

Association of long-term exposure to green space with cardiovascular health and the mediating role of triglyceride-glucose index in middle-aged and older Chinese adults: a nationwide cohort study

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ABSTRACT

BACKGROUND Few studies have investigated the associations between green space, the triglyceride-glucose (TyG) index, and cardiovascular health outcomes. This study aims to examine the relationships between green space and chronic cardiovascular diseases among middle-aged and older Chinese adults, while also evaluating the potential mediating effect of the TyG index.

METHODS Baseline and follow-up data were collected from the 2011 and 2015 waves, respectively, of the China Health and Retirement Longitudinal Study (CHARLS). Inverse probability of treatment weighting was used to address selection bias. City-level cluster-robust logistic regression analysis was used to assess associations between green space (2011–2014) and hypertension, heart disease, and dyslipidemia. Counterfactual exploratory mediation analysis examined the mediating role of the TyG index. Restricted cubic splines were used to explore the dose-response relationships between green space and the outcomes.

RESULTS Among 11,925 participants, each 1 standard deviation (0.0922) increment in the Normalized Difference Vegetation Index (NDVI) was associated with a 13% lower risk of hypertension (OR = 0.87, 95% CI: 0.83–0.92, $P < 0.001$), with a linear dose-response relationship. No significant independent associations were observed for heart disease (OR = 0.92, 95% CI: 0.82–1.03, $P = 0.142$) or dyslipidemia (OR = 0.96, 95% CI: 0.86–1.06, $P = 0.406$). Mediation analysis showed that the TyG index partially mediated the NDVI-hypertension association (indirect effect $P < 0.05$), the proportion mediated was 2.9% (95% CI: 1.9%–4.1%).

CONCLUSIONS Long-term residential green space exposure is significantly associated with a lower risk of hypertension in middle-aged and older Chinese adults, with the TyG index playing a modest partial mediating role. No significant independent associations were observed for heart disease or dyslipidemia. Enhancing urban greening may be an effective environmental strategy for the primary prevention of hypertension.

Non-communicable chronic diseases have imposed a substantial health burden worldwide. In China, chronic diseases among the elderly are a serious public health issue. Projections indicate that by 2040, the population of individuals over 60 years old will reach an estimated 402 million in China.^[1] With rapid socio-economic development and an accelerating trend of population aging, chronic diseases have emerged as a major public health concern in China, with cardiovascular diseases be-

ing particularly prevalent. Middle-aged and older adults, who have increased susceptibility, have become the primary focus for the prevention, management, and treatment of cardiovascular diseases.^[2] As global urbanization accelerates, the health benefits of green space have been increasingly recognized. Scientific studies have demonstrated that green space exerts a positive influence on cardiovascular health.^[3–6] Although research in this area has been expanding, only a limited number of studies have examined the impact of lo-

ng-term exposure to green space on chronic cardiovascular diseases among middle-aged and older adults using nationally representative data from China.

Insulin resistance (IR) plays a critical role in the development of atherosclerotic cardiovascular diseases and has been identified as an independent risk factor for their onset.^[7] In the general population, assessing IR is particularly important for evaluating cardiovascular risk.^[8] The triglyceride-glucose (TyG) index has been proposed as a simple and reliable surrogate marker for IR.^[9] Previous studies have shown that the TyG index is independently associated with atherosclerosis and cardiovascular diseases, such as hypertension,^[10,11] coronary heart disease (CHD),^[12] and dyslipidemia.^[13] To our knowledge, although some studies have examined the relationships among green space, cardiovascular risk biomarkers, and cardiovascular diseases,^[14,15] few studies have explored the association of the TyG index with green space and with chronic cardiovascular conditions simultaneously. The potential mediating effect of the TyG index in the relationships between green space and the risk of chronic cardiovascular diseases remains unclear.

Therefore, this study aims to investigate the association between long-term exposure to green space and the risk of hypertension, heart disease, and dyslipidemia among middle-aged and older Chinese adults, and to evaluate the potential mediating effect of the TyG index in these relationships.

METHODS

Study Population

This study utilized publicly available data from the Chi-

na Health and Retirement Longitudinal Study (CHARLS) (<http://charls.pku.edu.cn>). The CHARLS project was approved by the Biomedical Ethics Review Committee of Peking University, Beijing, China (IRB00001052-11015), and informed consent was obtained from all participants. Baseline and follow-up data were collected from the 2011 and 2015 waves, respectively, of the CHARLS. This interdisciplinary survey used nationally representative, high-quality data to examine individuals aged 45 years and older across 450 villages and communities in 28 provinces, including autonomous regions and municipalities. The baseline sample consisted of 17,708 participants. During the follow-up period, participants were excluded due to incomplete follow-up or missing laboratory examination information. Specifically, participants were excluded for the following reasons: (1) non-participation in the 2015 follow-up ($n = 3132$); (2) missing age information or age < 45 years ($n = 463$); (3) missing chronic disease history or follow-up data for hypertension, heart disease, and dyslipidemia ($n = 1033$); and (4) absence of any baseline blood test parameters ($n = 1155$). Ultimately, a total of 11,925 eligible participants were included (Figure 1). For each outcome, participants who reported a diagnosis of the corresponding disease at baseline were excluded to create a cohort free of the disease at baseline for incidence analysis.

