LETTER

Residential green space structures and mortality in an elderly prospective longitudinal cohort in China

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Abstract
Greenness is beneficial to health and is associated with lower mortality. Many studies used the normalized difference vegetation index (NDVI) to measure greenness. However, NDVI cannot be used to indicate landscape type. To go beyond NDVI, we aim to study the association between greenspace structures and all-cause mortality of older adults using the 2008–2014 waves of Chinese Longitudinal Healthy Longevity Survey. We calculated landscape indices to quantify three greenspace structure characteristics: area-edge, shape, and proximity. The health outcome was all-cause mortality. Among 12 999 individuals (average age at baseline 87.2 years, 5502 males), we observed 7589 deaths between 2008 and 2014. We did not find a consistent dose–response relationship between greenspace structures and all-cause mortality. However, there were some signals of associations. Compared with individuals living in the lowest quartile of the number of patches, the adjusted-hazard ratio (95% CI) of those in the highest quartile was 0.85 (0.80–0.92). In stratified analyses, the largest patch index and perimeter-area ratio had protective effects on males, individuals aged <90, those free of ADL disability, and with higher income. The protective influence of greenspace structures was not as evident compared to NDVI.

1. Introduction
Overall greenness is commonly assessed with normalized difference vegetation index (NDVI). A variety of radii is used to represent the residential proximity to greenspace. Specifically, buffer zones with 500, 300, or 250 m radius were used to reflect walking distances around the participants’ residences, representing immediate surrounding greenness [1]. Further, indices of greenspace structures, including area-edge, shape, contrast, core area, proximity, subdivision, isolation, and diversity, are used to reflect the pattern and allocation of spatially heterogeneous greenspaces [2]. Greenness is positively associated with improved physical activity, social contact, cognitive function, mental health [3], birth weight [4], and negatively associated with body weight [5], respiratory mortality [6], and all-cause mortality [7]. Moreover, greenness benefits to health appear to have the most potent effects in communities with socioeconomic deprivation [8].

Mortality is one of the crucial indicators reflecting population health level in the aging society. There was a significant decrease in the age-specific mortality rate of the Chinese elderly in recent years [9]. Compared with countries with the same economic
development level, the mortality rate of the elderly in China is lower, and the life expectancy had reached 77.3 years old in 2019. However, there is still a large gap between China’s current level with high-income countries (80.7 years old) and targeted life expectancy in 2030 (79.0 years old) [10]. Therefore, it is of great significance to explore the influence of environmental factors on mortality in order to improve the longevity of Chinese senior citizens.

Although previous findings promote policies to increase greenspaces to improve public health, most studies did not provide insight on the specific landscape features and their association with all-cause mortality [5], which is useful for urban planners working under constrained resources to make the best available use of space [11]. Some studies have found that green structures enhance health by improving mental health status [12–14], reducing cardiovascular and respiratory diseases [15], and further lowering mortality risk [16]. Therefore, more studies need to be done in various socioeconomic and geographical settings for reproducibility and generalizability. Research is lacking on the relationship between the greenspace structure and all-cause mortality of the elderly in developing countries, such as China, which has an aging population living in places with diverse geographical and socioeconomic characteristics.

This study selected a series of greenness structure indices describing greenspaces’ allocation and shape to address the critical gap of the overreliance on NDVI as a single measure of greenness. The purpose of this study is to test the overall effects of greenness structures on all-cause mortality of the Chinese elderly, assess the differences of various greenness structure indices’ health effects, and explore the greenness structures’ influences on mortality in subgroups, by using the Chinese Longitudinal Healthy Longevity Survey (CLHLS), a representative sample of the oldest-old population in China. The findings will provide useful information for policymaking in prolonging life and urban design of greenspaces’ allocation.

2. Materials and methods

2.1. Study population

The CLHLS was a national survey for investigating the determinants of healthy longevity among the older Chinese population in 22 provinces [17]. Baseline data collection began in 1998. Investigators conducted follow-up surveys with replacements for deceased elderly participants in 2000, 2002, 2005, 2008/09, 2011/12, and 2014 by randomly selecting half of the total number of counties in the 22 provinces. The survey drew areas from a population base of 1.1 billion people, representing 85% of the total population in China. Investigators interviewed all individuals about health determinants. The detailed study design and sample method were described in the published cohort profile. In this analysis, we used data from the 2008–2014 wave. The participants received baseline interviews in 2008/09, and follow-ups in 2012 and 2014. Our sample size of the 2008 wave consisted of 16 072 individuals. We excluded individuals if they were lost to follow-up at the first follow-up survey \(n = 2625\), had missing death dates \(n = 255\), and lack of greenspace indices \(n = 193\). There was no significant difference between baseline characters and socioeconomic structures of excluded individuals and the overall sample. Our final sample size consisted of 12 999 individuals. We used all-cause mortality between 2008 and 2014 reported by the next of kin as our health outcome.

