pagepress

Geospatial Health

Geospatial Health 2026; 21:1498
doi:10.4081/gh.2026.1498

Spatial risk of hypertension in rural China: modelling the effect of dietary, behavioural and climate factors

Jie Wang,[1] Enwei Zhang,[2] Kun Yang[3,4]

[1]Chongqing City Management University; [2]Institute of International Rivers and Eco-Security, Yunnan University, Kunming; [3]Faculty of Geography, Yunnan Normal University, Yunnan; [4]The Engineering Research Center of GIS technology in western China, National Ministry of Education, Yunnan Normal University, Kunming, China

Abstract

Hypertension poses a major health challenge for the rural elderly in China, but evidence on its spatial patterns and key influencing factors is still limited. This study examined the spatial distribution of hypertension prevalence among rural older adults assessing its associations with dietary, behavioural, socioeconomic and environmental variables. Pearson correlation and maximum entropy (MaxEnt) were used to analyze correlations and identify spatial risk levels. The results showed that hypertension prevalence was negatively correlated with grain intake (r=-0.600, p=0.002) and poultry consumption (r=-0.504,p=0.010) and alcohol use showed the highest contribution among behavioural variables (39.2%) in the MaxEnt model. Climate zones were also associated with prevalence (r=-0.260,p=0.010), with higher risk in temperate and some subtropical regions. The MaxEnt model showed good discriminatory ability (area under the curve (AUC)=0.871) in identifying hypertension high-risk areas mainly in northern and north-eastern rural China. This study provides spatial epidemiological evidence on hypertension among the rural elderly, suggesting that dietary patterns, alcohol consumption and climate conditions may be associated with spatial risk variation. These findings support the use of MaxEnt as an exploratory tool for chronic disease spatial analysis and may provide spatial reference for public health strategies and resource allocation.

Key words: rural elderly; hypertension; spatial distribution; socioeconomic factors; MaxEnt model, China.

Correspondence: Enwei Zhang Institute of International Rivers and Eco-Security, Yunnan University, Kunming, 650500, China.
E-mail: withwangjie@163.com

Introduction

In recent years, the prevalence of hypertension among the rural elderly in China has continued to rise, showing significant spatial variation across regions. Notably, clear high-risk clusters have emerged in the eastern coastal areas, the middle and lower reaches of the Yangtze River, and parts of south and southwest China (Lu *et al.*, 2017; Wei *et al.*, 2025). Globally, the burden of hypertension in rural areas of Low- and Middle-Income Countries (LMICs) is also increasing. A systematic review and meta-analysis covering 66 LMICs showed that between 1990 and 2020, the prevalence of hypertension in rural areas rose from approximately 23.8% to 29.3%, with a faster growth rate than in urban areas and a gradually narrowing urban–rural gap, suggesting that rural regions have become an emerging focus for hypertension prevention and control (Ranzani *et al.*, 2022). According to statistics from the World Health Organization, around 46% of hypertensive patients worldwide remain undiagnosed and only 8% achieve effective control, with rural areas being particularly affected (Schutte *et al.*, 2021).

In China, the situation of hypertension in rural areas is equally severe. A retrospective analysis based on national data from 2004 to 2018 showed that the prevalence of hypertension among adults increased from 24.9% to 38.1%, with a particularly notable rise in rural areas (Zhang *et al.*, 2023). Taking northeast China as an example, the prevalence of hypertension in rural areas has reached 25.9%, which is higher than the urban rate of 22.7%. However, the hypertension control rate in rural areas is only 5.0%, i.e. significantly lower than the 13.7% observed in cities, which reflects clear gaps in hypertension prevention, treatment and management capacity in rural communities (Wang *et al.*, 2018). The disparity in hypertension management between urban and rural middle-aged and elderly populations in China remains significant. Data from 2015 show that the awareness, treatment and control rates of hypertension in rural areas were 5.2%, 5.2% and 4.9% lower, respectively, than those in urban areas, differences that remained statistically significant even after adjusting for age and other confounders (Wang *et al.*, 2018; Cheng *et al.*, 2022). Between 2011 and 2021, the prevalence of hypertension in rural areas increased from 28.4% to 35.6% and socioeconomic disparities strongly influenced inequalities in hypertension management (Fan *et al.*, 2023). Although awareness and treatment rates improved during this period, the control rate remained low, and the economic burden caused by hypertension continued to grow. A cross-sectional study of rural residents aged 40 years and above in northeast China further confirmed this gap; even when applying the less stringent criteria of the Chinese guidelines, the hypertension control rate in rural areas was only 3.7%, *i.e.* far lower than the urban rate of 11.4%, which highlights the persistently low and uneven level of hypertension control in rural communities (Xing *et al.*, 2019). Research has shown that social behaviours, dietary patterns, and natural environmental factors all play important roles in the development and progression of hypertension. Multiple international reviews and meta-analyses indicate that high salt intake, alcohol consumption, obesity and physical inactivity are the main behavioural risk factors for hypertension (Mills *et al.*, 2020; Nan *et al.*, 2021). A large cross-sectional study of over 430,000 Chinese adults (excluding those already diagnosed) found that a higher frequency of coarse grain intake was significantly associated with a lower risk of undiagnosed hypertension; specifically, individuals who consumed coarse grains daily had about a 22% lower risk than non-consumers, and their mean blood pressure levels were significantly reduced, suggesting that incorporating coarse grains as staple foods may have important protective effects for hypertension prevention (Liu *et al.*, 2020). In addition, a study conducted in five rural counties in China reported that for every 0.1 increase in the Normalized Difference Vegetation Index (NDVI) of residential areas, the prevalence of hypertension among rural residents decreased by approximately 8%, while the mean systolic and diastolic blood pressure levels dropped by 0.88 and 0.64 mm Hg, respectively, thereby providing further evidence of the positive impact of a favourable natural environment on hypertension prevention and control (Jiang *et al.*, 2021).

In recent years, the MaxEnt model has been widely applied in spatial prediction studies of infectious diseases and environmental exposure risks due to its low dependence on complete geographic coordinates for cases, strong generalization ability and straightforward interpretability of results. For example, a study based on H7N9 avian influenza cases in China from 2013 to 2017 successfully used this model based on climate, NDVI, population density and other variables (Yang *et al*., 2025). They identified potential high-risk areas and the predicted risk closely matched the actual epidemic distribution, thereby verifying the applicability of MaxEnt in spatial epidemiology (Yang *et al*., 2025). In the field of chronic diseases, the application of MaxEnt is still in its early exploratory stage. For instance, a study using Geographically and Temporally Weighted Regression (GTWR) based on outpatient follow-up data of rural hypertension patients in Fujian Province found significant spatial disparities in follow-up frequency and healthcare utilization among elderly and low-income groups (Fu *et al.*, 2024). In addition, the China Health and Retirement Longitudinal Study (CHARLS), a nationally representative stratified survey that includes demographic characteristics, health status and behavioural information, has shown that air pollution of particulate matter of ≤2.5 µm ($PM_{2.5}$) is an important environmental risk factor for hypertension (Huang *et al.*, 2019). These authors also showed that this kind of pollution has a clear spatial distribution pattern, with every 10µg/m³ increase in $PM_{2.5}$ concentration associated with an approximately 11% higher risk of hypertension in adults (Hazard Ratio (HR)≈1.11).

