

Spatial spillover effects of
area-level socioeconomic factors
on life expectancy in Japan:
an ecological study

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Title

Spatial spillover effects of area-level socioeconomic factors on life expectancy in Japan: an ecological study

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Declaration of Interest

The authors report no competing interests.

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ABSTRACT

Background

Area-level socioeconomic status is a well-established determinant of geographical disparities in life expectancy. However, limited attention has been paid to spatial spillover effects, whereby socioeconomic conditions in neighbouring regions influence health outcomes. This study aimed to estimate the direct and spatial spillover effects of socioeconomic factors on life expectancy in Japan and to explore possible mechanisms underlying the observed spillover patterns.

Methods

Life expectancy at birth by sex at the municipal level in Japan for 2020 was the outcome variable. A spatial Durbin error model was used to estimate the direct and spatial spillover effects of ten regional socioeconomic factors, along with six control variables, on life expectancy. To ensure robustness, six spatial weight matrices were used. The results were compared with those obtained from a non-spatial linear regression model.

Results

Moran's I values for the residuals of the non-spatial model were statistically significant, indicating spatial autocorrelation. The unemployment rate and the proportion of individuals with no high school diploma showed negative direct and spillover effects, suggesting that being surrounded by regions with employment instability and low educational attainment is associated with lower life expectancy. Taxable income per capita showed no statistically significant spillover effects.

Conclusion

The findings indicate that socioeconomic conditions in neighbouring regions, in addition to those within a region, are associated with life expectancy. The observed spillover effects for employment and education support the role of collective resources in shaping regional health. These results indicate

the need to incorporate interregional socioeconomic contexts into public health strategies to address geographical disparities in health.

KEYWORDS

Spatial spillover, Socioeconomic status, Life expectancy, Geographical health disparities, Spatial regression

INTRODUCTION

Life expectancy has increased globally, rising by more than six years on average between 2000 and 2019.¹ However, geographical variations in life expectancy persist within countries.^{2–5} Area-level socioeconomic status is known to be a key determinant of these geographical disparities. Numerous studies have demonstrated that regions with lower socioeconomic status tend to exhibit shorter life expectancy.^{3,4,6,7} However, many of these studies have not accounted for the spatial nature of the data. Traditional non-spatial analyses typically assume that units of analysis are independent of one another. In reality, geographically adjacent regions, separated only by administrative boundaries, are unlikely to be entirely independent. Socioeconomic conditions in one region can potentially influence life expectancy in neighbouring regions. This phenomenon, where conditions or characteristics in one region affect outcomes in another, is referred to as spatial spillover.^{8,9} It is essential to account for spatial spillover effects because failing to do so when such effects are present can lead to biased estimates.¹⁰

Spatial spillover effects of area-level socioeconomic status on health can operate in two directions. First, spillovers can act in the same direction as direct effects. Here, direct effects refer to the impact of a region's socioeconomic status on its internal health outcomes. In this scenario, regions surrounded by socioeconomically advantaged neighbours exhibit better health outcomes than those surrounded by disadvantaged ones. This pattern is consistent with the collective resource model, which posits that

people in more affluent regions have better health because they have greater access to collective resources, such as services, job opportunities and social support.¹¹ Extending this concept, individuals in a deprived region may still benefit from being surrounded by relatively advantaged regions, through access to shared or nearby resources.^{12,13} In this study, we adopt this expanded interpretation of the collective resource model in the context of interregional spillovers.

The second possibility is that spillovers operate in the opposite direction from direct effects, where being surrounded by more advantaged regions leads to poorer health outcomes. Two mechanisms have been proposed to explain this phenomenon. The first is the psychosocial model, which posits that comparison with more affluent others evoke a sense of relative deprivation, resulting in psychological stress and ultimately worse mental and physical health.^{12,14,15} The second is the resource deprivation model, which posits that wealthier neighbouring regions may attract a disproportionate share of social capital, productive resources and labour force, thereby inhibiting the development of surrounding regions and contributing to poorer health outcomes.¹⁶

Previous research on the spatial spillover effects of area-level socioeconomic status on health outcomes has taken several analytical approaches. One common method uses a composite socioeconomic index, which summarizes multiple dimensions into a single measure. Studies employing this approach have yielded mixed findings: some support the collective resource model,^{13,17} while others lend support to the psychosocial model.¹² While the use of composite indices avoids multicollinearity and simplifies interpretation, this approach does not fully account for the possibility that underlying mechanisms may differ across individual variables.

An alternative approach is to model socioeconomic factors separately. This approach allows for explicit consideration of the variable-specific mechanisms that may operate in different directions. The present study adopts this latter approach to explore the direction and nature of variable-specific spatial spillover effects.

Although several studies have employed this variable-specific approach,^{15,16,18,19} further research is warranted for the following reasons. First, few studies have framed their findings within clear theoretical mechanisms. A notable exception is the study by Yang et al.,¹⁵ which offers a well-

developed interpretation. However, that study applied a spatial Durbin model, which may not be optimal in the present context, as discussed later in the Methods section.

Second, most prior studies relied on a single spatial weight matrix, typically based on queen contiguity. However, the geographic scope of shared resources or relevant reference groups for social comparison is not self-evident. To address this, this study considers multiple spatial structures to define regional adjacency and assess the robustness of the estimated spillover effects.

Third, previous studies have been conducted primarily in the United States^{15,18,19} and China.¹⁶ This study broadens the geographical scope by focusing on Japan, a country with one of the world's highest life expectancies,²⁰ and most rapidly aging populations.²¹ Despite its reputation for low inequality, Japan faces significant regional health disparities, which the national health strategy "Healthy Japan 21" aims to reduce.²² Socioeconomic disparities are evident not only at the individual or household level, but also across regions.^{23,24} We use municipalities as the unit of analysis because they are basic local government units responsible for local public services integral to residents' daily lives. As population decline and rapid ageing progress, inter-municipal collaboration has become increasingly essential for maintaining sustainable public services.²⁵ In this context, identifying spillover effects across municipal boundaries is particularly relevant. Understanding these dynamics in Japan can provide valuable insights for other countries facing similar demographic challenges.

Therefore, this study aims to estimate the direct and spatial spillover effects of socioeconomic factors on life expectancy at the municipal level in Japan. We compare results across multiple spatial weight matrices to assess the robustness of findings and explore the mechanisms that may underlie different spillover patterns.

METHODS

Study Units

The study units were municipalities in Japan as of April 2020. Municipalities (cities, towns and villages) are basic local government units that make up regional government units called prefectures. The Tokyo prefecture includes 23 special wards in addition to cities, towns and villages. In 2020, there

were 1,741 municipalities, consisting of 792 cities, 23 special wards of Tokyo, 743 towns and 183 villages. Nine municipalities with missing outcome data, for reasons described later, were excluded from the analysis.

Variables and Data Sources

Outcome

The outcome variable was life expectancy at birth by sex. Data were obtained from the 2020 life tables of municipalities issued by the Ministry of Health, Labour, and Welfare in Japan. Small-area estimation was already applied using additional information from prefectures, designated cities and special wards to stabilise the estimates for municipalities with small populations.²⁶ Life expectancy data were missing for nine municipalities in Fukushima and Kumamoto due to the Fukushima nuclear disaster evacuation orders and severe flooding in the Kuma River system, respectively.

Explanatory Variables

We selected ten area-level socioeconomic factors as exposure variables: the proportion of elderly couple households, elderly single households, single-mother households, rental households, sales and services workers, agricultural workers and blue-collar workers; the unemployment rate; taxable income per capita; and the proportion of individuals with no high school diploma. The first eight variables are components of the areal deprivation index (ADI), which is a composite index of regional socioeconomic position in Japan used in previous studies.²⁷ We added variables related to income and education, which are important socioeconomic factors alongside occupation and employment,²⁸ but were not included in the ADI. Taxable income data were obtained from the 2020 municipal tax statistics,²⁹ and other variables were derived from the 2020 Census.³⁰

We also included six control variables based on the literature^{16,18}: number of physicians per capita and participation rate in “Specific Health Checkups” among the individuals covered by municipal national health insurance, as a representation of healthcare resources; population density, as a proxy for urbanisation; average annual temperature and sunshine duration, to represent climate conditions; and the proportion of total urban park area to habitable land area, to represent green space availability. Specific Health Checkups is an annual health screening programme conducted by medical insurers for

individuals aged 40 to 74, focusing on the early detection and prevention of metabolic syndrome.³¹ The participation rate serves as an indicator of both health promotion efforts and resident health-related behaviours. Climatic conditions, including temperature and sunshine duration, have been associated with health outcomes such as cardiovascular mortality³² and suicide,³³ in previous studies. Green space availability, particularly the presence of parks, has been shown to be inversely associated with functional disability³⁴ and suicide mortality³⁵ in Japan. The data for these variables were compiled from several official sources. Physician data were from the 2020 Survey of Physicians, Dentists and Pharmacists³⁶ and checkup participation rates were from the 2020 report on the implementation status of Specific Health Checkups and Specific Health Guidance.³⁷ Population density data were obtained from the 2020 Census.³⁰ The average temperature and sunshine duration were calculated using the mesh climatological normals for 2020 from the Japan Meteorological Agency.³⁸ Park area data were obtained from the National Land Numerical Information for 2010,³⁹ which is the most recent nationwide dataset available.

Since a region's socioeconomic status can influence its healthcare resources and park availability, these variables could act as mediators between socioeconomic status and health outcomes. Therefore, we conducted sensitivity analyses excluding the two health-related variables and park area coverage. Multicollinearity among explanatory variables may be another concern, particularly when including multiple socioeconomic factors. However, the primary aim of this study is explanation, not prediction. Our goal is to estimate the association of each socioeconomic factor with the outcome while holding other variables constant. In explanatory modelling that seeks to approximate causal inference, it is important to adjust for confounding. High correlations among explanatory variables, which may reflect underlying confounding relationships, are not in themselves a valid reason to exclude a variable from the model. The reduced precision resulting from high correlations would be already reflected in wider confidence intervals, mitigating the risk of overinterpretation. This principle is analogous to causal inference settings, where adjusting for a strong confounder is necessary for valid estimation, despite potentially increasing variance.⁴⁰

Nonetheless, we calculated variance inflation factors (VIFs) to assess the degree of multicollinearity,

as shown in Supplementary Table S1. All VIF values were below the commonly used threshold of 10, and most were below 5, suggesting that multicollinearity was not severe. Additionally, we conducted a sensitivity analysis excluding the proportion of agricultural workers, the variable with the highest VIF, to evaluate its potential impact on the results.

Statistical Analysis

Overview of the models

Figure 1 shows the different spatial regression models that have been considered in the literature.⁸ The simplest model, shown in Figure 1, is the standard linear regression model, which takes the form

$$y = \alpha \iota_N + X\beta + \varepsilon,$$

where $\varepsilon = (\varepsilon_1, \dots, \varepsilon_N)^T$ is a vector of independently and identically distributed error terms and other notations follow Figure 1. This non-spatial model is often referred to as the ordinary least square (OLS) model because the parameters are defined as the asymptotic value of OLS estimates regardless of the correctness of the model specification.⁴¹

The most general model, known as the general nesting spatial (GNS) model, takes the form

$$y = \rho Wy + \alpha \iota_N + X\beta + WX\gamma + u, \quad u = \lambda Wu + \varepsilon,$$

where W is the spatial weight matrix, a row-normalised matrix that defines the spatial arrangement of units. The specification of W will be discussed later in this section. Compared to the OLS model, the GNS model incorporates three different interaction effects among units: (1) endogenous effects Wy , where the outcome of a unit depends on the outcomes of other spatial units; (2) exogenous effects WX , where the outcome of a unit depends on the explanatory variables of other spatial units; and (3) correlated effects Wu , where the error terms of different spatial units depend on each other.⁴² The scalar parameters ρ and λ represent the magnitude of endogenous and correlated effects respectively, while γ is a parameter vector representing the magnitude of exogenous effects.

Although the GNS model includes all three types of spatial effects simultaneously, at least one effect must be excluded (i.e., assumed to be 0), because otherwise the parameters are unidentified.^{41,42}

Data Analysis

All models included the 10 exposure variables and 6 control variables as explanatory variables and were fitted by sex. Sex-specific analyses were conducted because previous studies have suggested that disease structure and the association between socioeconomic status and health outcomes may differ between men and women.^{4,43} For a comparison purpose, we first fitted the non-spatial OLS model, from which the residuals for Moran's I test were obtained to examine the presence of spatial autocorrelation. As a spatial model, we employed the spatial Durbin error model (SDEM) for the analysis, which is derived from the GNS by omitting the endogenous effects:

$$y = \alpha\iota_N + X\beta + WX\gamma + u, \quad u = \lambda Wu + \varepsilon.$$

The assumption of no endogenous effects ($\rho = 0$ in GNS) would be justified in our application because it is implausible that life expectancy in one region directly impacts that of other regions without intervening changes in regional characteristics such as socioeconomic conditions. The direct effect is the effect of a change in an explanatory variable for a particular unit i on the outcome for the same unit and is given by $\partial y_i / \partial X_i = \beta$. Spatial spillover effects refer to the impact of changes in an explanatory variable for a particular unit i on the outcome for other units j ($\neq i$), represented by $\partial y_j / \partial X_i$,^{8,9} which equals $W_{ji}\gamma$, where W_{ji} is the (j, i) -th element of the spatial weight matrix W in the SDEM. Because the row sums of W are set to unity, γ can be interpreted as the sum of spillovers from all neighbouring units.