Exposure Factor

This study employed the Normalized Difference Vegetation Index (NDVI) to represent green space in each city. NDVI is a key parameter used to reflect crop growth and nutritional status, with values ranging from -1 to 1; higher positive values indicate greater vegetation coverage in urban ar-

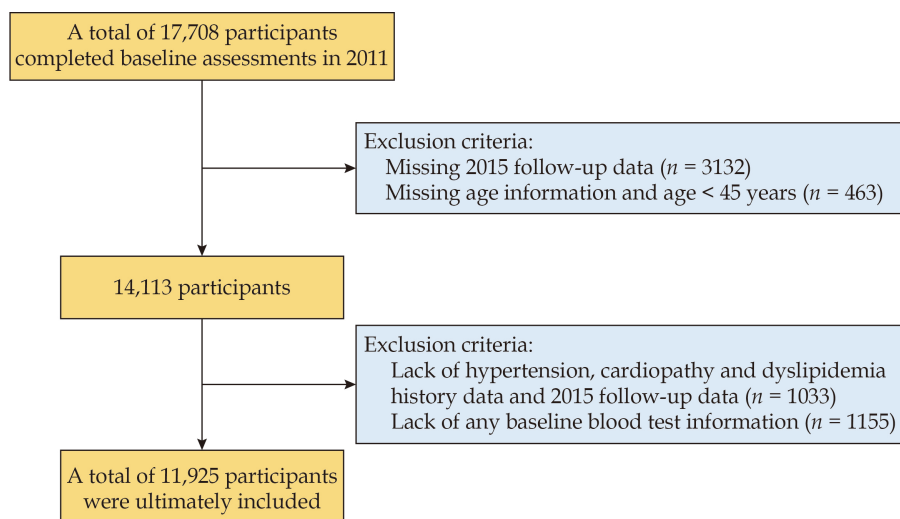


Figure 1 Flowchart of the participant.

eas.^[16] Monthly NDVI data were obtained from the MOD13-A3 dataset, which is regularly published by NASA (<https://www.earthdata.nasa.gov>). Using monthly NDVI time series, the maximum value composite of the 12-month period was derived to compute the annual NDVI for the years 2011–2014. The spatial resolution of the data is 1000 meters, as green space within this range is a strong predictor of physical health.^[17] Using the 2024 administrative boundary dataset at the provincial, municipal, and county levels [Map Review Number GS(2024)0650], released by the National Geographic Information Public Service Platform (Tianditu), the average NDVI value was calculated for each city. The final long-term exposure indicator was obtained by averaging the annual NDVI values over the four years.

TyG Index

Blood samples were collected in a fasting state by healthcare professionals, stored at -80°C , and analyzed in a central laboratory using an enzymatic colorimetric method. The calculation of the TyG index was based on the formula: $\text{TyG} = \ln [\text{fasting triglycerides (mg/dL)} \times \text{fasting glucose (mg/dL)} / 2]$. The TyG index was derived from blood samples collected at the 2015 follow-up, concurrent with the outcome assessment.

Outcome Variables

Hypertension, heart disease, and dyslipidemia were selected from the self-reported chronic disease data as outcome variables. Information on these conditions were obtained through the questions: “Have you been diagnosed with hypertension or heart disease or dyslipidemia by a physician?” Participants who were free of the condition at baseline and subsequently reported a physician diagnosis at follow-up were considered to have incident hypertension, heart disease, or dyslipidemia.

Covariates Assessment

Covariates were defined using baseline health examination data, including: (1) demographic characteristics: age, sex; (2) socioeconomic factors: education level (primary or below/junior high/senior high/college or above), marital status (married/other), residence (urban/rural), household income (log-transformed); (3) health behaviors: smoking (yes/no), drinking (yes/no); (4) anthropometric measurements: body mass index, calculated from standardized questions on height and weight; (5) chronic disease history: self-reported chronic diseases (yes/no); and (6) laboratory tests: blo-

od urea nitrogen, glucose, creatinine, total cholesterol, triglycerides, high-density lipoprotein cholesterol, low-density lipoprotein cholesterol, C-reactive protein, glycated hemoglobin A1c, uric acid, cystatin C. According to previous studies, it is also important to control for the effect of air pollution. Therefore, we selected the annual average concentration of baseline $\text{PM}_{2.5}$ as a confounding variable in the analysis. In addition, we adjusted for baseline urbanization rate and city-level gross domestic product to account for regional economic development and urban-rural structural differences. Data on $\text{PM}_{2.5}$, urbanization rate, and gross domestic product were obtained from the *China City Statistical Yearbook*.

