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The geographic environment and the frequency of falling: a study of mortality outcomes in elderly people in China

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Abstract

Falling has become the first and second cause of death due to injury among urban and rural residents in China. This mortality is considerably higher in the southern part of the country than in the North. We collected the rate of mortality due to falling for 2013 and 2017 by province, age structure and population density, taking topography, precipitation and temperature into account. 2013 was used as the first year of the study since this year marks the expansion of the mortality surveillance system from 161 counties to 605 counties making available data more representative. A geographically weighted regression was used to evaluate the relationship between mortality and the geographic risk factors. High levels of precipitation, steep topography and uneven land surfaces as well as a higher quantile of the population aged above 80 years in southern China are believed to have led to the significantly higher number of falling compared with that in the North. Indeed, when evaluated by geographically weighted regression, the factors mentioned found a difference between the South and the North with regard to falling of 81% and 76% for the years 2013 and 2017, respectively. Interaction effects were observed between geographic risk factors and falling that, apart from the age factor, could be explained by topographic and climatic differences. The roads in the South are more difficult to negotiate on foot, particularly when it rains, which increases the probability of falling. In summary, the higher mortality due to falling in southern China emphasizes the need to apply more adaptive and effective measures in rainy and mountainous region to reduce this kind of risk.

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Introduction

The risk of falling is an important global health problem for the elderly (WHO, 2018; Yoo *et al.,* 2019), especially for the group of people aged 75 years or more. According to the Institute for Health Metrics and Evaluation (IHME) the Global Burden of Disease (GBD) showed that in 2016, the standardized mortality rate with respect to injury including years of life lost (YLL) due to falling ranked third after transport injuries and interpersonal violence/self-harm (GBD, 2017). The consequences of falling, such as death, disability, limited function and limited activity, seriously affect the health of the elderly (Beard *et al.*, 2016). Among the elderly, about 28-35% and 40% of those aged over 65 years and over 75 years, respectively, will experience at least one fall per year (Rubenstein *et al.*, 2006). The corresponding annual rates in hospitals and sanatoriums for these age groups are 26% and 43%, respectively (Rubenstein & Josephson, 2002).

The cause of falling can be internal (personal) or external (due to the environment and or social situation) risk factors (Hong & Peng, 2017; Peng *et al.*, 2019). At present, studies on causes mainly focus on the internal factors reflecting susceptibility, e.g., physiological factors, diseases, physical and psychological factors, drugs, use of antidepressants, depression or risk taking (GBD, 2017; Bergen *et al.*, 2016; Roman *et al.*, 2013). In addition, diabetes, osteoporosis and other chronic diseases increase the vulnerability of the elderly and the risk of death from falling. However, few studies have dealt with the external risk factors, such as slippery or uneven ground, dazzling sunshine, bad weather, narrow stairs (often without handrails), shoes unfit to the terrain, which account for 30-50% of the risk factors (although varied between regions) (Zhang *et al.*, 2019). The main self-reported environmental factors were uneven road surfaces (20.3%), slippery roads (18.8%) and other obstacles (13.6%) (Zhao *et al.*, 2016). The bath-

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room is the most dangerous indoor place with regard to falling (Connell *et al.*, 1997). In addition, interaction effects of external risk factors and internal factors increase the risk.

The incidence rate of falling in mainland China increased substantially between 1990 and 2019 (Ye *et al.*, 2021). Based on the analysis of 240 causes in China from 1990 to 2013, the standardized mortality rate has increased by 12% in the past 20 years, which represents the largest increase among all injuries (Zhou *et al.*, 2016). As early as 2002, global disease burden had reported that China had the highest disease burden of falling in the world, the loss of disability adjusted life years (DALYs) was about twice in China compared other parts of the world (WHO, 2002). Falling has become the first major cause of old people in injury in China since 2020, and it brings serious disease burden for old people. Despite the inevitable risk, falling can be managed, detected and even prevented (Chaccour *et al.*, 2017). In southern China, the age-standardized mortality rate due to falling has always been higher than in northern China, which may be closely related to geographical factors.