The spatial weight matrix W describes the spatial arrangement of the spatial units. We compared results based on six different specifications of W , because the true spatial structure is unknown.⁴¹ The specifications of W considered were the queen contiguity matrix (where two spatial units sharing a common edge or vertex are considered neighbours); a five nearest-neighbour matrix; and four distance-based matrices with a cut-off of 30 km. These included an inverse distance matrix with an exponent of 1; a gravity distance matrix, which is an inverse distance matrix with an exponent of 2; an exponential distance matrix; and a double-power distance matrix. In all distance-based matrices, spatial weights decay with increasing distance, although the functional forms of this decay vary. Details of the mathematical specifications and an example of spatial weight matrix construction are provided in Supplementary Appendix. The cut-off point for the distance-based matrices was set to

avoid assuming that all regions are connected to one another, which would be implausible in the context of local spillovers.⁹ Distances were calculated as Euclidean distances between the geometric centroids of spatial units, with no adjustments made for the presence of bodies of water. For municipalities that had no adjacent neighbours under a given spatial weight matrix, we assigned a value of zero to their spatially lagged terms.

To examine residual spatial autocorrelation in the SDEM, we calculated Moran's I for the residuals. Additionally, we plotted the residuals against the fitted values to assess the assumption of normality.

Software

We used *spdep* (for Moran's I statistics and weight matrix construction) and *spatialreg* (for fitting SDEM) packages. All statistical analyses were conducted using R version 4.4.1.

RESULTS

The descriptive statistics are shown in Table 1. The mean (standard deviation) of life expectancies across municipalities in 2020 were 81.34 (0.81) years for men and 87.52 (0.56) years for women. Figure 2 illustrates the geographical variation in life expectancy across municipalities. The maximum and minimum municipal life expectancies for men were 83.4 years and 78.1 years, respectively, whereas for women, they were 89.0 years and 85.5 years, respectively.

Figure 3 illustrates the residuals from the non-spatial OLS model. Moran's I of the residuals was calculated based on six different specifications of the weight matrix W , as shown in Table 2. The Moran's I values ranged from 0.4 to 0.5 for both sexes across all spatial weight matrices, indicating the presence of spatial autocorrelation in the residuals of the non-spatial model ($p < 0.001$ for all statistics). We also calculated Moran's I for the residuals of the SDEM model, which was not statistically significant, suggesting that spatial autocorrelation was adequately addressed.

The results from the SDEM and OLS models are shown in Table 3, which includes the specifications using the queen contiguity, five nearest-neighbours, and inverse distance weight matrices. Results based on the other three distance-based weight matrices (gravity distance, exponential distance, and double-power distance) are provided in Supplementary Table S2. Residuals from the SDEM were

plotted against the fitted values to assess the normality assumption. The resulting plot, shown in Supplementary Figure S1, did not suggest any major deviations from normality. We also conducted two sensitivity analyses: one excluding the two healthcare-related variables and park area coverage, and another excluding the proportion of agricultural workers, which had the highest VIF among the explanatory variables. The results of these models are presented in Supplementary Tables S3 and S4, respectively. In both analyses, the estimated associations showed similar patterns to those observed in the main analysis.

The magnitude of the correlated effect λ , which represents spatial dependence in the error terms, was consistently estimated to be between 0.6 and 0.8 for both men and women across most spatial weight matrices. A lower value was observed only with the exponential distance matrix, where λ was 0.42 (95% CI: 0.39, 0.45) for men and 0.38 (0.34, 0.41) for women. Under the assumption that the life expectancies of neighbouring regions do not depend directly on one another, the value of λ can be interpreted as follows. If two regions have the identical values for the explanatory variables, but the life expectancies in their surrounding regions differ uniformly by one year, then the life expectancies in these two regions would differ by approximately λ years.

The variables that consistently showed negative direct effects across all specifications of W for both sexes included the proportion of elderly single households, the proportion of workers in agriculture, forestry and fisheries, the proportion of blue-collar workers, the unemployment rate and the proportion of individuals without high school diploma. The proportion of single-mother households had direct effects only on male life expectancy. The proportion of elderly couple households exhibited positive direct effects for both men and women, whereas taxable income per capita had positive direct effects only for men.

Variables that showed consistently negative spillover effects across all spatial weight matrices, in the same direction as their direct effects, were the unemployment rate and the proportion of individuals without a high school diploma for both sexes, and the proportion of single-mother households for men. The non-spatial OLS model overestimated the magnitude of the negative direct effects for these variables. For example, a 1% increase in the unemployment rate was estimated to be associated with

a decrease in male life expectancy by 0.14 years (95% CI -0.17, -0.11) in the non-spatial OLS model, whereas the estimates of the direct effect from the SDEM ranged from -0.08 and -0.05. Even under the exponential distance specification, which produced the largest negative estimate, the effect was -0.08 (95% CI: -0.11, -0.05), smaller than that from the OLS model. In addition, the magnitude of the spillover effects of the unemployment rate was greater than that of the direct effects.

On the other hand, no variable showed consistently positive spillover effects across all spatial weight matrix specifications. The proportion of elderly couple households showed positive spillover effects for men in four out of six spatial weight matrices, in the same direction as the direct effects; in the remaining two matrices, the estimates were not statistically significant. The proportion of elderly single households showed positive spillover effects in some specifications for both men and women. Notably, these effects were in the opposite direction from the direct effects. In other specifications, the estimates were not statistically significant.

Taxable income per capita, a key socioeconomic factor alongside employment and education, showed no statistically significant spillover effects for either sex across any of the spatial weight matrix specifications.

DISCUSSION

This study examined the association between area-level socioeconomic factors and life expectancy in Japan, explicitly accounting for spatial spillover effects. Compared to the SDEM, the non-spatial OLS model tended to overestimate or underestimate direct effects. Several variables related to employment, education and household composition exhibited direct effects on life expectancy. Among them, the unemployment rate and the proportion of individuals with no high school diploma also showed negative spillover effects, consistent with the direction of their respective direct effects. The spillover effects of taxable income per capita were not statistically significant for either sex.

The residuals of the OLS model showed evidence of spatial dependence for both men and women, with significant Moran's I values across all spatial weight matrix specifications. This suggested that the assumption of randomly distributed residuals in the OLS model was not met. The SDEM results

further demonstrated the presence of spatial spillover effects for some variables. Additionally, spatially correlated effects were observed for both sexes, with significant estimates of λ across all spatial weight matrix specifications. These findings suggest the necessity of accounting for spatial effects in the analysis to obtain reliable estimates.¹⁰

The results from the SDEM indicated that several variables related to employment and occupational structure had negative direct effects on life expectancy, including the proportion of agricultural workers, blue-collar workers and the unemployment rate. These findings align with previous research showing that employment instability and occupational disadvantage are associated with adverse health outcomes.^{44,45} The proportion of individuals without a high school diploma also exhibited a negative direct effect, supporting prior evidence that lower educational attainment is associated with poorer health outcomes.²⁸ Regarding household composition, the proportion of elderly single households was negatively associated with life expectancy, supporting existing evidence that social isolation among older adults increases mortality risk.⁴⁶ Conversely, the proportion of elderly couple households had positive direct effects. Given that most regions experience both ageing and nuclear family structures,⁴⁷ the higher proportion of elderly couples may reflect a household environment that facilitates mutual support, which could positively influence health outcomes.

Regarding spatial spillover effects, the unemployment rate and the proportion of individuals with no high school diploma showed negative spillover effects, consistent with the direction of their direct effects. In other words, regions surrounded by areas with high unemployment and low educational attainment tended to have lower life expectancy. This finding supports the collective resource model, which posits that adverse socioeconomic conditions in neighbouring regions can reduce access to shared resources that support health.^{11–13} In Japan, spheres of daily living and employment often extend beyond municipal boundaries.³⁰ The educational attainment of a population reflects local educational resources, and a higher concentration of educated individuals may foster regional social norms that promote healthier behaviours,²⁸ producing contextual effects on health. Similarly, labour market conditions in surrounding regions are likely to influence local employment stability. In this context, not only actual job availability but also a sense of job security may function as a collective

resource. Prior research has shown that low perceived employment security is associated with poor health outcomes, even among individuals in stable employment.⁴⁸

Notably, our study contrasts with a study in China that reported a resource deprivation mechanism for employment and education spillovers, where regional development in one area draws resources away from its neighbours.¹⁶ The difference may be attributable to two factors. First, the Chinese study used provinces as the spatial unit, which are considerably larger than the municipalities used in our analysis. Therefore, their observed pattern may reflect broad urban-rural dynamics rather than interactions within more granular regional economies. Second, and perhaps more importantly, distinction lies in the phase of economic development and its reflection in regional dynamics. Japan has transitioned from an era of rapid, centralized growth to a more mature, integrated economy characterized by population decline.^{24,49} In this context, regions are more interdependent, and spillover effects are more likely to reflect shared resources within established economic zones. In contrast, the Chinese study reflects a period when the country was experiencing intense, geographically uneven growth that concentrated capital in growth poles,^{24,49} generating strong “backwash effects” that drew resources away from neighbouring regions.⁵⁰ Consequently, the findings from our study may be more applicable to other countries with relatively mature economies.

Spillover effects in the opposite direction from the direct effects were observed for the proportion of elderly single households under some spatial weight matrices, but the finding was not consistent across all models and should be interpreted with caution. If the observed positive spillover effect does reflect an underlying mechanism, it could be explained by the resource deprivation model.¹⁶ Regions with fewer elderly residents tend to be younger and more economically active, and may attract a larger share of people, services and investments, including healthcare and long-term care resources. As a result, neighbouring regions with higher concentrations of elderly residents may experience relative underinvestment, which could negatively affect population health. However, this interpretation remains tentative due to the limited robustness of the finding.

Taxable income per capita, a key socioeconomic factor alongside employment and education, did not show statistically significant spillover effects. Regarding income-related spillover effects, two

opposing mechanisms have been proposed. One is the psychosocial model, which has long been proposed as a mechanism linking income inequality to adverse health outcomes.^{14,51} This model posits that social comparison with more affluent others induces psychological stress, which in turn leads to poorer health. Although the reference group for such comparisons is not explicitly defined, a previous study conducted in Japan⁵² reported that individuals with relatively lower income compared to others within the same prefecture were more likely to report poor self-rated health. The other mechanism is the collective resource model, which suggests that economic advantage in surrounding regions is positively associated with health outcomes through shared resources.^{13,15,16} There are several possible explanations for the absence of statistically significant spillover effects of income. First, income-related spillover effects on health may simply not exist. Second, the spatial extent of reference groups involved in social comparison and the geographical range over which collective resources are distributed may differ from the municipal level used in this analysis. Third, the potential negative effects arising from social comparison and the potential positive effects resulting from shared resources may have offset one another. However, the current study design does not allow us to determine which of these explanations may be most relevant.

Implications

The findings of this study suggest that regional public health policy may need to consider the socioeconomic conditions of neighbouring regions, in addition to its internal conditions. The study also has implications for the construction of regional socioeconomic indices. Existing official indices developed in countries such as the UK,^{53–56} the US⁵⁷ and Australia,⁵⁸ which have been used for targeting public health policy, are typically based solely on absolute conditions within a specific region. However, the presence of spatial spillover effects indicates that incorporating measures of relative socioeconomic conditions, compared to surrounding regions, might also be important for guiding public health policy.

Strengths and Limitations

The strength of this study lies in its use of a spatial econometric model to estimate the association between area-level socioeconomic conditions and life expectancy, which mitigated potential biases

that traditional non-spatial models are prone to. Compared to a few previous studies that have utilized spatial econometric models,^{15,16,18,19} this study provided a detailed explanation of the theoretical background for selecting the SDEM among various spatial regression models. Additionally, by evaluating different spatial weight matrices, the study demonstrated robust results that were consistent across alternative specifications of the neighbouring structure.

