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ORIGINAL ARTICLE

Spatial variations and macroeconomic determinants of life expectancy and mortality rate in China: a county-level study based on spatial analysis models

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Abstract

Objectives The life expectancy and mortality rate always exhibit remarkable spatial variations. Their spatial distribution patterns and economic determinants in China were explored.

Methods Four indexes including lifespan expectancy at birth (LEB), infant mortality rate (IMR), under-5 mortality rate (U5MR) and crude mortality rate (CMR) at county level in China were calculated. The spatial distribution patterns of these indexes were illustrated. Meanwhile, spatial regressive model was applied to explore the relations between major macroeconomic determinants and these indexes.

Results Spatial dependence of these four indexes in China was identified, and the positive spatial autocorrelation indicated a clustering feature rather than stochastic distribution. Additionally, local Moran's I statistics revealed opposite local spatial clusters of LEB and IMR, U5MR in China, that LEB showed that high value clusters in the southwest and low value clusters in the eastern part and northern Xinjiang, and IMR/U5MR exhibited that low value clusters in the east and high value clusters in the west. The spatial regression revealed that income per capita influenced positively on LEB and CMR, and GDP per capita was associated positively with IMR and U5MR.

Conclusions Geographical factors should be highly considered, and the L–L LEB or H–H IMR/U5MR clustered areas need to be integrated as a whole to formulate public health and economic development plans.

Keywords Life expectancy at birth · Infant and childhood mortality rate · Spatial distribution patterns · Macroeconomic determinants · China

Introduction

Life expectancy at birth (LEB) and mortality rate including infant mortality rate (IMR) and under-5 mortality rate (U5MR) are considered as important indicators of the overall level of public health conditions (WHO 2013). Indeed, these indexes always exhibit remarkable spatial variations and clustering features (Jablon and Bailar 1980; Cossman et al. 2007; Singh et al. 2011; United Nations 2011; Nolte and McKee 2012; Wang et al. 2014b, 2015a, b, 2016; Hondula et al. 2015; You et al. 2015). Furthermore, the social and economic development has important impacts on LEB and mortality rate (UNDP 2010), and their relations with public health level are increasingly aroused the scientific concern (Sorlie et al. 1995; Szreter 1997; Smith 1999; Wang et al. 2011). During the rapid development of China's economy and society since the reform and opening policy, the level of public

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health of Chinese people has been greatly improved (Marten et al. 2014). It was reported that the IMR decreased rapidly and LEB increased substantially in China in recent years (Salomon et al. 2013; Yang et al. 2013; Xu et al. 2014). Furthermore, several studies have been conducted to probe the spatial distribution of life expectancy, population death and aging population in China (Li et al. 2000; Hu et al. 2015; Wang et al. 2015a, b). These studies denoted an obvious difference of the death rate and lifespan level among different areas in China.

However, the existing studies on LEB, IMR and U5MR have not taken into account spatial distribution features in China. There have been few analyses of the spatial features including spatial autocorrelation and spatial clustering of LEB and mortality rate at high-resolution level in China as well. Meanwhile, it is still obscure about the relationship between the LEB and mortality rate and macroeconomic determinants in China, where the territory is vast and the development is complex and imbalanced.

To attain a better understanding of the spatial patterns and macroeconomic determinants of life expectancy and mortality rate in China, we investigated the spatial dependence/autocorrelation of LEB and mortality indexes, probed their macroeconomic determinants and revealed the potential implications for public health policy with spatial features.

Methods

Index selection

More detailed and accurate demographic data from the sixth Chinese national census in 2010 provided a basis for investigating the spatial variations in LEB and mortality in China. In this study, by using specific demographic data of more than 2000 counties in China from the sixth national census, four main indexes including life expectancy at birth (LEB), crude mortality rate (CMR), infant mortality rate (IMR) and under-5 mortality rate (U5MR) were calculated. Meanwhile, main macroeconomic indexes at county level in China as the relevant variables were also collected (Table 1).

Life expectancy at birth

Life expectancy is the mean number of years of life remaining at a given age based on the mortality rates observed at a given year (Shryock et al. 1976). Life expectancy at birth (LEB) refers to life remaining at birth, which provides an estimate of the average expected lifespan under certain conditions based on the current mortality rates. LEB is widely used in the assessment of health status, economic development and life quality in a specific population (WHO 2013).

Crude mortality rate

Crude mortality rate (CMR) refers to the total number of deaths per year per 1000 people. The CMR can be higher for some developed countries than in developing countries, despite a higher life expectancy in developed countries (http://data.worldbank.org/indicator/SP.DYN.CDRT.IN).

Infant mortality rate

Infant mortality refers to the deaths of young children, typically those less than 1 year of age. It can be measured by infant mortality rate (IMR), which can be calculated by the number of deaths of children under 1 year of age per 1000 live births (Wise 2017).

Under-5 mortality rate

The under-5 mortality rate (U5MR) is an important statistic, considering that the IMR has a strict limit on focusing on children only under 1 year of age. U5MR, also known as child mortality, is a core indicator for child health and well-being (You et al. 2015). Both of IMR and U5MR have been included in the target of the Sustainable Development Goals of the United Nations. In this paper, LEB, IMR and U5MR were considered as the main health indexes and CMR was taken as a reference indicator.

Macroeconomic indexes

The social and economic development has important impacts on LEB and mortality rate (UNDP 2010). Extensive studies indicated that the LEB and mortality rate were usually influenced by economic conditions (Hobcraft et al. 1984; Wilkinson 1992; Wilson and Daly 1997; Acemoglu and Johnson 2007; Wang et al. 2015a; Cutler et al. 2016). Several main macroeconomic indexes at county level in China were considered as the relevant variables in this paper (Table 1). All the economic indexes collected in this study were from National Earth System Science Data Sharing Infrastructure, National Science & Technology Infrastructure of China (http://www.geodata.cn).