This study focused on the spatial distribution patterns of hypertension among the rural elderly in China by integrating social and behavioural factors such as alcohol consumption, grain and poultry intake as well as natural environmental variables including climate zones and green space coverage. We aimed at identification of the potential driving factors of high-risk hypertension, since this would support targeted interventions and optimize regional health resource allocation in the context of the age structure of the rural population.

Materials and Methods

The dependent variable in the research approach was hypertension defined as self-reported or physician-diagnosed systolic blood pressure and/or diastolic blood pressure We followed the guidelines issued by the Chinese Society of Cardiology; the Chinese Medical Association; the Hypertension Committee of Cross-Straits Medicine Exchange Association; the Cardiovascular Disease Prevention and Rehabilitation Committee; and the Chinese Association of Rehabilitation Medicine (2024).

Data sources

Data on food consumption, population density, Gross Regional Product (GRP), Digital Elevation Model (DEM), climate zones and NDVI were obtained from national statistical yearbooks and the Chinese Academy of Sciences.

Individual sample data

Case information was obtained from the harmonized CHARLS, which not only includes demographic characteristics, health status, but also behavioural information of the rural elderly population (Zhao *et al*., 2023).

Basic geographic data

The base map data consisted of the 2015 township administrative boundary dataset for China, which provides spatial distributions of township-level administrative boundaries for all provinces, cities, and counties as of 2015 (Xu, 2023).

Socioeconomic and environmental data

Socioeconomic data included rural household food consumption, population density and GRP. The environmental data included (NDVI and DEM. Relevant data were obtained from the National Bureau of Statistics (https://www.stats.gov.cn/) and the Resource and Environment Science and Data Center of the Chinese Academy of Sciences (Xu, 2017). To ensure spatial consistency, all data were reprojected using a unified coordinate system (WGS_1984_UTM_Zone) and resampled to the same raster resolution for subsequent spatial correlation analysis and MaxEnt spatial modelling.

Investigated variable definitions

Elderly population

Individuals , according to the Chinese standards for aging (Kowal & Dowd, 2001).

Food intake

Grain and poultry consumption were measured as annual per capita consumption (kg/person/year), based on data from the National Bureau of Statistics of China.

Socioeconomic factors

Population density was defined as the number of people per square kilometer (persons/km²), and GRP was used as an indicator of regional economic development.

Climate zones

Climatic zones were classified into eight categories based on standard climatic regionalization data from the Chinese Academy of Sciences, including plateau climate zone, northern temperate zone, middle temperate zone, southern temperate zone, northern subtropical zone, middle subtropical zone, southern subtropical zone, and tropical zone.

Individual-level factors

Body mass index (BMI)

BMI was calculated as weight in kilograms divided by the square of height in meters (kg/m²), which was based on measured anthropometric data from the CHARLS survey previously used by Wang *et al.* (2021), *i.e.* underweight:<18.5kg/m²; normal: between 18.5≤and<24.0kg/m²;overweight: between 24.0≤and<28.0kg/m²; and obese: ≥28.0kg/m².

Education

The education level was categorized into three groups: "junior high school or below", "senior high school or below" and "college or above".

Diabetes

Defined as self-reported or physician-diagnosed diabetes, which means fasting plasma glucose ≥126 mg/dL or glycated haemoglobin (HbA1c) ≥6.5% based on the American Diabetes Association criteria (El Sayed *et al.*, 2023).

Smoking

Smoking status was categorized as a binary variable indicating whether the individual was a current/former smoker (yes) or had never smoked regularly (no).

Alcohol consumption

Alcohol consumption was based on the CHARLS dataset and defined as whether respondents reported any alcohol intake within the past year (yes/no). Detailed quantitative information on alcohol consumption (*e.g.*, frequency or amount) was not consistently available and therefore could not be incorporated into the analysis.

Depressive symptoms

Depressive symptoms were evaluated using the 10-item Center for Epidemiologic Studies Depression Scale (CES-D10). A threshold score of ≥10 was applied to define clinically relevant depressive symptoms, consistent with prior validation studies in Chinese populations (Cartierre *et al.*, 2011).

Methods

Factor-coupling and spatial association analysis

This study employed the Band Collection Statistics tool to conduct spatial correlation analyses between the rasterized hypertension prevalence of the rural elderly population derived from the harmonized CHARLS and various socioeconomic and natural environmental factors, including population density, GRP, food consumption, NDVI and DEM. Pearson's correlation analysis was applied to preliminarily assess the linear relationships between hypertension prevalence and these variables. The Pearson correlation coefficient (r) was calculated to quantify the strength and direction of associations, with statistical significance evaluated using corresponding *p*-values.

This tool enables multivariate statistics for multiple raster bands and can automatically generate covariance and correlation matrices. It has been widely applied in spatial epidemiology and ecological modelling for factor coupling and integrated spatial analysis (Tsutsumida *et al.*, 2019; Niraj *et al.*, 2023). The correlation between bands is calculated as the ratio of the covariance to the product of the Standard Deviations (SDs), consistent with the definition of the Pearson correlation coefficient, as defined by the following formula for calculating the covariance (Eq. 1) and the correlation coefficient (Eq. 2) between raster layers:

$$Cov_{ij} = \frac{1}{N-1}\sum_{k=1}^{N}(Z_{ik} - \mu_i)(Z_{jk} - \mu_j) \quad \text{Eq. 1}$$

$$Corr_i = \frac{Cov_{ij}}{\sigma_i \sigma_j} \quad \text{Eq. 2}$$

where Z_{ik} and Z_{jk} are the values of layers i and j at pixel k, respectively; μ_i and μ_j the mean values of layers i and j; σ_i and σ_j the SDs of layers i and j; and N the total number of raster pixels.

This correlation analysis provides supporting evidence for exploring the preliminary associations between hypertension prevalence among the rural elderly and social behaviours, dietary factors and environmental variables, serving as an essential input and validation basis for subsequent MaxEnt spatial risk modelling.

Hypertension risk modelling using MaxEnt

Originally designed for making least-biased probabilistic predictions given partial information in physics and statistics (Wang *et al.,* 2021), MaxEnt is a spatial distribution modelling tool based on the principle of maximum entropy, which has been widely applied in recent years to studies of potential species distributions, environmental risk assessment, and disease spatial risk prediction (Zhang *et al*., 2021; Ansari *et al*., 2022). Due to its capacity for multi-variable integration and spatial heterogeneity detection, this approach has increasingly been used for the spatial modelling of the distribution of both infectious and non-communicable diseases.