Physical vulnerability increases risk of death after falling (Bergen *et al.*, 2016) and the deterioration of overall motor capacity at old age increases the risk (Spirduso *et al.*, 2005). Geographical differences in 2013 and 2017 were investigated in relation to mortality due to falls. The objectives of this study were to: i) investigate the differences of mortality due to falling between southern and northern China; ii) find the relationship between geographic factors and mortality caused by falling in China; and iii) provide a strategy for targeted improvement.

Materials and Methods

Data collection

China Centers for Disease Control and Prevention (China CDC) has established an integrated, national, mortality surveillance system based on an iterative method involving multistage stratification to provide a provincially representative data of total and cause-specific mortality (Liu *et al.*, 2016). Since 2013, the system surveys all of China's 31 provinces targeting 605 counties, which include 24% of the Chinese population, with each death in the system coded according to the international classification of diseases-10 (ICD-10), which guarantees accuracy and robustness of the data rates (He et al., 2020). We used this information to calculate the nationwide, age-standardized rate of mortality due to falling comparing the data for 2013 (for males and females separately and for both together) and those for 2017 (for males and females together).

Relevant factors that might influence falling were collected to explore north-south difference of mortality rate caused by falling. A large number of this kind of incidents involved the elderly and occurred in when they were taking a bath; thus, the frequency of bathing is an important risk factor. People who live in southern China normally take a bath every day in the summer because of hot temperatures and good availability of water resources, while the corresponding frequency for the northern residents is much lower, especially in north-western China. Precipitation is another important factor related to falling because many old people fall when the road outside is slippery. Precipitation increases the moisture degree of surface and reduces friction. Topography is also an important factor because uneven and steeper road surfaces add the probability of falling. The rising mortality rate in China related to falling may also be related to the increasing age of the population. With age increasing, balance, vision, hearing and other sensory systems decline and the mortality risk increases (Tineiti *et al.*, 1994).

Temperature, precipitation, topography and the 80+ age rate were selected as variables to study the spatial difference for mortality due to falling in China. The data of precipitation and temperature were obtained from China Meteorological Administration (http://data.cma.cn). The population density map (spatial resolution: 1 km^2) and topographical map were collected from official governmental websites (http://www.resdc.cn). The 80+ rate was obtained from the sixth population census (2010) of China.

Statistical methodology

Population-weighted provincial topographic factors

Slope and relief are crucial, topographic factors of the land surface, where the former reflects the steepness and the latter the difference of the highest and lowest elevation in a region, which is measured as amplitude. Using the digital elevation model (DEM) (http://www.resdc.cn), we calculated the slope and amplitude for each 1 km ×1 km grid cell in the topographical map. Average slope or relief amplitude of each region can not be used represent the slope or relief of many residential areas, as provinces in China consist of both plain and mountainous area, while the population density varies depending on area. Therefore, provincial population density-weighted slope (PWS) and population density-weighted relief (PWR) were calculated by the following formulas:

$$PWS_i = \frac{\sum_{i=1}^{n}(P_i \times S_i)}{\sum_{i=1}^{n} P_i} \quad \text{(Eq. 1)}$$

$$PWR_i = \frac{\sum_{i=1}^{n}(P_i \times R_i)}{\sum_{i=1}^{n} P_i} \quad \text{(Eq. 2)}$$

where n is number of grid cells in each province; P_i the population of grid cell i; S_i the slope of grid cell i; and R_i the relief amplitude of grid cell i.

