Association between Greenness Structures and Frailty in an Elderly Prospective Longitudinal Cohort in China

Qile He
Duke Kunshan University
Hao-Ting Chang
National Cheng Kung University
Chih-da Wu
National Cheng Kung University
John Ji (johnji@gmail.com)
Duke Kunshan University https://orcid.org/0000-0002-5002-118X

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Authors: Qile He[1], Hao-Ting Chang[2], Chih-da Wu*[3,4], John S. Ji*[1,5]

Affiliations:

1. Environmental Research Center, Duke Kunshan University, Kunshan, China
2. Department of Environmental and Occupational Health, National Cheng Kung University, Tainan 70101, Taiwan
3. Department of Geomatics, National Cheng Kung University, Tainan 70101, Taiwan
4. National Institute of Environmental Health Sciences, National Health Research Institutes, Miaoli 350, Taiwan
5. Nicholas School of the Environment, Duke University, Durham, NC, USA

***Co-corresponding Author:**

John S. Ji, Sc.D.
Address: No. 8 Duke Avenue, Kunshan, Jiangsu, China 215316
Telephone: +86 (0512) 36657255
E-mail: john.ji@dukekunshan.edu.cn

Chih-da Wu, Ph.D.
Address: No. 1 University Rd., Tainan 70101, Taiwan
Telephone: +886-6-275-7575 ext 63841
Email: chidawu@mail.ncku.edu.tw

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Abstract

Background: Frailty is the accumulation of aging-induced deficits, leading to vulnerability and death. There is evidence of negative associations between greenspaces measured with normalized difference vegetation index (NDVI) and frailty. However, NDVI is not as informative as greenness structure indices which reflect characters such as shape and connectivity. We aim to study the association between greenness structures and frailty in an elderly Chinese cohort.

Methods: We included older adults from 2008-2014 waves of the China Longitudinal Healthy Longevity Survey (CLHLS). We used greenspace indices from satellite to quantify greenspace structures at county-level: area-edge, shape, and proximity, and calculated frailty index (FI) as a health outcome. We did cross-sectional analyses using linear regression and logistical regression, and longitudinal analyses using the generalized estimating equations (GEE). All models were adjusted for covariates.

Results: Among 8,776 participants at baseline, the mean LPI, SHAPE, COHESION, and FI were 7.93, 8.11, 97.6, and 0.17. The correlation between NDVI and greenness structure was unnoticeable. In cross-sectional analyses, we found negative consistent dose-response relationships for greenspace structures and frailty, especially in females, city residents, people without a spouse, and with deteriorated frailty. Compared to participants living in the lowest quartile of greenness structure, those in the highest quartile of LPI, SHAPE, and COHESION had 32%, 44%, and 37% lower odds of frailty. However, we did not find a significant association in longitudinal analyses due to higher mortality rate and FI of participants without follow-up surveys.

Conclusions: The larger value of area-edge, shape, and proximity is related to a lower likelihood of frailty. Assessing complex shapes and connecting fragmentary greenspaces are informative to public health through city planning.

Keywords: Greenspace structures, Vegetation index, Frailty, Healthy longevity

Introduction

Frailty refers to a geriatric syndrome that increases a person's vulnerability due to degenerative changes and chronic diseases, reflecting cumulative physical, psychological, and social deficits, which leads to higher risks of hospitalization, falls, depression, and mortality[1-3]. Frailty is a good predictor of health and well-being, representing an intermediate stage between robust health and the end of life. Urbanization and population aging from the developing world have been phenomenal and renewed the interest in studying older adults' well-being. China is one of the fastest aging countries and has the largest oldest-old population globally. As aging deepens, the number of older adults in frail increases. A study in China reported that 7.0% of adults aged 60 years or older were frail[4].

There is evidence of an association between greenness and frailty-related factors in population health studies. A study in Hong Kong found that higher residential greenness levels could improve frailty by mediating through physical activity, the number of diseases, and cognitive functions[5]. A longitudinal study with 16,238 older adults with a 12-year follow-up in China assessed greenery exposure at the neighborhood level, proving that higher residential greenness levels are related to a lower likelihood of frailty, specifically in urban areas[6]. Besides, mechanisms by which exposures to greenspaces promote healthy aging have been extensively studied. First, more greenspaces in the residential environment could lead to fewer incidences of loneliness, more social support, and improved social cohesion in the neighbourhood[7]. Second, greenspaces may be a resource for psychological restoration[8]. Exposure to greenspaces is associated with reduced stress and providing the opportunity to restore directed attention[9,10], which may benefit cognitive aging. Third, older adults living in areas with higher access to greenspaces do more physical activities, which play a significant role in maintaining functioning and health[11]. Last, increased exposure to greenspaces has been associated with lower exposure to environmental stressors such as air pollution, noise, and heat, which are detrimental to health[12].