MaxEnt's model performance is evaluated using the Receiver Operating Characteristic (ROC) curve and the Area Under This Curve (AUC). The evaluation of the relative contribution of each environmental variable is given as the permutation importance (expressed in percent) that is used to find the predictive performance. The ROC curve plots sensitivity against 1 − specificity across thresholds, and the AUC provides a threshold-independent measure of model discrimination (from 0.5 = random to 1 = perfect). The MaxEnt captures the contributions of multiple variables to the spatial distribution pattern. In our case, the dataset was randomly divided into training (75%) and testing (25%) subsets, and the model was run multiple times to obtain average AUC values.

The variable importance was assessed using the Jackknife test, which evaluates model gain when each variable is used in isolation and when omitted from the full model. Variables yielding high gain when used alone or causing substantial decreases in gain when excluded were considered influential.

For assessing the risk of hypertension among the rural elderly, where sample point distribution is often uneven and data may be missing in certain areas, MaxEnt can reproduce the potential spatial distribution pattern to the greatest extent possible under the constraints of limited known samples and multiple environmental variables. This capability helps identify high-risk clusters and provides guidance for targeted prevention and control strategies. When the true distribution of the study object is unknown, the model assumes that all locations within the study area have equal distribution probability. Under the constraints imposed by observed sample points and environmental variables, the model estimates the probability distribution of maximum entropy yielding the least biased distribution consistent with those constraints.

In this study, the set of pixels representing hypertension prevalence was denoted by the probability density function satisfying the normalization condition:

$$\sum_{x\in X}\pi(x)=1 \quad \text{Eq. 3}$$

with the entropy defined as:

$$H(\pi)=-\sum_{x\in X}\pi(x)\,ln\,\pi(x) \quad \text{Eq. 4}$$

where $H(\pi)$ is the entropy of the probability distribution; $\pi(x)$ the probability of hypertension occurrence at location x; and ln represents the natural logarithm.

The optimal probability distribution is obtained by the maximum entropy under the given constraints:

$$\pi^* = arg\max_{\pi} H(\pi) \quad \text{Eq. 5}$$

subject to:

$$\sum_{x\in X}\pi(x)f_k(x)=C_k\ (k=1,2,\cdots,k) \quad \text{Eq. 6}$$

where π^* denotes the optimal probability distribution; arg $\max_{\pi}$ H(π) represents the maximization of entropy; $f_k(x)$ denotes the k-th environmental or socio-behavioural feature at location x; c_k represents the empirical expectation of $f_k(x)$ derived from the sample data; and k is the total number of features. Given the observed sample points and constraints from social behaviours, dietary structure, and environmental factors, the maximum entropy distribution was used to estimate the potential spatial distribution of hypertension risk among the rural elderly. This approach facilitates the identification of high-risk areas and supports targeted community-level interventions.

Results

Association of dietary and behavioural factors with hypertension

The prevalence of hypertension among the rural elderly showed varying degrees of association with key dietary and behavioural indicators. Both grain and poultry consumption had significant negative correlations with hypertension prevalence (r=-0.600, p=0.002) and (r=-0.504,p=0.010), respectively. Vegetable consumption showed a weak, negative correlation (r=-0.356,p=0.081), which was not statistically significant but approached the threshold. Although showing a weak negative correlation with hypertension prevalence, consumption of red meat (beef, pork, mutton) and aquatic products were not statistically significant. The weak positive correlation with egg consumption (r=0.274, p=0.185) was also no statistically significant. No significant correlations were observed between hypertension prevalence and socioeconomic indicators, including population density population density (r=0.011, p=0.911) and GRP (r=0.078, p=0.443) as shown in Table 1.

The results for grain consumption levels were generally consistent with the correlation analysis. Hypertension prevalence was highest in the 120-160 kg range (41.9±11.8%) and showed a decreasing trend with increasing grain intake, declining to 37.6 (± 12.4%) in the 160-200 kg range and further to (27.8±8.1%) in the 200-240 kg range. No cases were observed in the lowest (0-120 kg) and highest in the 240-280 kg consumption groups, as shown in Figure 1 and Table 2.

Hypertension prevalence was relatively high in the 0–5 kg and 5-7.5 kg poultry consumption groups (39.9±11.67%) and (40.3±11.4%), respectively, decreased markedly to (26.8±9.2%) in the 7.5–10 kg range but remained at (27.0±5.4%) in the 10-12.5 kg group. The lowest values were observed in the 12.5-15 kg range (22.8±13.1%). These patterns suggest a potential negative association between poultry consumption and hypertension prevalence, as shown in Figure 2 and Table 3.

Association of environmental factors and its spatial distribution

The Pearson correlation analysis indicated that hypertension among the rural elderly is significantly negatively correlated with climate zones (r=−0.260, p=0.010). However, neither NDVI (r=0.078, p=0.443) nor DEM (r=0.148, p=0.146) were statistically correlated with hypertension prevalence although they did show weak positive values (Table 4). The hypertension prevalence varied significantly across different climate zones. The highest values were observed in the southern temperate zone (55.0±10.0%), followed by the northern temperate zone (47.8±12.9%) and the southern subtropical zone (43.4±12.0%). The central temperate zone (38.8±10.1%) and central subtropical zone (35.8±8.9%) showed moderate levels, while the northern subtropical zone (16.0±0%) and northern tropical zone (24.0±10.7%) had relatively lower prevalence rates. No cases were recorded in the plateau and tropical climate zones. This pattern is generally consistent with the correlation results, as shown in Figure 3 and Table 5.

Spatial risk distribution based on the MaxEnt model

The spatial distribution of hypertension risk among the rural elderly showed a clear east–west gradient. High-risk areas (levels 4 and 5) were found to be concentrated mainly in the eastern coastal provinces, the middle and lower reaches of the Yangtze River as well as parts of south and southwest China. In contrast, low-risk zones (levels 1 and 2) were predominantly distributed in the Northwest and in the plateau regions. Missing data regions (gray) largely corresponded to high-altitude or sparsely populated areas where sampling coverage is limited. This pattern is generally consistent with the correlation results shown in Figure 4.

The ROC curve (Figure 5) indicated an average AUC value of

Table 1. Correlation of hypertension prevalence with dietary patterns and socioeconomic factors among rural elderly in China.