Spatial autocorrelation (Moran's I)

We used Moran's I to find if there was spatial autocorrelation of falling at provincial scale.

$$I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n} w_{i,j} z_i z_i}{S_0 \sum_{i=0}^{n} z_i^2}, S_0 = \sum_{i=1}^{n}\sum_{j=1}^{n} w_{i,j} \quad \text{(Eq. 3)}$$

where Z_i denotes the deviation of an attribute for province i from its mean $(x_i - \bar{X})$, $w_{i,j}$ the spatial weight between province i and j, n equal to the total numbe r of provinces, and S_0 the aggregate of all the spatial weights. The Global Moran's Index is bounded by -1.0 and 1.0. The expected value is -1/(n-1). Values exceeding this value indicate positive spatial autocorrelation, in which either high values or low values are spatially clustered.

We used MGWR to find relationships between geographic factors and falling. In MGWR, local effects of spatial objects are taken into consideration to improve accuracy of the results. In the model, precipitation, temperature, PWS, PWR and the rate of people older than 80 years were the independent variables and the rate of mortality due to falling the dependent variable.

$$y_i = \beta_0(u_i, v_i) + \sum_{k=1}^{p} \beta_k (u_i, v_i) x_{ik} + \varepsilon_i \quad \text{(Eq. 4)}$$

where Y is the mortality rate with respect to falling at position i;x_i the independent variable k (that can be temperature, precipitation, age or slope) at position i; (u_i, v_i) the coordinates of position i, $\beta_0(u_i, v_i)$ the intercept; $\beta_k(u_i, v_i)$ regression parameter of variable k at position i; and ε_i the residual.

Generalized additive model (GAM)

We used GAM to investigate the joint effect between geographical risk factors with regard to the number of falls resulting in death. In this study, we constructed a thin plate spline function for qualitative analysis of interaction effects on mortality due to falling to be displayed in 3D surface graph:

$$\text{Log}[\text{E}(Y)] = \alpha + TS(x_i, x_j) + S(x_i) + S(x_j) \quad \text{(Eq. 5)}$$

where Y denotes the mortality rate with respect to falling, α the intercept, *TS* denotes the thinplate spline and *S* the smoothing function. ESRI ArcGIS v. 10.2 (https://www.esri.com/) and MGWR v. 2.2 (https://sgsup.asu.edu) were used for MGWR, PWS, PWR; R software, v. 4.2.1 (https://www.r-project.org/) was used for GAM.

Results

The mortality due to falling is continuously rising in China since 2005 to become the first in urban environments and second in rural areas cause of death by injury in 2019 as shown in Figure 1. In addition, mortality caused by falling and its proportion all injuries for each age group have also increased since 2005 as shown in Table 1. For the group of 85+ olds, falling has become one of the four major causes of death exceeded only by circulation system diseases, respiratory diseases and tumors for both urban and rural residents in China (National Health Commission of People's Republic of China, 2021).

Figure 2 shows the spatial character of registered falls in 2013 and 2017 among the 31 provinces in China. At the first to eleventh ranks, the age-standardized mortality rate for falls was higher in southern China than anywhere else in the country.

Figure 3 indicates that the rate for those older than 80 years was higher in the eastern coastal area than in the central and western inland areas, the former of which positively associated with high economy performance. Precipitation increases from north-western to south-eastern China and the temperature from the North to the South. Topography is steeper in southern than in northern China, *e.g.*, provinces in the Southeast (Zhejiang and Fujian) and