Statistical Analysis

Descriptive statistics were used to summarize baseline data: continuous variables were presented as mean $\pm$ SD, and categorical variables were presented as counts (percentages). Missing covariates were handled using multiple imputation by chained equations, generating 20 complete datasets with 50 iterations. The missing proportions, missing patterns, and imputation diagnostics are provided in the supplemental material, [Tables 1S & 2S](#) and [Figure 1S](#).

To correct for potential selection bias due to baseline differences between included and excluded participants, we applied inverse probability of treatment weighting (IPTW) to estimate associations in a weighted pseudo-population.^[18] Propensity scores were estimated using logistic regression with inclusion status as the dependent variable and all baseline covariates as independent variables.^[18] Stabilized weights were used to estimate the average treatment effect,^[19] and weights were truncated at the 1st and 99th percentiles to reduce the influence of extreme values. Covariate balance before and after weighting was assessed using standardized mean differences (SMD), with $\text{SMD} < 0.10$ indicating good balance.^[20] All subsequent primary analyses were conducted on the IPTW-weighted data.

Spearman's correlation analysis was performed to evaluate the associations between NDVI, TyG index, hypertension, dyslipidemia, and heart disease.

Four sequentially adjusted logistic regression models were constructed: Model 1 adjusted for sociodemographic factors; Model 2 additionally adjusted for health behaviors and chronic diseases; Model 3 further adjusted for anthropometric and biochemical indicators; and Model 4 further adjusted for environmental and contextual factors. NDVI was standardized per 1 standard deviation (SD), and cluster-robust



st standard errors with city as the clustering variable were used.

Based on the results of multivariable regression analyses, subsequent mediation and restricted cubic spline (RCS) analyses were performed only for outcomes that showed a statistically significant association. We used the counterfactual mediation analysis framework developed by Imai, *et al.*^[21] implemented via the mediation package in R statistical software 4.4.1 (R Foundation for Statistical Computing, Vienna, Austria).^[22] The average causal mediation effect and average direct effect were estimated on the log-odds scale, while the total and direct effects were also presented as odds ratios (ORs). Bootstrapping was used to derive 95% CI, an indirect effect was considered statistically significant if the CI did not contain zero. The identification assumptions included no unmeasured exposure-mediator, mediator-outcome, or exposure-outcome confounding, and no mediator-outcome interaction. Because the TyG index was measured simultaneously with the outcome, this analysis was defined as exploratory mediation analysis. RCS were used to explore dose-response relationships, with the median as the reference and non-linearity tested by likelihood ratio tests.

Sensitivity analyses included: (1) using 2011–2013 NDVI as an alternative exposure window; (2) comparing standard logistic regression with cluster-robust regression; and (3) assessing the impact of unmeasured confounding on mediation results using the sensitivity parameter ρ proposed by Imai, *et al.*^[21] ($\rho = 0$ indicates no unmeasured confounding, $|\rho| \geq 0.30$ indicates high robustness). All analyses were performed across the 20 imputed datasets and results were pooled using Rubin's rules. A two-sided P -value < 0.05 was considered statistically significant. All statistical analyses were conducted using R statistical software 4.4.1 (R Foundation for Statistical Computing, Vienna, Austria).

RESULTS

Baseline Characteristics

A total of 11,925 participants were included in this study. The mean age was 58.9 years, 47.5% of participants were male, 64.3% of participants were rural residents, mean $PM_{2.5}$ was $412.0 \mu g/m^3$, and mean NDVI (2011) was 0.74. Baseline self-reported prevalence rates were 25.5% for hypertension, 11.9% for heart disease, and 10.0% for dyslipidemia (Table 1).

IPTW Covariate Balance Assessment

To reduce observed covariate confounding, IPTW was us-

Table 1 Baseline characteristics of the study population.