Variable Grade	Grain	Vegetable	Red meat	Poultry	Egg	Aquatic products	Population density	GRP
Correlation coefficient	-0.600	-0.356	-0.171	-0.504	0.274	-0.263	0.011	0.078
p	0.002**	0.081	0.413	0.010*	0.185	0.204	0.911	0.443

*GRP, gross regional product; * p≤0.05; ** p≤0.01.*

0.871, which is significantly higher than 0.7, confirming the discriminative power and stability of the constructed model. The Jackknife test indicated that alcohol consumption had one of the highest individual contributions. However, it should be said that the 39.2% contribution measured reflects the model's sensitivity to the presence of alcohol consumption rather than a quantitative or dose–response relationship. The grain consumption showed the largest permutation importance (45.6%), with the climate zones also showing a notable contribution (14.7%). Other variables, including age, BMI, diabetes and dyslipidemia showed relatively lower contributions (Figure 6 and Table 6). Overall, hypertension prevalence among the rural elderly shows spatial heterogeneity at the regional level.

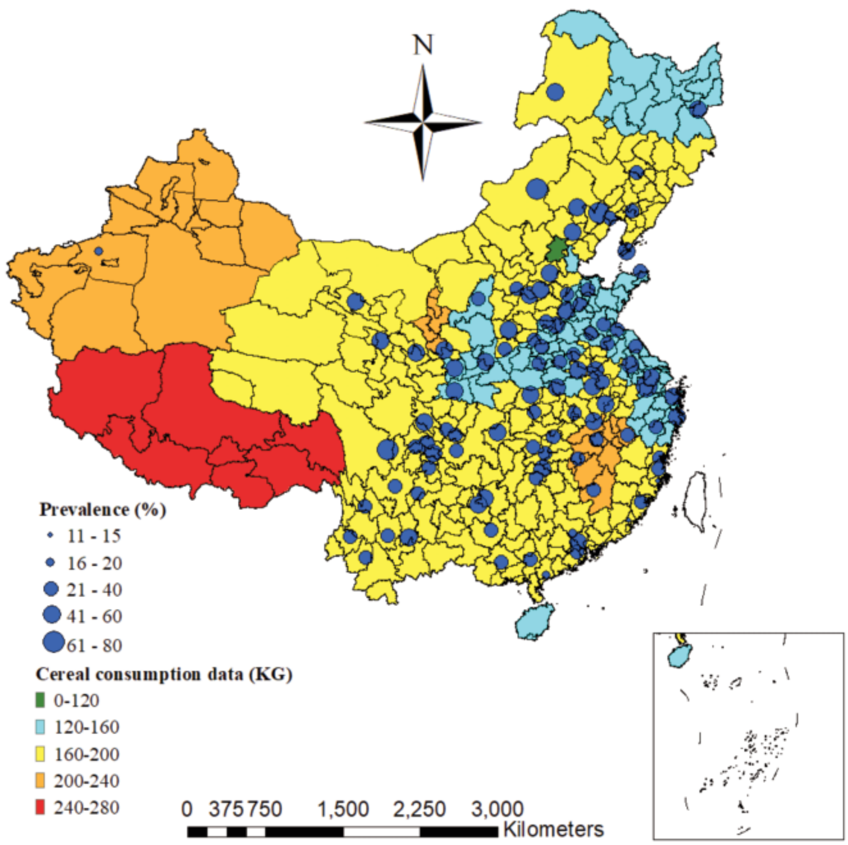

Figure 1. Spatial distribution of hypertension prevalence and grain consumption among the rural elderly in China.

Table 2. Correlation of hypertension prevalence with grain intake.

Annual grain consumption (kg)	Hypertension prevalence (%)	SD
0~120	0	0
120~160	41.9	11.8
160~200	37.7	12.4
200~240	27.8	8.1
240~280	0	0

SD, standard deviation.

Table 3. Correlation of hypertension prevalence with poultry consumption.

Annual poultry consumption (kg)	Hypertension prevalence (%)	SD
0~5	39.9	11.7
5~7.5	40.3	11.4
7.5~10	26.8	9.2
10~12.5	27.0	5.4
12.5~15	22.8	13.1

SD, standard deviation.

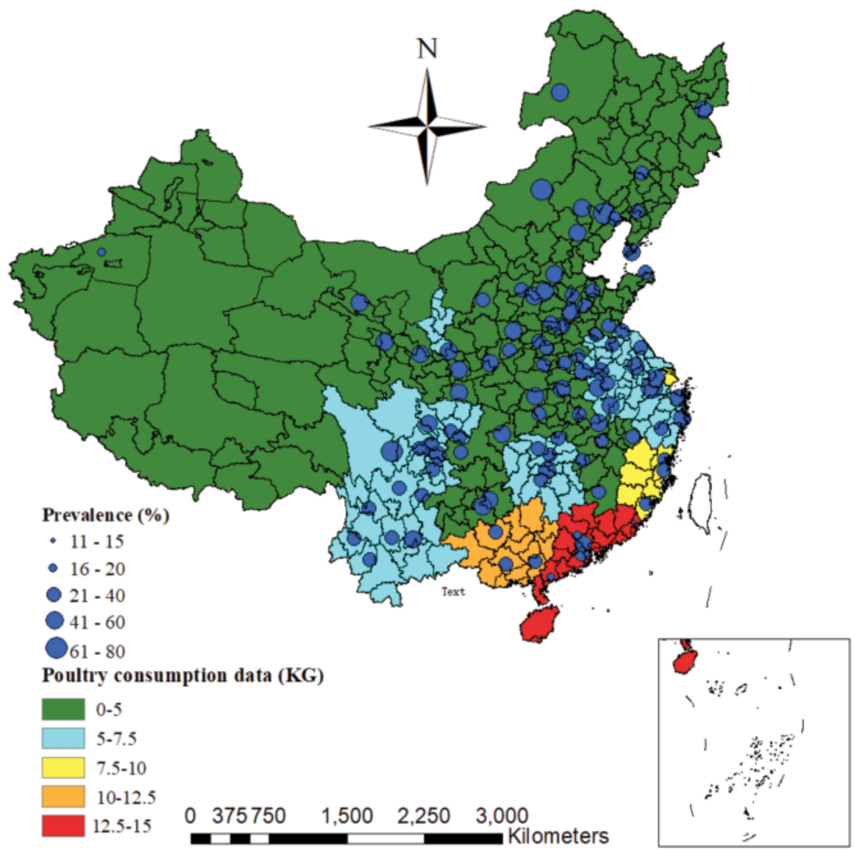

Figure 2. Spatial distribution of hypertension prevalence and poultry consumption among the rural elderly in China.

Table 4. Correlation of hypertension prevalence and environmental factors.

Grade Variable	NDVI	DEM	Climate zone
Correlation coefficient	0.078	0.148	-0.260
p	0.443	0.146	0.010**

*NDVI, normalized difference vegetation index; DEM, digital elevation model; * p≤0.05; ** p≤0.01.*

Table 5. Hypertension prevalence across climatic zones rural elderly populations in China.

Climate zone	Hypertension prevalence (%)	SD
Plateau climate	0	0
Northern temperate	47.8	12.9
Central temperate	38.8	10.1
Southern temperate	55.0	10.0
Northern subtropical	16.0	0
Central subtropical	35.8	8.9
Southern subtropical	43.4	12.0
Northern tropical	24.0	10.7
Central tropical	0	0

SD, standard deviation.