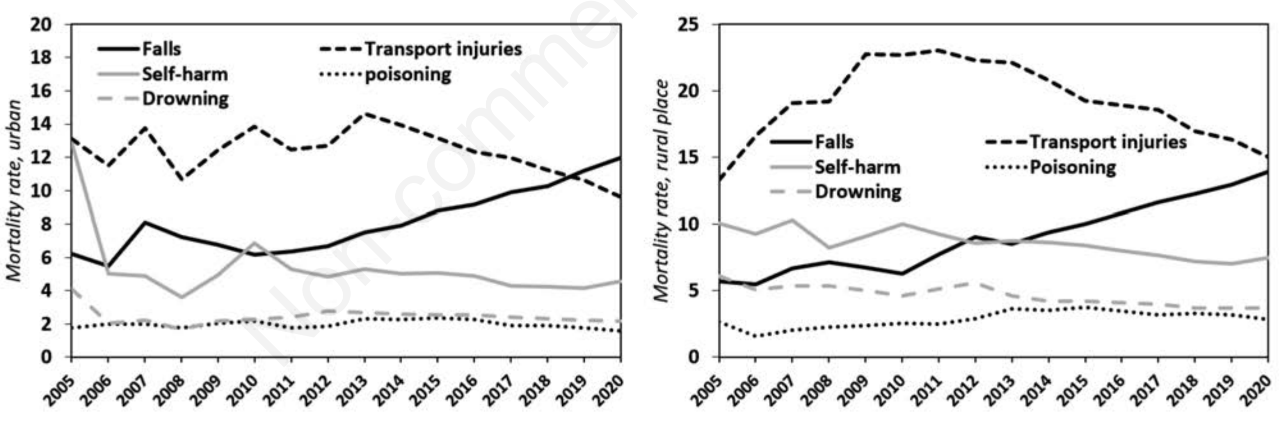

Figure 1. Mortality rates due to major injuries in China in the 2005-2020 period. Mortality rate shown per 100,000.

Table 1. Mortality rates and proportions in elderly groups in China.

Age (years)	Place (type)	Rate of mortality caused by falling*				Proportion of death caused by falling (%) **			
		2005	2010	2015	2020	2005	2010	2015	2020
85+	Urban	289.56	283.14	372.57	412.59	53.3	46.3	60.9	66.4
	Rural	107.25	325.51	343.04	461.33	29.1	43.5	56.0	61.8
80-84	Urban	105.1	73.05	100.42	123.75	30.5	32.2	47.7	56.0
	Rural	60.69	64.44	105.72	145.77	25.4	21.6	38.9	47.5
75-79	Urban	41.49	32.27	39.89	47.93	18.3	24.9	35.7	40.2
	Rural	35.95	31.02	46.81	62.7	20.3	16.1	27.2	34.0

*per 100,000; **among all deaths caused by injury.

the Southwest (Guizhou, Yunnan, Chongqing, Sichuan and Guangxi) are continuous hilly regions. The distribution of built environment in the plains and the mountainous region is shown in Figure 4.

The results of Moran's *I*, used to identify spatial autocorrelation of mortality due to falling, are shown in Table 2. There was spatial autocorrelation of falling mortality (P-values in Table 2 are less than 0.001), the mortality caused by falling was statistically higher in southern than in northern China. Therefore, we can use the MGWR because there is spatial autocorrelation in the dependent variable.

