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Combined effect of heatwaves and residential greenness on the risk of stroke among Chinese adults: A national cohort study

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A R T I C L E I N F O

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A B S T R A C T

Heatwaves have been associated with an increased risk of stroke, while residential greenness may offer protective benefits. This prospective cohort study examined 22,702 participants aged 35 years or older, with no prior history of cardiovascular disease (CVD), from the China Hypertension Survey (CHS) conducted between 2012 and 2015. Participants were followed up between 2018 and 2019. Heatwaves were defined as daily maximum temperatures exceeding the 92.5th percentile of the warm season for at least three consecutive days. Residential greenness was quantified using the Normalized Difference Vegetation Index (NDVI) within buffers of 300, 500, and 1000 m from participants' residences. Multivariable Cox proportional hazards models evaluated the independent and combined effects of heatwaves and greenness on stroke risk, while restricted cubic spline analyses explored nonlinear relationships. Interaction effects were assessed using both multiplicative and additive Cox regression models. During follow-up, 597 stroke events occurred. Each additional 3-day increase in heatwave days was associated with an increased stroke risk (HR: 1.19, 95 % CI: 1.08–1.31). Interaction analyses demonstrated a synergistic effect between heatwaves and lower residential greenness ($NDVI_{300\ m}$, $NDVI_{500\ m}$ and $NDVI_{1000\ m}$) on stroke risk, with significant additive(RERI > 0, $P < 0.05$) and multiplicative interactions (HR > 1, $P < 0.05$). The strongest protective effects of greenness were observed within a 500 m buffer zone, particularly for individuals under 60 years, rural residents, and those with higher educational attainment. This study highlights the potential benefits of enhancing greenness for cardiovascular health and provides valuable insights for environmental governance and public health policy in China.

1. Introduction

Stroke, defined as a sudden loss of brain function lasting more than 24 h or leading to death, caused by vascular issues (Aho et al., 1980; Feigin et al., 2018), remains a leading cause of mortality and long-term disability worldwide, particularly in low-and middle-income countries (Feigin and Wolabi, 2023; Ma et al., 2021). According to the Global Burden of Disease (GBD) study, stroke accounted for approximately 160.4 million disability-adjusted life-years (DALYs) globally in 2021 (GBD 2021 Diseases and Injuries Collaborators, 2024b). In China, the

Abbreviations: CVD, cardiovascular disease; NDVI, the Normalized Difference Vegetation Index; HR, hazard ratios; RERI, relative risk due to interaction; IQR, interquartile ranges; ICD, International Classification of Diseases; BMI, body mass index; RCS, restricted cubic spline curves; $PM_{2.5}$, particulate matter with an aerodynamic diameter ≤ 2.5μm.

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prevalence of stroke have reached 26 million in 2021, increasing 104.3 % since 1990, and stroke-related disability-adjusted life years (DALYs) have risen by 45.3 %, causing enormous strain on families and the healthcare system (Ji et al., 2025). While traditional risk factors such as smoking, obesity, and hypertension are well-established contributors to stroke (GBD 2021 Risk Factors Collaborators, 2024a; Li et al., 2022), emerging evidence suggests that environmental exposures, such as extreme temperatures and limited green space, may exert significant influences on cerebrovascular risk (Liu et al., 2022a, 2022b; Whyte et al., 2024). In China, rapid urbanization and an aging population have made stroke a priority for public health, further magnifying the impact of these environmental factors.

Global surface temperatures have continued to rise, with the World Meteorological Organization reporting a 1.55°C increase above pre-industrial levels in 2024, marking it the hottest year on record (Romanello et al., 2024; WMO, 2025). This warming trend has heightened the disease burden associated with high temperatures, and the risks will continuously increase (Bo et al., 2023; Romanello et al., 2024; Wang et al., 2023a). In 2024, southern China experienced a 74-day heatwave—the second most severe since 1961 (Zhou et al., 2025). Heatwaves, defined as high temperature events lasting for several consecutive days (Qi et al., 2021; Wang et al., 2023b; Yin et al., 2018), have been associated with a 22.0 % increase in cardiovascular mortality risk across 130 Chinese counties (Sun et al., 2021). Although many studies in China have examined the relationship between ambient temperature and stroke (Chen et al., 2023; Deng et al., 2024; He et al., 2021; Qian et al., 2024), research specifically focused on heatwaves remains limited. Moreover, more than 50 % focusing on stroke mortality and are geographically restricted to specific regions (Chen et al., 2015; Deng et al., 2024; Yang et al., 2019). However, the evidence for the association between heatwaves and the risk of stroke incidence among Chinese population remains limited.

Rapid urbanization in China has led to growing environmental concerns, particularly the urban heat island effect and a decline in urban green space (Xie et al., 2024; Zhou et al., 2023a). Green spaces, defined as open areas with natural vegetation, such as parks, street greenery, and urban gardens, are valued for improving physical and mental health (Liu et al., 2022b; Yuan et al., 2021). Exposure to these spaces mitigates heat-related risks, reduces stress, and promotes activity, potentially preventing stroke (Avellaneda-Gómez et al., 2022; Jia et al., 2024; Scheer et al., 2024). Previous studies on the association between green space and stroke have reported inconsistent findings (Whyte et al., 2024; Yang et al., 2021). Several studies conducted in China suggest that green space may reduce the risk of both ischemic and hemorrhagic stroke (Jia et al., 2024; Liu et al., 2024). However, many of these studies are limited to specific regions or stroke subtypes and are constrained by cross-sectional study designs (Bao et al., 2021; Wang et al., 2022b; Xie et al., 2024).