Discussion

Associations with dietary and behavioural factors

Previous studies have reported consistent associations between whole grain intake and hypertension outcomes. A meta-analysis of 28 prospective cohort studies found that higher whole grain intake was associated with a lower risk of hypertension (Aune *et al.*, 2016). Similar findings have been reported in Chinese populations, where higher intake levels were associated with reduced incidence risk (HR ≈ 0.82) (Kolak *et al.*, 2022). Moreover, results from randomized controlled trials have shown that oat intake can reduce systolic blood pressure by an average of about 2.8 mmHg (Llanaj *et al.*, 2022). These findings are generally consistent with negative correlation between grain intake and hypertension prevalence observed in this study.

Poultry consumption also showed a negative association with hypertension prevalence. Previous studies have suggested that replacing red meat with poultry may be associated with improved cardiovascular outcomes (Zhang & Zhang, 2018). Several cohort studies conducted in East Asian and Western adult populations have further confirmed that poultry intake is negatively associated with blood pressure levels (Tark *et al.*, 2025), which aligns with the present findings. Our finding of alcohol consumption giving

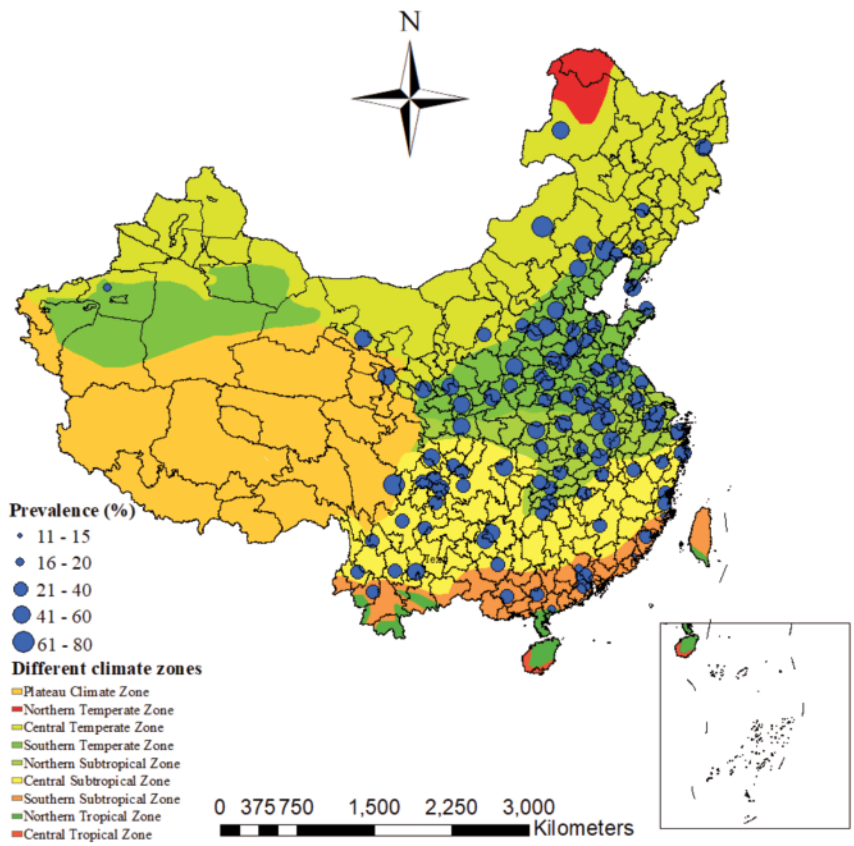

Figure 3. Spatial distribution of hypertension prevalence and climate zones among the rural elderly in China.

Table 6. Variable contribution and permutation importance in the MaxEnt model.

Variable	Contribution (%)	Permutation importance (%)
Alcohol intake	39.2	23.8
Grain consumption	27.1	45.6
Poultry consumption	0.7	4.1
Climate zones	14.7	16.8
Age	4.5	1.7
Body mass index (BMI)	3.9	0.8
Diabetes	2.8	3.8
Depressive symptoms	2.6	0.9
Cesd-10	1.9	0.1

the highest contribution among the behavioural variables is consistent with previous studies reporting that higher levels of alcohol intake are associated with increased hypertension risk (Wang *et al.*, 2022). A systematic review and meta-analysis also reported higher alcohol consumption levels tend to have an elevated risk of hypertension (HR >1) (Roerecke *et al.*, 2018; Cecchini *et al.*, 2024). However, the MaxEnt data may reflect this high contribution of alcohol consumption as a model prediction rather than a dose–response or quantitatively graded effect.

Although vegetable intake was not found to be statistically sig-

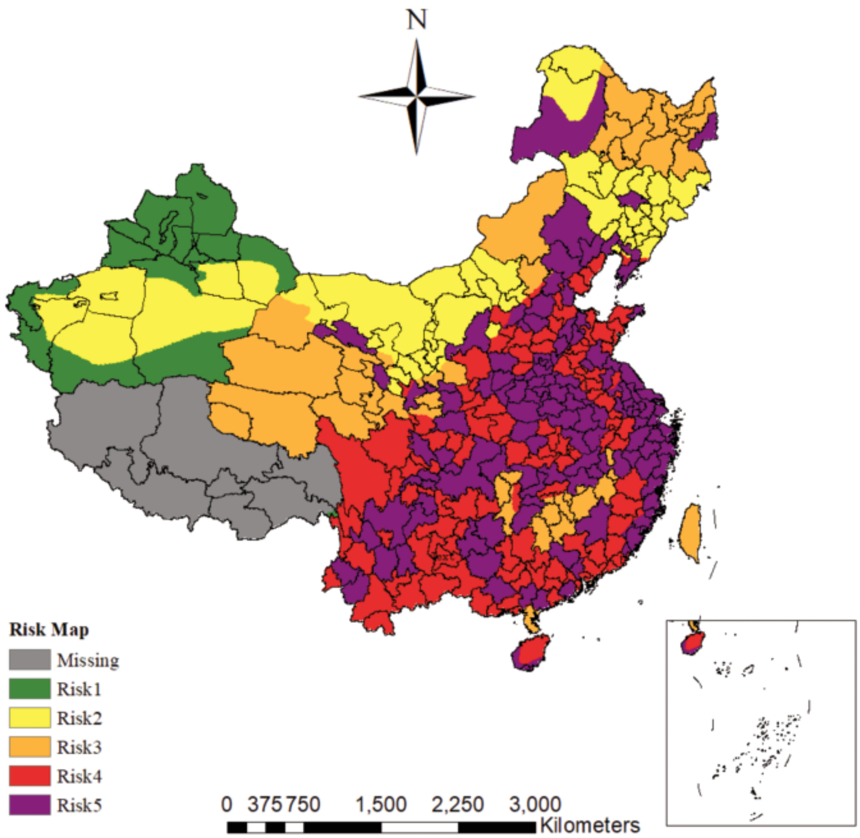

Figure 4. Spatial risk map of hypertension in rural elderly populations.