Characteristic	Value
Sample size	11,925
Age, yrs	58.88 $\pm$ 9.16
Body mass index, kg/m ²	24.02 $\pm$ 28.92
Income	8.95 $\pm$ 2.48
Blood urea nitrogen, mg/dL	15.78 $\pm$ 4.46
Glucose, mg/dL	109.74 $\pm$ 35.70
Creatinine, mg/dL	0.78 $\pm$ 0.19
Total cholesterol, mg/dL	193.35 $\pm$ 38.66
Triglycerides, mg/dL	134.19 $\pm$ 109.15
High-density lipoprotein cholesterol, mg/dL	51.09 $\pm$ 15.65
Low-density lipoprotein cholesterol, mg/dL	115.94 $\pm$ 34.37
C-reactive protein, mg/L	2.62 $\pm$ 6.91
Hemoglobin A1c, %	5.25 $\pm$ 0.78
Uric acid, mg/dL	4.45 $\pm$ 1.22
Cystatin C, mg/L	0.99 $\pm$ 0.24
$PM_{2.5}$, $\mu g/m^3$	412.04 $\pm$ 500.27
NDVI (2011)	0.74 $\pm$ 0.10
Urbanization rate, %	0.46 $\pm$ 0.15
Gross domestic product, billion RMB	211.83 $\pm$ 258.74
Gender	
Female	6258 (52.5%)
Male	5667 (47.5%)
Residence	
City	4261 (35.7%)
Rural	7664 (64.3%)
Marital status	
Other	1386 (11.6%)
Married	10,539 (88.4%)
Education level	
Below primary school	5548 (46.5%)
Primary school	2582 (21.7%)
Junior high school	2498 (20.9%)
High school and above	1297 (10.9%)
Smoking status	
No	8224 (69.0%)
Yes	3701 (31.0%)
Drinking status	
No	7946 (66.6%)
Yes	3979 (33.4%)
Hypertension	
No	8884 (74.5%)
Yes	3041 (25.5%)
Heart disease	
No	10,503 (88.1%)
Yes	1422 (11.9%)

Continued

Characteristic	Value
Dyslipidemia	
No	10,728 (90.0%)
Yes	1197 (10.0%)
Any chronic disease	
No	3837 (32.2%)
Yes	8088 (67.8%)

Data are presented as means $\pm$ SD or n (%). NDVI: Normalized Difference Vegetation Index.

ed to construct a weighted pseudo-population. Before weighting, there were substantial imbalances between the included and excluded groups across multiple covariates, with the largest SMD for continuous variables reaching 0.176 (cystatin C), and categorical variables also showed significant differences (e.g., married proportion, rural residence, smoking; all $P < 0.05$). After IPTW weighting, all SMDs for the weighted covariates were reduced to below 0.10 (range: 0.001–0.055), and all between-group P -values > 0.05 (supplemental material, Table 3S).

Associations of Key Variables

Spearman's correlation analysis showed that NDVI was si-

gnificantly negatively correlated with TyG index ($\rho = -0.036$, $P < 0.001$), hypertension ($\rho = -0.042$, $P < 0.001$), and dyslipidemia ($\rho = -0.035$, $P < 0.001$), but showed no significant correlation with heart disease ($\rho = 0.005$, $P > 0.05$). The TyG index was significantly positively correlated with hypertension ($\rho = 0.127$, $P < 0.001$), dyslipidemia ($\rho = 0.159$, $P < 0.001$), and heart disease ($\rho = 0.058$, $P < 0.001$). Strong positive correlations were also observed among the disease outcomes: hypertension with dyslipidemia ($\rho = 0.249$, $P < 0.001$), hypertension with heart disease ($\rho = 0.225$, $P < 0.001$), and dyslipidemia with heart disease ($\rho = 0.213$, $P < 0.001$) (Table 2).

Cluster-robust Logistic Regression of NDVI with Hypertension, Heart Disease, and Dyslipidemia

The distribution of NDVI in the analytical sample is shown in supplemental material, Table 4S (mean: 0.7361, SD: 0.0922). Using weighted multivariable logistic regression with IPTW and city-level cluster-robust standard errors (Table 3), after full adjustment (Model 4), each 1 SD (0.0922) increment in NDVI was associated with a 13% lower risk of hypertension (OR = 0.87, 95% CI: 0.83–0.92, $P < 0.001$). For heart disease, the OR was 0.92 (95% CI: 0.82–1.03, $P = 0.142$); for dyslipidemia, the OR was 0.96 (95% CI: 0.86–1.06, $P = 0.406$),

Table 2 Spearman's correlations among NDVI, TyG index, hypertension, heart disease, and dyslipidemia.

Variable	NDVI	TyG index	Hypertension	Dyslipidemia	Heart disease
NDVI	1.000	−0.036	−0.042	−0.035	0.005
TyG index		1.000	0.127	0.159	0.058
Hypertension			1.000	0.249	0.225
Dyslipidemia				1.000	0.213
Heart disease					1.000

NDVI: Normalized Difference Vegetation Index; TyG: triglyceride-glucose.

Table 3 Weighted cluster-robust logistic regression: associations of NDVI with hypertension, heart disease, and dyslipidemia.