2.2. Assessment of greenness structures

Landscape indices were typically grouped into eight characteristics: area and edge metrics, shape, contrast, core area, proximity, subdivision, isolation, and diversity [18]. According to previous research [5, 15], we considered the area and edge, shape, and proximity as our exposure measurements. We selected one index for each characteristic in the main model, including the largest patch index (LPI) (area and edge), perimeter-area ratio (PARA) (shape), and numbers of patches (proximity) as the indices (calculation unit: hectare) in this study by using FRAGSTATS 4.2 [19] (figure 1). China’s administrative divisions had three levels: provinces, counties and townships. There are 2846 county-level areas in China as the basic units of local administration. We calculated county-level greenspace indices obtained from the outputs of Advanced Land Observing Satellite Research and Application Project with a 25 m × 25 m grid size, based on the whole built environment of the county where each individual lived in 2008 [20] (box S1 (available online at stacks.iop.org/ERL/16/094003/mmedia)). Considering the computing capability of Fragstat software and the tremendous data storage required due to the vast study area of China, a 100 m × 100 m grid size was finally used in our calculations. The LPI shows the percentage of the landscape comprised of the largest patch. The PARA measures a patch shape’s complexity by calculating the ratio of the perimeter of greenspace per square meter. The number of patches (NPs) measures the number and density of patches within a specific area (table S1). Therefore, higher index values of the LPI, PARA, and NP mean larger greenspaces, more complex patch shapes, and more dense greenspaces.

2.3. Covariates

The study entrant year was the year when individuals entered the cohort. The age was divided into four groups, including the elderly (65–79), octogenarian (80–89), nonagenarian (90–99), and centenarian (100+). Activities of daily livings (ADLs) assessed self-care capacity by using six self-reported questions:
Figure 1. Greenspace indices.
‘Do you need assistance in bathing/dressing/toileting/transfer/eating/continence?’ We defined individuals as free of ADL disability (ADL = 0) if all the six answers were no. As long as one of the answers was yes, the interviewee was defined as with ADL disability (ADL = 1). The literacy and annual household income were defined according to the questionnaire of CLHLS. Marital status (‘currently married and living with spouse’ or ‘other (separated, divorced, widowed, or never married’), smoking status (‘current smoker’, ‘former smoker’ or ‘non-smoker’), alcohol consumption (‘current drinker’, ‘former drinker’ or ‘non-drinker’), physical activity (‘current’, ‘former’, or ‘never’), residential location (city, town and rural area) were categorical variables. The residence area was divided into three levels according to the population, socioeconomic development, and urbanization level. Urban areas were residents’ committees and other districts connected to the construction of districts and municipal offices in municipal districts and cities without districts. Towns were residents’ committees and other districts connected to the construction of districts and municipal offices located in county seats and other towns located outside urban areas. Rural areas were places that do not belong to cities or towns [21]. The geographical region was considered based on residential address: central China (Henan, Hubei, Hunan, and Jiangxi provinces), eastern China (Anhui, Fujian, Jiangsu, Shandong, Shanghai, and Zhejiang provinces), northeastern China (Heilongjiang, Jilin, and Liaoning provinces), northern China (Beijing, Inner Mongolia, Hebei, Shanxi and Tianjin provinces), northwestern China (Shaanxi, Ningxia, Xinjiang, Qinghai, and Gansu province), southern China (Guangdong, Guangxi, and Hainan provinces), and southwestern China (Chongqing, Yunnan, Guizhou, Xizang and Sichuan provinces). The contemporaneous NDVI was estimated at the date of death for individuals who had died, and at the last interview date for those who were alive and those lost to follow-up. NDVI measurements were obtained from the moderate resolution imaging spectro-radiometer in the National Aeronautics and Space Administration’s Terra Satellite around each individual’s residence location based on latitude and longitude with a buffer zone of 500 m. To adjust the influences of biodiversity resulting from greenspace, we considered the number of species with a high probability of being hosts for zoonosis diseases and the biodiversity index in 2008 as covariates. The annual average temperature in 2008 was city-level, and PM$_{2.5}$ was a 3 year average (2006–2008) at the individual level.