The MGWR results are shown in Table 3, and the value of

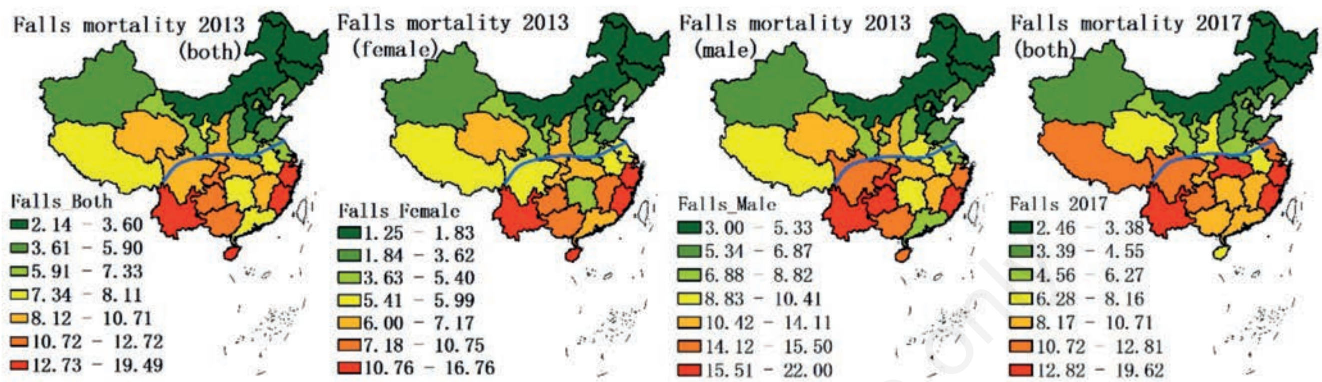

Figure 2. Distribution of the standardized mortality rate of reported fallings in China 2013 and 2017 Mortality rate shown per 100,000. The blue line (between Qingling Mountain and Huai River) represents the north–south boundary. Gender division not available for 2017.

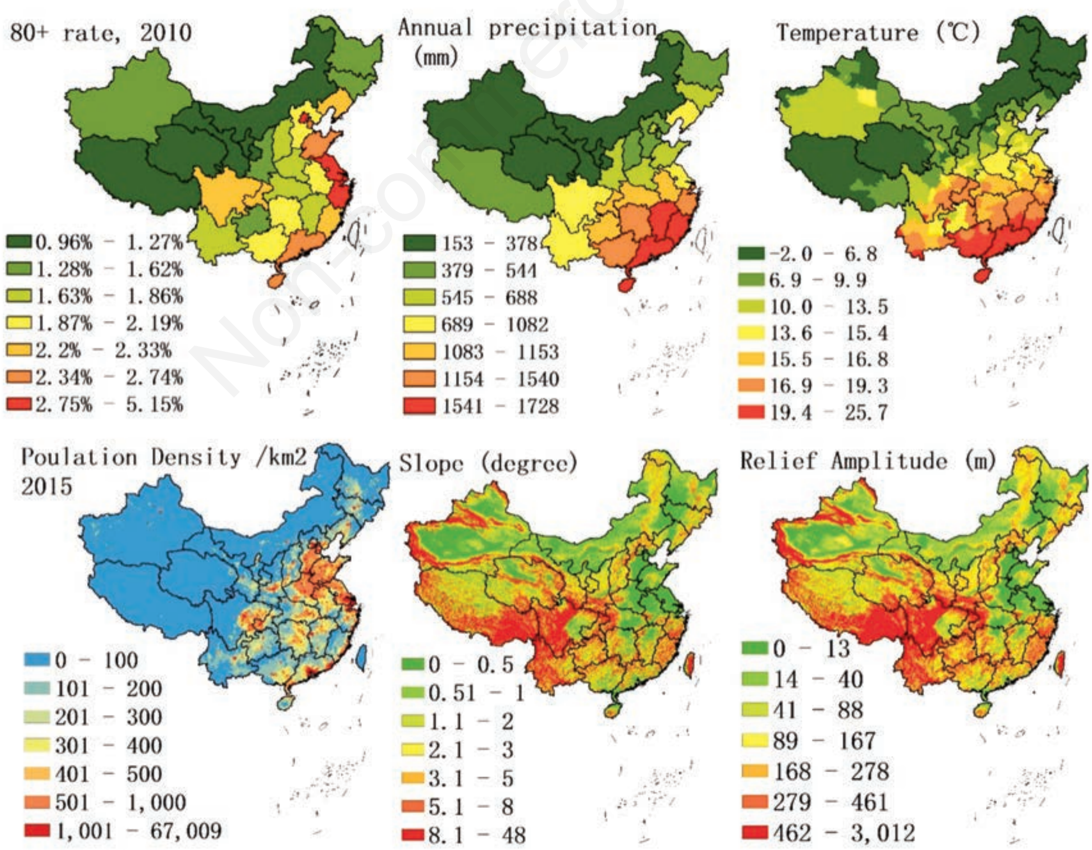

Figure 3. The provincial distribution in China of risk factors with regard to falling.

provincial mortality due to falling predicted by precipitation, temperature, 80+ rate and slope are shown in Figure 5. There are two models shown in the table for 2013 and 2017, one with four variables and the other with only three (temperature not included). This is because temperature and precipitation have a similar geographical distribution in China, *i.e.* south China is both rainier and hotter than north China, so provinces with higher average temperatures over the year, also have much precipitation. However, the effect of temperature and precipitation with respect to falling may be different. Therefore, models 3 and 4 were designed to observe the effect of precipitation and topography.