Outcome	<i>n</i>	Model 1		Model 2		Model 3		Model 4	
		OR (95% CI)	<i>P</i> -value	OR (95% CI)	<i>P</i> -value	OR (95% CI)	<i>P</i> -value	OR (95% CI)	<i>P</i> -value
Hypertension	8884	0.89 (0.84–0.95)	< 0.001	0.89 (0.84–0.95)	< 0.001	0.89 (0.83–0.94)	< 0.001	0.87 (0.83–0.92)	< 0.001
Heart disease	10,503	0.94 (0.83–1.06)	0.307	0.94 (0.83–1.05)	0.268	0.93 (0.83–1.05)	0.262	0.92 (0.82–1.03)	0.142
Dyslipidemia	10,728	0.94 (0.86–1.03)	0.208	0.94 (0.86–1.03)	0.199	0.93 (0.85–1.03)	0.173	0.96 (0.86–1.06)	0.406

Model 1: adjusted for sociodemographic factors (age, sex, marital status, urban/rural, education, and log-income). Model 2: adjusted for variables in Model 1 plus the health behaviors (smoking and drinking) and chronic diseases. Model 3: adjusted for variables in Model 2 plus the anthropometric and biochemical indicators (body mass index, blood urea nitrogen, glucose, creatinine, total cholesterol, triglycerides, high-density lipoprotein in cholesterol, low-density lipoprotein cholesterol, C-reactive protein, hemoglobin A1c, uric acid, and cystatin C). Model 4: adjusted for variables in Model 3 plus the environmental and contextual factors (PM_{2.5}, urbanization rate, and gross domestic product). Effect sizes are per 1 standard deviation (0.0922) increment in NDVI. NDVI: Normalized Difference Vegetation Index.



both not statistically significant. These findings remained consistent across the four sequentially adjusted models, indicating a robust inverse association between NDVI and hypertension, whereas no clear independent associations were observed for heart disease or dyslipidemia.

Counterfactual Exploratory Mediation Analysis of NDVI, TyG Index, and Hypertension

After IPTW weighting and adjustment for all covariates (Table 4), the total effect of NDVI on hypertension was OR = 0.97 (95% CI: 0.97–0.98), and the direct effect (after adjusting for TyG) was OR = 0.98 (95% CI: 0.97–0.98); both were statistically significant ($P < 0.05$). The indirect effect (i.e., the effect mediated through TyG) was average causal mediation effect = -0.0007 (95% CI: -0.0010 to -0.0005), with a 95% CI that did not include zero, indicating a significant mediation. The proportion mediated was 2.9% (95% CI: 1.9%–4.1%). These findings suggest that the TyG index is a partial mediator of the NDVI–hypertension association.

Dose-response Relationship Analysis

RCS analysis with three knots (20th, 50th, 80th percentiles; median as reference) was used to examine the dose-response relationship between NDVI and hypertension. As shown in Figure 2, NDVI exhibited a significant linear inverse association with hypertension ($P_{\text{overall}} = 1.24 \times 10^{-6}$, $P_{\text{nonlinear}} = 0.1655$). The risk of hypertension decreased steadily with increasing NDVI, with no clear threshold or plateau. RCS results for NDVI–TyG and TyG–hypertension are provided in the supplemental material, Figures 2S & 3S.

Sensitivity Analysis Results

To assess the robustness of the primary findings, three sensitivity analyses were performed: (1) using an alternative exposure window (2011–2013 average NDVI) for regression; (2) comparing standard logistic regression with city-level cluster-robust standard error regression; and (3) evaluating the impact of unmeasured confounding on the mediation analysis.

ter-robust standard error regression; and (3) evaluating the impact of unmeasured confounding on the mediation analysis.

Alternative exposure window (2011–2013 NDVI average)

Using the 2011–2013 average NDVI as the exposure, the fully adjusted (Model 4) regression was repeated (supplemental material, Table 5S). Per 1 SD (0.0915) increment in NDVI, the OR for hypertension was 0.88 (95% CI: 0.83–0.93, $P < 0.001$), nearly identical to the primary analysis (OR = 0.88, 95% CI: 0.83–0.93). For heart disease, the OR was 0.93 (95% CI: 0.82–1.05, $P = 0.223$); for dyslipidemia, the OR was 0.96 (95% CI: 0.87–1.07, $P = 0.507$). These results are consistent with the primary findings, indicating that the choice of exposure window does not materially affect the conclusions.

Comparison of standard versus cluster-robust standard errors

Sensitivity analysis using standard logistic regression was compared with the primary cluster-robust approach (supplemental material, Table 6S). For hypertension, both methods gave OR = 0.87 ($P < 0.001$); the cluster-robust standard errors was slightly smaller (–17.2% change), and the inference remained unchanged. For heart disease, standard regression showed a significant result (OR = 0.92, $P = 0.022$), whereas the cluster-robust regression did not (OR = 0.92, $P = 0.142$); the standard errors increased by 55.8%, leading to a change in inference. For dyslipidemia, both methods were non-significant ($P > 0.05$). These findings indicate that clustering at the city level mainly affects the standard error estimates for heart disease, making the use of cluster-robust standard errors essential.