Data quality and calculation methods

Demographic data at county level were from the sixth Chinese national census in 2010. The data quality was much better than previous censuses, for the under-enumeration rate of the sixth census was even lower than those in some developed countries (Zhao and Chen 2011). In this

Table 1 Summary of descriptive statistics of major macroeconomic indexes at county level in China, 2010

Independent variables	Macroeconomic indexes	Mean value	SD	Unit	*N*
x_1	Gross domestic product (GDP)	13,141.19	24,171.65	Million RMB yuan	1510
x_2	Per capita GDP (GDP_{pc})	26,065.53	27,858.63	RMB yuan	1313
x_3	Total fixed asset investment (TFAI)	8121.50	8965.61	Million RMB yuan	1289
x_4	Local financial general budget revenue (LFGBR)	707.03	1277.92	Million RMB yuan	1510
x_5	Local financial general budget expenditures (LFGBE)	1441.46	1268.99	Million RMB yuan	1510
x_6	Total retail sales of consumer goods (RSCG)	4502.79	7766.20	Million RMB yuan	1437
x_7	Per capita disposable income of urban residents ($DIUR_{pc}$)	15,772.25	4856.04	RMB yuan	993
x_8	Per capita net income of rural residents ($NIRR_{pc}$)	5983.68	2679.65	RMB yuan	1375

SD standard deviations, *RMB renminbi* the official currency of the P. R. China

study, the calculation method of LEB was based on the method of life table (Anderson 1999), and the calculation methods of CMR, U5MR and IMR were from (You et al. 2015; Wise 2017). It lacks of demographic data at county level in Heilongjiang, Liaoning, Hebei, Henan, Hunan, Guizhou and Sichuan provinces, so prefecture-level data were used instead. In addition, population migration and mobility were not considered in this study.

Spatial analysis models

The exploratory spatial analysis could provide valuable instruments for spatial health research (Douven and Scholten 1995). In this study, spatial autocorrelation analysis and spatial autoregressive model were conducted to provide a spatial-related model of LEB and mortality rate and their relations with macroeconomic determinants.

Spatial autocorrelation

To evaluate the spatial distribution patterns of life expectancy and mortality rate, the spatial autocorrelation at county level in China was examined based on the Moran's *I* and local spatial autocorrelation (local Moran's *I*) calculated by GeoDa. Specifically, the general clustering feature of the indexes in this study was probed by Moran's *I*, and the specific areas where the clustering occurs were examined by local Moran's *I*. Subsequently, statistically significant local clusters of these indexes were mapped. In order to deal with potential inaccuracies in the polygon file (such as rounding errors), the queen criterion which defines neighbors as spatial units sharing a common edge or a common vertex was used to determine neighbors in this study.

Spatial regressive model (SRM)

Regression was considered as one of the most favored methods for exploring the impact factors of public health in the existing literature on the topic. Specifically, spatial regression model (SRM) can provide information on spatial relationships among the variables involved, which can demonstrate whether variables present in proximate areas (in this study, proximate counties) are more important than those present in distant areas (Ward and Gleditsch 2008). Given these qualities, SRM analysis including spatial lag model (SLM) and spatial error model (SEM) was conducted in this study to investigate potential economic influence and determinants on LEB and mortality rate at county level in China. Ordinary least squares with defined dependent and independent variables, frequently used to estimate the underlying determinants (Qiu and Wu 2011; Su et al. 2017), was applied in this study as well. Furthermore, the Lagrange-multiplier (LM) diagnostics for spatial dependence were conducted to choose an appropriate spatial autoregressive model from SLM or SEM. Row-standardized weights were used for this diagnostic test to make sure the results were robust.

Statistical and mapping methods

The spatial distribution and local spatial autocorrelation maps (Fig. 2) were drawn by using Arc GIS version 10.0 (Environmental Systems Research Institute Inc., Redlands, CA). All statistical analyses were performed by using SPSS version 19.0 and GeoDa version 1.6.6.

Results

Spatial distribution patterns of life expectancy and mortality rate at county level in China

The statistical data revealed different trends of the indicators of LEB, IMR, U5MR and CMR in China in recent decades (Fig. 1). LEB in China experienced a trend of rapid growth, especially after 1960s, when it exceeded the world average level, and it has kept 5 years higher than the world average level approximately since 1980s (Fig. 1a). On the contrary, CMR showed an obvious decline trend in 1960s, and it became lower than the world average level since 1961, and it has maintained this low level since then (Fig. 1b). The variation in U5MR and IMR in China has both exhibited stable decline trends which were similar to the world trend since 1990, and the level of these two indexes in China was quite lower than the world average level (Fig. 1c, d). In sum, Chinese public health level indexed by LEB, IMR, U5MR has been greatly improved compared with the world average values.

The spatial distribution of CMR, IMR and U5MR in China in 2010 was illustrated (Fig. 2). CMR values exhibited a declining trend from the south to the north China. High-CMR areas were mainly in the eastern coastal area, Sichuan Basin and the Tibetan Plateau, while the lowest areas were mainly in Inner Mongolia, Xinjiang and Yunnan provinces. IMR and U5MR values exhibited an obvious decline trend from the west to the east. The areas with highest values of IMR and U5MR were mainly concentrated in northwestern and southwestern China, and the Qinghai–Tibetan Plateau area (Fig. 2). Pervious study revealed that the geographical distribution trend of LEB showed an obvious declining pattern from the east to the west rather than difference between the north China and the south China (Wang et al. 2015b). High-LEB areas were mainly concentrated in the northern Xinjiang, northeastern China, Yangtze River Delta, Guangdong, Guangxi and Hainan provinces, while the lowest areas are mainly in Yunnan, Guizhou, Qinghai and Tibet (Wang et al. 2015b). In contrast, IMR and U5MR exhibited contrary patterns that obviously declined from the west to the east.

It is showed that the LEB of males was lower and their CMR, IMR and U5MR were higher than females. The standard deviation of LEB and CMR of male was higher than female, and the IMR and U5MR showed a contrary tendency (see Electronic Supplemental Material S-Table 1). Furthermore, the sexual difference exhibited a consistency among different county-level administrative units in China which indicated similar distribution patterns between sexes and lacked obvious spatial difference. Therefore, the total values of these four indexes were chosen rather than indexes between different sexes in this study.