Table 3 and Figure 5 showed that precipitation, slope, 80+ rate, when evaluated via geographically weighted regression, explained 80% and 76% of spatial difference of the falling in 2013 and 2017, respectively.

Figure 6 depicts the interactive effect between each three different factors on mortality due to falling graphically using 3D visualization graphs. The mortality was positively associated with temperature, precipitation and slope. The mortality rate after falling incidents can be seen to rise linearly with increase both in temperature and precipitation, as it also does with temperature and slope. However, the effect of slope and precipitation on the mortality rate after falling was clearly nonlinear.

Discussion

Some coastal provinces in China have a low to moderate mortality rate due to falling in the population quantile of people older than 80 years, such as Liaoning, Hebei, Tianjing, Shandong,

Table 2. The spatial autocorrelation of mortality due to falling.

	2013 both	2013 male	2013 female	2017 both
Moran's I	0.300	0.215	0.267	0.260
Z-score	4.013	4.741	3.649	3.532
P	0.000***	0.000***	0.000***	0.000***

Table 3. Outcome of geographically weighted regression of the mortality rate due to falling.

Indicator	Variable	*EV*	*t*	P	SR	AIC	BIC	R^2	Adj.R^2
Age-standardized mortality due to falling 2013	Precipitation	0.212	1.447	0.148	134.1	84.14	108.8	0.843	0.811
	Slope	0.553	6.873	0.000***					
	Temperature	0.470	3.182	0.001**					
	80+ rate	0.095	1.028	0.304					
Age-standardized mortality due to falling 2017	Precipitation	0.444	2.867	0.004**	185.9	105.9	127.9	0.769	0.727
	Slope	0.613	7.215	0.000***					
	Temperature	0.143	0.919	0.358					
	80+ rate	0.080	0.822	0.411					
Age-standardized mortality due to falling 2013	Precipitation	0.600	6.843	0.000***	124.4	87.25	108.3	0.826	0.797
	Slope	0.536	6.205	0.000***					
	80+ rate	0.143	1.464	0.143					
Age-standardized mortality due to falling 2017	Precipitation	0.562	6.540	0.000***	188.7	98.59	119.7	0.791	0.756
	Slope	0.607	7.179	0.000***					
	80+ rate	0.095	0.989	0.323					

EV, Estimate value; *t*, *t*-test; SR, standard residual; AIC, Akaike information criterion; BIC, Bayesian information criterion; R^2, level of goodness of fit; Adj. R^2, adjusted R^2; ** significant at P<0.01 level; ***significant at P<0.001 level.

Figure 4. Built environment in plain and mountainous region in China. Left: Jiangsu Province; Middle: Guizhou Province; Right: Zhejiang Province.

Jiangsu and Shanghai. These provinces are all characterized by vast plains and age-related index (the 80+ rate) was not statistically significant in our study. This result is in accordance with previous findings (Jeon *et al.*, 2017; Park *et al.,* 2008; Yoo *et al.,* 2011) that there were no significant differences in the demographic characteristics (age, sex, education level, economic status) between people who experienced falls and those who did not. These conclusions are that although age poses an important risk factor with regard to falling, more even road surfaces and effective social measurements can temper the increase of mortality due to falling.