However, the health effects of environmental factors like heatwaves and green spaces may not act independently. The *Lancet* Countdown highlights the expansion of urban green space as a key strategy for climate change mitigation and adaptation, noting its role in reducing heatwave exposure among urban populations (Zhang et al., 2023). Increasing green coverage can help offset the urban heat island effect, providing essential relief during extreme temperatures and mitigating heatwave-related health risks (Ji et al., 2023; Keith et al., 2024; Rajagopalan et al., 2024). Emerging evidence also points to a possible interaction between temperature and greenness in influencing stroke risk. A European study reported that lower greenness combined with seasonal temperature patterns was associated with higher stroke incidence (de Bont et al., 2023).Similarly, a study in Shandong, China, found that residential greenness modified the association between non-optimal temperatures and stroke mortality, though it did not focus specifically on heatwaves (He et al., 2022). Additionally, although joint effects of heatwaves and greenness have been explored for outcomes like preterm birth (Sun et al., 2020; Ye et al., 2024), hypertension (Zhou et al., 2023a), and mortality (Choi et al., 2022), research on their combined impact on stroke—particularly in China—remains limited. To address this gap, we investigated the independent and interactive effects of heatwaves and residential greenness on stroke risk among Chinese adults based on a large-scale prospective cohort study. Our findings aim to clarify whether higher levels of residential greenness can mitigate the adverse effects of heatwaves on stroke, providing critical insights for policymakers to design effective adaptation and mitigation strategies.

2. Methods

2.1. Study design and population

The China Hypertension Survey (CHS) was conducted from October 2012 to December 2015, and the design was published previously (Wang et al., 2014, 2018, 2019). Briefly, a stratified multistage random sampling method was used to obtain a nationally representative sample of the Chinese population aged ≥ 15 years, covering all 31 provinces in mainland China. For this sub-study, all selected urban and rural areas were further stratified into eastern, central and western regions based on geographic location and economic level. Using simple random sampling (SRS) method, 16 cities and 17 counties were selected, with at least three communities or villages randomly chosen from each region. Ultimately, 30,036 individuals aged ≥ 35 years, with complete baseline information including sex, name, and valid blood samples, were followed up in 2018 and 2019. For our study, we excluded subjects missing values for important variables at baseline (N = 2498), with a self-reported history of CVD at baseline (N = 1318), being lose during follow-up (N = 3518), resulting in 22,702 individuals eligible for analysis (Fig. 1). This study was approved by the Ethics Committee of Fuwai Hospital (Beijing, China), and written informed consent was obtained from all participants.

2.2. Assessment of heatwave

In this study, we collected daily maximum temperature data from 30 districts/counties in China between 2009 and 2019 through surface meteorological observation stations, and used these data to calculate the number of heatwave days in one year before stroke occurrence. The meteorological data for the 30 districts/counties included in this study were obtained from one meteorological station within each district or county. For residential units not covered by a weather station, data from the nearest weather monitoring station were used.

There is no universally consistent definition of a heatwave. In China, the heatwave is typically defined as three or more consecutive days of daily maximum temperatures exceeding 35℃ (Tan et al., 2007). However, considering the wide range of temperatures, diverse climates and different adaptive capacities across China, some studies have used different temperature thresholds (absolute or percentile) and durations to define a heatwave (Gao et al., 2015; Yang et al., 2019; Yin et al.,

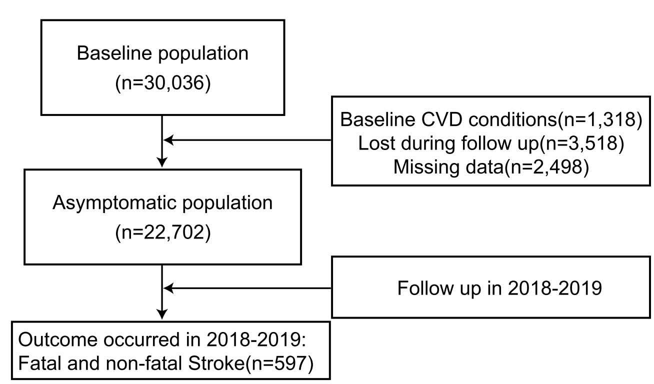

Fig. 1. Participant Flowchart. Note: CVD, cardiovascular disease.

2018). In our study, we define a heatwave as at least three consecutive days with daily maximum temperatures exceeding the 92.5th percentile for the warm season (1 May to 30 September), calculated based on local temperature distributions. We used the number of heatwave days in one year before the occurrence of stroke to represent extreme heat exposure.

2.3. Assessment of residential greenness

We used the Normalized Difference Vegetation Index (NDVI) to measure the level of residential greenness within a 300-meter, 500-meter, and 1000-meter radius of participants' residential addresses ($NDVI_{300\ m}$, $NDVI_{500\ m}$, and $NDVI_{1000\ m}$). The NDVI data were derived from the Chinese monthly satellite archives of the Moderate Resolution Imaging Spectroradiometer (MODIS) product. NDVI is calculated as the ratio of the difference between the reflectance in the near-infrared region and the red visible light to the sum of these two measurements, ranging from −1.0–1.0 (Rouse et al., 1974). Negative NDVI values are usually indicate blue space or water, while larger values indicate denser green vegetation. In our study, we used the average cumulative NDVI level at each participant's residential addresses from the year of the baseline survey to the year of the stroke occurred to reflect their long-term exposure to greenness.

2.4. Covariates

We used directed acyclic graphs to select several variables that might confound the association, and age (<60 years, ≥60 years), sex, urbanization (urban area, rural area), educational level (junior high school or below, high school or above), geographic region (eastern, central, or western), family history of CVD, and body mass index (BMI= weight (kg)/ height squared (m^2)) (<18.5, 18.5–23.9, 24.0–27.9, ≥28.0) were included in the final analysis. Additionally, we controlled for average years of education represent socioeconomic status (SES) at district/ county levels, with data collected from the Statistical Yearbook, the China 2000 Census, the National Bureau of Statistics, and the China National Knowledge Infrastructure.