Although previous researchers have identified the benefits of overall greenness measured with normalized difference vegetation index (NDVI) in different spatial scales[6], the association between specific greenspace structures and frailty was not well understood. This study provides new insights into the role of greenspace structures in preventing older adults' frailty. Greenspace structure is an indispensable component of environmental systems and is essential to residents. Recently, increasing attention has been focused on exploring how characteristics (e.g., location, patch connectivity) of certain greenspaces can affect health benefits[13]. Some researchers proved that green structure can enhance health by improving mental health status[14-16], reducing cardiovascular and respiratory diseases[17], and further lowering mortality risk[18]. Therefore, more research studies need to be done to explore the effects of greenness structures on health.

The purpose of this study is to test the effects of residential greenspace structures measured with three characteristics: area-edge, shape, and proximity on the frailty of the Chinese elderly by using the CLHLS, a representative sample of older adults in China.

Methods

Study Population

The CLHLS was a national survey for investigating the determinants of healthy longevity among the older Chinese population in 22 provinces. The survey has drawn areas from a population base of 1.1 billion people, representing 85 percent of China's total population. Investigators interviewed individuals about socioeconomic characteristics, lifestyle, physical capacity, cognitive function, and psychological status. The IRB approval and other information were described in the published cohort profile[19]. This study used the 2008-2014 data which consisted of 16,072 individuals received baseline interviews in 2008/09, and follow-ups in 2012 and 2014. We excluded individuals who had missing demographic characters (N=3,073), frailty index (N=4,215), and NDVI (N=8) at baseline year. There was no significant difference between baseline characters of excluded individuals and the overall sample. Final sample size was 8,776 at baseline year.

Greenness databases

Landscape indices were typically grouped into eight characteristics: area and edge, shape, contrast, core area, proximity, subdivision, isolation, and diversity[20]. We considered the area and edge, shape, and proximity as our exposure measurements[17,21]. We selected one index for each characteristic in the main model, including the largest patch index (area and edge), mean shape index (shape), and patch cohesion index (proximity) as the indices (calculation unit: hectare) by using FRAGSTATS 4.2 (figure 1) (table S1)[22]. We calculated county-level greenspace indices obtained from the outputs of the Advanced Land Observing Satellite (ALOS) based on the whole built environment of the county where each individual lived in 2008 [23] (box S1). Considering the computing capability, we used 100m*100m grid size in calculations. The largest patch index (LPI) shows the percentage of the landscape comprised of the largest patch.

The shape index (SHAPE) measures a patch shape's complexity by calculating how far it deviates from a circle or square of the same area. The patch cohesion index (COHESION) measures the physical connectedness of the corresponding patch type. Therefore, higher index values of the LPI, SHAPE, and COHESION mean larger greenspaces, more complex patch shapes, and more dense greenspaces.

Moreover, we used NDVI from the Moderate Resolution Imaging Spectro-Radiometer (MODIS) based on the longitude and latitude of each residential address as a measure of greenness surrounding the residence[24]. NDVI ranges from −1.0 to 1.0, with larger values indicating higher levels of vegetative density[25]. We deleted negative values, which represented blue space or water. We calculated contemporaneous NDVI at the individual's residential address at the death date for individuals who had died /the last interview date for those who were alive and those lost to follow-up. The correlation between NDVI and greenness structure was not noticeable. Therefore, the relationship between greenspaces and frailty can be more accurately described using separate greenspace structures than using general NDVI values.

Assessment of Frailty

We used the Frailty Index (FI) to measure frailty status as the previous study[6,26]. FI is based on the accumulation of aging-induced deficits, which is defined as the ratio of the number of deficits existing in an individual divided by the total amount considered[27]. FI included 38 self-reported items, including instrumental activities of daily living, functional limitations, activities of daily living, cognitive function, self-reported health status, interviewer-rated health status, mental health, auditory and visual ability, heart rhythm, and chronic diseases (table S2).