Global spatial autocorrelation

Global Moran's I statistics with Z test were calculated to compare the spatial autocorrelations of these four indexes (see Electronic Supplemental Material S-Table 2). The

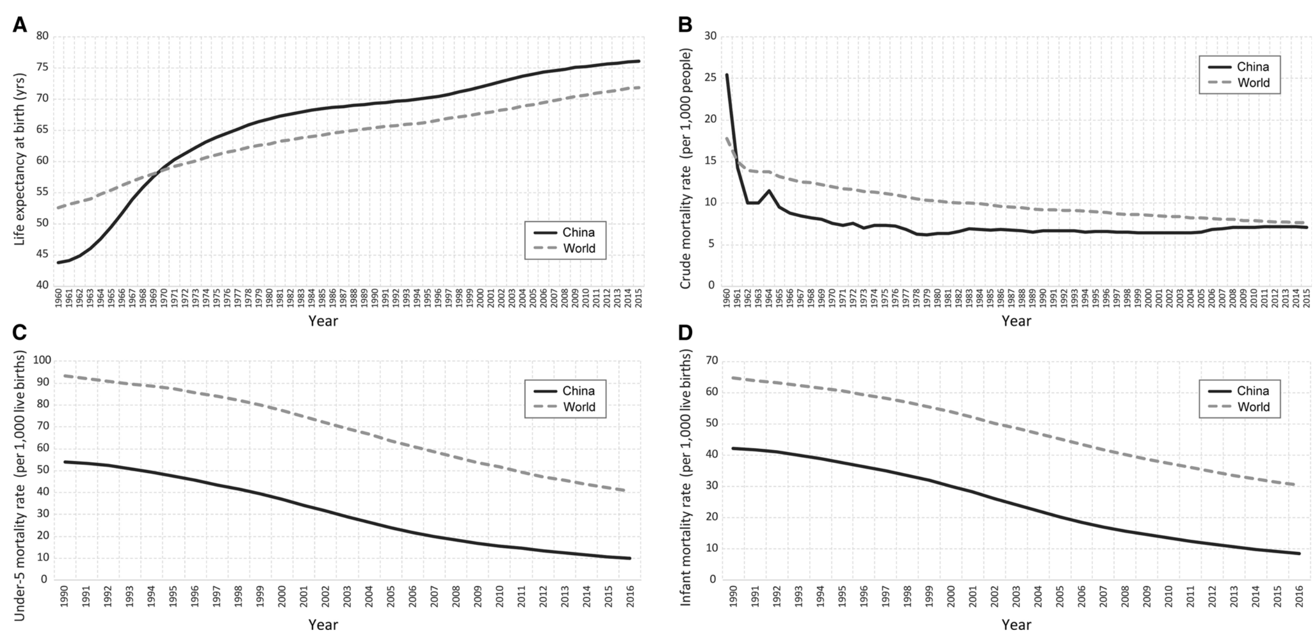

Fig. 1 Average of life expectancy at birth (LEB), infant mortality rate (IMR), under-5 mortality rate (U5MR) and crude mortality rate (CMR) in China and the world since 1960 and 1990, respectively. *Sources*: World Bank Open Data from https://data.worldbank.org/

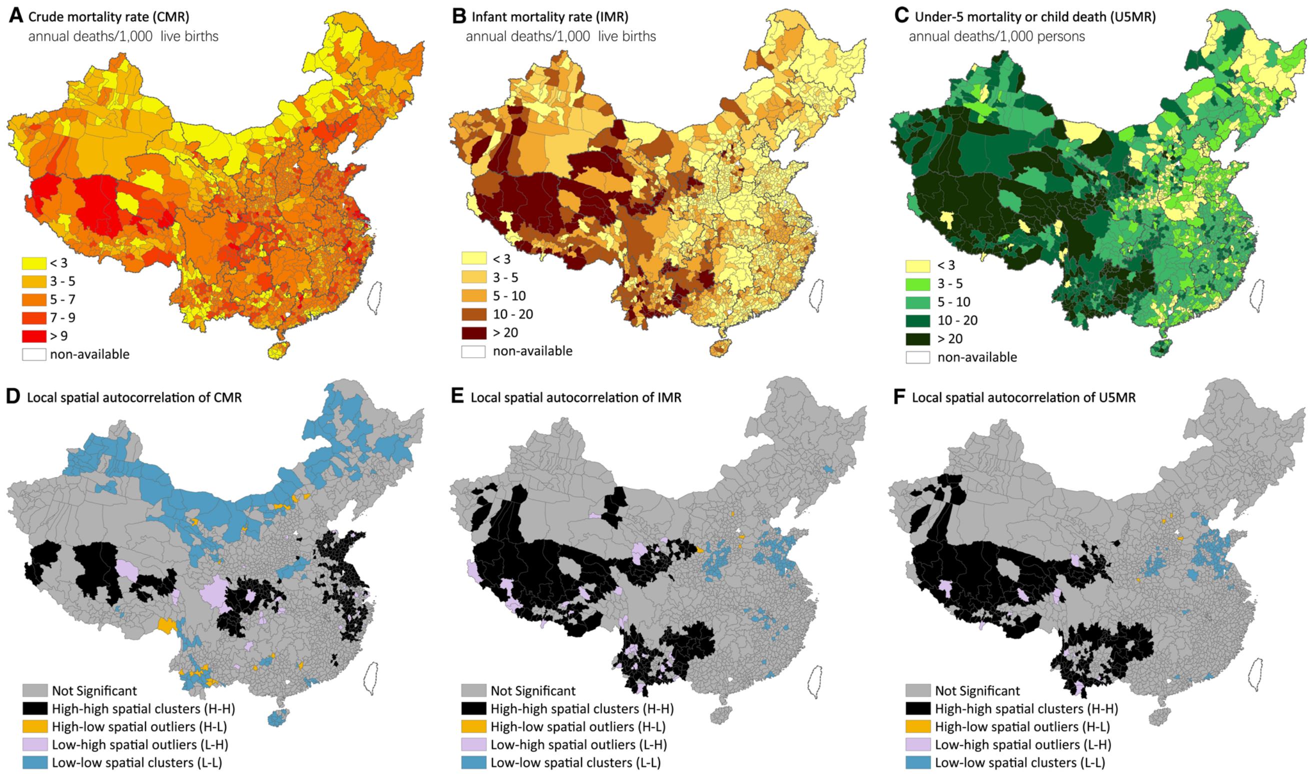

Fig. 2 Maps of spatial distribution (**a**–**c**) and local spatial autocorrelation (**d**–**f**) of crude mortality rate (CMR), infant mortality rate (IMR) and under-5 mortality rate (U5MR) at county level in China in 2010. High–high (H–H) and low–low (L–L) = spatial clusters; high–low (H–L) and low–high (L–H) = spatial outliers