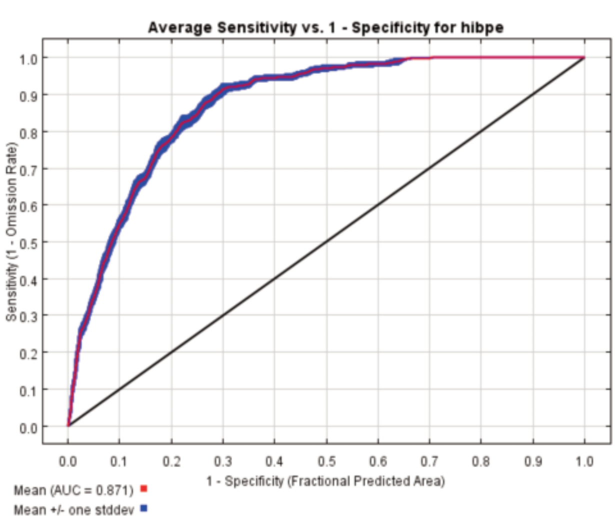

Figure 5. Receiver operating characteristic (ROC) curve of rural elderly hypertension spatial risk model.

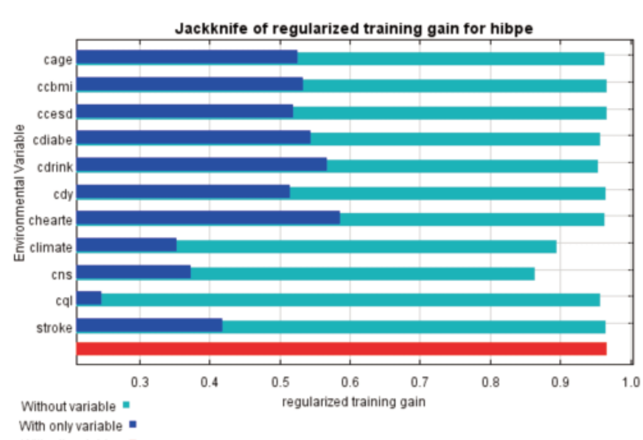

Figure 6. Jackknife test of social and environmental variables in the MaxEnt model.

nificant in this study, previous large-scale prospective cohort studies in China (He *et al.*, 2023) have reported inverse associations between fruit and vegetable intake and hypertension risk (relative risk ≈ 0.65). A broader meta-analysis also suggested that increased fruit and vegetable intake is associated with a reduced risk of hypertension (relative risk ≈ 0.97), corresponding to an approximate 3% reduction (He *et al.*, 2023; Madsen *et al.*, 2023). It should be noted that these RR estimates were obtained from prior cohort studies and are cited for contextual interpretation only, as the present study did not estimate relative risk. These findings suggest that further investigation is warranted to better understand this relationship.

Associations with environmental factors

In the environmental dimension, climatic zones were found to be negatively associated with hypertension prevalence among the rural elderly, with temperate and some subtropical regions showing generally higher prevalence rates. This pattern is broadly consistent with previous studies. Previous research has reported that diurnal temperature variability is associated with modest increases in blood pressure. For example, data from the China Hypertension Survey indicate that a 2.28 °C increase in diurnal temperature variability is associated with an average increase of 0.4 mmHg in SBP among hypertensive patients in subtropical regions (95% CI: 0.07–0.75). In temperate, continental climate zones, has been shown to increase by approximately 0.3 mmHg and 0.6 mmHg among hypertensive and pre-hypertensive populations, respectively, with stronger effects observed during warmer seasons (Yan *et al.*, 2024). Although these changes appear small at the individual level, they may still be relevant at the population level, particularly under sustained environmental exposure. Additionally, previous reviews have suggested that seasonal temperature variability may be associated with variations in blood pressure (Rossios *et al.*, 2023). NDVI and DEM did not show any significant association with hypertension prevalence in the single-variable analysis. Previous studies have suggested that the relationship between green space coverage and hypertension risk may be non-linear or context-dependent (Jiang *et al*., 2021). In rural areas, elevation and vegetation may influence health outcomes indirectly through local microclimatic conditions rather than through direct effects. Further investigation is warranted to better understand these relationships.

Methodological considerations

The present study suggests that the MaxEnt model can be used to explore spatial hypertension risk patterns when integrating social behaviours, dietary structures and macro-environmental variables, achieving an AUC of 0.871. This high level was also reached in a a study simulating the spatial risk of dengue fever in the Pearl River Delta, in which case socioeconomic variables accounted for up to 55% of the explanatory power (Liu *et al.*, 2018). Moreover, the results suggest that MaxEnt can capture the combined contributions of behavioural and environmental variables to spatial variation. However, sparse samples in plateau and remote areas may affect the stability of local. In addition, due to data resolution constraints, the characterization of individual behavioural trajectories, healthcare accessibility and dynamic climate exposure remains limited. Future studies could incorporate multi-level spatial modelling approaches (e.g., Multi-Scale Geographically Weighted Regression (MGWR) and Geodetector) and introduce higher-resolution environmental and behavioural data to further improve the robustness and interpretability of spatial risk analysis (Wang *et al*., 2016; Li *et al.*, 2017; Duan *et al.*, 2024). From a methodological perspective, the results suggest that the MaxEnt model has potential applicability in the spatial epidemiology of chronic diseases and can serve as an exploratory tool for identifying spatial risk patterns. However, model performance depends on the coverage and completeness of input variables. Due to data resolution limitations, the representation of individual-level behavioural and exposure factors remains constrained, which may limit the model's ability to capture fine-scale spatial heterogeneity. In addition, model performance was primarily assessed using AUC, and the lack of spatial cross-validation may lead to potential overestimation of predictive accuracy in regions with spatial autocorrelation. Therefore, the results should be interpreted with caution.

Conclusions

This study highlights the spatial heterogeneity of hypertension among the rural elderly and its association with multiple factors, including dietary patterns, alcohol consumption, and climatic conditions. By applying the MaxEnt model in an exploratory manner, this study provides empirical evidence for identifying spatial risk patterns. These findings may provide spatial reference for public health strategies and resource allocation. However, the findings should be interpreted as associational and exploratory rather than causal or predictive.

The results provide empirical evidence for identifying high-risk areas of hypertension among the rural elderly in China and for understanding its multi-dimensional driving mechanisms. It also may provide spatial reference for targeted, region-specific chronic disease prevention and resource allocation. These findings should be interpreted as associational and exploratory rather than causal or predictive. Future research could incorporate multi-level spatial modelling approaches and high-resolution behavioural trajectory data and long-term climate datasets to further improve the explanatory framework for rural hypertension spatial heterogeneity, thereby supporting chronic disease prevention and public health decision-making in the context of an aging society.