2.5. Outcome measure and follow-up

The outcome of this study was stroke events occurring at any point before the follow-up survey conducted in 2018–2019, categorized as non-fatal or fatal strokes, including subarachnoid hemorrhage, intracerebral hemorrhage, ischemic stroke, and unspecified stroke. During the follow-up, we contacted participants or their proxies through face-to-face interviews, telephone calls, or mailed questionnaires to track stroke events. We further verified these events by reviewing medical records or death certification. Initial recording of participants' stroke events was completed by local investigators and subsequently reviewed by the Central Review Committee of Fuwai Hospital (Beijing, China) to confirm the final diagnosis.

2.6. Statistical analysis

In this study, categorical variables were presented as numbers (percentages), and medians (interquartile ranges, IQR) were used to measure cumulative NDVI levels and the average number of heatwave days in one year before stroke events. A multivariable Cox proportional-hazards model was applied to estimate the risk of stroke events associated with heatwaves and residential greenness, adjusting for age, sex, urbanization, geographic region, family history of CVD, educational level, BMI and average years of education. Survival time was measured in years from the investigation date to the recorded date of stroke event occurrence. Hazard ratio(HR) and 95 % confidence intervals (CI) were computed for each 0.1-unit decrease in cumulative NDVI and each 3-day increase in heatwave days. Stratified analyses were conducted by sex, age, educational level and urban or rural residence. Trends in stroke for heatwave days were plotted using restricted cubic spline curves (RCS), as well as at different NDVI levels to explore their nonlinear characteristics (Harrell, 2001).

Cox multiplication interaction models tested the multiplicative effects of heatwaves and lack of greenness on the risk of stroke events, reflecting the statistical interplay of risk factors. The interaction term was calculated by creating a multiplicative term for each 3-day increase in heatwaves and each 0.1-unit decrease in the greenness level, reporting HR and 95 % CI to indicate the degree of effect of exposure. An interaction term HR > 1 indicates a positive multiplicative interaction. We also investigated whether sociodemographic characteristics (including age, sex, residence area, and education level) modified the interaction effect of heatwaves and greenness on stroke risk.

The multiplicative interaction term does not imply additivity. Epidemiologists have suggested that biological interaction should be evaluated on an additive scale rather than a multiplicative scale (Andersson et al., 2005; Hallqvist et al., 1996; Rothman, 1976). Therefore, we estimated the additive interaction between heatwaves and lack of greenness on stroke risk using the relative excess risk due to interaction (RERI), the attributable proportion (AP), and the interaction index (S) (Knol et al., 2011; Richardson and Kaufman, 2009; Van Der Weele and J. Knol., 2014). Similar to the multiplicative interaction, we grouped heatwaves and cumulative NDVI by their median value, each into low and high level groups. That was, the combination of heatwave days and cumulative NDVI was divided into four categories for calculation, and the formula was as below:

$$\boldsymbol{RERI} = \boldsymbol{HR_{A+B+}} - \boldsymbol{HR_{A+B-}} - \boldsymbol{HR_{A-B+}} + \mathbf{1}$$

$$\boldsymbol{AP} = \frac{\boldsymbol{RERI}}{\boldsymbol{HR_{A+B+}}}$$

$$\boldsymbol{S} = \frac{\boldsymbol{HR_{A+B+}} - \mathbf{1}}{(\boldsymbol{HR_{A+B-}} - \mathbf{1}) + (\boldsymbol{HR_{A-B+}} - \mathbf{1})}$$

HR_{A+B+} represents the hazard ratio when both risk factors are at high levels, whereas HR_{A+B-} and HR_{A-B+} represent the hazard ratios when one of the risk factors is at a high level independently. RERI is an intuitive concept with special public health significance, indicating increased risk due to additive interactions. RERI and S have the same meaning, with AP indicating the attributable proportion due to interaction. RERI > 0, AP > 0, and S > 1 denote a positive interaction on an additive scale.

The analyses were conducted with SAS version 9.4 (SAS Institute Inc., Cary, NC USA), and all statistical tests were two-sided with a significance level of $P < 0.05$.

3. Results

Table 1 presents the baseline characteristics of participants based on cumulative NDVI and the number of heatwave days in one year before stroke. The study cohort included 22,702 participants, 60.2 % of whom were adults aged 35–59 years. The median cumulative NDVI was 0.39 (IQR 0.19), and the average number of heatwave days in one year before stroke events was 7 (IQR 5). Participants living in areas with higher residential greenness tended to be of Han ethnicity, reside in rural areas, and have higher educational levels. In contrast, those exposed to more heatwaves were more likely to live in western regions.

During the follow-up, 597 individuals experienced fatal or nonfatal stroke events. In the multivariable-adjusted Cox regression analysis, each 3-day increase in heatwave days was associated with a higher stroke risk (HR: 1.19, 95 % CI: 1.08, 1.31) (Table 2). Stratified analysis revealed that participants aged 60 years or older had a higher risk associated with heatwaves (HR: 1.21, 95 % CI: 1.09–1.36) compared to those aged 35–59 years (HR: 1.12, 95 % CI: 0.92–1.37). Higher residential greenness, as measured by cumulative NDVI, was associated with a reduced stroke risk among participants in rural areas (HR: 1.26, 95 % CI: 1.13–1.41) and those with higher educational attainment (HR:

Table 1
Baseline characteristics.