global Moran's *I* indicated significant positive spatial autocorrelation of U5MR, IMR and CMR. The global spatial autocorrelation of LEB indicated a significant positive autocorrelation (Wang et al. 2015b). This study revealed that U5MR, IMR and CMR show more significant positive spatial autocorrelation than LEB (Electronic Supplemental Material S-Table 2), which reflects the obvious intensity of the geographical relationship of these indexes between observations in a neighboring area, and the positive Moran's *I* indicates the clustering of similar values across geographical space.

Local spatial autocorrelation

Figure 2d–f exhibits the areas with significant locations color-coded by different local spatial autocorrelations (local Moran's *I*) of CMR, IMR and U5MR, respectively. These maps showed significant areas with $p < 0.05$ as high–high spatial clusters (black), low–low spatial clusters, high–low spatial outliers, low–high spatial outliers and no significant areas. The local spatial autocorrelation of CMR showed that the H–H areas were located in eastern, middle China and Tibet area, and L–L areas were in northern and southern China (Fig. 2d). The local spatial autocorrelation of IMR and U5MR revealed a similar trend that H–H areas are concentrated in western and southwestern China and L–L areas were in Eastern China (Fig. 2e, f). Previous study of LEB local spatial autocorrelation indicated that the H–H areas located in Yangtze River Delta, south China and northern Xinjiang Autonomous Region, and L–L areas were concentrated in southwestern China (Wang et al. 2015b). In sum, the significant spatial autocorrelations of these four indexes indicated the clustering both of high value and low value rather than stochastic distribution.

Macroeconomic factors based on spatial regressive model

As for indexes of LEB and CMR, both the LM (lag) and LM (error) statistics were highly significant for row-standardized spatial matrix (Table 2). This indicated there was strong spatial dependence in this case. Thus, the robust LM-test can be applied to LEB and CMR for both the SEM and SLM. However, robust LM-tests of spatial error model of IMR and U5MR were not significant (Table 2). Therefore, the standard and robust LM-tests suggested that the SLM was a better model in comparison with the SEM in this case. Hence, the SLM was adopted to further explore the spatial effects of economic factors.

Table 2 Lagrange multiplier (LM) diagnostics for spatial dependence

Indexes	Statistic	Spatial weights matrix		
		DF	Row-standardized value	*p*-value
LEB	LM (lag)	1	1935.4	< 0.00001
	Robust LM (lag)	1	756.7	< 0.00001
	LM (error)	1	1193.2	< 0.00001
	Robust LM (error)	1	14.5	0.00014
CMR	LM (lag)	1	1595.7	< 0.00001
	Robust LM (lag)	1	495.7	< 0.00001
	LM (error)	1	1131.6	< 0.00001
	Robust LM (error)	1	31.7	< 0.00001
IMR	LM (lag)	1	928.0	< 0.00001
	Robust LM (lag)	1	91.4	< 0.00001
	LM (error)	1	837.2	< 0.00001
	Robust LM (error)	1	0.6	0.45889
U5MR	LM (lag)	1	1237.7	< 0.00001
	Robust LM (lag)	1	91.9	< 0.00001
	LM (error)	1	1150.7	< 0.00001
	Robust LM (error)	1	5.0	0.02608

LEB life expectancy at birth, *CMR* crude mortality rate, *IMR* infant mortality rate, *U5MR* under-5 mortality rate, *LM* Lagrange multiplier, *Robust LM* robust Lagrange multiplier, *DF* degree of freedom

p-value: probability of observing an event at least as extreme as a test statistic

The regression results from SLM and OLS were shown in Table 3. Results of the SLM revealed that the local financial general budget expenditures (LFGBE), per capita disposable income of urban residents ($DIUR_{pc}$), per capita net income of rural residents ($NIRR_{pc}$) were positively and significantly related to LEB at county level in China, whereas local financial general budget revenue (LFGBR) played a significantly negative influence on LEB (Table 3). SLM results of CMR were similar to those of LEB, besides the total fixed asset investment (TFAI) showing positively and significantly relations to CMR. Conversely, GDP_{pc} and LFGBE showed a significant positive correlation with U5MR and IMR, whereas LFGBR was negatively correlated with IMR and U5MR (Table 3). The spatial parameters were both large and statistically significant as indicated by *p*-value (< 0.00001). The OLS results showed a similar trend with the results of SLM.

Goodness-of-fit statistics such as the Akaike Information Criterions (AICs) and log-likelihoods were applied to estimate the fitting degree of regressions (Electronic Supplemental Material S-Table 3). The AICs for the OLS model were found higher than SLM, and values of *R*-squared of SLM were obviously higher than those of OLS. These indicated that the data were better fitted using spatial analysis techniques than OLS. Ignoring potential spatial effects in the regression analysis would, as these results revealed, reduce the model's effectiveness (S-Table 3). Meanwhile, higher-order contiguity weights (order of contiguity = 2) were constructed, which showed a similarity to the first-order weights. It showed a consistency between queen and rook contiguities in SLM modeling as well. Accordingly, the spatial sensitivity was not obvious based on the results of spatial regressive model.

Taken together, the results of SLM and OLS indicated several features of the economic determinants of LEB and mortality rate. First, LFGBR and LFGBE showed significant negative and positive relations to these four indexes, respectively. Second, per capita income both of urban and rural residents exhibited positive and significant relations to LEB and CMR, whereas GDP showed no significant relation to these two indexes. In comparison, GDP_{pc} showed a significantly positive relation to IMR and U5MR, and $income_{pc}$ showed no significant relations to these two indexes.