We scored each term as 0 (absence of deficit) or 1 (presence of deficit) for 38 of 39 terms. We scored the other 1 term as 2 if the participants reported 2 or more severe illnesses that caused hospitalization or being bedridden in the past 2 years, such as stroke, cancer, and cataract. FI was equal to the number of reported deficits divided by the total number of included deficits. FI was a continuous variable and ranged from 0 to 1. A higher value indicated poorer frailty. We also classified the continuous FI into two statuses: non-frail (FI $\leqslant$0.21) and frail (FI > 0.21)[28]. Changes of FI were the difference in FI scores measured between the last survey and the baseline, categorized as no change or decrease, and an increase.

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+). Literacy, marital status, smoking status, alcohol consumption, physical activity, residential location were categorical variables and defined according to the questionnaire. The residence area was divided into city, town, and rural areas[29]. The seven geographical regions were considered based on residential address. The PM2.5 was a three-year average (2006-2008) at the individual level.

Statistical analysis

We hypothesized that larger value of area-edge, shape, and proximity were protective factors for Chinese seniors' frailty, and the strength of this protection varied among the subgroups. First, we used Pearson correlation coefficient ≥0.7 as a criterion for excluding the greenspace indices given their collinearity. Second, a cross-sectional analysis was conducted using linear regression and logistic regression to assess the associations between residential greenness and frailty at baseline, adjusted for the study entrant year, age, sex, marital status, geographic region, urban or rural residential location, literacy, annual household income, BMI, smoking status, alcohol consumption, exercise status, and three-year average $PM_{2.5}$. The linear regression was conducted to assess NDVI, greenspace structures, and continuous baseline FI scores. We also used a logistic regression model to calculate the odds ratio (OR) and 95% CIs to indicate associations between indices of greenspace structures and binary FI status. Considering the nonlinearity followed the process reported in the recent study, the three indices were further categorized into quartiles to describe demographic characteristics and do analysis[30]. The lowest quartiles were the reference groups. Third, a longitudinal analysis was performed using the generalized estimating equations model of greenness structure indices and FI among participants with a follow-up survey. Fourth, the participants were categorized with no change or decreased FI scores, and an increase in FI scores at the end of the follow-up. The participants with no change or a decrease in FI scores were defined as the reference group in two separate models. Additionally, we used contemporaneous NDVI classified into quartiles to reconfirm the association of exposure to overall greenness on frailty. All statistical analyses were conducted using R 3.6.3.

Sensitivity Testing and Subgroup Analysis

We conducted sensitivity tests to examine the indices' robustness[31]. We selected three other indices: edge density (ED) for area-edge, area-weighted mean fractal dimension index

(FRAC) for shape, and percentage of like adjacencies (PLADJ) for proximity. ED equals the sum of the lengths of all greenspace edge segments per hectare. FRAC is another measure of shape complexity. PLADJ is calculated from the adjacency matrix, which measures the degree of aggregation of the focal patch type. Higher index values of the ED, FRAC, and PLADJ mean more greenspaces, more complex patch shape, and closer to greenspaces[32,33]. Besides, we did four subgroup analyses based on sex, age, literacy, urban or rural residential location, and marital status.

Results

As shown in table 1, among 8,776 individuals, 4,135 (47.12%) participants were men, 5,342 (60.87%) lived in rural regions, and 3,295 (37.55%) were married and living with a spouse. The mean baseline LPI, SHAPE, COHESION, and FI were 7.93, 8.11, 97.6, and 0.17. People living in bigger, more complex and more tightly connected green areas tended to be female, educated, living in town, and not married or living with a spouse. People with healthier lifestyles such as keeping exercising, do not smoke or drink have higher value of greenness structure indices. Another important finding was that the average NDVI values of men and women are the same (0.41), but the frailty index is different, which may be related to varying levels of exposure to greenspace structures.