Characteristic	Total (N, %)	Cumulative NDVI[a]		Heatwave days	
		Median (IQR)	*P* value	Median (IQR)	*P* value
Total	22,702 (100)	0.39 (0.19)	< .0001	7 (5)	< .0001
Age group			<.0001		<.0001
35–59 years old	13,676 (60.2)	0.39 (0.17)		7 (5)	
≥60 years old	9026 (39.8)	0.40 (0.20)		8 (5)	
Gender			0.3066		0.2341
Male	10,505 (46.3)	0.39 (0.19)		7 (5)	
Female	12,197 (53.7)	0.39 (0.18)		7 (5)	
Ethnicity			<.0001		<.0001
Han Chinese	20,315 (89.5)	0.40 (0.19)		7 (5)	
Ethnic minority	2387 (10.5)	0.37 (0.10)		7 (5)	
Educational level			<.0001		<.0001
Elementary middle school or lower	11,593 (51.1)	0.44 (0.16)		8 (4)	
High school or above	11,109 (48.9)	0.37 (0.19)		6 (5)	
Residence			<.0001		<.0001
Urban	10,130 (44.6)	0.34 (0.20)		6 (6)	
Rural	12,572 (55.4)	0.43 (0.15)		8 (4)	
Region			<.0001		<.0001
East	9263 (40.8)	0.38 (0.15)		5 (5)	
Central	9460 (41.7)	0.40 (0.17)		7 (3)	
West	3979 (17.5)	0.34 (0.26)		11 (5)	
Alcohol consumption			0.9028		0.0258
No	16,384 (72.2)	0.39 (0.18)		7 (5)	
Yes	6318 (27.8)	0.39 (0.19)		7 (5)	
Smoking types			<.0001		0.0157
Current	5731 (25.2)	0.40 (0.18)		7 (5)	
Former	1216 (5.4)	0.39 (0.18)		7 (5)	
Never	15,755 (69.4)	0.39 (0.18)		7 (5)	
BMI (kg/m^2)			<.0001		<.0001
<18.5	659 (2.9)	0.42 (0.18)		8 (4)	
18.5–23.9	9554 (42.1)	0.40 (0.18)		8 (5)	
24.0–27.9	8533 (37.6)	0.39 (0.19)		7 (5)	
≥28.0	3956 (17.4)	0.38 (0.19)		6 (5)	
Diabetes Mellitus			<.0001		<.0001
Without	20,416 (89.9)	0.39 (0.18)		7 (5)	
With	2286 (10.1)	0.38 (0.19)		7 (6)	
Hyperlipidemia			<.0001		<.0001
Without	14,978 (66.0)	0.40 (0.19)		8 (5)	
With	7724 (34.0)	0.38 (0.18)		7 (5)	
Hypertension			0.1202		<.0001
Without	13,745 (60.6)	0.39 (0.18)		8 (5)	
With	8957 (39.4)	0.39 (0.20)		7 (5)	
Family history of CVD			0.0003		<.0001
Without	19,416 (85.5)	0.39 (0.18)		7 (5)	
With	3286 (14.5)	0.39 (0.18)		7 (5)	
$PM_{2.5}$			0.0064		<.0001
Low level (29.03–49.52)	12,019 (52.9)	0.39 (0.16)		8 (4)	
High level(49.53–109.94)	10,683 (47.1)	0.40 (0.21)		7 (6)	

Abbreviations: NDVI, normalized difference vegetation index; IQR. interquartile range; BMI, body mass index; CVD, cardiovascular disease; PM, particulate matter; $PM_{2.5}$, one-year annual $PM_{2.5}$ before stroke.
[a] The average cumulative NDVI level within 300 m of the residential address.

1.11, 95 % CI: 1.00–1.29).

When modeled separately using cubic spline curves, a clear dose-response relationship was observed. Stroke risk decreased with increasing cumulative NDVI (Fig. 2) and increased with more heatwave days (Fig. 3).

Further analysis examined the multiplicative interaction between heatwaves and residential greenness at three buffer distances (300 m, 500 m, and 1000 m) (Table 3). The results demonstrated positive and statistically significant synergistic interactions between heatwaves and low levels of greenness at all three buffer distances, indicating an increased stroke risk due to the combined exposure. Specifically, the HRs for these interactions were as follows: HR = 1.58 (95 % CI: 1.14–2.21) for $NDVI_{300\ m}$, HR = 2.02 (95 % CI: 1.45–2.81) for $NDVI_{500\ m}$, and HR = 1.84 (95 % CI: 1.32–2.56) for $NDVI_{1000\ m}$. These results suggest that the combined effect of heatwaves and low greenness increased stroke risk by 46 %, 102 %, and 84 %, respectively. Stratified analysis revealed that these synergistic effects were more pronounced among participants under 60 years of age, in rural areas, and among those with lower educational levels. In rural areas, the interaction was most pronounced, with an HR of 2.65 (95 % CI: 1.66–4.22) for $NDVI_{500\ m}$, while in urban areas, the interaction was either negative or not statistically significant.

Table 4 presents the results of the additive interaction analysis. Statistically significant additive interactions were observed for all buffer zones, with the strongest effect at $NDVI_{500\ m}$ (RERI: 0.66, 95 % CI: 0.38–0.94; AP: 0.52, 95 % CI: 0.30–0.74). For $NDVI_{300\ m}$ and $NDVI_{1000\ m}$, the RERI values were 0.48 (95 % CI: 0.17–0.79) and 0.61 (95 % CI: 0.30–0.91), respectively, indicating significant additive effects. Subgroup analysis showed that the additive interaction between heatwaves and lower greenness was more pronounced among individuals aged 35–59 years, rural residents, those with lower education levels, those with hypertension or hyperlipidemia, and those without diabetes (Fig. 4).

Table 2
The hazard ratio for stroke associated with greenness and heatwave.