2.4. Statistical analysis

We hypothesized that area-edge, shape, and proximity were protective factors for Chinese seniors’ all-cause mortality. First, we used Pearson correlation coefficient $\geq 0.7$ as a criterion for excluding the greenspace indices given their collinearity (table S2). Then we conducted Cox proportional hazard models to calculate hazard ratios (HRs) and 95% CIs to indicate associations between indices of greenspace structures and all-cause mortality. Considering the nonlinearity followed the process reported in a recent study [22], the three indices were further categorized into quartiles to describe demographic characteristics and do analysis (table S3). The lowest quartiles were the reference groups. Additionally, we used contemporaneous NDVI classified into quartiles to reconfirm the association of exposure to overall greenness on all-cause mortality. We adjusted for covariates that could be potential confounders or predictors of mortality: the study entrant year, age, sex, ADL, marital status, geographic region, urban or rural residential location, literacy, annual household income, smoking status, alcohol consumption, exercise status, biodiversity index, numbers of hosts for zoonosis, contemporaneous NDVI, annual average temperature, and 3 year average PM$_{2.5}$.

2.5. Sensitivity testing and subgroup analysis

We conducted three sensitivity tests to examine the indices’ robustness in determining the association between the indices of greenspaces and all-cause mortality [23]. First, we selected other indices based on the three characteristics of greenspace structures: edge density (area and edge), shape index (shape), and proximity index (proximity). Edge density equals the sum of the lengths of all greenspace edge segments per hectare. The shape index measures a patch shape’s complexity by calculating how far it deviates from a circle or square of the same area. The proximity index is considered the size and proximity of all patches whose edges are within a specified search radius of the focal patch. Higher index values of the edge density, shape index, and proximity index mean more greenspaces, more complex patch shape, and closer to greenspace [19, 24]. Second, we restricted our analysis to urbanized areas. Third, we analyzed central China particularly because it crosses the boundary between north and south China, having significant climate and environmental differences.

We also did four subgroup analyses. Individuals were divided into groups based on sex, age, ADLs, and annual household income: male and female; 65–89 years old and >90 years old; free of ADL disability and with ADL disability; low income (<20 000 RMB) and high income ($\geq$20 000 RMB). Our stratified analyses were chosen on potential effect modification of these variables, and to better elucidate the effect of greenness across demographic and comorbid categories. The HR and 95% CI were calculated to determine the association between greenspace structures and all-cause mortality according to the stratified variables.
3. Results

Table 1 shows the baseline characteristics of exposures by quartiles. Among 12,999 individuals, 5,502 (42.31%) participants were men, 6,122 (47.1%) were over 90 years old, and 8,253 (63.5%) lived in rural regions. Compared with higher quartiles, individuals living in the area with the lowest levels of LPI were more likely to be city and town residents (40.8%), never drinkers (70.4%), and living in eastern China (54.1%). Compared with the first quartile, residents at the highest PARA level were more likely to be rural inhabitants (65.7%), low-income groups (73.5%), and residents of eastern China (48.6%) (table S4-1). Compared with people living in the area with higher NP, those living in the area with the lowest level of the NP were more likely to be nonagenarian (30.6%) and eastern people (56.9%) (table S4-1). The median LPI at baseline was 1.82 (25th to 75th percentile 0.34–11.57), PARA was 50.85 (33.58–71.76) and NP was 76.00 (28.00–150.00) (table S3). Besides, NDVI (corrcoef = −0.04, P < 0.01) and LPI (corrcoef = −0.42, P < 0.01) were negatively correlated with PM2.5, indicating that greenspaces with a larger size performed better in regulating ambient PM2.5 levels. NP is the number of green patches in an area. Higher values in NP mean that larger greenspaces were divided into small pieces, which might not be functional in air pollution mitigation, resulting in a positive correlation (corrcoef = 0.12, P < 0.01) between NP and PM2.5. In addition, smaller values of PARA represent a simple geometric characteristic, which usually happens in human-made urban green lands mainly composited by limited tree species with greater functions in microclimate/air pollution regulation. Thus, a positive association (corrcoef = 0.46, P < 0.01) between PARA and PM2.5 was observed in our case (table S2). Among 12,999 individuals, we observed 7,589 deaths between 2008 and 2014. Individuals who were younger, female, free of ADL disability, urban residences, married and living with their spouse, current drinker, exercise regularly and did not smoke tended to have a longer survival time than their counterparts (table S5).