Discussion

Two main features of spatial distribution patterns of the four indexes (LEB, IMR, U5MR and CMR) can be concluded. First, spatial dependence was identified by using global Moran's *I* statistics at county level in China in that the positive spatial autocorrelation indicated a clustering feature rather than stochastic distribution. Second, the different types of distribution patterns can be identified by using local Moran's *I* statistics. CMR showed spatial

Table 3 Regression coefficients of spatial lag model (SLM) and ordinary least square (OLS)

Independent variables	Abbreviations	Spatial lag model (SLM)				Ordinary least square (OLS)			
		Coefficient	Std. Error	*z* value	*p*-value	Coefficient	Std. Error	*t* value	*p*-value
Dependent variable = LEB									
x_1	GDP	− 3.099743e−7	3.920984e− 7	− 0.7905524	0.42921	− 3.108758e−7	6.725198e−7	− 0.4622552	0.64397
x_2	GDP_{pc}	3.770231e−5	2.610608e−5	1.444197	0.14868	8.291404e−5	4.51333e−5	1.837092	0.06632
x_3	TFAI	1.685738e−9	1.1651e−6	0.001446861	0.99885	1.075246e−6	2.038052e−6	0.527585	0.59779
x_4	LFGBR	− 8.515952e−5	1.423033e−5	− 5.984368	< **0.00001**	− 0.0001715787	2.642981e−5	− 6.491861	< 0.00001
x_5	LFGBE	0.0001001601	1.143555e−5	8.758654	< **0.00001**	0.0002182562	2.063255e−5	10.57825	< 0.00001
x_6	RSCG	3.068765e−6	2.377936e−6	1.290516	0.19687	− 8.134225e−7	4.107078e−6	− 0.1980539	0.84314
x_7	$DIUR_{pc}$	0.0002108239	6.045408e−5	3.48734	**0.00049**	0.000143541	0.00010494	1.367838	0.17149
x_8	$NIRR_{pc}$	0.001212415	0.0002250044	5.388406	< **0.00001**	0.004670006	0.0003838087	12.16754	< 0.00001
Dependent variable = CMR									
x_1	GDP	2.934044e−8	4.39082e−8	0.6682224	0.50399	5.194828e−8	5.885165e−8	0.8826987	0.37750
x_2	GDP_{pc}	− 4.445426e−6	2.925658e−6	− 1.519462	0.12865	1.819538e−6	3.949578e−6	0.4606917	0.64506
x_3	TFAI	3.148572e−7	1.304982e−7	2.412732	**0.01583**	6.282178e−7	1.783483e−7	3.522421	0.00044
x_4	LFGBR	− 1.363807e−5	1.601121e−6	− 8.517828	< **0.00001**	− 1.843702e−5	2.312851e−6	− 7.971554	< 0.00001
x_5	LFGBE	1.174057e−5	1.284926e−6	9.137157	< **0.00001**	1.844256e−5	1.805537e−6	10.21444	< 0.00001
x_6	RSCG	− 1.515951e−7	2.663183e−7	− 0.5692252	0.56920	− 3.962519e−7	3.59407e−7	− 1.102516	0.27035
x_7	$DIUR_{pc}$	1.821236e−5	6.765638e−6	2.691891	**0.00710**	1.813515e−5	9.183216e−6	1.974814	0.04840
x_8	$NIRR_{pc}$	0.0001948237	2.515588e−5	7.744657	< **0.00001**	0.0003761269	3.358678e−5	11.19866	< 0.00001
Dependent variable = IMR									
x_1	GDP	− 2.534085e−8	1.541522e−7	− 0.1643885	0.86943	− 2.609709e−8	1.86482e−7	− 0.1399443	0.88852
x_2	GDP_{pc}	3.961652e−5	1.027707e−5	3.854846	**0.00012**	7.751907e−5	1.251494e−5	6.194121	< 0.00001
x_3	TFAI	2.695272e−7	4.58058e−7	0.5884127	0.55626	4.234696e−7	5.651283e−7	0.7493335	0.45371
x_4	LFGBR	− 1.736066e−5	5.578849e−6	− 3.111872	**0.00186**	− 3.388186e−5	7.328682e−6	− 4.623186	< 0.00001
x_5	LFGBE	2.561051e−5	4.490134e−6	5.703729	< **0.00001**	5.514003e−5	5.721168e−6	9.637897	< 0.00001
x_6	RSCG	− 9.175627e−7	9.351514e−7	− 0.9811916	0.32650	− 2.36933e−6	1.138845e−6	− 2.080467	0.03759
x_7	$DIUR_{pc}$	1.746115e−5	2.373796e−5	0.7355795	0.46199	− 9.927597e−6	2.909866e−5	− 0.3411702	0.73304
x_8	$NIRR_{pc}$	− 9.143849e−5	8.677514e−5	− 1.053741	0.29200	− 0.000240869	0.0001064257	− 2.26326	0.02371
Dependent variable = U5MR									
x_1	GDP	− 3.835445e−9	2.356817e−7	− 0.01627383	0.98702	− 6.030458e−10	3.000038e−7	− 0.002010128	1.00000
x_2	GDP_{pc}	3.833176e-5	1.56989e−− 5	2.441684	**0.01462**	9.416363e−5	2.013348e−5	4.676968	< 0.00001
x_3	TFAI	4.0518e−7	7.00323e−7	0.5785616	0.56288	1.934986e−7	9.09153e−7	0.2128339	0.83158

Table 3 (continued)

Independent variables	Abbreviations	Spatial lag model (SLM)				Ordinary least square (OLS)			
		Coefficient	Std. Error	*z* value	*p*-value	Coefficient	Std. Error	*t* value	*p*-value
x_4	LFGBR	− 2.892819e−5	8.533644e−6	− 3.389899	**0.00070**	− 6.166252e−5	1.179005e−5	− 5.230046	< 0.00001
x_5	LFGBE	4.281061e−5	6.880537e−6	6.221986	**< 0.00001**	0.0001000755	9.203957e−6	10.87309	< 0.00001
x_6	RSCG	− 1.100353e−6	1.429685e−6	− 0.7696466	0.44151	− 3.301276e−6	1.832123e−6	− 1.801886	0.07169
x_7	$DIUR_{pc}$	− 2.485745e−6	3.627164e−6	− 0.06853135	0.94536	− 8.005999e−5	4.681261e−5	− 1.710223	0.08736
x_8	$NIRR_{pc}$	− 1.226085e−5	0.0001326663	− 0.09241867	0.92637	− 0.00018626	0.0001712129	− 1.087885	0.27675