However, this study also has limitations. First, our analysis could not include all potentially relevant regional factors. Several variables were omitted due to the lack of systematically available data at the municipality level across Japan, including social capital,^{15,59} health behaviours (e.g., diet, smoking, and physical activity)^{7,18} and other preventive care and health promotion efforts by municipalities. We also omitted key environmental factors, namely air quality indicators^{60,61} and forest coverage.³⁵ Nevertheless, their exclusion is unlikely to have substantially biased our results. Regarding air quality, with over 98% of monitoring stations meeting national standards for pollutants like PM_{2.5} and NO₂ in 2020,⁶² we reasoned that regional variation and the overall health impact were minimal. Regarding forest coverage, it is improbable that regions with a higher socioeconomic status tend to have greater forest coverage. Therefore, its exclusion may lead to an underestimation, but not an overestimation, of the negative direct and spillover effects of adverse socioeconomic conditions on health outcomes. The second limitation concerns the handling of bodies of water in the analysis. For municipalities with islands or highly concave coastlines, the computed geometric centroid may fall within a body of water, far from the main populated or economic landmass.⁶³ In addition, Euclidean distance does not reflect the actual cost or time of travel between regions, as it disregards geographical barriers such as seas and does not account for transportation networks like roads or marine routes. While we believe the fundamental spatial patterns identified in our analysis remain valid, these limitations may affect the accuracy of estimated spatial relationships.

Third, and related to the previous point, the spatial structure adopted in this study may not fully reflect the complexity of actual inter-regional interactions. More advanced approaches, such as kernel based weights with adaptive bandwidths, network based weights incorporating real-world transport links,⁶⁴ or cost distance analyses that treat water bodies as high cost barriers⁶³ could potentially provide more

realistic representations of spatial connectivity.

Fourth, this study did not account for spatial heterogeneity, where the associations between variables may vary across regions. The influence of neighbouring regions' socioeconomic conditions may differ between rural and urban regions.

Fifth, this study uses data aggregated at the municipal level and therefore does not account for socioeconomic heterogeneity within each municipality. A single municipality can contain significant internal variation, such as affluent and deprived neighbourhoods. Future research using data at a finer geographical scale would be beneficial for exploring these intra-municipal dynamics.

Sixth, the results of the primary analysis using the SDEM can be interpreted only as associational rather than causal. This limitation arises partly from the cross-sectional and ecological design of the study but also reflects a challenge inherent in spatial analysis. Specifically, causal inference in spatial contexts is difficult because the Stable Unit Treatment Value Assumption (SUTVA), a key assumption in Rubin's causal model, is violated due to spatial dependence and heterogeneity.⁶⁵ Advancing approaches for spatial causal inference represents a critical area for future research.^{66,67}

CONCLUSION

This study examined the association between area-level socioeconomic status and life expectancy at the municipal level in Japan, using a model that explicitly accounted for spatial spillover effects. Compared to the non-spatial model, the spatial model produced more interpretable estimates. The findings revealed distinct patterns of direct and spillover effects across different socioeconomic variables. In particular, the observed spillover effects for employment and education support the role of collective resources in shaping regional health. The results underscore the importance of considering not only internal conditions but also the broader regional environment when addressing geographic disparities in health.

Abbreviations

ADI: Areal deprivation index

GNS: General nesting spatial model

OLS: Linear regression model estimated by ordinary least squares

SDEM: Spatial Durbin error model

VIF: variance inflation factor

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Table 1 Descriptive statistics of variables in 2020

Variables	Description	Mean (SD)	Min	Max
N		1732		
<i>Outcomes</i>				
Life expectancy at birth for men (years)		81.34 (0.81)	78.10	83.40
Life expectancy at birth for women (years)		87.52 (0.56)	85.50	89.00
<i>Explanatory variables</i>				
Elderly couple households (%)	Proportion of households consisting of a husband aged 65 or older and a wife aged 60 or older only	14.82 (3.63)	3.39	31.51
Elderly single households (%)	Proportion of households consisting of one person aged 65 or over only	14.53 (4.84)	4.51	35.28
Single mother households (%)	Proportion of single-mother households	1.24 (0.48)	0.00	4.74
Rental households (%)	Proportion of households living in rented dwellings or apartments	24.99 (12.34)	2.06	81.32
Sales & services workers (%)	Proportion of workers in sales and service occupations	21.83 (4.07)	7.79	56.66
Agricultural workers (%)	Proportion of workers in agriculture, forestry and fisheries	9.82 (9.39)	0.03	75.14
Blue-collar workers (%)	Proportion of workers in manufacturing process, transport/machine operation, construction/mining and carrying/cleaning/packaging	31.48 (7.11)	5.20	51.70
Unemployment rate (%)	Proportion of unemployed persons in the labour force population	3.65 (1.15)	0.24	10.63
Taxable income (million yen)	Taxable income per capita	1.31 (0.37)	0.59	6.66
No high school diploma (%)	Proportion of persons without high school diploma among persons aged 15 and older who were not attending the school at the census date	19.67 (8.90)	1.32	53.18
Physicians (per 1000 persons)	Number of physicians per capita	1.79 (1.96)	0.00	28.04
Health checkups (%)	Participation rate in Specific Health Checkups among the individuals covered by municipal national health insurance	38.46 (11.06)	4.69	92.00
Population density (1000 persons per sq. km)	Population density	1.07 (2.61)	0.00	23.18
Temperature (°C)	Annual average temperature	12.77 (3.82)	1.85	24.21
Sunshine (1000 hours)	Annual average sunshine duration	1.81 (0.25)	1.13	2.37
Park area coverage (%)	Proportion of total park area to habitable land area	0.94 (1.48)	0.00	14.6

Table 2 Moran's I of residuals from OLS and SDEM models

Sex	Spatial weight matrix	OLS		SDEM	
		Moran's I statistics	P value	Moran's I statistics	P value
Men	Queen contiguity	0.46	<.001	-0.05	1.00
	Five nearest-neighbours	0.47	<.001	-0.04	1.00
	Inverse distance	0.42	<.001	-0.02	0.96
	Gravity distance	0.45	<.001	-0.04	0.99
	Exponential distance	0.50	<.001	-0.04	0.91
	Double-power distance	0.43	<.001	-0.03	0.99
Women	Queen contiguity	0.47	<.001	-0.05	1.00
	Five nearest-neighbours	0.46	<.001	-0.04	1.00
	Inverse distance	0.43	<.001	-0.03	0.99
	Gravity distance	0.45	<.001	-0.04	1.00
	Exponential distance	0.50	<.001	-0.04	0.91
	Double-power distance	0.44	<.001	-0.04	0.99

Table 3 Results from the spatial Durbin error model (SDEM) and OLS model in 2020

	Model W	Men											
		SDEM											
		Queen contiguity				Five nearest-neighbours				Inverse distance			
		β	(95% CI)	γ	(95% CI)	β	(95% CI)	γ	(95% CI)	β	(95% CI)	γ	(95% CI)
		OLS											
		-											
		β											
Intercept		82.46	(81.66, 83.27)			81.92	(80.23, 83.62)			82.71	(81.92, 83.51)		
Elderly couple households (%)		0.04	(0.03, 0.05)	0.02	(-0.01, 0.05)	0.04	(0.03, 0.06)	0.04	(0.01, 0.07)	0.05	(0.03, 0.06)	0.04	(0.01, 0.07)
Elderly single households (%)		-0.04	(-0.05, -0.03)	0.03	(0.01, 0.06)	-0.04	(-0.05, -0.03)	-0.00	(-0.02, 0.02)	-0.04	(-0.05, -0.03)	0.00	(-0.02, 0.03)
Single mother households (%)		-0.08	(-0.15, -0.02)	-0.21	(-0.37, -0.06)	-0.08	(-0.14, -0.02)	-0.15	(-0.31, 0.00)	-0.08	(-0.14, -0.01)	-0.20	(-0.36, -0.05)
Rental households (%)		-0.00	(-0.01, 0.00)	0.01	(0.00, 0.02)	-0.00	(-0.01, 0.00)	0.00	(-0.00, 0.01)	-0.00	(-0.01, 0.00)	0.00	(-0.01, 0.01)
Sales & services workers (%)		-0.01	(-0.02, -0.00)	-0.00	(-0.02, 0.01)	-0.01	(-0.02, -0.00)	0.01	(-0.01, 0.03)	-0.02	(-0.02, -0.01)	-0.01	(-0.03, 0.01)
Agricultural workers (%)		-0.02	(-0.03, -0.01)	-0.01	(-0.02, -0.00)	-0.02	(-0.02, -0.01)	-0.01	(-0.02, 0.01)	-0.02	(-0.03, -0.01)	-0.02	(-0.03, -0.01)
Blue-collar workers (%)		-0.02	(-0.03, -0.02)	0.00	(-0.01, 0.01)	-0.03	(-0.03, -0.02)	0.01	(-0.01, 0.02)	-0.03	(-0.04, -0.02)	-0.01	(-0.03, 0.00)
Unemployment rate (%)		-0.06	(-0.09, -0.03)	-0.12	(-0.19, -0.05)	-0.06	(-0.09, -0.04)	-0.12	(-0.18, -0.05)	-0.05	(-0.08, -0.02)	-0.10	(-0.16, -0.03)
Taxable income (million yen)		0.30	(0.17, 0.43)	-0.12	(-0.37, 0.13)	0.27	(0.14, 0.40)	-0.05	(-0.32, 0.22)	0.24	(0.13, 0.36)	0.24	(-0.12, 0.60)
No high school diploma (%)		-0.01	(-0.01, -0.00)	-0.04	(-0.05, -0.03)	-0.01	(-0.01, -0.00)	-0.03	(-0.05, -0.02)	-0.01	(-0.01, -0.00)	-0.02	(-0.03, -0.01)
Physicians (per 1000 persons)		0.00	(-0.01, 0.02)	0.01	(-0.03, 0.04)	0.00	(-0.01, 0.02)	0.01	(-0.02, 0.05)	0.00	(-0.01, 0.01)	0.06	(0.01, 0.11)
Health checkups (%)		0.01	(0.00, 0.01)	0.01	(0.00, 0.01)	0.01	(0.00, 0.01)	0.01	(0.00, 0.01)	0.01	(0.01, 0.01)	0.01	(0.00, 0.02)
Population density (1000 per km ²)		-0.00	(-0.03, 0.02)	-0.09	(-0.13, -0.05)	0.01	(-0.01, 0.04)	-0.07	(-0.11, -0.03)	-0.02	(-0.04, -0.00)	-0.13	(-0.18, -0.07)
Temperature (°C)		-0.03	(-0.06, -0.01)	0.03	(-0.01, 0.06)	-0.02	(-0.06, 0.01)	0.03	(-0.02, 0.07)	-0.01	(-0.04, 0.01)	0.02	(-0.02, 0.06)
Sunshine (1000 hours)		0.16	(-0.15, 0.47)	0.13	(-0.31, 0.56)	0.03	(-0.34, 0.40)	0.21	(-0.28, 0.70)	-0.16	(-0.49, 0.17)	0.40	(-0.10, 0.91)
Park area coverage (%)		-0.01	(-0.03, 0.01)	0.03	(-0.02, 0.08)	-0.01	(-0.03, 0.01)	0.01	(-0.04, 0.05)	-0.01	(-0.02, 0.01)	0.08	(0.01, 0.16)
λ		0.66	(0.62, 0.71)	-		0.69	(0.65, 0.73)	-		0.73	(0.69, 0.77)	-	
AIC		2151.4		-		2083.2		-		2136.8		-	

	Model W	Women											
		SDEM											
		Queen contiguity				Five nearest-neighbours				Inverse distance			
		β	(95% CI)	γ	(95% CI)	β	(95% CI)	γ	(95% CI)	β	(95% CI)	γ	(95% CI)
		OLS											
		-											
		β											
Intercept		88.5	(87.84, 89.16)			88.65	(87.28, 90.02)			88.88	(88.23, 89.53)		
Elderly couple households (%)		0.02	(0.01, 0.03)	-0.01	(-0.03, 0.02)	0.02	(0.01, 0.03)	0.01	(-0.02, 0.03)	0.02	(0.01, 0.03)	0.00	(-0.02, 0.03)
Elderly single households (%)		-0.01	(-0.02, -0.01)	0.03	(0.01, 0.05)	-0.02	(-0.03, -0.01)	0.02	(0.00, 0.04)	-0.02	(-0.03, -0.01)	0.02	(-0.00, 0.04)
Single mother households (%)		-0.03	(-0.08, 0.02)	-0.04	(-0.17, 0.09)	-0.02	(-0.08, 0.03)	-0.04	(-0.16, 0.09)	-0.03	(-0.08, 0.02)	-0.00	(-0.13, 0.12)

