1983–2013, respectively. Deposit, investment, and GDP represent the per capita household savings deposit, per capita fixed-asset investment, and per capita GDP in a county during the period 2009–2013, respectively.
greater than 25° had a significant positive impact on the poverty level in the central, western and southern regions, but the impact on the eastern and northeastern regions was statistically insignificant. Interestingly, we also found that the per capita arable land area had a significant and statistically positive impact on the incidence of poverty in central China. This may be since the central region was the main grain-producing area in China, and ensuring food security was still the priority task of the regional government, and farmers’ income from agriculture had been slow to increase. Precipitation had a negative impact on the incidence of poverty in the southern region, and temperature also exerted a negative and statistically significant impact on the western and southern regions. Furthermore, the improvement of infrastructure can help alleviate poverty. The increase in road density had a significant negative impact on the incidence of poverty in the central, western, and northern regions, but its impact in eastern and northeastern regions was statistically insignificant. This indicates that the traffic in the Northeast Plain and the eastern region had little effect on farmers’ income increase. As expected, economic growth helped alleviate rural poverty. Economic growth was significant and negatively correlated with poverty incidence in the central and northeastern regions, and southern and northern regions. The effect of fixed asset investment on poverty level in eastern and western regions was also significant and statistically negative.

**Discussion**

The causes of poverty were complex and diverse and varied across regions and individuals. The distribution of the poor has unique geographic characteristics. Statistics from the World Bank (2015) show that in 2015, 85% of the world’s poor people were concentrated in South Asia and sub-Saharan Africa, with obvious spatial clustering characteristics. Like the world, the distribution of the poor in rural China also has significant regional characteristics. Through China’s continuous efforts in poverty reduction since 1978, China’s rural poor people have gradually gathered in remote mountainous areas in the central and western regions and have

| Variable          | Eastern | Northeastern | Central | Western | Northern | Southern |
|-------------------|---------|--------------|---------|---------|----------|----------|
| Sickness          | -0.0019 | 0.0002***    | 0.0014*** | 0.0001*** | 0.0003   | 0.0019*** |
| Disability        | -0.0022* | -0.0024**    | -0.0023*** | -0.0016* | -0.0024*** | -0.0018*** |
| Education         | 0.0011  | 0.0020       | 0.0058*** | 0.0018*** | 0.0065*** | -0.0004  |
| Capital shortage  | -0.0007 | 0.0001       | -0.0011  | 0.0026*** | 0.0014*** | 0.0011*** |
| Labor shortage    | -0.0013 | -0.0000      | -0.0017  | 0.0004   | 0.0020*** | -0.0007  |
| Cropland shortage | -0.0099 | 0.0025       | 0.0104*** | -0.0058***| -0.0181  | 0.0014   |
| Skills shortage   | -0.0002 | 0.0136***    | -0.0008  | 0.0028*** | 0.0017*** | -0.0002  |
| Elevation         | 0.0002*** | 0.0001***    | 0.0001*** | -0.0000  | 0.0000*** | 0.0000*** |
| Slope25           | -0.0014 | -0.0028      | 0.0026*** | 0.0011*** | 0.0016*** | 0.0017*** |
| Precipitation     | -0.0001 | -0.0001      | -0.0000  | 0.0000   | 0.0000   | -0.0000** |
| Temperature       | 0.0030  | 0.0058*      | 0.0000   | -0.0021* | 0.0012   | -0.0076***|
| Road density      | -0.0337 | -0.0257      | -0.0487***| -0.0471***| -0.0565***| -0.0192  |
| Deposit           | 0.0000  | 0.0000       | -0.0000  | -0.0000  | 0.0000*** | -0.0000* |
| Investment        | -0.0000* | 0.0000       | 0.0000   | -0.0000**| -0.0000  | 0.0000   |
| GDP               | -0.0000 | -0.0000*     | -0.0000***| -0.0000  | -0.0000***| -0.0000***|
| Observations      | 126     | 104          | 485      | 872      | 838      | 749      |
| R²                | 0.7179  | 0.4921       | 0.6010   | 0.3469   | 0.4803   | 0.5408   |