Table 2 and figure 2 illustrated the association between greenspace structures and all-cause mortality of Chineses elderly. After full adjustment, we found that compared with participants living in the lowest quartile of greenspace indices, individuals in higher quartiles had lower mortality risk, but no significant dose-response relationship was observed. The lowest HR was 0.88 for LPI in the second quartile (95% CI: 0.82–0.94, P = 0.004), 0.92 for PARA in the second and fourth quartile (95% CI: 0.86–0.99, P = 0.03), and 0.85 for NP in the fourth quartile (95% CI: 0.80–0.92, P = 0.003) relative to the reference level. The overall protective effect of greenspace structure was weaker than that of NDVI. Considering the independent effects of the low-correlated three greenspace structure indices, the results of fully adjusted model including all indices as continuous variables and covariates were shown is table S6. PARA and NP were significant protective factors for mortality. In addition to the core greenspace structure variables, some personal characteristic variables had significant effects on mortality. Females, individuals married and living with a spouse, urban citizens, current exercisers, and people without ADL disability had a lower risk of mortality.

Figure 3 illustrated the results of sensitivity analysis. Figure 3(a) revealed HRs when using other greenspace indices such as edge density, shape index, and proximity index. The assessments of city, town, and central China were shown in figures 3(b) and (c). As presented in figure 3(a), HRs for all categorization of greenness were <1, indicating the specific indices type did not bias the results. In general, consistent results were observed in urbanized areas (figure 3(b)) and central China (figure 3(c)). The lowest HR (95% CI) for LPI was 0.85 (0.71, 0.99) and was observed in the second quartile, that for PARA was 0.87 (0.73, 1.03) and was observed in the fourth quartile, and that for the NP was 0.81 (0.68, 0.96) and was observed in the second quartile.

Moreover, the variables of sex, age, ADLs, and annual household income were used for subgroup analysis (figure 4). LPI was associated with lower HRs for all-cause mortality in males, individuals aged <90 years old, and people with high annual household income. PARA was associated with lower HRs on male individuals or those free of ADL disability and with high income. The protective function of NP was shown in all subgroups.

4. Discussion

In this prospective cohort study of the elderly in China, we did not observe a consistent dose-response relationship between indices of greenspace structures and all-cause mortality of Chinese elderly. There are limited studies on greenspace structures and health until now, and the linear conservation trend has not been found in existing studies, too. Therefore, further research should be undertaken to investigate the related issues and verify the results. Nevertheless, we found a protective correlation in the same direction in every quartile (HR < 1). NP is a protective factor for all-cause mortality of the Chinese elderly. LPI only has protective effects on males, individuals less than 90 years old, and people with high income in some quarters. PARA is a protective factor for males, people over 90 years old, free of ADL disability, and with high annual household income. This suggests a larger area, more complex shape, more concentrated greenspace, and greater proximity might reduce the all-cause mortality of certain groups. The finding represents promising opportunities for public health interventions, particularly in cities and towns, and
Table 1. Characteristics of CLHLS participants by quartile of the LPI (N = 12 999).