Table 2 presents the association between greenness structure indices and frailty. In the adjusted linear regression at baseline, there was an association between a higher value of greenness structure indices and better frailty condition after adjustment. We observed a significant dose-response relationship in the quartiles group. Each 0.1-unit increase in LPI, SHAPE, and COHESION was statistical significantly associated with a 0.026-point, 0.028-point, and 0.025-point lower FI score in the fourth quartile. In the adjusted logistic regression, an increase in all greenness structure indices was associated with an OR less than 1 of frailty. Participants in the highest quartile had the lowest OR of LPI (0.676, 95%CI: 0.579-0.789, P<.001), SHAPE (0.650, 95%CI: 0.556-0.760, P<.001), and COHESION (0.635, 95%CI: 0.541-0.744, P<.001). However, we did not find a similar association in the adjusted GEE model.

Table 3 reports the relationship between greenness structure indices and changes in FI. During the follow-up period, deteriorated frailty was observed among 1,974 (69.14%) of participants. Compared with the participants who had stable or improved frailty, those with deteriorated frailty had lower ORs of LPI (0.989 vs. 0.999) and SHAPE (0.997 vs. 1.010), and a higher OR of COHESION (0.951 vs. 0.949) after adjustment.

The results of sensitivity analysis were basically consistent with the main model, indicating the specific indices type did not bias the results (table S4). Furthermore, the subgroup analysis showed consistent findings in the cross-sectional analysis (figure 2). We observed a significant association among the female participants, aged over 100 years old, uneducated, city residents, not married and living with a spouse, compared with their counterparts.

Discussion

In this prospective cohort study of the elderly in China, we found a consistent dose-response negative relationship for greenspace structures and frailty in cross-sectional analyses, indicating a larger area, more complex shape, more concentrated greenspaces, and greater proximity might reduce the risk of the frailty of older adults. However, we did not find a significant association in the longitudinal analysis. Partly because there were a large number of deaths and lost to follow-up after the baseline survey. Therefore, their FI scores in 2014 were unavailable. Compared with these people, participants with follow-up surveys had better frailty at baseline (table S3), causing the protective effect of greenspace structure to became unobvious. Therefore, further research should be undertaken to investigate the related issues and verify the results.

Previous research has established that older people living in neighborhoods with a higher percentage of greenspaces had a higher likelihood of improvement in frailty status[5,6]. Our findings further increase understanding of how greenness structures specifically supplement NDVI's practical implications on urban greenspace planning by giving evidence on the possibility that green structures improve frailty through different paths. First, large area-edge and good proximity can improve frailty by increasing opportunities for physical exercise, which is a mediator of the relationship between greenspaces and frailty transitions by improving physical, cognitive, and psychological function[5 34]. Meanwhile, most people prefer to enter green areas with larger size, which can afford plenty of room to do diverse health-related activities[35]. Good greenness connectivity maintained by green ecological corridors also provides opportunities for physical activities[36]. Second, there is evidence that greenspace may influence health by directly promoting cognitive functions and well-being, strongly related to the onset of frailty[24,37]. Complex shapes of greenspaces diversify public spaces and enhance neighborhood satisfaction[38], and interconnecting greenspaces play a critical role in providing comfortable environments[39], which could increase memory, attention[40], and mental health[41]. Third, exposure to air pollution has been linked to respiratory diseases, and may be contributory to frailty[42]. Minimized fragmentation and increased the largest patch percentage of green structure could lower the mortality of pneumonia and chronic lower respiratory diseases by and the mediation effects through reducing air pollutants[43].

The present study observed that greenspace indices' protective effects were more evident on city residents, people who were unmarried and not living with a spouse, and with deteriorated frailty. A study in the Netherlands reported the significant association between greenspaces and different perceived general health among different levels of urbanization[44]. China has witnessed rapid urbanization widening the gap of unequal landscaping plans in urban and rural areas[45,46]. Another possible explanation for urban-rural differences is that the lower socioeconomic status, high competing risk from communicable diseases, and a persistent lack of universal health coverage in rural areas weaken the greenspaces' positive function[47]. Additionally, it might also be due to the urban-rural difference in FI at baseline (urban 0.18 vs. rural 0.16). Besides, previous research has established that marriage could cause a difference in frailty. In our study, individuals who were unmarried and not living with a spouse were frailer than their counterparts (0.20 vs. 0.11). This can be explained by the relationship between frailty and psychosocial factors. Spouses might bring positive emotions which related to individual health[48]. Therefore, if greenspaces can provide widowed elderly people with another form of positive emotions, it will fill the marriage gap. We also found that participants with increasing frailty were more likely to be beneficial from large and complex greenspaces. If the area and shape of greenness can indeed delay the frailty process, greenspace planning can become a tool for healthy aging.