Rental households (%)	-0.00	(-0.00, 0.00)	0.00	(-0.00, 0.01)	-0.00	(-0.00, 0.00)	-0.00	(-0.01, 0.00)	-0.00	(-0.00, 0.00)	-0.00	(-0.01, 0.01)	-0.00	(-0.00, 0.00)
Sales & services workers (%)	-0.01	(-0.01, 0.00)	0.00	(-0.01, 0.01)	-0.01	(-0.01, 0.00)	0.00	(-0.01, 0.02)	-0.01	(-0.01, -0.00)	-0.01	(-0.02, 0.00)	-0.00	(-0.01, 0.00)
Agricultural workers (%)	-0.01	(-0.01, -0.00)	-0.01	(-0.01, 0.00)	-0.01	(-0.01, -0.00)	-0.00	(-0.01, 0.01)	-0.01	(-0.01, -0.00)	-0.02	(-0.03, -0.01)	-0.01	(-0.02, -0.00)
Blue-collar workers (%)	-0.02	(-0.02, -0.01)	-0.00	(-0.01, 0.01)	-0.02	(-0.02, -0.01)	-0.00	(-0.02, 0.01)	-0.02	(-0.03, -0.01)	-0.01	(-0.03, -0.00)	-0.01	(-0.02, -0.01)
Unemployment rate (%)	-0.04	(-0.06, -0.02)	-0.10	(-0.16, -0.05)	-0.04	(-0.06, -0.01)	-0.13	(-0.18, -0.07)	-0.03	(-0.05, -0.00)	-0.08	(-0.13, -0.03)	-0.10	(-0.13, -0.08)
Taxable income (million yen)	0.02	(-0.09, 0.12)	-0.10	(-0.30, 0.11)	0.05	(-0.06, 0.16)	-0.15	(-0.37, 0.07)	0.07	(-0.03, 0.16)	-0.03	(-0.32, 0.26)	-0.07	(-0.18, 0.04)
No high school diploma (%)	-0.01	(-0.01, -0.00)	-0.02	(-0.03, -0.01)	-0.01	(-0.01, -0.00)	-0.02	(-0.04, -0.01)	-0.01	(-0.01, -0.00)	-0.01	(-0.02, -0.00)	-0.03	(-0.03, -0.02)
Physicians (per 1000 persons)	0.00	(-0.01, 0.01)	0.01	(-0.01, 0.04)	0.00	(-0.01, 0.01)	0.01	(-0.02, 0.04)	-0.00	(-0.01, 0.01)	0.01	(-0.03, 0.05)	0.01	(-0.00, 0.02)
Health checkups (%)	0.01	(0.00, 0.01)	0.01	(0.00, 0.01)	0.00	(0.00, 0.01)	0.01	(0.00, 0.01)	0.01	(0.00, 0.01)	0.01	(0.00, 0.01)	0.01	(0.01, 0.01)
Population density (1000 per km ²)	0.00	(-0.02, 0.02)	-0.04	(-0.08, -0.01)	0.01	(-0.01, 0.03)	-0.03	(-0.06, 0.00)	-0.00	(-0.02, 0.02)	-0.05	(-0.09, -0.00)	-0.01	(-0.02, 0.00)
Temperature (°C)	0.04	(0.02, 0.06)	-0.00	(-0.03, 0.03)	-0.01	(-0.04, 0.02)	0.05	(0.01, 0.09)	0.04	(0.01, 0.06)	-0.00	(-0.03, 0.03)	0.04	(0.03, 0.05)
Sunshine (1000 hours)	-0.36	(-0.62, -0.11)	0.28	(-0.07, 0.64)	-0.13	(-0.43, 0.18)	-0.07	(-0.47, 0.33)	-0.61	(-0.88, -0.34)	0.55	(0.15, 0.96)	-0.17	(-0.29, -0.05)
Park area coverage (%)	-0.01	(-0.02, 0.01)	0.02	(-0.02, 0.06)	-0.00	(-0.02, 0.01)	0.01	(-0.03, 0.05)	-0.01	(-0.02, 0.01)	0.02	(-0.04, 0.08)	-0.01	(-0.03, 0.01)
λ	0.66	(0.62, 0.70)	-		0.68	(0.64, 0.72)	-		0.72	(0.67, 0.76)	-		-	
AIC	1467.6		-		1399.9		-		1449.9		-		2283.3	

SDEM: Spatial Durbin error model; OLS: Linear regression model estimated by ordinary least squares; W: Spatial weight matrix; AIC: Akaike information criteria

The specifications of the weight matrix W considered were the queen first-order contiguity, five nearest neighbours, and inverse distance with a cut-off distance of 30 km.

β , γ , and λ quantify the magnitude of direct effects of explanatory variables, spillover effects of explanatory variables, and correlated effects of the error terms, respectively.

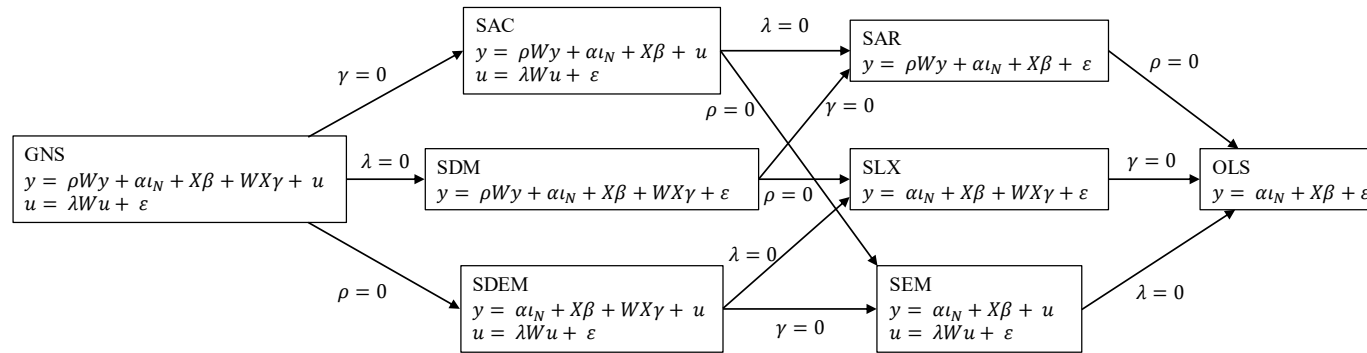


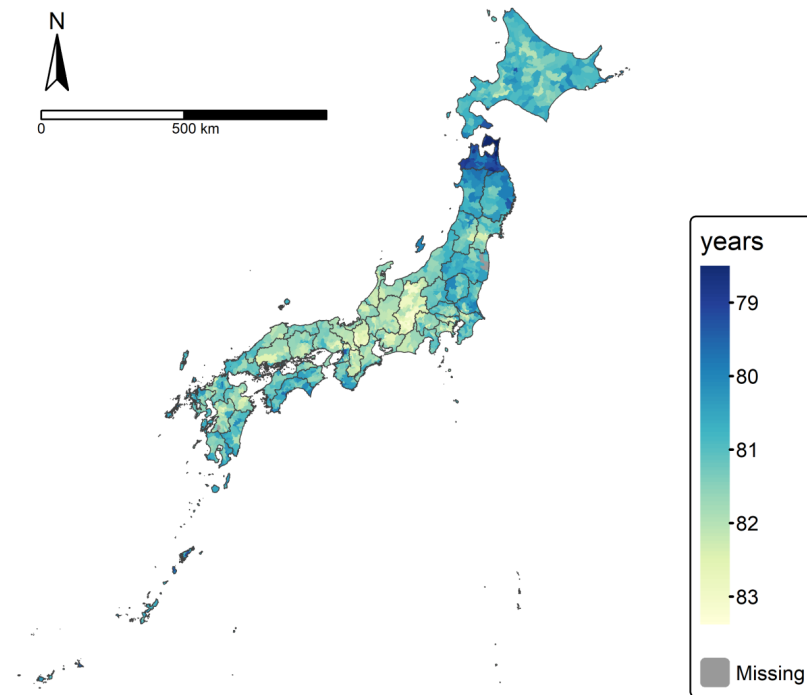
Figure 1 Comparison of different spatial econometric models

GNS: General nesting spatial model; SAC: Spatial autoregressive combined model; SDM: Spatial Durbin model; SDEM: Spatial Durbin error model;

SAR: Spatial autoregressive model; SLX: Spatial lag of X model; SEM: Spatial error model; OLS: Ordinary least squares model.

N : The number of units, K : The number of explanatory variables, y : An $N \times 1$ vector of the outcome, X : An $N \times K$ matrix of the explanatory variables, ι_N : An $N \times 1$ vector of ones.

(a)



(b)

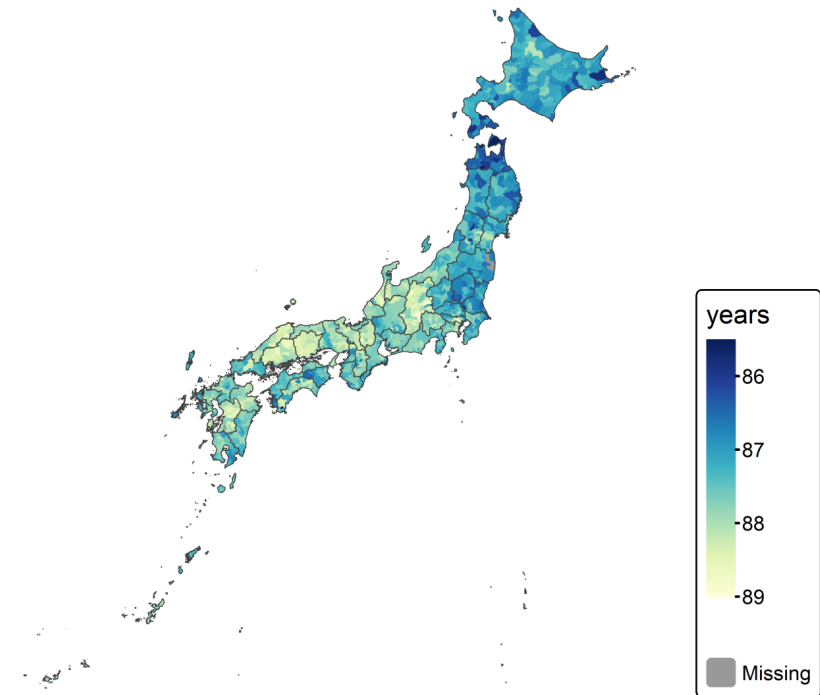
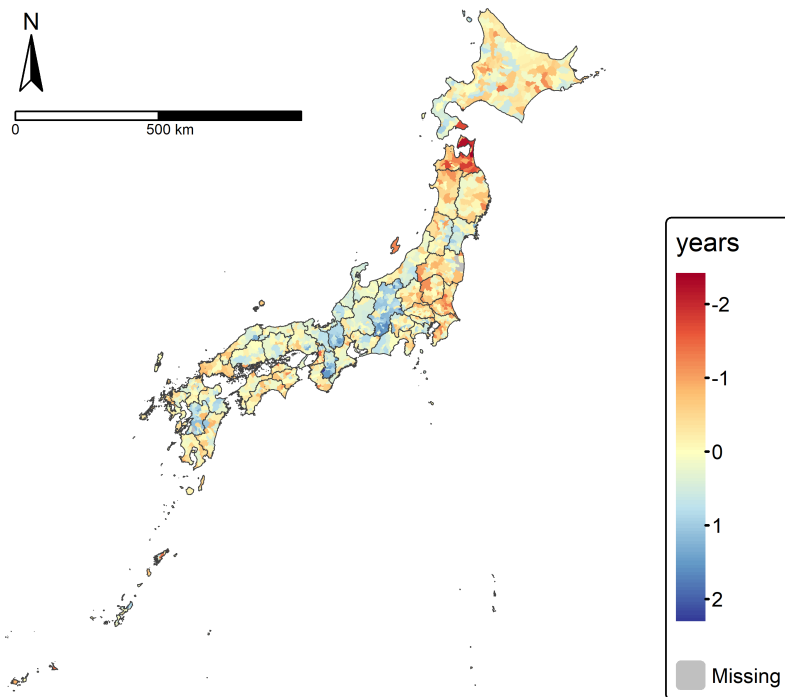


Figure 2 Life expectancy at birth across Japan's municipalities in 2020
a. Life expectancy for men (years) b. Life expectancy for women (years)

(a)



(b)

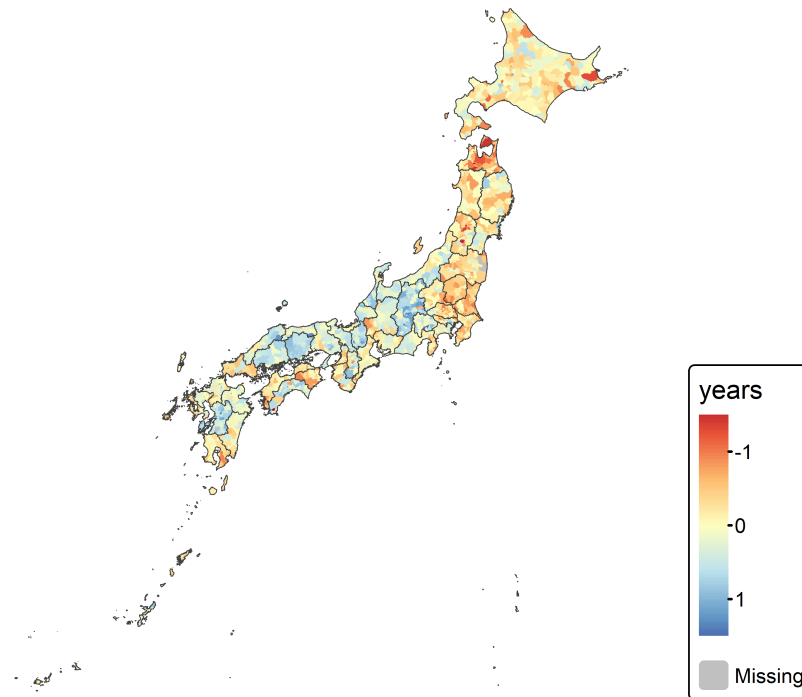


Figure 3 Residuals of the OLS model in 2020
a. Men (years) b. Women (years)

Supplementary materials

Appendix 1. Definition and example of spatial weight matrix construction

Three different specifications of spatial weight matrix before row-normalization is defined as follows, where K is a positive integer, D is a positive real number, W_{ij} is the (i, j) -th element of the spatial weight matrix before row-normalization, and d_{ij} is the distance between the centroids of area i and area j .