	N(n%)	No. of cases	Model 1	Model 2	Model 3	
			cumulative NDVI	Heatwave days	cumulative NDVI	Heatwave days
All participants	22702	597	1.03(0.95-1.10)	**1.19(1.08-1.31)**	**1.05(0.99-1.12)**	**1.20(1.09-1.32)**
Stratified by sex						
Male	10,505 (46.3)	343	1.04(0.95-1.15)	**1.19(1.04-1.35)**	1.06(0.96-1.17)	**1.20(1.05-1.37)**
Female	12,197 (53.7)	254	1.00(0.89-1.12)	**1.20(1.04-1.39)**	1.02(0.91-1.14)	**1.20(1.04-1.39)**
Stratified by age group						
35-59 years old	13,676 (60.2)	133	1.15(0.99-1.36)	1.12(0.92-1.37)	**1.17(1.01-1.38)**	1.16(0.94-1.42)
≥60 years old	9026 (39.8)	464	1.00(0.92-1.08)	**1.21(1.09-1.36)**	1.02(0.94-1.10)	**1.22(1.09-1.36)**
Stratified by residence						
Urban area	10,130 (44.6)	269	0.85(0.76-0.94)	**1.31(1.15-1.49)**	0.88(0.80-0.98)	**1.26(1.10-1.44)**
Rural area	12,572 (55.4)	328	**1.26(1.13-1.41)**	1.08(0.93-1.24)	**1.26(1.13-1.41)**	1.06(0.92-1.22)
Stratified by education						
Elementary middle school or lower	11,593 (51.1)	413	1.00(0.91-1.08)	**1.20(1.06-1.35)**	1.01(0.92-1.10)	**1.20(1.06-1.35)**
High school or above	11,109 (48.9)	184	**1.11(1.00-1.29)**	1.16(0.97-1.39)	**1.14(1.01-1.32)**	1.19(1.00-1.43)
Stratified by region						
North area	13911(61.3)	350	0.89(0.81-0.99)	**1.33(1.15-1.55)**	0.93(0.84-1.03)	**1.30(1.12-1.52)**
South area	8791(38.7)	247	1.02(0.90-1.16)	0.94(0.80-1.11)	1.01(0.89-1.16)	0.94(0.80-1.12)

Note: All models were adjusted for age, sex, urbanization and geographical region, educational level, family history of CVD, body mass index and average years of education.
Model 1 tested the independent effect of each 0.1-unit decrease in cumulative $NDVI_{300m}$ on stroke.
Model 2 tested the independent effect of each 3-day increase in heatwave days in one year before the outcome on stroke.
Model 3 tested the effects of each 0.1-unit decrease in cumulative $NDVI_{300m}$ and each 3-day increase in heatwave days in one year before the outcome on stroke.

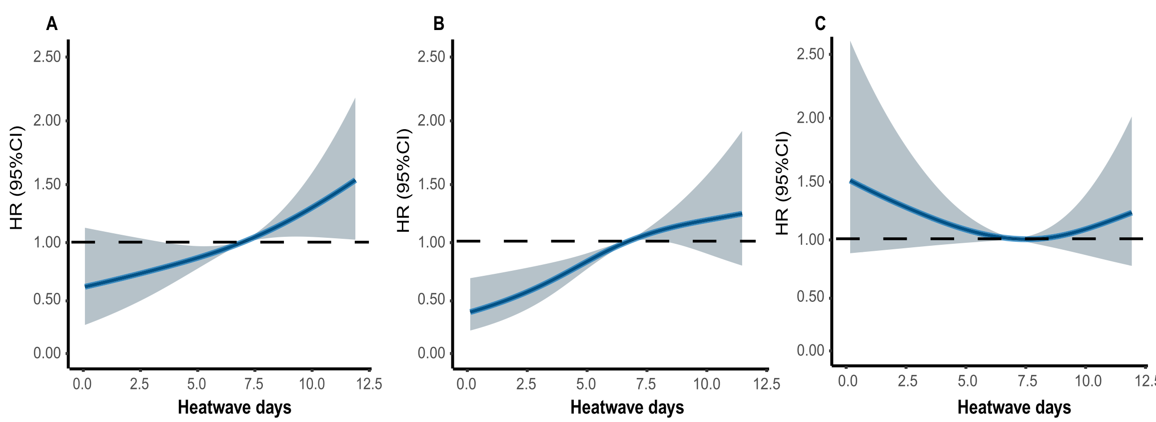

Fig. 2. Association curves between heatwave days and stroke incidence under different levels of cumulative $NDVI_{300\ m}$. Note: A shows the overall association without stratification by NDVI. B and C show the associations stratified by low and high levels of cumulative NDVI, respectively. Shaded areas represent 95 %CI. All models were adjusted for age, sex, urbanization and geographical region, educational level, family history of CVD, body mass index and average years of education.

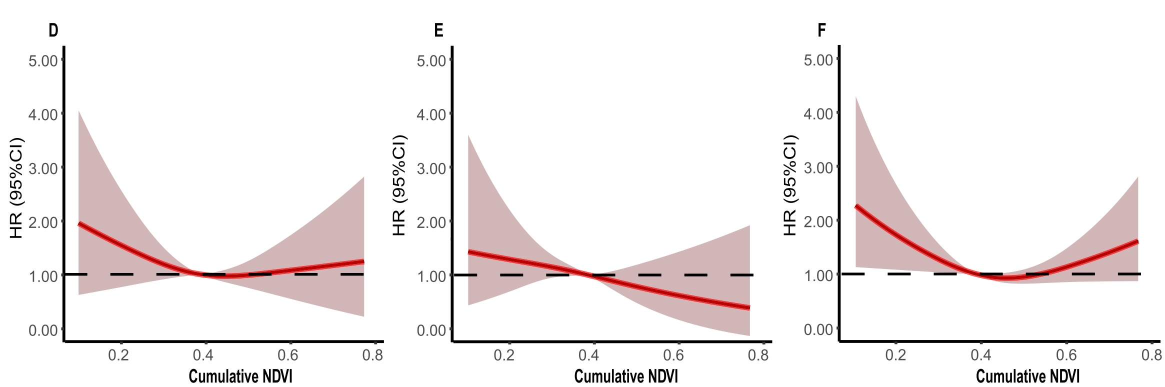

Fig. 3. Association curves between cumulative $NDVI_{300\ m}$ and stroke incidence under different levels of heatwave days. Note: D shows the overall association without stratification by heatwave days. E and F show the associations under low and high heatwave days, respectively. Shaded areas represent 95 %CI. All models were adjusted for age, sex, urbanization and geographical region, educational level, family history of CVD, body mass index and average years of education.

4. Discussion

To our knowledge, this prospective cohort study is the first to examine the interaction between heatwaves and residential greenness on stroke risk among Chinese adults. Our findings show that heatwaves independently increase stroke risk, particularly among females, older

Table 3
The multiplicative interaction pattern between heatwaves and greenness on stroke.