We observed a gender difference in the association between greenness structure and frailty. Females tended to live in bigger and more complex green areas, and benefit more from greening patterns than males. This is not consistent with the previous study in Hong Kong and the UK, which reported the health benefits of residential greenness on frailty mortality only among males but not females[5,49]. The mechanisms of this discrepancy are currently unclear.

This study had several limitations. First, 5,921 individuals did not have FI scores in 2014 because of death or lost follow-up, which might affect the longitudinal analysis accuracy. However, the cross-sectional design could help decrease the potential selection bias and dropout bias from the longitudinal analysis. Second, we only used greenness structures indices in 2008. Future studies might use data in different periods to substantiate our analyses. Third, we could not get information about the specific types of vegetation, the time participants spent in the greenspaces, and participants' activity patterns via satellite. Fourth, there may be some confounders and potential mediators (e.g., neighborhood safety, social network) that we could not account for in the models. Nevertheless, this study involved significant strengths. First, as far as we know, our study is the first on the association between greenspace structures and frailty in older adults from a cohort that covers the majority of regions in the country. Besides, we used high-quality geographic information system data to quantify greenspace structures and included a wide range of demographic and socioeconomic variables to control potential confounding. This research provides insights for the comparison of effects of NDVI and greenspace structures on frailty. A further study could assess the specific mechanism of the combined impact of NDVI and structures on health.

Conclusion and Implications

A protective association of greenness was identified in this study. We found that larger areas, more complex shapes, and greater proximity were associated with a lower likelihood of frailty among Chinese older adults. We observed a stronger association among females, individuals aged over 100 years old, uneducated, city residents, not married and living with a spouse, and with deteriorated frailty. Our findings have important implications for planning policy to design greenspaces in promoting health and preventing frailty in the process of urbanization and population aging. This study also lays a path for further research to understand which characteristics of greenspaces have the most substantial influence on frailty.

Conflicts of Interest

No conflict of interest exists in submitting this manuscript.

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Author Contribution

Authors contributed equally to this work.

Ethical statement:

All analyses were based on a previous public cohort approved by Ethics committee (https://doi.org/10.18170/DVN/UWS2LR), thus no ethical approval and patient consent are required in this study.

Data availability

The data that support the findings of this study are available upon request from investigators of the Chinese Longitudinal Healthy Longevity Survey (https://doi.org/10.18170/DVN/UWS2LR) and https://www.eorc.jaxa.jp/ALOS/a/en/dataset/fnf_e.htm?fbclid=IwAR3Z3N2Sv_k71Sma-fuwdIGrZ6GM5W0smChWu9J-JljTGMjI6p3TWNpRdfI.

Code availability

Code and software associated with these analyses is available at https://cran.r-project.org/web/packages/gee/index.html and https://www.umass.edu/landeco/research/fragstats/fragstats.html.

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Table 1. Baseline Characteristics of CLHLS participants (N = 8,776).