Sensitivity analysis for unmeasured confounding in mediation

The sensitivity parameter ρ represents the correlation between

Table 4 Exploratory counterfactual mediation analysis: TyG index as mediator between NDVI and hypertension.

Effect	Coefficient (95% CI)	OR (95% CI)	Significant	Proportion mediated
Total effect (NDVI→Hypertension)	-0.0258 (-0.0278 to -0.0241)	0.97 (0.97–0.98)	Yes	–
Direct effect (NDVI→Hypertension, adjusted for TyG index)	-0.0251 (-0.0271 to -0.0233)	0.98 (0.97–0.98)	Yes	–
Indirect effect (NDVI→TyG index→Hypertension)	-0.0007 (-0.001 to -5×10^{-4})	Not available	Yes	2.9% (95% CI: 1.9%–4.1%)

NDVI per 1 standard deviation (0.0922). The inverse probability of treatment weighting weights applied. Based on 20 imputed datasets. Adjusted for all covariates. Results pooled using Rubin's rules. NDVI: Normalized Difference Vegetation Index; TyG: triglyceride-glucose.



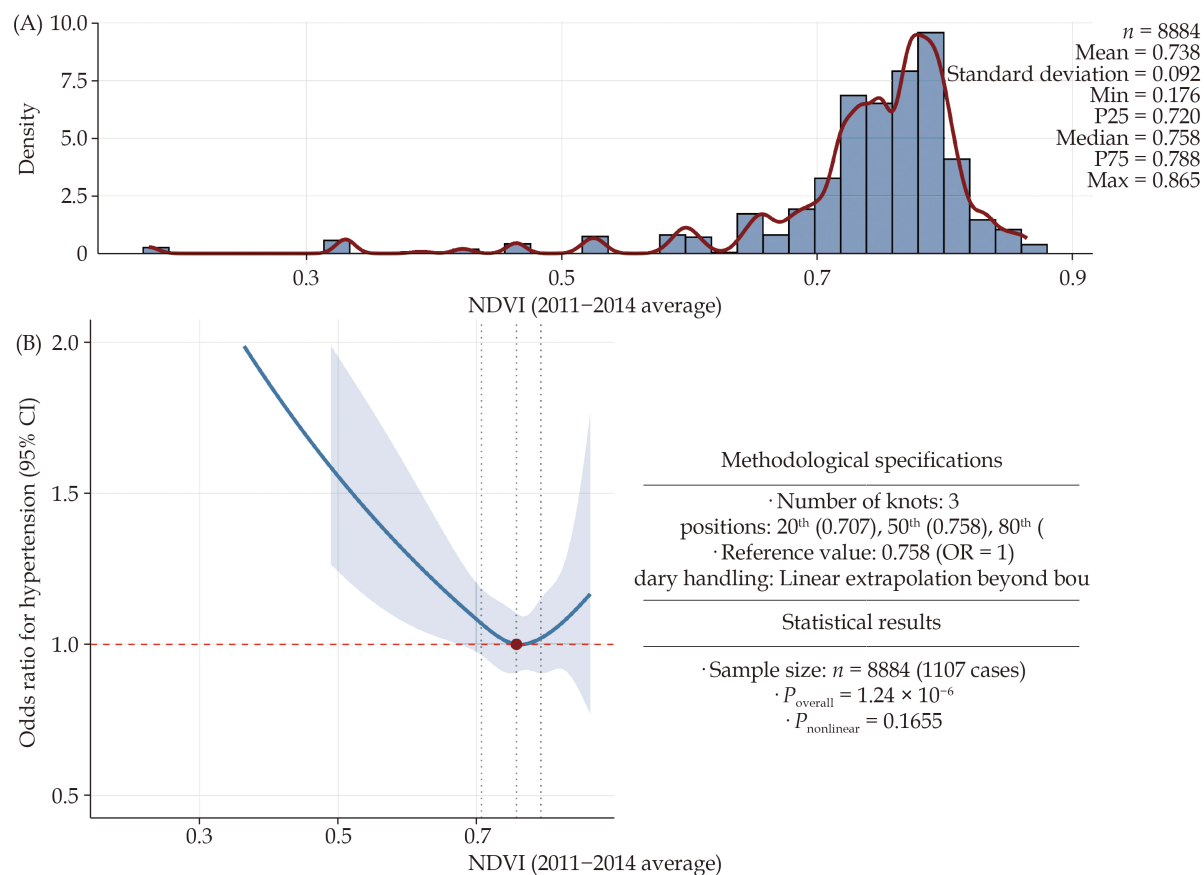


Figure 2 NDVI distribution (A) and dose-response relationship (B) with hypertension. Restricted cubic spline analysis with three knots (20th, 50th, 80th percentiles; median as reference) was performed. The model was adjusted for all covariates (Model 4). The solid line represents the odds ratio, and the shaded area represents the 95% CI. The histogram at the bottom shows the distribution of NDVI. $P_{\text{overall}} = 1.24 \times 10^{-6}$, $P_{\text{nonlinear}} = 0.1655$. NDVI: Normalized Difference Vegetation Index.