	Cumulative $NDVI_{300\ m}$			Cumulative $NDVI_{500\ m}$			Cumulative $NDVI_{1000\ m}$		
	HR[a]	95 %CI[b]	*P* value	HR[a]	95 %CI[b]	*P* value	HR[a]	95 %CI[b]	*P* value
All participants	**1.58**	**1.14–2.21**	**0.0063**	**2.02**	**1.45–2.81**	**< .0001**	**1.84**	**1.32–2.56**	**0.0003**
By sex									
male	1.52	0.99–2.36	0.0590	**1.69**	**1.10–2.61**	**0.0175**	**1.58**	**1.02–2.44**	**0.0415**
female	1.66	1.00–2.75	0.0516	**2.40**	**1.45–3.97**	**0.0007**	**2.10**	**1.27–3.49**	**0.0039**
By age group									
35–59 years old	**3.09**	**1.51–6.30**	**0.0019**	**3.08**	**1.48–6.39**	**0.0026**	**4.23**	**2.03–8.81**	**0.0001**
≥ 60 years old	1.35	0.93–1.98	0.1147	**1.87**	**1.29–2.71**	**0.0010**	**1.50**	**1.03–2.19**	**0.0332**
By residence									
Urban area	0. 90	0.52–1.58	0.7216	0.86	0.48–1.53	0.6051	1.01	0.57–1.76	0.9843
Rural area	**1.69**	**1.06–2.68**	**0.0274**	**2.65**	**1.66–4.22**	**< .0001**	**1.98**	**1.25–3.14**	**0.0035**
By education level									
Elementary middle school or lower	**1.71**	**1.13–2.58**	**0.0108**	**2.32**	**1.54–3.51**	**< .0001**	**1.84**	**1.22–2.78**	**0.0036**
High school or above	1.53	0.78–3.01	0.2149	1.72	0.87–3.38	0.1394	1.85	0.95–3.61	0.0712

Abbreviation: $NDVI_{300\ m}$, the average cumulative NDVI level within 300 m of the residential address; $NDVI_{500\ m}$, the average cumulative NDVI level within 500 m of the residential address; $NDVI_{1000\ m}$, the average cumulative NDVI level within 1000 m of the residential address; HR, hazard ratio; CI, confidence interval.
[a] HR for multiplicative interaction.
[b] 95 % CI for multiplicative interaction.
All models were adjusted for age, sex, urbanization and geographical region, educational level, family history of CVD, body mass index and average years of education. Statistically significant ($P < 0.05$) associations are given in bold.

Table 4
Additive interaction of heatwaves and greenness on the incidence of stroke.

Heatwave days	category	$\mathbf{NDVI_{300\ m}}$		$\mathbf{NDVI_{500\ m}}$		$\mathbf{NDVI_{1000\ m}}$	
		HR	95 %CI	HR	95 %CI	HR	95 %CI
No	High level	[Ref.]	-	[Ref.]	-	[Ref.]	-
No	Low level	1.02	0.78–1.31	0.89	0.69–1.15	0.98	0.75–1.27
Yes	High level	0.81	0.61–1.08	0.72	0.54–0.95	0.76	0.58–1.02
Yes	Low level	**1.30**	**1.00–1.76**	1.27	0.95–1.69	**1.35**	**1.01–1.81**
RERI		**0.48**	**0.17–0.79**	**0.66**	**0.38–0.94**	**0.61**	**0.30–0.91**
AP		**0.37**	**0.13–0.60**	**0.52**	**0.30–0.74**	**0.45**	**0.23–0.67**
S		1.72	-	0.67	-	1.34	-

Abbreviation: $NDVI_{300\ m}$, the average cumulative NDVI level within 300 m of the residential address; $NDVI_{500\ m}$, the average cumulative NDVI level within 500 m of the residential address; $NDVI_{1000\ m}$, the average cumulative NDVI level within 1000 m of the residential address; HR, hazard ratio; CI: confidence interval.
All models were adjusted for age, sex, urbanization and geographical region, educational level, family history of CVD, body mass index and average years of education. Statistically significant ($P < 0.05$) associations are given in bold.

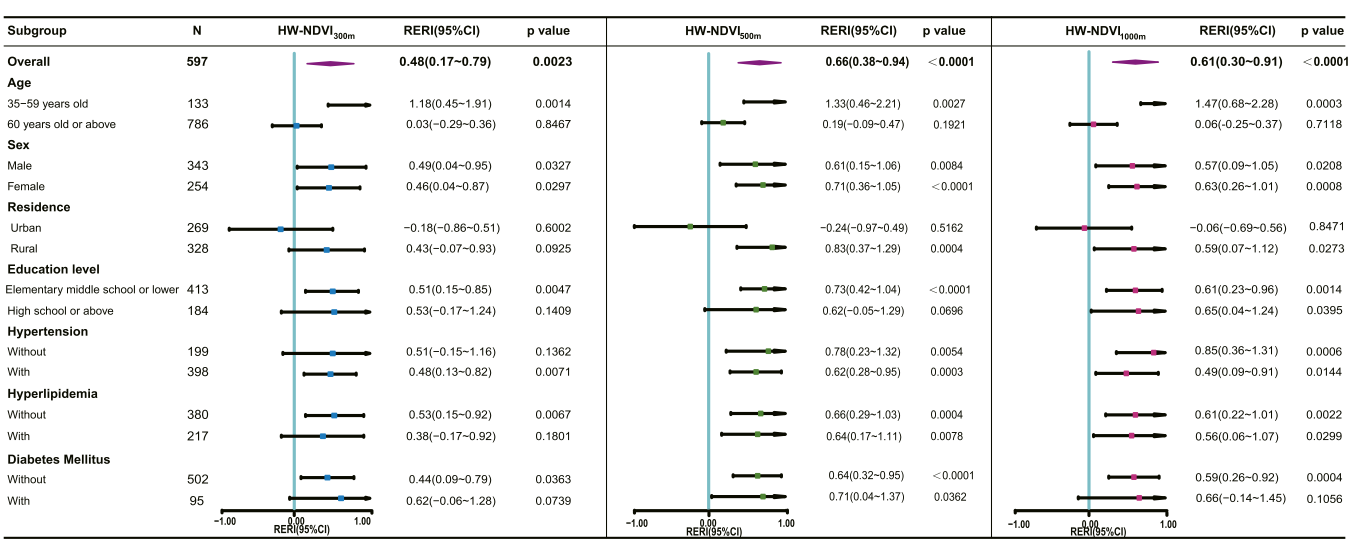

Fig. 4. Additive interaction of heatwaves and residential greenness on the incidence of stroke by subgroups.