	Definition
Queen-contiguity matrix	$W_{ij} = \begin{cases} 1 & \text{if area } i \text{ shares an edge or a vertex with area } j \\ 0 & \text{otherwise} \end{cases}$
K -nearest neighbours matrix	$W_{ij} = \begin{cases} 1 & \text{if area } j \text{ is one of the } k \text{ nearest neighbors of area } i \\ 0 & \text{otherwise} \end{cases}$
Inverse distance matrix with a cut-off distance of D	$W_{ij} = \begin{cases} d_{ij}^{-1} & \text{if } d_{ij} \leq D \\ 0 & \text{if } d_{ij} > D \end{cases}$
Gravity distance matrix with a cut-off distance of D	$W_{ij} = \begin{cases} d_{ij}^{-2} & \text{if } d_{ij} \leq D \\ 0 & \text{if } d_{ij} > D \end{cases}$
Exponential distance matrix with a cut-off distance of D	$W_{ij} = \begin{cases} \exp(-0.01d_{ij}) & \text{if } d_{ij} \leq D \\ 0 & \text{if } d_{ij} > D \end{cases}$
Double-power distance matrix with a cut-off distance of D	$W_{ij} = \begin{cases} (1 - (d_{ij}/D)^2)^2 & \text{if } d_{ij} \leq D \\ 0 & \text{if } d_{ij} > D \end{cases}$

Consider a hypothetical map illustrated in Figure A1. The distances between the centroids of four areas are shown in Table A1. The spatial weight matrix corresponding to this map is given as follows.

	Before row-normalization	After row-normalization
Queen-contiguity matrix	$\begin{pmatrix} 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & 0 \\ 1 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & 0 & 0.50 & 0.50 \\ 0 & 0 & 1 & 0 \\ 0.33 & 0.33 & 0 & 0.33 \\ 0.50 & 0 & 0.50 & 0 \end{pmatrix}$

Two-nearest neighbours matrix	$\begin{pmatrix} 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & 1 \\ 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & 0 & 0.50 & 0.50 \\ 0 & 0 & 0.50 & 0.50 \\ 0 & 0.50 & 0 & 0.50 \\ 0.50 & 0 & 0.50 & 0 \end{pmatrix}$
Inverse distance matrix with a cut-off distance of 15 km	$\begin{pmatrix} 0 & 0 & 0.07 & 0.08 \\ 0 & 0 & 0.14 & 0 \\ 0.07 & 0.14 & 0 & 0.11 \\ 0.08 & 0 & 0.11 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & 0 & 0.44 & 0.56 \\ 0 & 0 & 1 & 0 \\ 0.21 & 0.45 & 0 & 0.35 \\ 0.43 & 0 & 0.57 & 0 \end{pmatrix}$

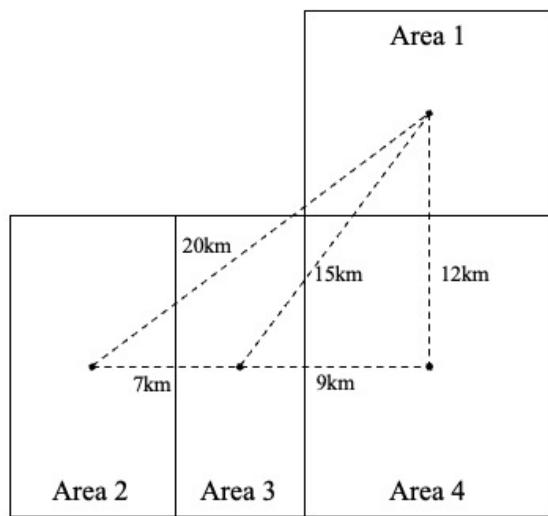


Figure A1. Hypothetical map consisting of four areas

Table A1. Distances between the areas in the hypothetical map

	Area 1	Area 2	Area 3	Area 4
Area 1	-	20 km	15 km	12 km
Area 2	20 km	-	7 km	16 km
Area 3	15 km	7 km	-	9 km
Area 4	12 km	16 km	9 km	-

Supplementary Table S1. Variance inflation factors for explanatory variables

Explanatory variables	VIF		
	Model 1	Model 2	Model 3
Elderly couple households	3.39	3.37	3.32
Elderly single households	3.80	3.75	3.79
Single mother households	1.65	1.64	1.64
Rental households	2.75	2.73	2.55
Sales & services workers	2.51	2.49	1.37
Agricultural workers	5.98	5.71	-
Blue-collar workers	4.68	4.49	1.83
Unemployment rate	1.68	1.57	1.65
Taxable income	3.27	3.15	2.98
No high school diploma	3.74	3.67	3.10
Physicians	1.26	-	1.23
Health checkups	1.19	-	1.19
Population density	2.64	2.47	2.57
Temperature	2.19	2.18	2.04
Sunshine	1.88	1.87	1.83
Park area coverage	1.55	-	1.52

Model 1 is the main model including all ten socioeconomic variables and five control variables.

Model 2 excludes the number of physicians per capita, the participation rate in Specific Health Checkups and the proportion of total park area to habitable land area from Model 1.

Model 3 excludes the proportion of agricultural workers from Model 1.

VIF: Variance inflation factor.

Supplementary Table S2. Results from the main SDEM based on three distance-based spatial weight matrices (gravity distance, exponential distance and double-power distance)

		Men						Women					
		Gravity distance		Exponential distance		Double-power distance		Gravity distance		Exponential distance		Double-power distance	
Intercept		82.61	(81.81, 83.42)	81.83	(81.04, 82.61)	82.32	(81.52, 83.12)	88.75	(88.09, 89.42)	88.23	(87.59, 88.88)	88.69	(88.04, 89.34)
β													
	Elderly couple households	0.05	(0.03, 0.06)	0.06	(0.05, 0.08)	0.05	(0.03, 0.06)	0.02	(0.01, 0.03)	0.03	(0.02, 0.04)	0.02	(0.01, 0.03)
	Elderly single households	-0.04	(-0.05, -0.03)	-0.04	(-0.05, -0.03)	-0.04	(-0.05, -0.03)	-0.02	(-0.02, -0.01)	-0.01	(-0.02, -0.00)	-0.02	(-0.02, -0.01)
	Single mother households	-0.08	(-0.15, -0.02)	-0.09	(-0.16, -0.02)	-0.08	(-0.15, -0.02)	-0.03	(-0.08, 0.03)	-0.01	(-0.07, 0.04)	-0.02	(-0.08, 0.03)
	Rental households	-0.00	(-0.01, 0.00)	-0.00	(-0.01, 0.00)	-0.00	(-0.01, 0.00)	-0.00	(-0.00, 0.00)	-0.00	(-0.00, 0.00)	0	(-0.00, 0.00)
	Sales & services workers	-0.01	(-0.02, -0.00)	-0.01	(-0.02, 0.00)	-0.01	(-0.02, -0.00)	-0.01	(-0.01, 0.00)	-0.00	(-0.01, 0.00)	-0.01	(-0.01, 0.00)
	Agricultural workers	-0.02	(-0.02, -0.01)	-0.02	(-0.02, -0.01)	-0.02	(-0.03, -0.01)	-0.01	(-0.01, -0.00)	-0.01	(-0.01, -0.00)	-0.01	(-0.01, -0.00)
	Blue-collar workers	-0.03	(-0.03, -0.02)	-0.02	(-0.03, -0.01)	-0.03	(-0.04, -0.02)	-0.02	(-0.02, -0.01)	-0.02	(-0.02, -0.01)	-0.02	(-0.03, -0.01)
	Unemployment rate	-0.06	(-0.08, -0.03)	-0.08	(-0.11, -0.05)	-0.05	(-0.08, -0.03)	-0.03	(-0.05, -0.01)	-0.06	(-0.09, -0.04)	-0.03	(-0.05, -0.01)
	Taxable income	0.25	(0.12, 0.37)	0.26	(0.13, 0.40)	0.29	(0.17, 0.40)	0.06	(-0.04, 0.16)	0.01	(-0.10, 0.12)	0.08	(-0.02, 0.17)
	No high school diploma	-0.01	(-0.01, -0.00)	-0.02	(-0.02, -0.01)	-0.01	(-0.01, -0.00)	-0.01	(-0.01, -0.00)	-0.02	(-0.02, -0.01)	-0.01	(-0.01, -0.00)
	Physicians	0.00	(-0.01, 0.02)	0.00	(-0.01, 0.01)	0.00	(-0.01, 0.02)	0.00	(-0.01, 0.01)	0.01	(-0.01, 0.02)	0.00	(-0.01, 0.01)
	Health checkups	0.01	(0.01, 0.01)	0.01	(0.01, 0.01)	0.01	(0.01, 0.01)	0.01	(0.00, 0.01)	0.01	(0.01, 0.01)	0.01	(0.00, 0.01)
	Population density	0.00	(-0.02, 0.03)	0.00	(-0.02, 0.02)	-0.02	(-0.04, 0.00)	0.00	(-0.02, 0.02)	-0.00	(-0.02, 0.02)	0	(-0.02, 0.02)
	Temperature	-0.02	(-0.04, 0.01)	-0.02	(-0.04, 0.00)	-0.02	(-0.04, 0.01)	0.04	(0.02, 0.06)	0.03	(0.01, 0.05)	0.04	(0.02, 0.06)
	Sunshine	-0.17	(-0.51, 0.17)	0.09	(-0.21, 0.39)	-0.01	(-0.34, 0.32)	-0.63	(-0.91, -0.35)	-0.32	(-0.57, -0.06)	-0.58	(-0.85, -0.31)
	Park area coverage	-0.01	(-0.03, 0.01)	-0.01	(-0.03, 0.01)	-0.01	(-0.02, 0.01)	-0.01	(-0.03, 0.00)	-0.01	(-0.03, 0.01)	-0.01	(-0.02, 0.01)
γ													
	Elderly couple households	0.03	(0.00, 0.05)	0.01	(-0.00, 0.03)	0.04	(0.01, 0.06)	0.01	(-0.02, 0.03)	0.00	(-0.01, 0.01)	0.00	(-0.02, 0.02)
	Elderly single households	0.01	(-0.02, 0.03)	0.01	(0.00, 0.03)	0.00	(-0.02, 0.03)	0.01	(-0.00, 0.03)	0.01	(0.00, 0.02)	0.02	(-0.00, 0.04)
	Single mother households	-0.20	(-0.33, -0.07)	-0.11	(-0.17, -0.04)	-0.16	(-0.29, -0.02)	-0.00	(-0.11, 0.11)	-0.01	(-0.07, 0.04)	0.02	(-0.08, 0.13)
	Rental households	0.00	(-0.00, 0.01)	0.00	(-0.00, 0.01)	0.00	(-0.01, 0.01)	-0.00	(-0.01, 0.00)	-0.00	(-0.00, 0.00)	0	(-0.01, 0.00)
	Sales & services workers	-0.01	(-0.03, 0.00)	-0.01	(-0.02, -0.00)	-0.01	(-0.02, 0.01)	-0.01	(-0.02, 0.01)	-0.00	(-0.01, 0.01)	-0.01	(-0.02, 0.00)
	Agricultural workers	-0.02	(-0.03, -0.01)	-0.01	(-0.02, -0.00)	-0.02	(-0.03, -0.01)	-0.01	(-0.02, -0.00)	-0.00	(-0.01, 0.00)	-0.01	(-0.02, 0.00)
	Blue-collar workers	-0.01	(-0.03, -0.00)	0.00	(-0.00, 0.01)	-0.01	(-0.02, 0.01)	-0.01	(-0.02, -0.00)	0.00	(-0.00, 0.01)	-0.01	(-0.02, 0.00)
	Unemployment rate	-0.09	(-0.15, -0.04)	-0.06	(-0.09, -0.03)	-0.09	(-0.15, -0.04)	-0.07	(-0.12, -0.03)	-0.05	(-0.07, -0.03)	-0.09	(-0.13, -0.04)
	Taxable income	0.19	(-0.08, 0.46)	0.02	(-0.11, 0.16)	0.21	(-0.10, 0.52)	-0.04	(-0.26, 0.18)	-0.10	(-0.21, 0.02)	-0.06	(-0.31, 0.20)
	No high school diploma	-0.02	(-0.03, -0.01)	-0.02	(-0.03, -0.01)	-0.03	(-0.04, -0.01)	-0.01	(-0.02, -0.01)	-0.01	(-0.02, -0.01)	-0.02	(-0.03, -0.01)
	Physicians	0.04	(0.00, 0.07)	0.01	(-0.01, 0.02)	0.04	(0.01, 0.08)	0.00	(-0.03, 0.03)	0.00	(-0.01, 0.02)	0.02	(-0.01, 0.05)
	Health checkups	0.01	(0.01, 0.02)	0.01	(0.00, 0.01)	0.01	(0.00, 0.01)	0.01	(0.00, 0.01)	0.00	(0.00, 0.01)	0.01	(0.00, 0.01)
	Population density	-0.14	(-0.18, -0.09)	-0.05	(-0.07, -0.03)	-0.11	(-0.16, -0.05)	-0.05	(-0.08, -0.01)	-0.01	(-0.03, 0.00)	-0.04	(-0.08, 0.00)
	Temperature	0.02	(-0.01, 0.06)	0.03	(0.00, 0.05)	0.03	(-0.01, 0.06)	-0.00	(-0.03, 0.03)	0.01	(-0.01, 0.03)	0.00	(-0.03, 0.03)
	Sunshine	0.44	(-0.04, 0.92)	0.12	(-0.19, 0.43)	0.19	(-0.27, 0.66)	0.54	(0.16, 0.93)	0.10	(-0.17, 0.36)	0.47	(0.09, 0.84)
	Park area coverage	0.07	(0.01, 0.12)	0.01	(-0.01, 0.03)	0.07	(0.01, 0.14)	0.01	(-0.04, 0.05)	0.01	(-0.01, 0.02)	0.03	(-0.02, 0.08)
λ		0.70	(0.66, 0.74)	0.42	(0.39, 0.45)	0.68	(0.64, 0.72)	0.67	(0.63, 0.71)	0.38	(0.34, 0.41)	0.67	(0.63, 0.71)
AIC		2119.0		2498.6		2186.9		1466.8		1855.1		1480.7	