|                   | LPI Q1 (n = 3187) | LPI Q2 (n = 3331) | LPI Q3 (n = 3038) | LPI Q4 (n = 3243) | Overall (n = 12 999) |
|-------------------|-------------------|-------------------|-------------------|-------------------|---------------------|
| Age               |                   |                   |                   |                   |                     |
| 65–79             | 854 (26.8%)       | 979 (27.7%)       | 772 (25.4%)       | 885 (27.3%)       | 3490 (26.8%)        |
| 80–89             | 809 (25.4%)       | 855 (24.2%)       | 844 (27.8%)       | 879 (27.1%)       | 3387 (26.1%)        |
| 90–99             | 884 (27.7%)       | 886 (25.1%)       | 900 (29.6%)       | 920 (28.4%)       | 3590 (27.6%)        |
| ≥100              | 640 (20.1%)       | 811 (23.0%)       | 522 (17.2%)       | 559 (17.2%)       | 2532 (19.5%)        |
|                   |                   |                   |                   |                   |                     |
| Sex               |                   |                   |                   |                   |                     |
| Male              | 1329 (41.7%)      | 1521 (43.1%)      | 1283 (42.2%)      | 1369 (42.2%)      | 5502 (42.3%)        |
| Female            | 1858 (58.3%)      | 2010 (56.9%)      | 1755 (57.8%)      | 1874 (57.8%)      | 7497 (57.7%)        |
|                   |                   |                   |                   |                   |                     |
| Residence         |                   |                   |                   |                   |                     |
| City and town     | 1301 (40.8%)      | 1111 (31.5%)      | 1138 (37.5%)      | 1196 (36.9%)      | 4746 (36.5%)        |
| Rural             | 1886 (59.2%)      | 2420 (68.5%)      | 1900 (62.5%)      | 2047 (63.1%)      | 8253 (63.5%)        |
|                   |                   |                   |                   |                   |                     |
| Annual household  |                   |                   |                   |                   |                     |
| income (RMB)      |                   |                   |                   |                   |                     |
| <20 000           | 2261 (70.9%)      | 2646 (74.9%)      | 2046 (67.3%)      | 2267 (69.9%)      | 9220 (70.9%)        |
| ≥20 000           | 926 (29.1%)       | 885 (25.1%)       | 992 (32.7%)       | 976 (30.1%)       | 3779 (29.1%)        |
|                   |                   |                   |                   |                   |                     |
| Education year    |                   |                   |                   |                   |                     |
| Mean (SD)         | 1.97 (3.40)       | 1.83 (3.23)       | 2.08 (3.46)       | 1.84 (3.13)       | 1.93 (3.30)         |
| Marital status    |                   |                   |                   |                   |                     |
| Married and living with spouse | 969 (30.4%) | 1184 (33.5%) | 884 (29.1%) | 948 (29.2%) | 3985 (30.7%) |
| Other             | 2218 (69.6%)      | 2347 (66.5%)      | 2154 (70.9%)      | 2295 (70.8%)      | 9014 (69.3%)        |
|                   |                   |                   |                   |                   |                     |
| Exercise          |                   |                   |                   |                   |                     |
| Current           | 862 (27.0%)       | 952 (27.0%)       | 836 (27.5%)       | 897 (27.7%)       | 3547 (27.3%)        |
| Former            | 406 (12.7%)       | 402 (11.4%)       | 431 (14.2%)       | 401 (12.4%)       | 1640 (12.6%)        |
| Never             | 1919 (60.2%)      | 2177 (61.7%)      | 1771 (58.3%)      | 1945 (60.0%)      | 7812 (60.1%)        |
| Smoking           |                   |                   |                   |                   |                     |
| Current           | 559 (17.5%)       | 672 (19.0%)       | 520 (17.1%)       | 522 (16.1%)       | 2273 (17.5%)        |
| Former            | 496 (15.6%)       | 570 (16.1%)       | 525 (17.3%)       | 464 (14.3%)       | 2055 (15.8%)        |
| Never             | 2132 (66.9%)      | 2289 (64.8%)      | 1993 (65.6%)      | 2257 (69.6%)      | 8671 (66.7%)        |
| Alcohol           |                   |                   |                   |                   |                     |
| Current           | 574 (18.0%)       | 650 (18.4%)       | 537 (17.7%)       | 544 (16.8%)       | 2305 (17.7%)        |
| Former            | 370 (11.6%)       | 433 (12.3%)       | 475 (15.6%)       | 496 (15.3%)       | 1774 (13.6%)        |
| Never             | 2243 (70.4%)      | 2448 (69.3%)      | 2026 (66.7%)      | 2203 (67.9%)      | 8920 (68.6%)        |
| Geographical region |                   |                   |                   |                   |                     |
| Central China     | 638 (20.0%)       | 708 (20.1%)       | 495 (16.3%)       | 373 (11.5%)       | 2214 (17.0%)        |
| Eastern China     | 1725 (54.1%)      | 1388 (39.3%)      | 949 (31.2%)       | 643 (19.8%)       | 4705 (36.2%)        |
| Northeastern China| 257 (8.1%)        | 370 (10.5%)       | 156 (5.1%)        | 150 (4.6%)        | 933 (7.2%)          |
| Northern China    | 141 (4.4%)        | 148 (4.2%)        | 226 (7.4%)        | 36 (1.1%)         | 551 (4.2%)          |
| Northwestern China| 291 (9.1%)        | 7 (0.2%)          | 46 (1.5%)         | 65 (2.0%)         | 409 (3.1%)          |
| Southern China    | 17 (0.5%)         | 549 (15.5%)       | 535 (17.6%)       | 1514 (46.7%)      | 2615 (20.1%)        |
| Southwestern China| 118 (3.7%)        | 361 (10.2%)       | 631 (20.8%)       | 462 (14.2%)       | 1572 (12.1%)        |
| Contemporaneous NDVI | 0.40 (0.20)  | 0.42 (0.20) | 0.40 (0.20) | 0.43 (0.20) | 0.41 (0.20) |