adults, urban residents, and individuals with lower educational attainment. Importantly, we found that heatwaves and low levels of greenness can interact synergistically on both additive and multiplicative scales, increasing stroke risk. These interaction effects varied across sociodemographic subgroups, underscoring the importance of considering population vulnerability in environmental health research.

The primary contribution of this study lies in identifying a statistically and biologically meaningful interaction between heatwaves and residential greenness in relation to stroke risk. While previous studies have shown that greenness can buffer the health impacts of heatwaves, most have focused on outcomes such as preterm birth, hypertension, or mortality(Ye et al., 2024; Zhang et al., 2021a; Zhou et al., 2023a). Our findings extend this evidence by demonstrating a similar protective effect of greenness on stroke, a long-term and severe health outcome. Notably, we observed the strongest mitigation effect within 500-meter buffer zones, reinforcing the importance of proximity. These results are consistent with previous research, including a study in China that found higher greenness levels reduced heatwave-related mortality (Zhang et al., 2021b), and research in Australia showing lower rates of heat-related preterm births with greater green space exposure (Ye et al., 2024). Our study adds to this literature by using a large-scale cohort and multiple spatial scales to confirm that nearby green space plays a critical role in moderating heat-related stroke risk. However, we did not examine the interaction between air pollution and heatwaves, despite growing evidence suggesting that these environmental exposures may jointly increase cardiovascular risk (Sun et al., 2020; Zhou et al., 2023a; Zhou et al., 2023b). Recent studies highlight that concurrent exposure to high temperatures and air pollution, particularly in urban areas, may have synergistic effects on stroke risk(Deng et al., 2024; Wang et al., 2025). This interaction may be particularly pronounced in areas with high air pollution, where heat accelerates the negative health impacts of polluted air, leading to heightened cardiovascular risk (Du et al., 2024; Rahman et al., 2022).

The biological mechanisms by which greenness mitigates the adverse effects of heatwaves on stroke risk may be multifactorial. Green spaces help reduce ambient temperatures through shading and evapotranspiration, thereby mitigating the urban heat island effect (Bao et al., 2021). In particular, green spaces dominated by trees (i.e., the canopy layer) provide stronger cooling effects during extreme heat (Sun et al., 2020). Additionally, exposure to greenery promotes physical activity, reduces stress, and supports mental health, all of which may reduce stroke risk (He et al., 2022; Liu et al., 2022b; Nieuwenhuijsen, 2021). On a physiological level, green spaces may stabilize heart rate, reduce sweating, and improve hydration—all of which may buffer the adverse cardiovascular effects of heat stress (Orioli et al., 2019).

Subpopulation analyses revealed that the synergistic effects of heatwaves and low greenness were more pronounced among rural residents and individuals with lower educational attainment. In rural areas, weak infrastructure and limited health-care services may exacerbate vulnerability to heatwaves. On the one hand, cooling infrastructure and emergency response systems are often lacking, with limited availability and accessibility of public cooling centers. On the other hand, healthcare resource shortages and restricted access to healthcare often lead to delays in the diagnosis and treatment of heat-related illnesses(Dewi et al., 2023; Hu et al., 2019). Although rural areas generally have more natural vegetation, agricultural workers are often exposed to prolonged heat without adequate protection(de Schrijver et al., 2023; Fastl et al., 2024; Wang et al., 2022a). Similarly, individuals with lower education levels may lack awareness, resources, or adaptation strategies (Peng et al., 2022; Tao et al., 2023). Education is often a proxy for socioeconomic status, which affects housing quality, healthcare, and environmental exposure (Kim and Kim, 2017).

Our study's findings on heatwaves and stroke risk align with existing research (Alsaiqali et al., 2022; Qi et al., 2021). The mechanisms linking heatwaves and stroke risk are complex and multifaceted, involving both direct physiological effects and broader systemic stressors. Sudden temperature changes exceeding 5°C within 24 h, whether increases or decreases, have been identified as specific triggers for ischemic stroke, doubling cerebrovascular stress and stroke risk (Kyobutungi et al., 2005). Heatwaves impair thermoregulation, leading to dehydration, hemoconcentration, and increased blood viscosity, which promote thrombus formation and exacerbate stroke risk (Nawaro et al., 2023). Additionally, high temperatures cause endothelial dysfunction, systemic inflammation, and cardiovascular strain, which heighten stroke risk, especially among older adults with reduced thermoregulatory capacity (Cheng et al., 2019; Hansen et al., 2011; Liu et al., 2022a).

Stratified analyses revealed greater adverse effects of heatwaves on urban residents compared to rural populations. This aligns with prior studies showing that urban areas, due to the urban heat island effect, experience higher temperatures and limited nighttime cooling, increasing susceptibility to heatwave impacts (Heaviside et al., 2016; Zhang et al., 2021b). Urban residents also face compounded risks from population density, limited green space, and air pollution (Kang et al., 2020). While access to cooling infrastructure like air conditioning can mitigate risks, socioeconomically disadvantaged urban populations may have limited access to these resources, amplifying their vulnerability (Macintyre and Heaviside, 2019). Moreover, older adults are particularly susceptible due to reduced thermoregulation and comorbidities like CVD and chronic obstructive pulmonary disease (Arsad et al., 2022). These findings align with prior research identifying the elderly as a high-risk group during heatwaves (Xu et al., 2024).This implies the need for precautions to protect these vulnerable populations during severe heatwaves, which may become more frequent in the future.