Supplementary Table S3. Results from the SDEM excluding healthcare-related control variables (number of physicians per capita and participation rate in Specific Health Checkups) and the proportion of total park area to habitable land area

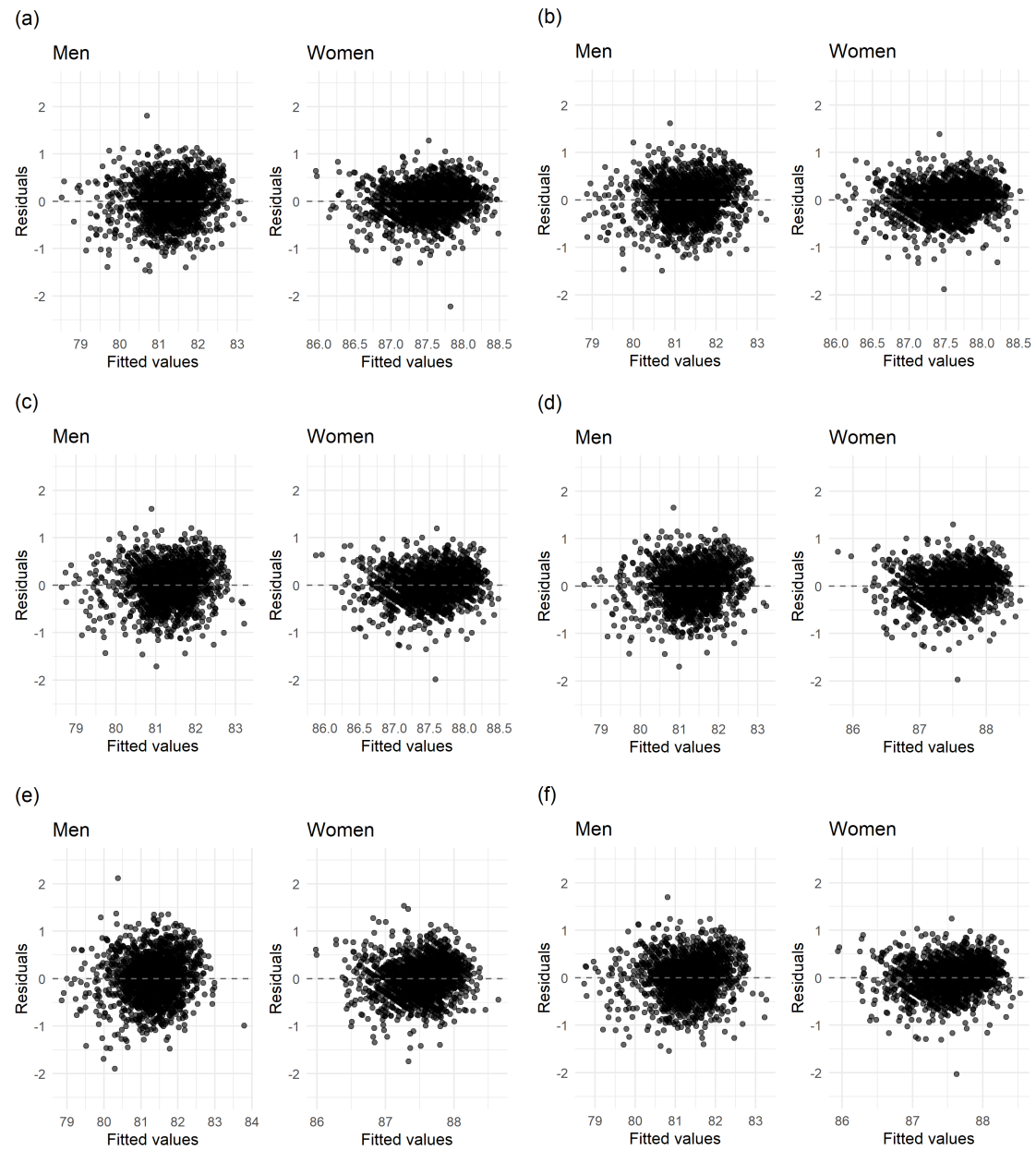
		Men											
		Queen contiguity		Five nearest-neighbours		Inverse distance		Gravity distance		Exponential distance		Double-power distance	
Intercept		82.95	(82.15, 83.75)	82.77	(81.08, 84.47)	83.29	(82.50, 84.08)	83.19	(82.39, 83.99)	82.62	(81.84, 83.41)	82.93	(82.13, 83.73)
β													
	Elderly couple households	0.04	(0.03, 0.05)	0.04	(0.03, 0.06)	0.05	(0.03, 0.06)	0.04	(0.03, 0.06)	0.06	(0.05, 0.08)	0.05	(0.03, 0.06)
	Elderly single households	-0.04	(-0.05, -0.03)	-0.05	(-0.06, -0.04)	-0.04	(-0.05, -0.03)	-0.04	(-0.05, -0.03)	-0.05	(-0.06, -0.03)	-0.04	(-0.05, -0.03)
	Single mother households	-0.09	(-0.16, -0.03)	-0.09	(-0.16, -0.03)	-0.09	(-0.15, -0.02)	-0.09	(-0.16, -0.03)	-0.11	(-0.18, -0.04)	-0.09	(-0.16, -0.02)
	Rental households	-0.00	(-0.01, 0.00)	-0.00	(-0.01, 0.00)	-0.00	(-0.01, 0.00)	-0.00	(-0.01, 0.00)	-0.00	(-0.01, 0.00)	-0.00	(-0.01, 0.00)
	Sales & services workers	-0.01	(-0.02, -0.00)	-0.01	(-0.02, -0.00)	-0.02	(-0.02, -0.01)	-0.01	(-0.02, -0.00)	-0.00	(-0.01, 0.00)	-0.01	(-0.02, -0.00)
	Agricultural workers	-0.02	(-0.02, -0.01)	-0.02	(-0.02, -0.01)	-0.02	(-0.03, -0.01)	-0.02	(-0.02, -0.01)	-0.02	(-0.02, -0.01)	-0.02	(-0.03, -0.01)
	Blue-collar workers	-0.02	(-0.03, -0.02)	-0.03	(-0.03, -0.02)	-0.03	(-0.04, -0.02)	-0.03	(-0.03, -0.02)	-0.02	(-0.03, -0.01)	-0.03	(-0.04, -0.02)
	Unemployment rate	-0.08	(-0.10, -0.05)	-0.08	(-0.10, -0.05)	-0.07	(-0.09, -0.04)	-0.07	(-0.10, -0.04)	-0.11	(-0.14, -0.08)	-0.07	(-0.10, -0.04)
	Taxable income	0.28	(0.15, 0.40)	0.26	(0.13, 0.39)	0.23	(0.11, 0.34)	0.24	(0.11, 0.36)	0.22	(0.09, 0.35)	0.26	(0.15, 0.38)
	No high school diploma	-0.01	(-0.01, -0.00)	-0.00	(-0.01, 0.00)	-0.01	(-0.01, -0.00)	-0.01	(-0.01, -0.00)	-0.02	(-0.02, -0.01)	-0.01	(-0.01, -0.00)
	Population density	-0.00	(-0.03, 0.02)	0.01	(-0.01, 0.04)	-0.02	(-0.04, -0.00)	0.00	(-0.02, 0.02)	0.01	(-0.02, 0.03)	-0.02	(-0.04, 0.00)
	Temperature	-0.02	(-0.05, 0.00)	-0.02	(-0.06, 0.01)	-0.01	(-0.04, 0.01)	-0.01	(-0.04, 0.01)	-0.02	(-0.04, 0.01)	-0.01	(-0.04, 0.01)
	Sunshine	0.07	(-0.25, 0.38)	0.02	(-0.35, 0.40)	-0.25	(-0.58, 0.08)	-0.27	(-0.61, 0.07)	-0.01	(-0.31, 0.29)	-0.10	(-0.43, 0.23)
γ													
	Elderly couple households	0.02	(-0.01, 0.05)	0.04	(0.01, 0.07)	0.04	(0.01, 0.07)	0.03	(0.00, 0.06)	0.01	(-0.00, 0.03)	0.04	(0.01, 0.06)
	Elderly single households	0.03	(0.00, 0.05)	0.00	(-0.02, 0.02)	0.00	(-0.03, 0.03)	0.00	(-0.02, 0.03)	0.01	(0.00, 0.02)	0.00	(-0.02, 0.02)
	Single mother households	-0.21	(-0.36, -0.05)	-0.15	(-0.31, 0.01)	-0.21	(-0.37, -0.05)	-0.21	(-0.35, -0.08)	-0.12	(-0.19, -0.05)	-0.16	(-0.30, -0.03)
	Rental households	0.01	(0.00, 0.02)	0.00	(-0.01, 0.01)	0.01	(-0.00, 0.01)	0.01	(-0.00, 0.01)	0.00	(-0.00, 0.01)	0.00	(-0.00, 0.01)
	Sales & services workers	0.00	(-0.01, 0.02)	0.01	(-0.01, 0.04)	-0.01	(-0.02, 0.01)	-0.01	(-0.02, 0.01)	-0.01	(-0.02, 0.00)	-0.00	(-0.02, 0.01)
	Agricultural workers	-0.01	(-0.02, 0.00)	-0.00	(-0.02, 0.01)	-0.02	(-0.03, -0.01)	-0.02	(-0.03, -0.01)	-0.01	(-0.01, -0.00)	-0.01	(-0.03, -0.00)
	Blue-collar workers	0.00	(-0.01, 0.02)	0.01	(-0.01, 0.02)	-0.01	(-0.03, 0.00)	-0.01	(-0.03, -0.00)	0.00	(-0.00, 0.01)	-0.01	(-0.02, 0.01)
	Unemployment rate	-0.15	(-0.21, -0.08)	-0.14	(-0.20, -0.07)	-0.10	(-0.17, -0.04)	-0.10	(-0.16, -0.05)	-0.08	(-0.10, -0.05)	-0.11	(-0.16, -0.05)
	Taxable income	-0.14	(-0.39, 0.10)	-0.06	(-0.33, 0.21)	0.30	(-0.06, 0.67)	0.25	(-0.02, 0.53)	0.01	(-0.13, 0.15)	0.26	(-0.06, 0.57)
	No high school diploma	-0.04	(-0.05, -0.03)	-0.03	(-0.05, -0.02)	-0.02	(-0.03, -0.00)	-0.02	(-0.03, -0.01)	-0.02	(-0.02, -0.01)	-0.02	(-0.04, -0.01)
	Population density	-0.07	(-0.11, -0.03)	-0.07	(-0.11, -0.02)	-0.11	(-0.17, -0.05)	-0.12	(-0.17, -0.08)	-0.05	(-0.07, -0.03)	-0.09	(-0.14, -0.04)
	Temperature	0.02	(-0.01, 0.06)	0.03	(-0.02, 0.07)	0.02	(-0.02, 0.06)	0.03	(-0.01, 0.07)	0.03	(0.00, 0.06)	0.03	(-0.00, 0.07)
	Sunshine	0.25	(-0.19, 0.70)	0.19	(-0.31, 0.69)	0.52	(-0.01, 1.04)	0.54	(0.05, 1.03)	0.22	(-0.09, 0.54)	0.28	(-0.20, 0.76)
λ		0.69	(0.65, 0.73)	0.71	(0.67, 0.75)	0.76	(0.72, 0.79)	0.72	(0.69, 0.76)	0.44	(0.41, 0.47)	0.70	(0.67, 0.74)
AIC		2181.6		2103.7		2177.7		2163.2		2569.0		2232.6	