High proportions of older people. There has yet to be similar research in mainland China, while previous studies in Taiwan and the US have shown protective functions of greenspace structures, such as mean patch area, edge density, shape index, and proximity index. For instance, most people prefer to enter wooded green areas with high values of the mean patch size [25], which can reduce the risk of all-cause mortality by affording plenty of room to do health-related activities. Besides, increased complexity, better connectivity, and aggregation of greenspace seem to decrease the heart disease risk, chronic lower respiratory disease, and neoplasms [16] by acting on lifestyle and environmental factors. Green complexes diversify public spaces and enhance neighborhood satisfaction [26]. Green ecological corridors play a critical role in maintaining good greenness connectivity, integrating all landscape resources, providing opportunities for daily physical activities [27] and comfortable urban-rural environments [28].

The present study observed that greenspaces have distinct protective associations on male individuals, individuals aged <90 years old, free of ADL disability, and high annual household incomes. A probable explanation is that males are more likely to use greenspaces for physical activity [29], and females may not enter greenspaces if they think the spaces are unsafe [30]. Besides, younger aged people were
Table 2. Association between HRs (estimates with 95% CIs) for all-cause mortality and indices of all population.

### LPI

| Quartiles | N   | HR (95% CI) | P-value | HR (95% CI) | P-value | HR (95% CI) | P-value |
|-----------|-----|-------------|---------|-------------|---------|-------------|---------|
| Q1        | 3187| Ref         | Ref     | Ref         | Ref     | Ref         | Ref     |
| Q2        | 3270| 0.92 (0.87–0.98) | <0.05* | 0.90 (0.84–0.96) | <0.01** | 0.88 (0.82–0.94) | <0.01** |
| Q3        | 3287| 0.96 (0.90–1.02) | 0.19    | 0.98 (0.92–1.04) | 0.54    | 0.98 (0.92–1.07) | 0.82    |
| Q4        | 3255| 0.94 (0.88–0.99) | <0.05* | 0.96 (0.90–1.09) | 0.16    | 0.99 (0.923–1.09) | 0.96    |

### PARA

| Quartiles | N   | HR (95% CI) | P-value | HR (95% CI) | P-value | HR (95% CI) | P-value |
|-----------|-----|-------------|---------|-------------|---------|-------------|---------|
| Q1        | 3192| Ref         | Ref     | Ref         | Ref     | Ref         | Ref     |
| Q2        | 3289| 1.02 (0.96–1.09) | 0.48    | 0.97 (0.91–1.03) | 0.34    | 0.92 (0.86–0.99) | <0.05*  |
| Q3        | 3217| 1.05 (0.99–1.12) | 0.13    | 1.00 (0.94–1.07) | 0.88    | 0.97 (0.90–1.04) | 0.39    |
| Q4        | 3301| 1.05 (0.99–1.12) | 0.12    | 0.99 (0.92–1.05) | 0.63    | 0.92 (0.85–0.99) | <0.05*  |

### NPs

| Quartiles | N   | HR (95% CI) | P-value | HR (95% CI) | P-value | HR (95% CI) | P-value |
|-----------|-----|-------------|---------|-------------|---------|-------------|---------|
| Q1        | 2976| Ref         | Ref     | Ref         | Ref     | Ref         | Ref     |
| Q2        | 3298| 0.89 (0.84–0.95) | <0.01** | 0.94 (0.88–0.99) | <0.05*  | 0.87 (0.81–0.93) | <0.01** |
| Q3        | 3385| 0.88 (0.83–0.94) | <0.01** | 0.91 (0.85–0.97) | <0.01** | 0.92 (0.86–0.99) | <0.05*  |
| Q4        | 3340| 0.93 (0.87–0.99) | <0.05*  | 0.90 (0.84–0.96) | <0.01** | 0.85 (0.80–0.92) | <0.01** |