In the current study, topography was found to be the primary factor of spatial difference of mortality after falls in China. As illustrated in Figures 3 and 4, provinces with steep slopes and large relief amplitudes in the South, e.g., Guizhou, Chongqi, Yunnan, Zhejiang and Fujian, had the highest mortality rate due to falling in China. In northern China, this kind of mortality in provinces with steep slopes, *e.*g., Ningxia, Shaanxi and Gansu located in the Loess Plateau, have always been higher than in the provinces located in the plains. Previous studies have shown that over half of those aged 65+ years have been reported to have fallen on roads, stairs or in the yard. Among all road accident, 35.0% were located in urban areas and 30.8% in rural areas (Zhang *et al.*, 2019). Residents in the mountainous regions often have to climb hillsides for farm work or shopping and this topography increases the difficulty of walking, especially for the old people. Besides, built environment in the mountainous regions is more complex and difficult to reach as houses are usually built on hillsides, forcing people to climb stairs frequently, even if they do not leave their home. Thus, fall prevention in southern China and mountainous region should be a priority for the elderly. From 2009 to 2020, mortality due to falling has continuously been higher in rural places in China. The fact that the incidence of falling is higher among rural than urban older people (Cheng *et al.*, 2019) indicates the growing urbanization may lead to lower mortality due to falling in the mountainous regions. Cities and towns in these regions are usually located in relatively flat areas, a fact which reduces the risk of falling caused by steep and uneven road surfaces. In addition, cities have better medical conditions and timely treatment is available when a serious fall occurs. Since facilities are more adequate and available in cities than in rural areas, built and social environment, as well as available services and facilities, can reduce this risk (Chippendale *et al.*, 2015). Studies in developed countries have proved that sci-

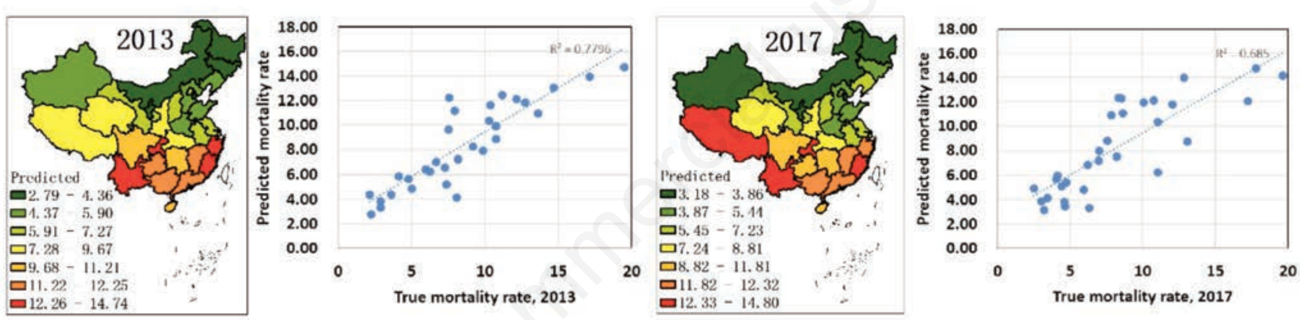

Figure 5. The mortality rate due to falling in China in relation to geographical factors. Mortality rate shown per 100,000.