	N	NDVI	LPI	SHAPE	COHESION	Baseline FI	P value
Overall	8,776	0.41 (0.20)	7.93 (12.3)	8.11 (7.58)	97.6 (2.69)	0.17 (0.15)	
Gender							<.001
Male	4,135	0.41 (0.20)	8.12 (12.4)	8.15 (7.51)	97.6 (2.66)	0.13 (0.13)	
Female	4,641	0.41 (0.20)	8.17 (12.5)	8.42 (7.96)	97.7 (2.73)	0.19 (0.15)	
Age							<.001
65-79	3,067	0.44 (0.19)	7.98 (12.2)	8.45 (8.03)	97.7 (2.60)	0.08 (0.08)	
80-89	2,524	0.42 (0.20)	8.50 (12.7)	8.40 (7.61)	97.8 (2.68)	0.15 (0.12)	
90-99	2,100	0.40 (0.20)	8.59 (12.8)	8.32 (7.54)	97.7 (2.75)	0.23 (0.15)	
>=100	1,085	0.40 (0.21)	7.28 (12.1)	7.98 (7.97)	97.4 (2.80)	0.30 (0.15)	
Literacy							<.001
No	5,100	0.42 (0.20)	7.95 (12.4)	8.29 (8.00)	97.5 (2.80)	0.19 (0.15)	
Yes	3,676	0.39 (0.20)	8.49 (12.6)	8.35 (7.37)	97.9 (2.50)	0.12 (0.12)	
Residence							<.001
City	1,471	0.24 (0.14)	5.67 (10.2)	6.21 (5.03)	97.4 (2.44)	0.18 (0.15)	
Town	1,963	0.43 (0.19)	9.88 (13.3)	9.54 (8.40)	98.0 (2.64)	0.16 (0.15)	
Rural	5,342	0.45 (0.19)	8.23 (12.6)	8.45 (8.04)	97.6 (2.78)	0.16 (0.14)	
Marriage							<.001
Married and living with spouse	3,295	0.42 (0.20)	7.53 (11.8)	7.94 (7.30)	97.6 (2.61)	0.11 (0.11)	
Other	5,481	0.41 (0.20)	8.42 (12.8)	8.47 (7.97)	97.7 (2.74)	0.20 (0.15)	
Exercise							<.001
Current	2,760	0.38 (0.20)	8.35 (12.6)	8.12 (7.22)	97.8 (2.50)	0.12 (0.10)	
Former	1,004	0.38 (0.20)	8.20 (12.3)	8.47 (7.39)	97.9 (2.57)	0.22 (0.17)	
Never	5,012	0.43 (0.20)	8.05 (12.4)	8.36 (8.09)	97.5 (2.81)	0.18 (0.15)	
Smoking							<.001

Current	1,732	0.42 (0.20)	7.76 (12.4)	8.05 (7.67)	97.5 (2.72)	0.11 (0.11)	
Former	1,454	0.40 (0.20)	7.36 (11.6)	7.67 (7.05)	97.6 (2.70)	0.16 (0.14)	
Never	5,590	0.41 (0.20)	8.43 (12.7)	8.53 (7.96)	97.7 (2.70)	0.18 (0.15)	
Alcohol							<.001
Current	1,686	0.43 (0.20)	7.98 (12.5)	8.31 (8.09)	97.6 (2.69)	0.12 (0.12)	
Former	1,206	0.41 (0.20)	9.04 (12.8)	8.73 (8.04)	97.9 (2.61)	0.17 (0.15)	
Never	5,884	0.41 (0.20)	8.01 (12.4)	8.22 (7.64)	97.6 (2.72)	0.18 (0.15)	
Geographical region							<.001
Central China	1,384	0.47 (0.20)	7.19 (14.1)	7.08 (6.60)	96.0 (3.25)	0.16 (0.14)	
Eastern China	3,242	0.43 (0.19)	4.51 (8.66)	5.60 (5.17)	97.0 (2.82)	0.17 (0.14)	
Northeastern China	702	0.24 (0.16)	5.96 (11.5)	7.02 (6.12)	97.9 (2.13)	0.18 (0.16)	
Northern China	408	0.28 (0.15)	2.82 (5.13)	4.83 (2.45)	97.1 (2.29)	0.20 (0.15)	
Northwestern China	288	0.42 (0.17)	5.98 (12.9)	5.80 (7.89)	99.6 (1.49)	0.17 (0.14)	
Southern China	1,839	0.43 (0.19)	16.5 (13.3)	14.3 (9.01)	99.3 (0.927)	0.16 (0.14)	
Southwestern China	913	0.43 (0.20)	10.2 (13.4)	10.9 (9.33)	98.8 (1.79)	0.15 (0.13)	

Table 2. Serial cross-sectional analysis (N = 8,776) and longitudinal analysis (N = 2,855) of the association between residential greenness structures and frailty.