The *p*-values in bold means statistical significance level of $p < 0.05$

LEB life expectancy at birth, *CMR* crude mortality rate, *IMR* infant mortality rate, *U5MR* under-5 mortality rate, *GDP* gross domestic product, GDP_{pc} per capita GDP, *TFAI* total fixed asset investment, *LFGBR* local financial general budget revenue, *LFGBE* local financial general budget expenditures, *RSCG* total retail sales of consumer goods, $DIUR_{pc}$ per capita disposable income of urban residents, $NIRR_{pc}$ per capita net income of rural residents

clustering with low values in north and high values in east–middle China. IMR and U5MR exhibited similar patterns that low value clusters in the east and high value clusters in the west. In contrast, LEB showed an opposite trend that high value clusters in the southwest and low value clusters in the Eastern China and northern Xinjiang autonomous region.

These findings were comparable to the spatial distribution of IMR and U5MR in Bangladesh, Nepal, India and Tanzania which exhibited a similar distribution pattern with spatial clusters, which showed that areas with higher mortality were spatially concentrated in certain regions such as eastern Bangladesh, far-western and mid-western Nepal, and central—eastern parts of India (Tottrup et al. 2009; Chin et al. 2011; Singh et al. 2011; Gruebner et al. 2017). Several related factors such as malaria endemicity, child health care and malnutrition were explored in these studies. In this paper, national macroeconomic indexes with spatial features were mainly considered as the influencing factors.

Generally, economic and social barriers prevented access to basic medical resources and thus contribute to an increasing infant mortality rate, and economic development was inversely related to a nation's infant mortality rate (Andrews et al. 2008), and several studies reported that better socioeconomic status was associated with low infant mortality (Hajizadeh et al. 2014; Wang et al. 2014b). In this study, macroeconomic factors based on spatial regressive model indicated that local financial general budget revenue and expenditures showed and significant negative and positive effect on these four indexes, respectively. Furthermore, $income_{pc}$ exhibited positively influence on LEB and CMR, and GDP_{pc} showed positively influence on IMR and U5MR. This finding may indicate different effects from income level and GDP on different public health indexes including as LEB and IMR and U5MR.

In sum, three possible interpretations can be indicated according to the main findings of this study. First, LEB and infant/under-5 mortality rates at county level in China may be influenced by its neighboring areas, and these influences may outweigh exposure factors specific to this area which indicates a spatial dependence. The spatial scale of this feature was identified at county level in China based on spatial analysis in this study. Second, the spatial patterns of LEB and mortality rates may be due to distribution of higher level factors, such as macroeconomic system. For example, the IMR variations in Brazil are associated with the geographical pattern of poverty (Szwarcwald et al. 2002). Furthermore, positive spatial autocorrelations provincial GDP_{pc} across China were detected (Bai et al. 2012). It can be inferred that this spatial pattern may influence the distribution of LEB and mortality rates at the

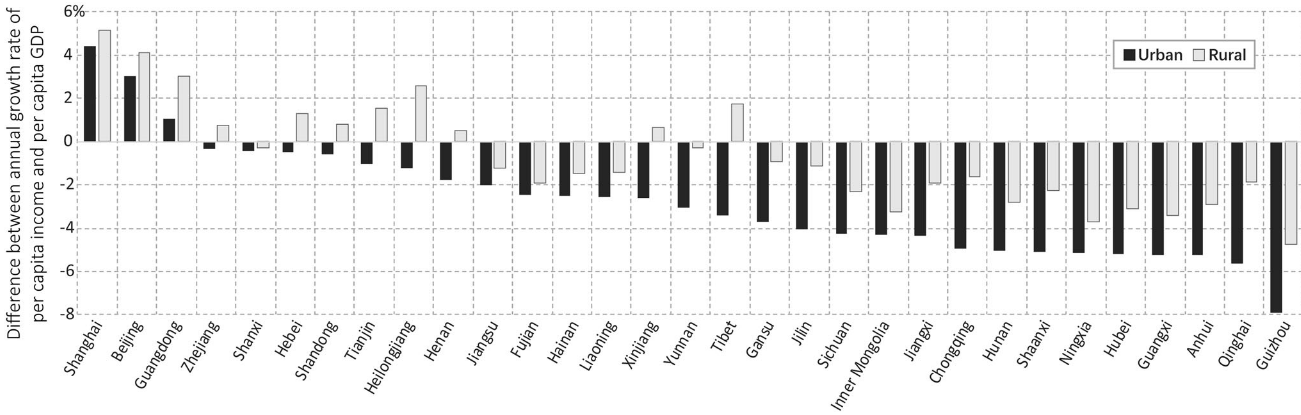

Fig. 3 Difference values (%) between the averages of annual growth rates of per capita income of urban and rural residents and per capita GDP at provincial level in China (2008–2013)

macrolevel. Last, different macroeconomic indexes (including GDP_{pc} and $income_{pc}$) exhibited different influences on LEB and infant/under-5 mortality rates. The average annual growth rates between the $income_{pc}$ and GDP_{pc} of rural and urban residents at provincial level in China were calculated (Fig. 3). Several developed provinces and municipalities such as Shanghai, Beijing, Guangdong and Zhejiang exhibited that the growth rates of $income_{pc}$ exceeded the growth of GDP_{pc}. Furthermore, the interprovincial difference showed a declining trend from the east to the west part of China, which was consistent with the unevenly distribution of economic development levels, which showed the consistency with the spatial difference of LEB, IMR and U5MR in China.

Policy implications

Economic growth can result in the improvement in infant and childhood mortality (Andrews et al. 2008). But in actual policy scenario, the imbalance of social–economic development may be a barrier to formulate these policies. Inequality in health outcomes such as IMR and LEB was widespread in developing economies (Dabla-Norris et al. 2015). In deed, this unbalanced spatial distribution was found in China similarly. Based on the main findings in this paper, two main policy implications can be concluded.