The dependent variable is the incidence of poverty. The shaded part in the first seven lines represents the poverty-causing factors at the household level, and the unshaded part in the back represents the poverty-causing factors at the regional level. Sickness indicates the proportion of poverty due to illness of family members; disability indicates the proportion of poverty caused by disability of family members; education means the proportion of children who become poor due to heavy school burden; capital shortage indicates the proportion of poverty caused by insufficient development funds; labor shortage indicates the proportion of poverty caused by lack of labor force; skills shortage indicates the proportion of poverty caused by lack of labor skills; cropland is the per capita cropland area of the poor in a county. Road density represents the road density of a county. Elevation and slope25 represent the average elevation and the proportion of area with a slope greater than 25° in a county, respectively. Precipitation and temperature are the annual average temperature and precipitation in a county during the period 1983–2013, respectively. Deposit, investment, and GDP represent the per capita household savings deposit, per capita fixed-asset investment, and per capita GDP in a county during the period 2009–2013, respectively.

***statistical significance at the 1% level; **statistical significance at the 5% level; *statistical significance at the 10% level
been geographically isolated to form isolated islands (Liu et al. 2017). Our results also indicate that by the end of 2013, China’s rural poor mainly lived in mountainous areas such as Liupan, Qinba, Wumeng, Dabie, Wuling and Taihang, and Yunnan-Guangxi-Guizhou rocky desertification areas, accounting for 55% of the country’s rural poor. According to the stratified poverty theory, poverty includes individual poverty and regional poverty. Individual poverty was more caused by the shortage of farmers’ livelihood capital, which is mainly manifested in the shortage or deprivation of natural, physical, social and financial capital. Due to illness, disability, disaster, education, and the lack of funds, technology and labor were the external manifestations of the lack of livelihood capital of poor farmers (Liu et al. 2017; Deng et al. 2020). Regional poverty is driven by the interaction of insufficient natural resource endowments, unfavorable location conditions, historical background, backward transportation conditions, and low levels of socio-economic development (Zhou and Liu 2022; Zhou et al. 2020). Complex terrain conditions were identified as an important determinant of regional poverty in China, which is consistent with previous studies (Bird and Shepherd 2003; Zhou and Xiong 2018; Zhou et al. 2020). Furthermore, restricted by factors such as geographical conditions, historical background, transportation, and economic development level, rural poverty in parts of southwestern China had lasted for thousands of years. For areas where conventional anti-poverty measures are not effective, China implemented large-scale relocations from 2015 to 2020, which has allowed more than 9.6 million rural poor people to stay away from an environment that is not suitable for human settlement and completely rid of the geo-environmental constraints (Zhou et al. 2019).

The poverty census or poverty targeting that integrates the geo-environmental and socio-economic variables is essential for effective poverty reduction. At the end of 2020, China eliminated absolute poverty in rural areas, 10 years ahead of the UN’s 2030 SDGs, and made a huge contribution to global poverty reduction (SCIO 2021). The success of China’s poverty eradication action can be attributed to the identification of the causes of poverty and the implementation of targeted and differentiated anti-poverty interventions based on regional and individual poverty targeting. The poverty census provided decision-making support for effective allocation of anti-poverty funds and targeted policy intervention in this country. Regional poverty and individual poverty interact. Regional poverty is more chronic poverty or chronic poverty, while individual poverty is temporary poverty (Liu et al. 2017; Zhou and Liu 2022). Only by synergistic mitigation of the two can the sustainable development of the region be realized. China adopted poverty-ending projects such as infrastructure construction, relocation, and land consolidation to solve the regional poverty problem. Land consolidation and infrastructure improvements have a significant positive effect on poverty reduction in China (Zhou et al. 2019; Zhang et al. 2020; Wang et al. 2021). Meanwhile, the Chinese government also improved the health, education, production, living conditions, and livelihoods of poor groups to stimulate their endogenous motivation and promote their employment and increase income, to achieve the elimination of individual poverty (Liu et al. 2017).