### NDVI

| Quartiles | N   | HR (95% CI) | P-value | HR (95% CI) | P-value | HR (95% CI) | P-value |
|-----------|-----|-------------|---------|-------------|---------|-------------|---------|
| Q1        | 3263| Ref         | Ref     | Ref         | Ref     | Ref         | Ref     |
| Q2        | 3245| 0.94 (0.91–0.97) | <0.01** | 0.91 (0.87–0.95) | <0.05*  | 0.88 (0.84–0.91) | <0.01** |
| Q3        | 3244| 0.90 (0.83–0.97) | <0.05*  | 0.87 (0.81–0.95) | <0.05*  | 0.84 (0.81–0.88) | <0.01** |
| Q4        | 3247| 0.89 (0.80–0.96) | <0.05*  | 0.83 (0.80–0.86) | <0.01** | 0.78 (0.75–0.82) | <0.01** |

Model 1 was unadjusted. Model 2 was adjusted for age and sex. Model 3 was further adjusted for the study entrant year, ADL, marital status, geographic region, urban or rural residential location, literacy, annual household income, smoking status, alcohol consumption, exercise status, biodiversity index, numbers of hosts for zoonosis, contemporaneous NDVI, annual average temperature, and 3 year average PM$_{2.5}$. *p<0.05, **p<0.01.
Figure 2. Association between HRs (estimates with 95% CIs) for all-cause mortality and indices of all population. The model was adjusted for the study entrant year, age, sex, ADL, marital status, geographic region, urban or rural residential location, literacy, annual household income, smoking status, alcohol consumption, exercise status, biodiversity index, numbers of hosts for zoonosis, contemporaneous NDVI, annual average temperature, and 3 year average PM$_{2.5}$. LPI: largest patch index. PARA_AM: perimeter-area ratio. NP: number of patches.

Figure 3. Sensitivity analysis of HRs (estimates with 95% CIs) of all-cause mortality and indices of (a) other indices of greenspace structures in China. (b) City and town areas in China. (c) Central China. All models were adjusted for the study entrant year, age, sex, ADL, marital status, geographic region, urban or rural residential location, literacy, annual household income, smoking status, alcohol consumption, exercise status, biodiversity index, numbers of hosts for zoonosis, contemporaneous NDVI, annual average temperature, and 3 year average PM$_{2.5}$. ED: edge density. SHAPE_AM: shape index. PROX_MN: proximity index. LPI: largest patch index. PARA_AM: perimeter-area ratio. NP: number of patches.
Figure 4. Subgroup analysis of the HRs (estimates with 95% CIs) of all-cause mortality and indices of greenspace structures according to (a) sex, (b) age, (c) ADLs, (d) annual household income.

All models were adjusted for the study entrant year, age, sex, ADL, marital status, geographic region, urban or rural residential location, literacy, annual household income, smoking status, alcohol consumption, exercise status, biodiversity index, numbers of hosts for zoonosis, contemporaneous NDVI, annual average temperature, and 3 year average PM$_{2.5}$. LPI: largest patch index. PARA_AM: perimeter-area ratio. NP: number of patches.
more likely to access greenspaces for physical activity because of their physical conditions and objective facilities [29]. According to previous research, the paved areas and paths are influential factors in greenspace’s protective effect. Older adults with limited mobility tend to be sedentary rather than physically active. Therefore, building urban greenspace infrastructure without considering well-defined and maintained paved areas and paths might not affect the oldest-old people substantially [31].

Moreover, we found that rural areas had a large diversity of various greenspace structures, but greenspace indices’ protective effects were more evident on people living in city and town areas (HR of LPI = 0.90, PARA = 0.99, NP = 0.90 in Q4) than in rural areas (HR of LPI = 1.06, PARA = 1.02, NP = 0.96 in Q4). This may be explained by the rapid urbanization and population aging over the past decades in China, which brought the gap between the inequality in landscaping plans between urban and rural areas [32]. Most cities and towns in China plan the greenspace system by integrating local typical natural resources without connection with nearby rural greenspace [33]. Therefore, in many economically underdeveloped rural areas, systematic greenspace planning has not been implemented yet [34].

Although greenspaces are greater in rural areas, they are not well developed like in urban areas. One manifestation of urban-rural landscaping gaps is the unequal accessibility of greenspace due to low walkability, such as lack of rural footpaths, leading to weaker greenspace health benefits in rural areas [35, 36]. Another possible explanation for this is that the distribution and accessibility of greenspace and individual demographic and socioeconomic factors are strongly associated with individual health issues [37]. Thus, the lower socioeconomic status, high competing risk from communicable diseases, and a persistent lack of universal health coverage in rural areas also weaken the greenspaces’ positive function, causing higher all-cause mortality in rural areas [38].