First, spatial clustering and spatial dependence of LEB and infant/under-5 mortality rate indicated that geographical factors should be given sufficient attention when planning and coordinating regional development. Furthermore, areas with low value of LEB or high value of infant/under-5 mortality rate should be integrated with public health improvement and economic development plans in their neighboring areas, which may contribute to promoting coordinated growth.

Second, in China, the $income_{pc}$ growth rate of urban residents was approximately equivalent to 75% of GDP_{pc} growth rate. Indeed, economic growth did not show a direct relation to the income gap (Wang 2006; Wang et al. 2014a; Su et al. 2015), and China's income inequality between different regions has grown rapidly during the last 40 years (Xie and Zhou 2014). Based on this study, differentiated policies and development strategy should be taken to improve the imbalanced distribution of income level and to gradually reduce the gap between growth rates of $income_{pc}$ and GDP_{pc} so as to lower the infant and childhood mortality. For example, southwestern China and the Qinghai–Tibetan Plateau areas were identified as the areas that most urgently need public attention for these areas exhibited spatial clustering of low value of life expectancy and high value of infant/under-5 mortality rate in China.

Limitations and future work

This study had some limitations. First, besides economic determinants, life expectancy and mortality rate may be influenced by many natural and social factors, such as climate, nutrition and healthcare. Second, only demographic and macroeconomic data from the Chinese national census in 2010 were collected. Besides, demographic data at county level in several provinces were not published.

Following extensions and improvements can be made by further studies. First, more specific indexes of social–economic conditions and environmental conditions can be furtherly collected in typical regions, and more in-depth and quantitative analysis is required to improve the understanding of the influence factors on the distribution of LEB and mortality. Second, it will be meaningful to obtain accurate historical data at county level in China and to conduct time series study in the future. Additionally, spatial variation in influence indicators of LEB and mortality can be recognized with more in-depth understanding. For example, spatial non-stationarity or heterogeneity of the input variable (such as social–economic and environmental conditions) can be probed by using the local weighted least squares method. Meanwhile, the relationships between the output and the input of the modeling application can also be explored by spatial sensitivity analysis in the future.

Conclusions

Spatial dependence of life expectancy at birth (LEB) and infant/under-5 mortality rate (IMR and U5MR) in China was identified by using global Moran's *I* statistics. The positive spatial autocorrelation indicated a clustering feature rather than stochastic distribution. Additionally, local Moran's *I* statistics revealed opposite local spatial clusters of LEB and IMR and U5MR in China, that high-LEB values clustered in Southwest China and low values clustered in the Eastern China and Xinjiang in Northwest China, and low IMR/U5MR values clustered in Eastern China and high values clustered in West China. Furthermore, macroeconomic determinants based on spatial regressive model indicated that $income_{pc}$ exhibited positively influence on LEB and CMR, and GDP_{pc} showed positively influence on IMR and U5MR.

Spatial clustering and spatial dependence of LEB and infant/under-5 mortality rate indicated that geographical factors should be highly considered and areas with low value of LEB or high value of infant/under-5 mortality rate should be integrated with public health and economic development plans with their neighboring areas. Furthermore, differentiated development strategies should be taken to improve imbalanced distribution of income level and to reduce the gap between growth rates of $income_{pc}$ and GDP_{pc}. In this study, southwestern China and the Qinghai–Tibetan Plateau area were identified the most in need to get policy interventions to improve economic and public health conditions.

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Compliance with ethical standards

Conflict of interest The authors confirm that this research involved no conflict of interest.

Ethical approval This article is based on a secondary analysis of administrative data and does not contain any studies with human participants performed by any of the authors.

References

Acemoglu D, Johnson S (2007) Disease and development: the effect of life expectancy on economic growth. J Polit Econ 115:925–985

Anderson RN (1999) A method for constructing complete annual US life tables. Vital Health Stat 2:1–28

Andrews KM, Brouillette DB, Brouillette RT (2008) Mortality, Infant A2 - Haith, Marshall M. In: Benson JB (ed) Encyclopedia of infant and early childhood development. Academic Press, San Diego, pp 343–359

Bai C-E, Ma H, Pan W (2012) Spatial spillover and regional economic growth in China. China Econ Rev 23:982–990. https://doi.org/10.1016/j.chieco.2012.04.016

Chin B, Montana L, Basagaña X (2011) Spatial modeling of geographic inequalities in infant and child mortality across Nepal. Health Place 17:929–936. https://doi.org/10.1016/j.healthplace.2011.04.006

Cossman JS, Cossman RE, James WL et al (2007) Persistent clusters of mortality in the United States. Am J Public Health 97:2148–2150

Cutler DM, Huang W, Lleras-Muney A (2016) Economic conditions and mortality: evidence from 200 years of data. National Bureau of Economic Research

Dabla-Norris ME, Kochhar MK, Suphaphiphat MN et al (2015) Causes and consequences of income inequality: a global perspective. International Monetary Fund

Douven W, Scholten HJ (1995) Spatial analysis in health research. In: De Lepper MJC, Scholten HJ, Stern RM (eds) The added value of geographical information systems in public and environmental health. Springer, Dordrecht, pp 117–133

Gruebner O, Khan M, Burkart K et al (2017) Spatial variations and determinants of infant and under-five mortality in Bangladesh. Health Place 47:156–164. https://doi.org/10.1016/j.healthplace.2017.08.012

Hajizadeh M, Nandi A, Heymann J (2014) Social inequality in infant mortality: What explains variation across low and middle income countries? Soc Sci Med 101:36–46. https://doi.org/10.1016/j.socscimed.2013.11.019

Hobcraft JN, Mcdonald JW, Rutstein SO (1984) Socio-economic factors in Infant and child mortality: a cross-national comparison. Popul Stud 38:193–223. https://doi.org/10.1080/00324728.1984.10410286

Hondula DM, Davis RE, Saha MV et al (2015) Geographic dimensions of heat-related mortality in seven US cities. Environ Res 138:439–452

Hu SB, Wang F, Yu CH (2015) Evaluation and estimation of the provincial infant mortality rate in china's sixth census. Biomed Environ Sci 28:410–420. https://doi.org/10.3967/bes2015.058