when the error terms of the mediator and outcome models, $\rho = 0$ indicates no unmeasured confounding. As shown in supplemental material, Table 7S, an unmeasured confounder with $|\rho| = 0.85$ would be required to completely nullify the indirect effect for hypertension. According to the Imai, *et al.*^[21] criterion ($|\rho| \geq 0.30$ indicating high robustness), our mediation finding is highly robust to unmeasured confounding.

DISCUSSION

In this study, we found that NDVI was significantly negatively associated with hypertension, but no independent significant associations were observed with heart disease or dyslipidemia. The TyG index played a modest partial mediating role in the NDVI-hypertension relationship. Dose-response analysis revealed a linear inverse association between NDVI and hypertension.

Specifically, each 1 SD (0.0922) increment in NDVI was associated with a 13% lower risk of hypertension. This effect re-

mained consistent across four sequentially adjusted models, and the sensitivity analysis using the 2011–2013 NDVI as an alternative exposure window yielded a similar result (OR = 0.88), indicating that the association was not influenced by the choice of exposure window. Previous studies have consistently supported a protective effect of green space against hypertension. For example, an early community-based cross-sectional study of participants aged 18–91 years reported that greenness exposure was associated with a 45% lower risk of hypertension in adults aged ≥ 65 years.^[23] A cohort of Chinese oldest-old showed that each 0.1 unit increase in NDVI was associated with a 9.6% lower risk of hypertension.^[24] A cross-sectional study of 24,845 urban residents in northeast China reported that each interquartile range increase in NDVI was associated with a 5% lower prevalence of hypertension.^[25] Another observational survey in five regions of central China found that greenness exposure was associated with an approximately 8% reduction in hypertension risk.^[26] Mechanistically, green space may lower blood pressure through



multiple pathways, including reducing air pollution, promoting physical activity, alleviating mental stress, and enhancing social interaction.^[27,28] Notably, we used city-level cluster-robust standard errors as the primary analytical method to account for within-city correlation. For hypertension, the difference between cluster-robust and conventional standard errors was -17.2%, but both methods yielded highly significant results ($P < 0.001$), indicating that the hypertension association was insensitive to clustering and highly robust.

In the primary analysis using cluster-robust standard errors, the association between NDVI and heart disease did not reach statistical significance. However, when the conventional logistic regression was applied in the sensitivity analysis, the association became significant, indicating a change in inference. This discrepancy reveals a key methodological issue: in the multi-stage stratified cluster sampling designs, individuals within the same city tend to share similar environmental exposures (e.g., green space, air pollution), healthcare resources, and lifestyles, making observations non-independent. Ignoring clustering leads to underestimated standard errors and an increased risk of type I errors. Therefore, cluster-robust standard errors represent a more conservative and appropriate choice. Our null finding for heart disease is consistent with some previous literature. For example, a meta-analysis reported that the incidence of stroke, dyslipidemia, and CHD decreased across the highest versus lowest green space exposure groups, but these results were not statistically significant.^[29] Another meta-analysis indicated only a 2% protective effect for CHD mortality, with significant heterogeneity.^[30] Nevertheless, other studies have reported significant associations; for instance, a UK Biobank cohort found that residential greenness was associated with a 17% lower risk of heart failure.^[31] The discrepancy between our findings and previous studies may be due to heterogeneity of heart disease subtypes (self-reported diagnosis cannot distinguish angina, myocardial infarction, heart failure, etc.), relatively few incident cases leading to limited power, and exposure measurement that did not differentiate green space types (e.g., forests may be more effective than grasslands). Nonetheless, the OR consistently pointed toward a protective direction, and future studies should employ more precise clinical outcomes and refined exposure assessment.