Cross-sectional analysis																				
Linear regression																				
	NDVI					**LPI**					**SHAPE**					**COHESION**				
	N	Coef.	95% CI		P	N	Coef.	95% CI		P	N	Coef.	95% CI		P	N	Coef.	95% CI		P
Q1	4,512	Ref				2,180	Ref				2,174	Ref				2,186	Ref			
Q2	1,421	-0.004	-0.011	0.003	0.29	1,979	-0.007	-0.014	0.001	0.08	2,211	-0.012**	-0.019	-0.004	0.00	2,187	-0.012**	-0.020	-0.005	0.00
Q3	1,420	-0.014*	-0.022	-0.007	<.001	2,422	-0.012**	-0.019	-0.005	0.00	2,187	-0.019**	-0.026	-0.012	<.001	2,201	-0.016**	-0.023	-0.008	<.001
Q4	1,423	-0.009**	-0.017	-0.001	0.02	2,195	-0.026**	-0.033	-0.019	<.001	2,204	-0.028**	-0.035	-0.021	<.001	2,202	-0.025**	-0.032	-0.018	<.001
Logistic regression																				
	NDVI					**LPI**					**SHAPE**					**COHESION**				
	N	OR	95% CI		P	N	OR	95% CI		P	N	OR	95% CI		P	N	OR	95% CI		P
Q1	4,512	Ref				2,180	Ref				2,174	Ref				2,186	Ref			
Q2	1,421	0.961	0.821	1.124	0.62	1,979	0.890	0.756	1.049	0.16	2,211	0.849*	0.724	0.996	0.04	2,187	0.811*	0.689	0.955	0.01
Q3	1,420	0.794**	0.674	0.937	0.01	2,422	0.849*	0.728	0.991	0.04	2,187	0.716**	0.609	0.841	<.001	2,201	0.753 **	0.642	0.882	0.00
Q4	1,423	0.886	0.751	1.047	0.16	2,195	0.676**	0.579	0.789	<.001	2,204	0.650**	0.556	0.760	<.001	2,202	0.635**	0.541	0.744	<.001
Longitudinal analysis																				
GEE-Continuous FI																				
	NDVI					**LPI**					**SHAPE**					**COHESION**				
	N	Coef.	95% CI		P	N	Coef.	95% CI		P	N	Coef.	95% CI		P	N	Coef.	95% CI		P
Q1	767					714					709					716				
Q2	696	0.006	-0.024	0.036	0.69	714	-0.031*	-0.059	-0.002	0.04	716	-0.030*	-0.059	-0.002	0.03	713	-0.013	-0.044	0.017	0.39
Q3	694	0.021	-0.010	0.051	0.12	714	-0.022	-0.051	0.007	0.13	715	-0.009	-0.039	0.022	0.58	712	0.003	-0.028	0.033	0.87
Q4	698	0.007	-0.025	0.039	0.68	713	-0.023	-0.054	0.009	0.15	715	-0.016	-0.047	0.016	0.33	715	-0.006	-0.037	0.025	0.69
GEE-Binary frailty status																				
	NDVI					**LPI**					**SHAPE**					**COHESION**				
	N	OR	95% CI		P	N	OR	95% CI		P	N	OR	95% CI		P	N	OR	95% CI		P

Q1	767					714					709					716				
Q2	696	0.911	0.597	1.390	0.66	714	0.849	0.550	1.310	0.46	716	0.897	0.584	1.377	0.62	713	0.915	0.581	1.441	0.70
Q3	694	1.204	0.775	1.871	0.41	714	0.841	0.545	1.298	0.44	715	1.036	0.664	1.617	0.88	712	1.209	0.768	1.904	0.41
Q4	698	0.970	0.618	1.524	0.90	713	0.741	0.468	1.175	0.20	715	1.009	0.636	1.601	0.97	715	0.820	0.522	1.287	0.39

* Adjusted for age, sex, the study entrant year, marital status, geographic region, urban or rural residential location, literacy, annual household income, BMI, smoking status, alcohol consumption, exercise status, $PM_{2.5}$. LPI: largest patch index. SHAPE: shape index. COHESION: patch cohesion index.

Table 3. ORs and 95% CI for changes in frailty. (N = 2,855).

	Participants	LPI		SHAPE		COHESION	
Model 1 *							
Changes in FI	N	OR (95% CI)	P value	OR (95% CI)	P value	OR (95% CI)	P value
Decrease or no change in FI	881	0.994 (0.971 to 1.017)	0.60	1.002 (0.967 to 1.039)	0.90	0.915 (0.818 to 1.024)	0.12
An increase in FI	1,974	0.987 (0.979 to 0.996) **	0.00	0.994 (0.980 to 1.007)	0.37	0.944 (0.908 to 0.982) **	0.00
Model 2 **							
Changes in FI	N	OR (95% CI)	P value	OR (95% CI)	P value	OR (95% CI)	P value
Decrease or no change in FI	881	0.999 (0.975 to 1.023)	0.93	1.010 (0.973 to 1.049)	0.59	0.949 (0.843 to 1.069)	0.39
An increase in FI	1,974	0.989 (0.980 to 0.997) **	0.01	0.997 (0.983 to 1.011)	0.64	0.951 (0.915 to 0.990) *	0.01

* Model 1 was unadjusted. **Model 2 was adjusted for age, sex, the study entrant year, marital status, geographic region, urban or rural residential location, literacy, annual household income, BMI, smoking status, alcohol consumption, exercise status, $PM_{2.5}$. LPI: largest patch index. SHAPE: shape index. COHESION: patch cohesion index.