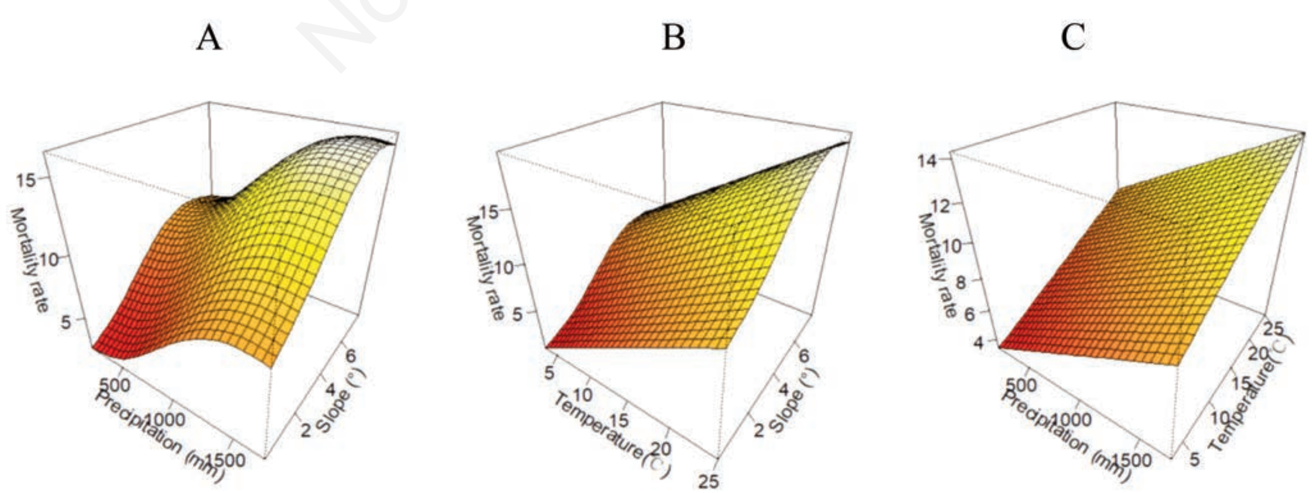

Figure 6. Bivariate response surfaces of the effect of three variables on the age-standardized rate of mortality due to falling in 2013. Mortality rate shown per 100,000. A) A clearly nonlinear association. B) A mainly linear association. C) A clearly linear association.

entific prevention can effectively reduce the incidence of elderly people of falling accidents (Gillespie *et al.*, 2012). Although older people in areas with steep slopes should potentially be fitter and stronger because the efforts required for climbing of stairs and moving around, they have a much higher mortality due to falls than in urban flat environments. It is possible that the deterioration of physical functions makes the elderly in mountainous area unable to cope with the complex terrain environment they live in.

Precipitation also plays an important part in the mortality rate due to falling in southern China. Frequent rainfall not only makes roads slippery outdoors, but also indoors because wet shoes and umbrellas contribute to water on the floors indoors. There is a contrary situation in northern China, where roads sometimes freeze in the winter and become slippery. On the other hand, outdoor temperatures often keep the elderly inside. Non-slip tiles with linear or granular surface can effectively guard against falling on wet days and could make roads in rainy areas safer. In addition, homes and other areas should be equipped to keep indoor floors dry if the weather is wet.

Obvious linear and non-linear associated effects were observed between the three geographic factors. Provinces with highest mortality due to falling in China, e.g., Fujian, Yunnan, Zhejiang, Hainan, Guizhou, Guangxi, all include complicated land surfaces, steep slopes, rainy climates and high temperatures. Effects of synergies between the three geographic factors reveal that mortality due to falling increases with more precipitation, steeper land surfaces and high temperatures.

There are some limitations of this study. First, the lack of detailed information with regard to particular locations of individual accidents leading to mortality after falling limited the possibility of calculating the fraction attributed by geographic factors. However, the hypothesis that people living in warmer climates would more often take baths and risk falling in their bathrooms was not supported with evidence. Second, the results provided by MGWR (should it be MGWR? Yes) and GAM did not only relate to older people but to people of all ages and included also incidents of falling from buildings and construction sites. Third, some social, economic and cultural factors (education, access to healthcare, attitudes to remaining active) can be confounders to the findings reported here.

Conclusions

The mortality rate due to falling is higher in southern China than in northern China with statistical significance. Precipitation, temperature and surface slope were found to be the key factors resulting in the north-south difference, while the south-western and south-eastern provinces with complex topography and much precipitation had the highest mortality rate of this kind. The steep slope in Zhejiang and Fujian resulted in a higher mortality rate due to falls compared with other south-eastern provinces, such as Jiangsu and Guangdong. There association between geographical risk factors and mortality by falling in southern China, emphasizes the need for efficient improvements with regard to safety, especially in the mountainous provinces to ensure a reduction of the adverse effects of natural environment.

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