Jablon S, Bailar JC (1980) The contribution of ionizing radiation to cancer mortality in the United States. Prev Med 9:219–226. https://doi.org/10.1016/0091-7435(80)90079-1

Li RB, Tan JA, Wang WY, Yang H (2000) The yearly change and regional difference of population life-span in China. Hum Geogr 15:1–6

Marten R, McIntyre D, Travassos C et al (2014) An assessment of progress towards universal health coverage in Brazil, Russia, India, China, and South Africa (BRICS). The Lancet 384:2164–2171. https://doi.org/10.1016/S0140-6736(14)60075-1

Nolte E, McKee CM (2012) In amenable mortality: deaths avoidable through health care—progress in the US lags that of three european countries. Health Aff (Millwood) 31:2114–2122

Qiu X, Wu S (2011) Global and local regression analysis of factors of American College Test (ACT) score for public high schools in the state of Missouri. Ann Assoc Am Geogr 101:63–83
Salomon JA, Wang H, Freeman MK et al (2013) Healthy life expectancy for 187 countries, 1990–2010: a systematic analysis for the Global Burden Disease Study 2010. The Lancet 380:2144–2162
Shryock HS, Siegel JS, Stockwell EG (1976) The methods and materials of demography. Academic Press, New York
Singh A, Pathak PK, Chauhan RK, Pan W (2011) Infant and child mortality in India in the last two decades: a geospatial analysis. PLoS ONE 6:e26856. https://doi.org/10.1371/journal.pone.0026856
Smith JP (1999) Healthy bodies and thick wallets: the dual relation between health and economic status. J Econ Perspect J Am Econ Assoc 13:144–166
Sorlie PD, Backlund E, Keller JB (1995) US mortality by economic, demographic, and social characteristics: the National Longitudinal Mortality Study. Am J Public Health 85:949–956
Su C-W, Liu T-Y, Chang H-L, Jiang X-Z (2015) Is urbanization narrowing the urban-rural income gap? A cross-regional study of China. Habitat Int 48:79–86
Su S, Lei C, Li A et al (2017) Coverage inequality and quality of volunteered geographic features in Chinese cities: analyzing the associated local characteristics using geographically weighted regression. Appl Geogr 78:78–93
Szreter S (1997) Economic growth, disruption, deprivation, disease, and death: on the importance of the politics of public health for development. Popul Dev Rev 23:693–728. https://doi.org/10.2307/2137377
Szwarcwald CL, de Andrade CLT, Bastos FI (2002) Income inequality, residential poverty clustering and infant mortality: a study in Rio de Janeiro, Brazil. Soc Sci Med 55:2083–2092. https://doi.org/10.1016/S0277-9536(01)00353-7
Tottrup C, Tersbol BP, Lindeboom W, Meyrowitsch D (2009) Putting child mortality on a map: towards an understanding of inequity in health. Trop Med Int Health 14:653–662. https://doi.org/10.1111/j.1365-3156.2009.02275.x
UNDP (2010) International Human Development Indicators
United Nations (2011) World population prospects the 2010 revision, demographic profiles, vol II
Wang X (2006) Income inequality in China and its influencing factors. WIDER working paper series 126. World Institute for Development Economic Research (UNU-WIDER)
Wang YC, McPherson K, Marsh T et al (2011) Health and economic burden of the projected obesity trends in the USA and the UK. The Lancet 378:815–825. https://doi.org/10.1016/S0140-6736(11)60814-3
Wang C, Wan G, Yang D (2014a) Income inequality in the People's Republic of China: trends, determinants, and proposed remedies. J Econ Surv 28:686–708
Wang H, Liddell CA, Coates MM, Mooney MD, Levitz CE et al (2014b) Global, regional, and national levels of neonatal, infant, and under-5 mortality during 1990–2013: a systematic analysis for the Global Burden of Disease Study 2013. The Lancet 384:957–979. https://doi.org/10.1016/S0140-6736(14)60497-9
Wang S, Luo K, Liu Y et al (2015a) Economic level and human longevity: spatial and temporal variations and correlation analysis of per capita GDP and longevity indicators in China. Arch Gerontol Geriatr 61:93–102
Wang S, Luo K, Liu Y (2015b) Spatio-temporal distribution of human lifespan in China. Sci Rep 5:13844
Wang H, Naghavi M, Allen C, Barber RM, Bhutta ZA et al (2016) Global, regional, and national life expectancy, all-cause mortality, and cause-specific mortality for 249 causes of death, 1980–2015: a systematic analysis for the Global Burden of Disease Study 2015. The Lancet 388:1459–1544. https://doi.org/10.1016/S0140-6736(16)31012-1
Ward MD, Gleditsch KS (2008) Spatial regression models. Sage, Thousand Oaks
WHO (2013) World Health Statistics 2011. WHO, Geneva
Wilkinson RG (1992) Income distribution and life expectancy. BMJ 304:165
Wilson M, Daly M (1997) Life expectancy, economic inequality, homicide, and reproductive timing in Chicago neighbourhoods. BMJ 314:1271
Wise PH (2017) Infant Mortality A2—Quah, Stella R. International encyclopedia of public health, 2nd edn. Academic Press, Oxford, pp 216–221
Xie Y, Zhou X (2014) Income inequality in today's China. Proc Natl Acad Sci 111:6928–6933
Xu Y, Zhang W, Yang R et al (2014) Infant mortality and life expectancy in China. Med Sci Monit Int Med J Exp Clin Res 20:379
Yang G, Wang Y, Zeng Y et al (2013) Rapid health transition in China, 1990–2010: findings from the Global Burden of Disease Study 2010. The Lancet 381:1987–2015
You D, Hug L, Ejdemyr S et al (2015) Global, regional, and national levels and trends in under-5 mortality between 1990 and 2015, with scenario-based projections to 2030: a systematic analysis by the UN Inter-agency Group for Child Mortality Estimation. The Lancet 386:2275–2286
Zhao Z, Chen W (2011) China's far below-replacement fertility and its long-term impact: comments on the preliminary results of the 2010 census. Demogr Res 25:819