For city residents, we found that the area-edge’s protective function is stronger than shape and proximity. The possible reason is the unbalanced allocation of urban greenspace resources. As an essential part of a healthy building environment, China’s current urban greenspace system has been defined in the Ministry of Housing and Urban-Rural Development Standards in 2002. Therefore, cities have implemented the network layout of the greenspace system on a large scale. However, many of them face the problem of insufficient and fragmented greenspace in the central area [33], and the complex and sizeable greenspaces are mainly in the suburbs. Given that the population density of the elderly people increases from the periphery to the center of the city, this mismatch between the distribution of greenspace infrastructure and elderly residents may influence the utility of greenspaces in urban areas. It indicates that urban greenspace resources’ optimal allocation should pay particular attention to the elderly’s demands [33]. Moreover, according to survey data and self-reported health data, nearly half of older adults have chronic diseases, which is a heavy burden of building a healthy China [32]. Higher greenspace levels could reduce the burden of chronic diseases by reducing stress, air pollution, humidity, and heat island impacts, and encouraging physical activity, social interaction, and community cohesion [39].

Since 2000, the difference in greenspace distribution has increased. The speed of greenspace construction was the fastest in the east, followed by the west and the center, and slowest in the northeast [40]. Besides, there was a trend of fragmentation and regularization of patch edges, especially in urban centers. Concentrated large greenspace regions experienced different degrees of degeneration [41]. In view of this adverse trend, later greenspace structures were probably worse than that in baseline, so the protective effects of greenspace indices may not be fully reflected in this study. Our finding indicates that residents living in southern China had higher LPI but lower PARA. Central and eastern residents had the highest PARA. In China, the urbanization rate is higher on the eastern coast and lower in the northwest [42]. Therefore, greater efforts are needed in urbanized eastern and southern China to further design the greenspace shape based on the existing large greenspace area. Northeast and northwest need to expand the greenness area and improve greenspace connectivity, especially in rural regions.

Our study has several strengths. First, as far as we know, our study is the first on the association between greenspace structures and all-cause mortality in old Chinese people from a large prospective cohort representing the majority of the oldest-old population in the country. Besides, our study included a wide range of demographic and socioeconomic variables to control for potential confounding. Our study had some limitations as well. First, there was no reliable data about cause-specific mortality in this cohort study, so we could not do path analysis. Second, we used multiple indices of greenness structures, which might increase the probability of false positives. Third, the data of greenspace structure was done via satellite. We did not have information about the specific and time-varying types of vegetation, the time participants spent in the greenspaces, and participants’ activity patterns. Fourth, the health outcome based on death reported by family members, which might have introduced recall bias. However, CLHLS has been widely acknowledged for its response rate and comparable data quality, and all-cause mortality is the only universally available outcome given that the cohort contains a high proportion of rural participants in many places, so the choice of outcome indicator should not affect the reliability of our results. Lastly, we did not have individual-level greenness structure data.
Therefore, future studies may use green structures indices in different periods with multiple comparisons at the county-level or city-level and confirm these analyses after considering the limitations.

5. Conclusion

In this cohort study of the elderly in China, we did not find a dose-response relationship between greenspace structures and all-cause mortality of the elderly in mainland China. We found that the associations between greenspace structures and all-cause mortality are not consistent among all the indices. The NPs is a significant protective factor of all-cause mortality, while PARA and the LPI have positive effects on males, individuals less than 90 years old, and people free of ADL disability and with high annual household income. One possible implication of this study is that a larger area, more complex shape, more concentrated greenspace, and greater proximity are beneficial to the longevity of some Chinese senior citizens. In China’s aging society, our findings provide a new research direction for researchers, urban planners, and health policymakers in prolonging life by adequately designing the allocation and pattern of greenspaces.

Data availability statement

The data that support the findings of this study are available upon request from investigators of the Chinese Longitudinal Healthy Longevity Survey.

The data that support the findings of this study are openly available at the following URL/DOI: https://sites.duke.edu/centerforaging/programs/chinese-lonitudinal-healthy-longevity-survey-clhls/data-use-agreement/.

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Ethical statement

All procedures followed were in accordance with the ethical standards of the responsible committee on human experimentation (institutional and national) and with the Helsinki Declaration of 1975, as revised in 2000. This study was approved by the Ethics Committee of Peking University and the Ethics Committee of the Duke-National University of Singapore. Informed consent was obtained from all participants for being included in the study. No animal or human studies were carried out by the authors.

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