	Women											
	Queen contiguity		Five nearest-neighbours		Inverse distance		Gravity distance		Exponential distance		Double-power distance	
Intercept	88.89	(88.23, 89.55)	89.31	(87.94, 90.68)	89.28	(88.63, 89.92)	89.17	(88.51, 89.83)	88.89	(88.25, 89.53)	89.12	(88.47, 89.77)
β												
Elderly couple households	0.02	(0.01, 0.03)	0.02	(0.01, 0.03)	0.02	(0.01, 0.03)	0.02	(0.01, 0.03)	0.03	(0.02, 0.04)	0.02	(0.01, 0.03)
Elderly single households	-0.02	(-0.03, -0.01)	-0.02	(-0.03, -0.01)	-0.02	(-0.03, -0.01)	-0.02	(-0.03, -0.01)	-0.01	(-0.02, -0.00)	-0.02	(-0.03, -0.01)
Single mother households	-0.04	(-0.09, 0.01)	-0.03	(-0.09, 0.02)	-0.04	(-0.09, 0.01)	-0.04	(-0.09, 0.02)	-0.03	(-0.09, 0.03)	-0.03	(-0.09, 0.02)
Rental households	-0.00	(-0.00, 0.00)	-0.00	(-0.00, 0.00)	-0.00	(-0.01, 0.00)	-0.00	(-0.00, 0.00)	-0.00	(-0.01, 0.00)	-0.00	(-0.01, 0.00)
Sales & services workers	-0.01	(-0.01, 0.00)	-0.01	(-0.01, 0.00)	-0.01	(-0.01, -0.00)	-0.01	(-0.01, 0.00)	-0.00	(-0.01, 0.00)	-0.01	(-0.01, 0.00)
Agricultural workers	-0.01	(-0.01, -0.00)	-0.01	(-0.01, -0.00)	-0.01	(-0.01, -0.00)	-0.01	(-0.01, -0.00)	-0.01	(-0.01, -0.00)	-0.01	(-0.01, -0.00)
Blue-collar workers	-0.02	(-0.02, -0.01)	-0.02	(-0.02, -0.01)	-0.02	(-0.03, -0.02)	-0.02	(-0.02, -0.01)	-0.02	(-0.02, -0.01)	-0.02	(-0.03, -0.01)
Unemployment rate	-0.05	(-0.07, -0.03)	-0.05	(-0.07, -0.03)	-0.04	(-0.06, -0.02)	-0.04	(-0.07, -0.02)	-0.08	(-0.11, -0.06)	-0.04	(-0.06, -0.02)
Taxable income	0.00	(-0.10, 0.11)	0.04	(-0.07, 0.15)	0.05	(-0.04, 0.14)	0.04	(-0.06, 0.15)	-0.02	(-0.14, 0.09)	0.06	(-0.04, 0.15)
No high school diploma	-0.01	(-0.01, -0.00)	-0.00	(-0.01, -0.00)	-0.01	(-0.01, -0.00)	-0.01	(-0.01, -0.00)	-0.01	(-0.02, -0.01)	-0.01	(-0.01, -0.00)
Population density	-0.00	(-0.02, 0.02)	0.01	(-0.01, 0.03)	-0.00	(-0.02, 0.01)	0.00	(-0.02, 0.02)	0.00	(-0.02, 0.02)	-0.00	(-0.02, 0.02)
Temperature	0.04	(0.02, 0.06)	-0.01	(-0.04, 0.02)	0.04	(0.02, 0.06)	0.04	(0.02, 0.06)	0.03	(0.01, 0.05)	0.04	(0.02, 0.06)
Sunshine	-0.44	(-0.69, -0.18)	-0.13	(-0.44, 0.18)	-0.68	(-0.94, -0.41)	-0.7	(-0.98, -0.42)	-0.39	(-0.65, -0.14)	-0.64	(-0.92, -0.37)
γ												
Elderly couple households	-0.00	(-0.03, 0.02)	0.00	(-0.02, 0.03)	0.00	(-0.02, 0.03)	0.01	(-0.02, 0.03)	0.00	(-0.01, 0.01)	0.00	(-0.02, 0.03)
Elderly single households	0.03	(0.01, 0.05)	0.02	(0.00, 0.04)	0.02	(-0.01, 0.04)	0.01	(-0.01, 0.03)	0.01	(-0.00, 0.02)	0.02	(-0.00, 0.03)
Single mother households	-0.04	(-0.17, 0.09)	-0.04	(-0.17, 0.08)	-0.01	(-0.14, 0.11)	-0.01	(-0.12, 0.10)	-0.02	(-0.08, 0.04)	0.02	(-0.09, 0.13)
Rental households	0.00	(-0.00, 0.01)	-0.00	(-0.01, 0.00)	-0.00	(-0.01, 0.01)	-0.00	(-0.01, 0.00)	0.00	(-0.00, 0.00)	-0.00	(-0.01, 0.00)
Sales & services workers	0.00	(-0.01, 0.02)	0.01	(-0.01, 0.02)	-0.01	(-0.02, 0.01)	-0.00	(-0.02, 0.01)	0.00	(-0.01, 0.01)	-0.01	(-0.02, 0.01)
Agricultural workers	-0.01	(-0.01, 0.00)	-0.00	(-0.01, 0.01)	-0.01	(-0.02, -0.00)	-0.01	(-0.02, -0.00)	-0.00	(-0.01, 0.00)	-0.01	(-0.01, 0.00)
Blue-collar workers	-0.00	(-0.01, 0.01)	-0.00	(-0.02, 0.01)	-0.01	(-0.02, 0.00)	-0.01	(-0.02, 0.00)	0.00	(-0.00, 0.01)	-0.01	(-0.02, 0.01)
Unemployment rate	-0.12	(-0.17, -0.06)	-0.15	(-0.20, -0.09)	-0.09	(-0.14, -0.03)	-0.09	(-0.13, -0.04)	-0.06	(-0.09, -0.04)	-0.10	(-0.14, -0.05)
Taxable income	-0.10	(-0.30, 0.10)	-0.17	(-0.39, 0.05)	-0.04	(-0.33, 0.25)	-0.04	(-0.27, 0.18)	-0.11	(-0.23, 0.00)	-0.04	(-0.30, 0.21)
No high school diploma	-0.02	(-0.03, -0.01)	-0.02	(-0.04, -0.01)	-0.01	(-0.02, 0.00)	-0.01	(-0.02, -0.00)	-0.01	(-0.02, -0.01)	-0.02	(-0.03, -0.01)
Population density	-0.03	(-0.07, 0.00)	-0.03	(-0.06, 0.01)	-0.03	(-0.08, 0.01)	-0.04	(-0.08, 0.00)	-0.01	(-0.03, 0.00)	-0.03	(-0.07, 0.01)
Temperature	-0.01	(-0.03, 0.02)	0.05	(0.02, 0.09)	-0.00	(-0.03, 0.03)	-0.00	(-0.03, 0.03)	0.01	(-0.01, 0.04)	0.00	(-0.02, 0.03)
Sunshine	0.38	(0.02, 0.74)	-0.09	(-0.50, 0.31)	0.62	(0.20, 1.04)	0.61	(0.21, 1.01)	0.17	(-0.10, 0.44)	0.52	(0.14, 0.91)
λ	0.68	(0.64, 0.72)	0.70	(0.66, 0.73)	0.74	(0.70, 0.78)	0.70	(0.66, 0.73)	0.39	(0.36, 0.42)	0.69	(0.65, 0.73)
AIC	1496.1		1417.3		1476.2		1495.5		1921.1		1512.1	

Supplementary Table S4. Results from the SDEM excluding the proportion of agricultural workers