References

Ansari M, Soriano-Paños D, Ghoshal G, White AD, 2022. Inferring spatial source of disease outbreaks using maximum entropy. Phys Rev E 106:014306.

Aune D, Keum N, Giovannucci E, Fadnes LT, Boffetta P, Greenwood DC, Tonstad S, Vatten LJ, Riboli E, Norat T, 2016. Whole grain consumption and risk of cardiovascular disease, cancer, and all cause and cause specific mortality: systematic review and dose-response meta-analysis of prospective studies. BMJ 353:i2716.

Cartierre N, Coulon N, Demerval R, 2011. Analyse confirmatoire de la version courte de la Center for Epidemiological Studies of Depression Scale (CES-D10) chez les adolescents. L'Encéphale 37:273-277.

Cecchini M, Filippini T, Whelton PK, Iamandii I, Di Federico S, Boriani G, Vinceti M, 2024. Alcohol Intake and Risk of Hypertension: A Systematic Review and Dose-Response Meta-Analysis of Nonexperimental Cohort Studies. Hypertension 81:1701-15.

Cheng H, Gu Y, Ma X, Tang H, Liu X, 2022. Urban–rural disparities in hypertension prevalence, awareness, treatment, and control among Chinese middle-aged and older adults from 2011 to 2015: a repeated cross-sectional study. BMC Cardiovasc Disord 22:319.

Chinese Society of Cardiology, Chinese Medical Association; Hypertension Committee of Cross-Straits Medicine Exchange Association; Cardiovascular Disease Prevention and Rehabilitation Committee, Chinese Association of Rehabilitation Medicine, 2024. Clinical practice guideline for the management of hypertension in China. Chin Med J 137:2907-2952.

Duan H, Cao Q, Wang L, Gu X, Ashrafi K, 2024. Exploring the relationships between 3D urban landscape patterns and PM2.5 pollution using the multiscale geographic weighted regression model. Prog Phys Geogr 48:368-88.

ElSayed NA, Aleppo G, Aroda VR, Bannuru RR, Brown FM, Bruemmer D, Collins BS, Hilliard ME, Isaacs D, Johnson EL, Kahan S, Khunti K, Leon J, Lyons SK, Perry ML, Prahalad P, Pratley RE, Seley JJ, Stanton RC, Gabbay RA, on behalf of the American Diabetes Association, 2023. 1. Improving Care and Promoting Health in Populations: Standards of Care in Diabetes-2023. Diabetes Care 46:S10-S18.

Fan L, Liu L, Zhao Y, Mo Y, Li J, Cai L, 2023. Trends in the prevalence and economic burden of hypertension and its socioeconomic disparities in rural southwestern China: two repeated cross-sectional studies. BMJ Open 13:e076694.

Fu R, Huang Z, Lin Y, Tang X, Zheng Z, Hu Z, 2024. Temporal-spatial distribution characteristics and associated socioeconomic factors of visiting frequency for rural patients with hypertension in Fujian Province, Southeast China. BMC Public Health 24:656.

He Z, Jia Y, Li J, Cao J, Liu F, Li H, Chen J, Hu D, Shen C, Zhao Y, Liu X, Yu L, Huang J, Lu X, Gu D, Chen S, 2023. Fruit and vegetable intake and the risk of arterial hypertension in China: A prospective cohort study. Chronic Dis Transl Med 9:309-19.

Huang K, Yang X, Liang F, Liu F, Li J, Xiao Q, Chen J, Liu X, Cao J, Shen C, Yu L, Lu F, Wu X, Zhao L, Wu X, Li Y, Hu D, Huang J, Liu Y, Lu X, Gu D, 2019. Long-Term Exposure to Fine Particulate Matter and Hypertension Incidence in China: The China-PAR Cohort Study. Hypertension 73:1195-1201.

Jiang J, Chen G, Li B, Li N, Liu F, Lu Y, Guo Y, Li S, Chen L, Xiang H. 2021. Associations of residential greenness with hypertension and blood pressure in a Chinese rural population: a cross-sectional study. Environ Sci Pollut Res 28:51693-51701.

Kolak E, Radić J, Vučković M, Bučan Nenadić D, Begović M, Radić M, 2022. Nutritional and Hydration Status and Adherence to Dietary Recommendations in Dalmatian Dialysis Patients. Nutrients 14:3553.

Kowal P, Dowd JE, 2001. Definition of an older person. Proposed working definition of an older person in Africa for the MDS Project. World Health Organization 10:5188-9286.

Li Q, Ren H, Zheng L, Cao W, Zhang A, Zhuang D, Lu L, Jiang H, 2017. Ecological niche modeling identifies fine-scale areas at high risk of dengue fever in the Pearl River delta, China. Int J Environ Res Public Health 14:619.

Liu B, Gao X, Ma J, Jiao Z, Xiao J, Wang H, 2018. Influence of host and environmental factors on the distribution of the Japanese encephalitis vector culex tritaeniorhynchus in China. Int J Environ Res Public Health 15:1848.

Liu X, Lai H, Mi B, Qi X, Gan W, Du H. 2020. Associations of Coarse Grain Intake with Undiagnosed Hypertension among Chinese Adults: Results from the China Kadoorie Biobank. Nutrients 12:3814.

Llanaj E, Dejanovic GM, Valido E, Bano A, Gamba M, Kastrati L, Minder B, Stojic S, Voortman T, Marques-Vidal P, Stoyanov J, Metzger B, Glisic M, Kern H, Muka T., 2022. Effect of oat supplementation interventions on cardiovascular disease risk markers: a systematic review and meta-analysis of randomized controlled trials. Eur J Nutr 61:1749-1778.

Lu J, Lu Y, Wang X, Li X, Linderman GC, Wu C, Cheng X, Mu L, Zhang H, Liu J, Su M, Zhao H, Spatz ES, Spertus JA, Masoudi FA, Krumholz HM, Jiang L, 2017. Prevalence, awareness, treatment, and control of hypertension in China: data from 1·7 million adults in a population-based screening study (China PEACE Million Persons Project). Lancet 390:2549-58.

Madsen H, Sen A, Aune D, 2023. Fruit and vegetable consumption and the risk of hypertension: a systematic review and meta-analysis of prospective studies. Eur J Nutr 62:1941-1955.

Mills KT, Stefanescu A, He J, 2020. The global epidemiology of hypertension. Nat Rev Nephrol 16:223-237.

Nan X, Lu H, Wu J, Xue M, Qian Y, Wang W, Wang X. 2021. The interactive association between sodium intake, alcohol consumption and hypertension among elderly in northern China: a cross-sectional study. BMC Geriatr 21:135.