Poverty eradication is a prerequisite for rural revitalization and sustainable development. Establishing sustainable anti-poverty mechanism is necessary and urgent. In addition to geo-environmental constraints, other factors such as global environmental change, climate change, extreme weather events, public health emergencies, and natural disasters will all cause or aggravate poverty or return to poverty to varying degrees (Hallegatte and Rozenberg 2017; Hallegatte et al. 2017; Patel et al. 2020; Baez et al. 2020). Climate change and public health emergencies also affected agricultural production, which in turn affects food trade and poverty (Hertel et al. 2010; Laborde et al. 2020). Previous studies have observed that natural disasters force 26 million people around the world into extreme poverty every year (Hallegatte et al. 2017; 2020). Without intervention, climate change would plunge 132 million people into poverty in the next decade (2020–2030) (Hallegatte and Walsh 2020). COVID-19 has also sounded a wake-up call for mankind, and it has forced hundreds of millions of people into extreme poverty (World Bank 2021). By the end of 2020, China has eliminated absolute rural poverty and made outstanding contributions to the world’s poverty reduction (SCIO 2021). However, China’s relative poverty and the risk of returning to poverty still exist, especially in the remote mountainous areas of China’s central and western regions. It is necessary to carry out the comprehensive identification of the areas at risk of returning to poverty and establish a perfect anti-poverty mechanism.

There are three uncertainties in this study. First of all, we try to establish the relationship between the formation mechanism of individual poverty and regional poverty, but as we know, the formation mechanism of individual poverty and regional poverty was complex and diverse, and we did not quantitatively reveal the internal logic between them. Secondly, the eastern region of this study only includes Hebei and Hainan provinces. In the past 8 years (2013–2020), China’s main anti-poverty battlefield has mainly targeted 22 provinces in the central and western regions, while Shandong and Liaoning in the east have a small number of poor people. However, due to the limited availability of data, these two provinces have been excluded in this study. Last but not least, poverty is dynamic and multidimensional. This study only focused on the geo-environmental and socio-economic determinants of individual poverty and
Poverty eradication has always been the greatest challenge facing human society. This study attempted to put forward the theory of stratified poverty, emphasizing the difference between the formation mechanism of individual poverty and regional poverty, and advocated the importance of coordinated promotion of regional and individual poverty alleviation. Based on this, this study further investigated the spatial pattern of rural poverty in China and identified the geo-environmental and socioeconomic determinants of rural poverty. Results show that at the end of 2013, more than half of China’s rural poor mainly lived in remote mountainous areas. The spatial distribution of rural poverty in China had obvious spatial autocorrelation and formed six main clusters spatially. The causes of poverty in rural China were complex and diverse, which varies from region to region and from individual to individual. The main reason for poverty of rural residents in China was the lack of livelihood capital and endogenous development power caused by family members’ illness and lack of land, capital and technology. Northeast China was mainly affected by the illness and lack of labor skills of family members. The factors causing poverty in southern and northern China were also different. The south was mainly restricted by the illness of family members and the lack of development funds, while the north was restricted by multiple factors, such as heavy education burden and insufficient capital, labor force and labor skills. Complicated terrain conditions, unfavorable locations, backward transportation and slow economic levels were the leading factors in the formation of regional poverty. The impact of individual livelihood capital, regional geo-environment and socio-economic development level on rural poverty in China varied across regions. During the period 2013–2020, China implemented extraordinary targeted poverty alleviation interventions or ending-poverty actions and created a miracle of lifting more than 80 million poor people out of poverty in less eight years.

Our findings have three important policy implications. Firstly, poverty targeting and poverty mapping were the basis and prerequisite for the scientific allocation of poverty alleviation funds and the targeted intervention of anti-poverty measures. In sub-Saharan African countries where the current poverty problem is still most prominent, the best way to achieve the SDG poverty eradication goal was to clarify the distribution characteristics of the poor population and the causes of poverty based on the targeting of the poor, and then adopt differentiated intervention measures. Secondly, compared with satellite imagery and mobile phone data, poverty mapping based on census data was more effective for effective intervention in anti-poverty measures. Finally, poverty is a complex social problem with multidimensional, regional and dynamic characteristics. Eliminating poverty requires the participation of sociology, economics, geography, and management, as well as the participation of governments, enterprises, and individuals. It is true that poverty eradication is a systematic project, which requires not only understanding the determinants of regional poverty and individual poverty, but also considering the synergy and scientificity of poverty eradication measures.

Acknowledgements We are particularly grateful to Dr. Heng Wang of the School of Agricultural Economics and Rural Development of Renmin University of China, for his help in data collection and processing.

Author contribution Yang Zhou, conceptualization, writing-review and editing, funding acquisition and supervision; Han Huang, methodology, data processing, writing original draft. All the authors read and approved the final manuscript.

Data availability The datasets used in this study are available from the corresponding author on reasonable request.

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