Furthermore, we did not find an independent association between NDVI and dyslipidemia. In sensitivity analysis, both conventional and cluster-robust regression gave consistent conclusions, with no change in inference due to clustering. This null finding differs from some large prospective co-

hort studies in China.^[32,33] Compared with previous research, the discrepancy may be because our study relied on self-reported physician diagnoses, which have low sensitivity and are prone to miss asymptomatic or mild cases. Such misclassification bias can substantially attenuate a true association, driving the effect towards the null. In addition, the wide heterogeneity in dietary patterns and physical activity levels across the national sample may have masked the weak protective effect of green space on lipids. Nevertheless, our finding is supported by some existing studies. For example, a study on Chinese older adults noted that the evidence on residential greenness and blood lipid levels was inconsistent.^[34]

Counterfactual mediation analysis showed that the indirect effect of the TyG index in the NDVI-hypertension relationship was statistically significant, but the proportion mediated was only 2.9%. This finding suggests that the protective effect of green space on blood pressure is largely independent of IR-related pathways, with the TyG index playing only a minor auxiliary role. To date, no study has directly examined the mediating role of the TyG index in the green space-hypertension relationship, but a meta-analysis confirmed a strong positive association between TyG and hypertension.^[35] Of note, the mediation proportion in our study (2.9%) is relatively low compared with other environmental health mediation studies but not unusual. For example, Zhang, *et al.*^[36] in a nationwide cross-sectional study covering 10,405 middle-aged and older adults across 120 Chinese cities, reported that the mediating proportion of the TyG index in the association between air pollutants (PM_{2.5}, PM₁₀, NO₂, SO₂, CO, O₃) and hypertension ranged from 9.94% to 21.89%. The effect of green space on blood pressure involves multiple pathways and mechanisms. Previous studies have confirmed that green space can lower blood pressure through various pathways, including reducing air pollutant exposure, alleviating mental stress (reducing sympathetic tone and catecholamine secretion), promoting physical activity, reducing oxidative stress, and improving endothelial function.^[37,38] These mechanisms, independent of the IR pathway, likely account for the vast majority of the blood pressure-lowering effect of green space. Moreover, the TyG index, as a surrogate marker of IR, may change relatively slowly and require longer exposure time to manifest, and the follow-up duration in our study may not have been sufficient to fully capture the cumulative effect mediated by TyG. Sensitivity analysis showed that an unmeasured confounder with $|\rho| = 0.85$ would be required to completely nullify the indirect effect, which is highly robust.



RCS analysis revealed a significant linear inverse association between NDVI and hypertension, with the risk of hypertension continuously decreasing across the entire NDVI range without a threshold or plateau. This linear pattern suggests that even a small increase in greenness could bring incremental health benefits, providing a quantitative basis for urban greening policies. Regarding hypertension, most studies have shown a linear and protective effect of greenness, but some research has provided evidence of a nonlinear association. For instance, a prospective cohort study in China found that greenness exposure was nonlinearly associated with hypertension risk in older adults, showing an inverse U-shaped curve.^[24]

STRENGTHS AND LIMITATIONS

The main strengths of this study include its use of the nationally representative CHARLS cohort of middle-aged and older Chinese adults, providing a solid data foundation for exploring the associations between green space and cardiovascular health. Unlike most previous studies that relied on single-year or single-region measures, we used satellite-derived NDVI data over four consecutive years (2011–2014) and calculated the multi-year average exposure, more accurately reflecting long-term cumulative green space exposure. Methodologically, we employed IPTW to control selection bias and, for the first time in a large-scale middle-aged and older population, combined city-level cluster-robust standard errors with systematic evaluation of the associations between the green space and cardiovascular diseases and its metabolic mediation pathway. To our knowledge, this is the first nationwide cohort study to simultaneously report the longitudinal association between NDVI and hypertension and the mediating role of the TyG index, providing new causal evidence and mechanistic insights for urban greening as a primary prevention strategy for cardiovascular diseases.

Several limitations are inherent in this study. Firstly, due to privacy protection in CHARLS, the specific residential addresses of participants could not be disclosed. Therefore, we used 1-km resolution NDVI data aggregated at the city level, which may introduce spatial misclassification bias. Future studies should use higher-resolution data and participant-specific buffers around residential addresses. Secondly, although we adjusted for a wide range of demographic, lifestyle, biochemical, air pollution, and socioeconomic factors, several important potential confounders (e.g., detailed dietary factors, specific medication use, and traffic noise) were not available in CHARLS. This remains a key limitation,

as these factors could be strong confounders or mediators. Thirdly, outcomes were based on self-reported physician diagnoses, which may be subject to recall bias or underreporting. Last but not least, in the mediation analysis, the TyG index and the outcome were measured simultaneously, weakening the causal order assumption. These limitations call for cautious interpretation of the results but do not undermine the overall robustness of the main findings. Future prospective studies with objective clinical outcomes and longer follow-up are warranted to further validate the causal effects and underlying mechanisms of green space exposure on cardiovascular health.

CONCLUSIONS

Long term residential green space exposure is significantly associated with a lower risk of hypertension in middle-aged and older Chinese adults, with the TyG index playing a modest partial mediating role. No significant independent associations were observed for heart disease or dyslipidemia. Enhancing urban greening may be an effective environmental strategy for the primary prevention of hypertension.

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