Niraj KC, Singh A, Shukla DP, 2023. Effect of the Normalized Difference Vegetation Index (NDVI) on GIS-enabled bivariate and multivariate statistical models for landslide susceptibility mapping. J Indian Soc Remote Sens 51:1739-1756.

Ranzani OT, Kalra A, Di Girolamo C, Curto A, Valerio F, Halonen JI, Basagaña X, Tonne C. 2022. Urban-rural differences in hypertension prevalence in low-income and middle-income countries, 1990–2020: A systematic review and meta-analysis. PLOS Med 19:e1004079.

Roerecke M, Tobe SW, Kaczorowski J, Bacon SL, Vafaei A, Hasan OSM, Krishnan RJ, Raifu AO, Rehm J, 2018. Sex□specific associations between alcohol consumption and incidence of hypertension: a systematic review and meta□analysis of cohort studies. J Am Heart Assoc 7:e008202.

Rossios K, Antza C, Kachtsidis V, Kotsis V, 2023. The modern environment: the new secondary cause of hypertension? Medicina (Kaunas) 59:2095.

Schutte AE, SrinivasapuraVenkateshmurthy N, Mohan S, Prabhakaran D, 2021. Hypertension in Low- and Middle-Income Countries. Circ Res 128:808-826.

Tark JY, Li R, Yu B, Wood AC, Padhye NS, de Oliveira Otto MC, 2025. Dietary Intake of Protein by Food Source and Incident Hypertension Among Diverse US Adults: The MESA Study. J Am Heart Assoc 14:e037813.

Tsutsumida N, Rodríguez-Veiga P, Harris P, Balzter H, Comber A, 2019. Investigating spatial error structures in continuous raster data. Int J Appl Earth ObsGeoinf 74:259-268.

Wang J-F, Zhang T-L, Fu B-J, 2016. A measure of spatial stratified heterogeneity. Ecol Indic 67:250-256.

Wang J, Sun W, Wells GA, Li Z, Li T, Wu J, Zhang Y, Liu Y, Li L, Yu Y, Liu Y, Qi C, Lu Y, Liu N, Yan Y, Liu L, Hui G, Liu B. 2018. Differences in prevalence of hypertension and associated risk factors in urban and rural residents of the northeastern region of the People's Republic of China: A cross-sectional study. PLOS ONE 13:e0195340.

Wang L, Zhou B, Zhao Z, Yang L, Zhang M, Jiang Y, Li Y, Zhou M, Wang L, Huang Z, Zhang X, Zhao L, Yu D, Li C, Ezzati M, Chen Z, Wu J, Ding G, Li X, 2021. Body-mass index and obesity in urban and rural China: findings from consecutive nationally representative surveys during 2004–18. Lancet 398:53-63.

Zhao Y, Chen X, Wang Y, Meng Q, Bo H, Chen C, Chen Y, Gong J, Jia Y, Wang G, Wu X, Yan L, Yang P, Zhou H, 2023. China Health and Retirement Longitudinal Study Wave 5 (2020) User Guide. National School of Development, Peking

University, Beijing, China.

Wang Y, Yao Y, Chen Y, Zhou J, Wu Y, Fu C, Wang N, Liu T, Xu K, 2022. Association between Drinking Patterns and Incident Hypertension in Southwest China. Int J Environ Res Public Health 19:3801.

Wang Z, Chen Z, Zhang L, Wang X, Hao G, Zhang Z, Shao L, Tian Y, Dong Y, Zheng C, Wang J, Zhu M, Weintraub WS, Gao R; China Hypertension Survey Investigators, 2018. Status of hypertension in China: results from the China hypertension survey, 2012–2015. Circulation 137:2344-56.

Wei J, Miao Y, Zhang J, Wu J, Shen Z, Bai J, Zhu D, Ren R, Li X, Zhen M, Zhang J, Cui J, Guo D, Dong W, Tarimo CS, Zhao Q, Liu R, Hu J, Li M, 2025. Spatial heterogeneity of blood pressure control and its influencing factors in elderly patients with essential hypertension: A small-scale spatial analysis. Health Place 92:103428.

Xing L, Jing L, Tian Y, Lin M, Du Z, Yan H, Ren G, Dong Y, Sun Q, Liu S, 2019. Urban–Rural disparities in status of hypertension in northeast China: a population-based study, 2017–2019. CLEP Volume 11:801-20.

Xu X, 2017. China population spatial distribution kilometer grid dataset. Resource and Environment Science and Data Center of Chinese Academy of Sciences

Xu X, 2023. China's Township Administrative Division Boundary Data. Resource and Environment Science and Data Center of Chinese Academy of Sciences

Yan X, Li J, Wu J, Lin S, Wang Z, Pei L, Zheng C, Wang X, Cao X, Hu Z, Tian Y, 2024. Association between short-term daily temperature variability and blood pressure in the Chinese population: From the China hypertension survey. Environ Int 184:108463.

Yang Z, Ren ZD, Wang J, Dong W, 2025. Based on the MaxEnt model the analysis of influencing factors and simulation of potential risk areas of human infection with avian influenza A (H7N9) in China. Front. Cell. Infect. Microbiol 14:1496991.

Jaynes ET, 1957a. Information Theory and Statistical Mechanics. Phys Rev 106:620-630.

Jaynes ET, 1957b. Information Theory and Statistical Mechanics. II. Phys Rev 108:171-190.

Zhang M, Shi Y, Zhou B, Huang Z, Zhao Z, Li C, Zhang X, Han G, Peng K, Li X, Wang Y, Ezzati M, Wang L, Li Y. 2023. Prevalence, awareness, treatment, and control of hypertension in China, 2004-18: findings from six rounds of a national survey. BMJ e071952.

Zhang Y, Tang J, Ren G, Zhao K, Wang X, 2021. Global potential distribution prediction of Xanthium italicum based on Maxent model. Sci Rep 11:16545.

Zhang Y, Zhang D, 2018. Red meat, poultry, and egg consumption

Received: 27 February; Accepted: 26 April 2026.

Contributions: Jie Wang designed the study, conducted the data analysis, and drafted the initial manuscript. Enwei Zhang supervised the study, contributed to the interpretation of results, and critically revised the manuscript for important intellectual content. Kun Yang contributed to data collection, provided methodological support, and assisted in revising the manuscript. All authors reviewed and approved the final version of the manuscript.

Conflict of interest: the authors declare no competing interests.

Availability of data and materials: the individual-level data analyzed in this study are publicly available from the China Health and Retirement Longitudinal Study (CHARLS) at http://charls.pku.edu.cn. Socio-environmental raster datasets were obtained from publicly accessible sources, including the Resource and Environment Science and Data Center of the Chinese Academy of Sciences (http://www.resdc.cn) and global remote sensing platforms.

Acknowledgements: we thank the CHARLS project for data support and acknowledge all contributors to the open geospatial datasets used in this study.