Interestingly, we did not observe a statistically significant independent association between greenness and stroke risk. While this finding contrasts with some earlier studies (Gu et al., 2023; Poulsen et al., 2023a; Poulsen et al., 2023b), it is consistent with others (Wang et al., 2022b; Yitshak-Sade et al., 2017). Several factors may explain this discrepancy, including low variability in greenness within our study population, unmeasured differences in green space quality, and potential confounding by comorbidities (Akpinar, 2017; Yitshak-Sade et al., 2017). Furthermore, although NDVI is a widely used and objective indicator of greenness, it only measures vegetation coverage and does not distinguish between specific types of green spaces (e.g., trees, grasslands, or farmland) and their functional characteristics (Donovan et al., 2022; World Health Organization., 2016). While parks can promote physical activity and social interaction, thereby offering potential cardiovascular benefits (Orstad et al., 2020), evidence on how different types of green spaces specifically affect stroke risk remains limited. For example, Poulsen et al. categorized green spaces into recreational areas, forests, private gardens, and agricultural lands, but did not separately report the associations of each type with stroke risk(Poulsen et al., 2023b). Therefore, improving exposure assessment methods in future research, particularly by distinguishing between green space types and their specific attributes, is critical to better understanding their differential impacts on stroke risk.

In addition to recording the health impacts of heatwaves and greenness, our findings provide practical implications for public health and climate adaptation policies. Urban planning efforts should prioritize the development of accessible, high-quality green spaces, especially in vulnerable communities. Strategies may include increasing tree canopy coverage, protecting green corridors, and ensuring equitable distribution of parks and green infrastructure (Jennings et al., 2017; Ulmer et al., 2016; Wolf et al., 2020). In rural areas, community-based greening measures such as agroforestry may provide both environmental and health benefits (Murage et al., 2025). Additionally, public health programs should integrate greenness into heatwave preparedness plans, especially for high-risk populations (Wolf et al., 2020).

With accelerating urbanization and climate change, the frequency and intensity of heatwaves are expected to rise in the future, increasing the burden of heat-related diseases such as stroke (Khatana et al., 2023). Projections indicate that under high-emission scenarios, the number of days exceeding critical heat thresholds will increase significantly by mid-century (Amoatey et al., 2025; Romanello et al., 2023). In this scenario, the protective role of greenness for health is likely to become increasingly important. Expanding and maintaining green infrastructure—particularly in heat-vulnerable areas—should be recognized as a long-term climate adaptation strategy to reduce the future health impacts of extreme heat (Romanello et al., 2023; Taylor et al., 2024). Governments are increasingly recognizing the importance of this issue.

In China, for example, a range of policies have been implemented to protect vulnerable populations from extreme heat, including a national high-temperature early warning system, pilot programs for climate-resilient cities, and the National Climate Change Adaptation Strategy 2035, which promotes urban greening and integrated health planning (Ji et al., 2023). Our findings support and further information for these efforts.

There are some strengths to our study. It is a large prospective cohort study with detailed demographic and behavioral information, allowing for a thorough examination of the effects of heatwaves and residential greenness on stroke events. We used relative thresholds to define heatwaves, considering the diverse climates and long-term adaptations of local residents across China. Most importantly, this is the first large-scale study to comprehensively explore the interaction between heatwaves and greenness on stroke outcomes.

Nonetheless, several limitations must be acknowledged. First, our study used meteorological data from observatories rather than personal exposure data, which may introduce estimation errors.Additionally, we did not distinguish the information on the types of green space, and changes in residential address during the follow-up period, which may lead to misclassification of greenness and heatwaves exposures. Second, our data collection was at the district and county level, potentially overlooking variations within smaller communities. Third, we focused on stroke, without analyzing more CVD subtypes due to data limitations. Fourth, the relatively short follow-up duration and few follow-up times limited the observed number of stroke events, so this study did not evaluate the interaction of air pollution and heatwaves on the risk of stroke, and it may also affect the causal inference of our findings. We will further investigate this relationship in future studies with extended follow-up durations. Finally, we also acknowledge potential residual confounding due to limitations in SES measurement. Although we adjusted for SES using average years of education at the district/county level, this ecological proxy may not fully capture individual-level differences in income, occupation, or living conditions (Sorjonen et al., 2021).

5. Conclusion

This prospective cohort study of Chinese adults highlights that heatwaves increase the risk of stroke. Conversely, higher residential greenness is associated with reduced stroke risk in rural populations and those with higher educational attainment. A synergistic interaction between heatwaves and low greenness was identified as increasing the risk of stroke, especially in rural areas and among people with lower levels of education. These findings highlight the potential protective role of residential greenness against heat-related stroke risk and emphasize the importance of integrating green infrastructure into urban and rural planning to mitigate the health impacts of climate change.

CRediT authorship contribution statement

Nuerguli Tuerdi: Writing – review & editing, Writing – original draft, Methodology, Visualization. **Xue Cao:** Software, Methodology, Conceptualization, Writing – review & editing. **Haosu Tang:** Data curation, Validation, Supervision. **Yujie Zhang:** Writing – review & editing. **Congyi Zheng:** Validation, Supervision. **Xin Wang:** Validation, Supervision. **Chenye Chang:** Writing – review & editing. **Yixin Tian:** Investigation. **Xue Yu:** Investigation. **Xuyan Pei:** Investigation. **Ye Tian:** Supervision, Resources. **Wei Wang:** Validation, Investigation. **Gang Huang:** Supervision, Resources. **Zengwu Wang:** Writing – review & editing, Supervision, Conceptualization, Resources.

Additional contributions

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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