		Men											
		Queen contiguity		Five nearest-neighbours		Inverse distance		Gravity distance		Exponential distance		Double-power distance	
Intercept		80.92	(80.25, 81.59)	80.15	(78.98, 81.33)	81.13	(80.46, 81.80)	81.06	(80.39, 81.74)	80.21	(79.60, 80.82)	80.78	(80.10, 81.45)
β													
	Elderly couple households	0.05	(0.03, 0.06)	0.05	(0.04, 0.06)	0.05	(0.04, 0.07)	0.05	(0.04, 0.06)	0.07	(0.06, 0.08)	0.05	(0.04, 0.07)
	Elderly single households	-0.04	(-0.05, -0.03)	-0.04	(-0.05, -0.03)	-0.04	(-0.05, -0.03)	-0.04	(-0.05, -0.03)	-0.04	(-0.05, -0.03)	-0.04	(-0.05, -0.03)
	Single mother households	-0.09	(-0.15, -0.02)	-0.08	(-0.14, -0.01)	-0.08	(-0.15, -0.02)	-0.09	(-0.16, -0.03)	-0.10	(-0.17, -0.03)	-0.09	(-0.15, -0.02)
	Rental households	0.00	(-0.00, 0.00)	0.00	(-0.00, 0.00)	0.00	(-0.00, 0.01)	0.00	(-0.00, 0.01)	0.00	(-0.00, 0.01)	0.00	(-0.00, 0.01)
	Sales & services workers	0.01	(0.00, 0.01)	0.01	(-0.00, 0.01)	0.00	(-0.00, 0.01)	0.01	(-0.00, 0.01)	0.01	(0.01, 0.02)	0.01	(-0.00, 0.01)
	Blue-collar workers	-0.01	(-0.01, -0.00)	-0.01	(-0.01, -0.00)	-0.01	(-0.02, -0.01)	-0.01	(-0.02, -0.01)	-0.00	(-0.01, 0.00)	-0.01	(-0.02, -0.01)
	Unemployment rate	-0.05	(-0.08, -0.03)	-0.05	(-0.08, -0.03)	-0.04	(-0.07, -0.01)	-0.05	(-0.08, -0.02)	-0.07	(-0.10, -0.05)	-0.05	(-0.07, -0.02)
	Taxable income	0.39	(0.27, 0.52)	0.37	(0.24, 0.49)	0.34	(0.22, 0.45)	0.34	(0.22, 0.46)	0.36	(0.24, 0.49)	0.38	(0.26, 0.49)
	No high school diploma	-0.02	(-0.02, -0.01)	-0.01	(-0.02, -0.01)	-0.02	(-0.02, -0.01)	-0.02	(-0.02, -0.01)	-0.03	(-0.03, -0.02)	-0.02	(-0.02, -0.01)
	Physicians	0.01	(-0.00, 0.02)	0.01	(-0.00, 0.02)	0.01	(-0.00, 0.02)	0.01	(-0.00, 0.02)	0.01	(-0.01, 0.02)	0.01	(-0.00, 0.02)
	Health checkups	0.01	(0.00, 0.01)	0.01	(0.00, 0.01)	0.01	(0.00, 0.01)	0.01	(0.00, 0.01)	0.01	(0.01, 0.01)	0.01	(0.01, 0.01)
	Population density	0.00	(-0.02, 0.03)	0.02	(-0.00, 0.04)	-0.02	(-0.04, 0.00)	0.00	(-0.02, 0.03)	0.01	(-0.01, 0.03)	-0.02	(-0.04, 0.00)
	Temperature	-0.03	(-0.06, -0.00)	-0.03	(-0.06, 0.01)	-0.02	(-0.04, 0.01)	-0.02	(-0.04, 0.01)	-0.02	(-0.04, 0.01)	-0.02	(-0.04, 0.01)
	Sunshine	0.24	(-0.07, 0.55)	0.04	(-0.34, 0.41)	-0.05	(-0.37, 0.28)	-0.03	(-0.36, 0.31)	0.18	(-0.11, 0.48)	0.10	(-0.23, 0.43)
	Park area coverage	-0.00	(-0.02, 0.02)	-0.00	(-0.02, 0.02)	0.00	(-0.02, 0.02)	0.00	(-0.02, 0.02)	-0.01	(-0.03, 0.02)	0.00	(-0.02, 0.02)
γ													
	Elderly couple households	0.01	(-0.02, 0.04)	0.05	(0.02, 0.08)	0.03	(-0.00, 0.06)	0.02	(-0.01, 0.05)	0.01	(-0.00, 0.02)	0.03	(0.00, 0.06)
	Elderly single households	0.03	(0.01, 0.06)	-0.00	(-0.03, 0.02)	0.00	(-0.02, 0.03)	0.01	(-0.02, 0.03)	0.02	(0.00, 0.03)	0.01	(-0.02, 0.03)
	Single mother households	-0.26	(-0.42, -0.11)	-0.18	(-0.34, -0.03)	-0.27	(-0.43, -0.12)	-0.26	(-0.39, -0.13)	-0.13	(-0.20, -0.06)	-0.21	(-0.35, -0.08)
	Rental households	0.01	(-0.00, 0.01)	0.00	(-0.00, 0.01)	0.00	(-0.01, 0.01)	0.00	(-0.00, 0.01)	0.00	(-0.00, 0.01)	0.00	(-0.01, 0.01)
	Sales & services workers	0.01	(-0.01, 0.02)	0.02	(0.00, 0.04)	0.00	(-0.01, 0.02)	0.00	(-0.01, 0.02)	-0.00	(-0.01, 0.01)	0.00	(-0.01, 0.02)
	Blue-collar workers	0.01	(-0.00, 0.02)	0.01	(0.00, 0.02)	0.00	(-0.01, 0.01)	0.00	(-0.01, 0.01)	0.01	(0.00, 0.02)	0.01	(-0.01, 0.02)
	Unemployment rate	-0.11	(-0.17, -0.04)	-0.11	(-0.18, -0.05)	-0.10	(-0.16, -0.03)	-0.09	(-0.15, -0.03)	-0.06	(-0.08, -0.03)	-0.09	(-0.15, -0.04)
	Taxable income	-0.10	(-0.35, 0.15)	0.01	(-0.25, 0.27)	0.15	(-0.21, 0.51)	0.14	(-0.13, 0.42)	0.02	(-0.11, 0.16)	0.15	(-0.17, 0.46)
	No high school diploma	-0.04	(-0.06, -0.03)	-0.03	(-0.04, -0.02)	-0.03	(-0.04, -0.02)	-0.03	(-0.04, -0.02)	-0.02	(-0.03, -0.02)	-0.03	(-0.04, -0.02)
	Physicians	0.02	(-0.02, 0.05)	0.02	(-0.01, 0.05)	0.08	(0.02, 0.13)	0.05	(0.02, 0.09)	0.01	(-0.00, 0.03)	0.05	(0.02, 0.09)
	Health checkups	0.01	(0.00, 0.01)	0.01	(0.00, 0.01)	0.01	(0.00, 0.01)	0.01	(0.00, 0.01)	0.01	(0.00, 0.01)	0.01	(0.00, 0.01)
	Population density	-0.09	(-0.13, -0.04)	-0.06	(-0.10, -0.02)	-0.11	(-0.16, -0.05)	-0.12	(-0.17, -0.08)	-0.05	(-0.07, -0.03)	-0.09	(-0.14, -0.04)
	Temperature	0.04	(0.01, 0.07)	0.04	(-0.01, 0.08)	0.03	(-0.00, 0.07)	0.04	(0.00, 0.08)	0.04	(0.01, 0.06)	0.04	(0.01, 0.08)
	Sunshine	-0.14	(-0.56, 0.28)	0.10	(-0.39, 0.60)	0.03	(-0.45, 0.52)	0.04	(-0.41, 0.49)	-0.12	(-0.42, 0.18)	-0.12	(-0.56, 0.32)
	Park area coverage	0.05	(-0.00, 0.09)	0.01	(-0.04, 0.06)	0.12	(0.04, 0.20)	0.09	(0.04, 0.15)	0.02	(-0.00, 0.04)	0.10	(0.03, 0.16)
λ		0.67	(0.63, 0.71)	0.69	(0.65, 0.73)	0.73	(0.69, 0.77)	0.70	(0.67, 0.74)	0.42	(0.39, 0.45)	0.68	(0.64, 0.72)
AIC		2190.9		2119.1		2182.5		2160.4		2533.7		2228.4	

	Women											
	Queen contiguity		Five nearest-neighbours		Inverse distance		Gravity distance		Exponential distance		Double-power distance	
Intercept	87.78	(87.24, 88.32)	87.98	(87.04, 88.92)	88.12	(87.58, 88.67)	88.01	(87.46, 88.56)	87.53	(87.05, 88.02)	88	(87.46, 88.54)
β												
Elderly couple households	0.03	(0.01, 0.04)	0.02	(0.01, 0.03)	0.02	(0.01, 0.03)	0.02	(0.01, 0.04)	0.03	(0.02, 0.04)	0.03	(0.01, 0.04)
Elderly single households	-0.01	(-0.02, -0.01)	-0.02	(-0.02, -0.01)	-0.02	(-0.02, -0.01)	-0.02	(-0.02, -0.01)	-0.01	(-0.02, 0.00)	-0.02	(-0.02, -0.01)
Single mother households	-0.03	(-0.09, 0.02)	-0.02	(-0.07, 0.03)	-0.04	(-0.09, 0.02)	-0.03	(-0.09, 0.02)	-0.02	(-0.07, 0.04)	-0.03	(-0.08, 0.03)
Rental households	0.00	(-0.00, 0.00)	-0.00	(-0.00, 0.00)	-0.00	(-0.00, 0.00)	-0.00	(-0.00, 0.00)	-0.00	(-0.00, 0.00)	-0.00	(-0.00, 0.00)
Sales & services workers	0.00	(-0.00, 0.01)	0.00	(-0.00, 0.01)	0.00	(-0.00, 0.01)	0.00	(-0.00, 0.01)	0.00	(-0.00, 0.01)	0.00	(-0.00, 0.01)
Blue-collar workers	-0.01	(-0.01, -0.01)	-0.01	(-0.01, -0.01)	-0.01	(-0.02, -0.01)	-0.01	(-0.02, -0.01)	-0.01	(-0.01, -0.00)	-0.01	(-0.02, -0.01)
Unemployment rate	-0.04	(-0.06, -0.01)	-0.03	(-0.05, -0.01)	-0.02	(-0.05, -0.00)	-0.03	(-0.05, -0.01)	-0.06	(-0.08, -0.04)	-0.03	(-0.05, -0.00)
Taxable income	0.06	(-0.04, 0.17)	0.09	(-0.01, 0.19)	0.11	(0.02, 0.20)	0.10	(0.00, 0.20)	0.06	(-0.05, 0.16)	0.12	(0.02, 0.21)
No high school diploma	-0.01	(-0.02, -0.01)	-0.01	(-0.01, -0.00)	-0.01	(-0.02, -0.01)	-0.01	(-0.02, -0.01)	-0.02	(-0.02, -0.01)	-0.01	(-0.01, -0.01)
Physicians	0.01	(-0.00, 0.02)	0.00	(-0.01, 0.02)	0.00	(-0.01, 0.01)	0.00	(-0.01, 0.01)	0.01	(-0.00, 0.02)	0.00	(-0.01, 0.01)
Health checkups	0.01	(0.00, 0.01)	0.00	(0.00, 0.01)	0.01	(0.00, 0.01)	0.01	(0.00, 0.01)	0.01	(0.01, 0.01)	0.01	(0.00, 0.01)
Population density	0.00	(-0.02, 0.02)	0.01	(-0.01, 0.03)	-0.00	(-0.02, 0.02)	0.00	(-0.02, 0.02)	0.00	(-0.01, 0.02)	-0.00	(-0.02, 0.02)
Temperature	0.04	(0.02, 0.06)	-0.01	(-0.04, 0.02)	0.04	(0.02, 0.06)	0.04	(0.02, 0.06)	0.03	(0.01, 0.05)	0.04	(0.01, 0.06)
Sunshine	-0.32	(-0.57, -0.07)	-0.12	(-0.43, 0.19)	-0.53	(-0.80, -0.27)	-0.54	(-0.82, -0.27)	-0.29	(-0.54, -0.04)	-0.53	(-0.79, -0.26)
Park area coverage	-0.00	(-0.02, 0.01)	-0.00	(-0.02, 0.01)	-0.00	(-0.02, 0.01)	-0.01	(-0.02, 0.01)	-0.01	(-0.03, 0.01)	-0.00	(-0.02, 0.01)
γ												
Elderly couple households	-0.01	(-0.03, 0.01)	0.01	(-0.02, 0.03)	-0.00	(-0.03, 0.02)	0.00	(-0.02, 0.02)	0.00	(-0.01, 0.01)	0.00	(-0.02, 0.02)
Elderly single households	0.03	(0.01, 0.05)	0.02	(0.00, 0.04)	0.02	(-0.00, 0.04)	0.02	(-0.00, 0.03)	0.01	(0.00, 0.02)	0.02	(0.00, 0.04)
Single mother households	-0.07	(-0.19, 0.06)	-0.05	(-0.18, 0.07)	-0.04	(-0.17, 0.08)	-0.03	(-0.14, 0.08)	-0.02	(-0.08, 0.03)	-0.00	(-0.11, 0.11)
Rental households	0.00	(-0.01, 0.01)	-0.00	(-0.01, 0.00)	-0.00	(-0.01, 0.01)	-0.00	(-0.01, 0.00)	-0.00	(-0.00, 0.00)	-0.00	(-0.01, 0.00)
Sales & services workers	0.00	(-0.01, 0.02)	0.01	(-0.01, 0.02)	-0.00	(-0.01, 0.01)	0.00	(-0.01, 0.01)	0.00	(-0.00, 0.01)	-0.00	(-0.01, 0.01)
Blue-collar workers	0.00	(-0.01, 0.01)	0.00	(-0.01, 0.01)	-0.00	(-0.01, 0.01)	-0.00	(-0.01, 0.01)	0.00	(-0.00, 0.01)	-0.00	(-0.01, 0.01)
Unemployment rate	-0.10	(-0.15, -0.04)	-0.13	(-0.18, -0.07)	-0.08	(-0.13, -0.03)	-0.07	(-0.12, -0.02)	-0.05	(-0.07, -0.03)	-0.09	(-0.13, -0.04)
Taxable income	-0.09	(-0.29, 0.11)	-0.13	(-0.34, 0.08)	-0.11	(-0.39, 0.18)	-0.07	(-0.29, 0.15)	-0.10	(-0.21, 0.01)	-0.09	(-0.34, 0.16)
No high school diploma	-0.02	(-0.03, -0.01)	-0.02	(-0.03, -0.01)	-0.02	(-0.03, -0.01)	-0.02	(-0.03, -0.01)	-0.01	(-0.02, -0.01)	-0.02	(-0.03, -0.01)
Physicians	0.02	(-0.01, 0.05)	0.01	(-0.02, 0.04)	0.02	(-0.02, 0.06)	0.01	(-0.02, 0.04)	0.01	(-0.00, 0.02)	0.02	(-0.01, 0.05)
Health checkups	0.00	(0.00, 0.01)	0.01	(0.00, 0.01)	0.01	(0.00, 0.01)	0.01	(0.00, 0.01)	0.00	(0.00, 0.01)	0.00	(0.00, 0.01)
Population density	-0.04	(-0.07, -0.00)	-0.03	(-0.06, 0.00)	-0.03	(-0.08, 0.02)	-0.04	(-0.07, 0.00)	-0.01	(-0.03, 0.00)	-0.03	(-0.07, 0.01)
Temperature	0.00	(-0.02, 0.03)	0.06	(0.02, 0.09)	0.01	(-0.02, 0.04)	0.01	(-0.02, 0.03)	0.02	(-0.01, 0.04)	0.01	(-0.02, 0.04)
Sunshine	0.15	(-0.19, 0.49)	-0.12	(-0.51, 0.28)	0.32	(-0.07, 0.71)	0.31	(-0.05, 0.68)	0.02	(-0.23, 0.27)	0.32	(-0.04, 0.67)
Park area coverage	0.03	(-0.01, 0.06)	0.01	(-0.03, 0.05)	0.04	(-0.02, 0.10)	0.02	(-0.02, 0.07)	0.01	(-0.01, 0.02)	0.04	(-0.01, 0.10)
λ	0.66	(0.62, 0.70)	0.68	(0.64, 0.72)	0.72	(0.68, 0.76)	0.68	(0.63, 0.72)	0.38	(0.35, 0.41)	0.67	(0.63, 0.71)
AIC	1477.3		1407.0		1464.3		1478.5		1861.7		1490.2	



Supplementary Figure S1. Residuals vs fitted values plot for the main SDEM

(a) Queen contiguity; (b) Five nearest-neighbours; (c) Inverse distance; (d) Gravity distance; (e) Exponential distance; (f) Double-power distance