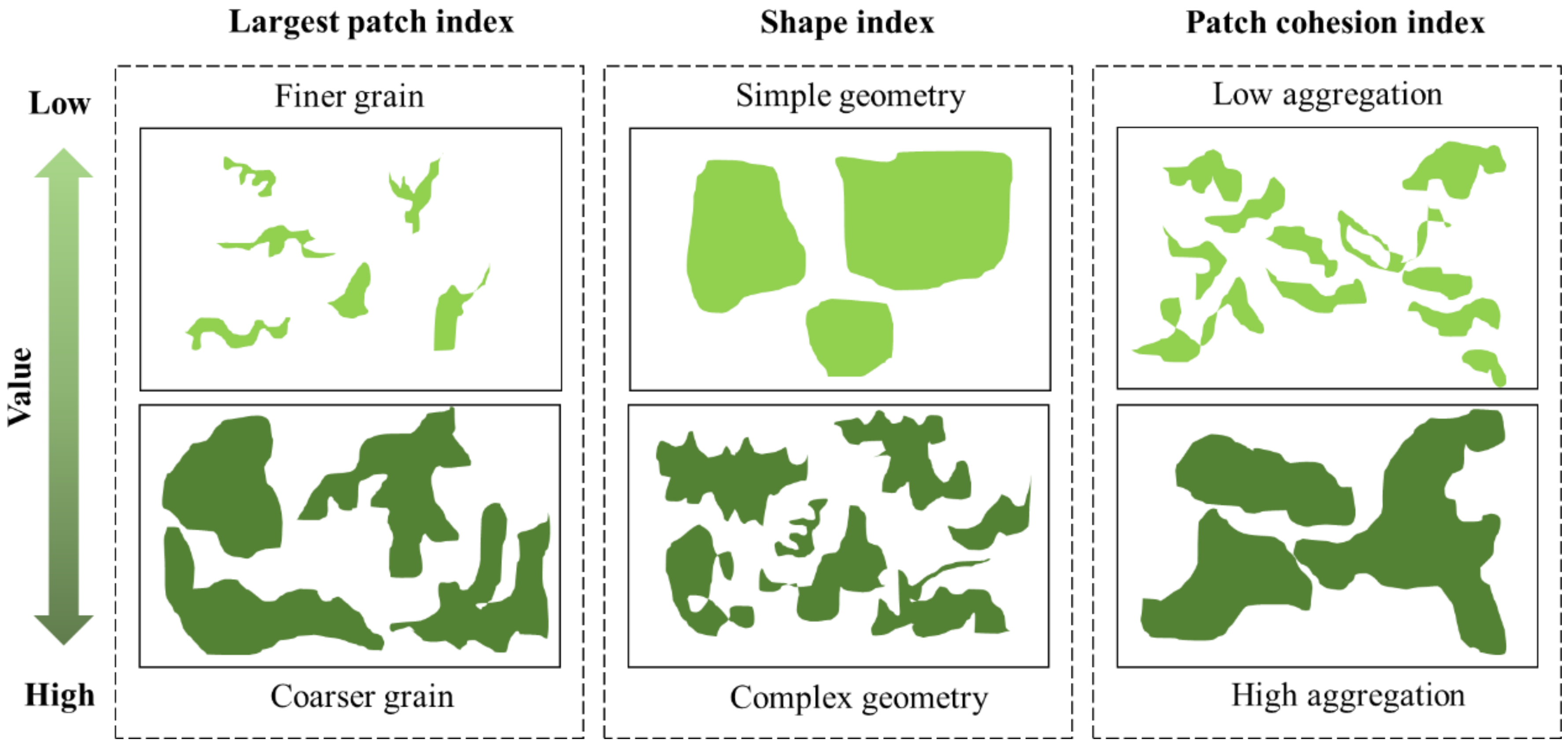

Figure 1. Greenspace indices

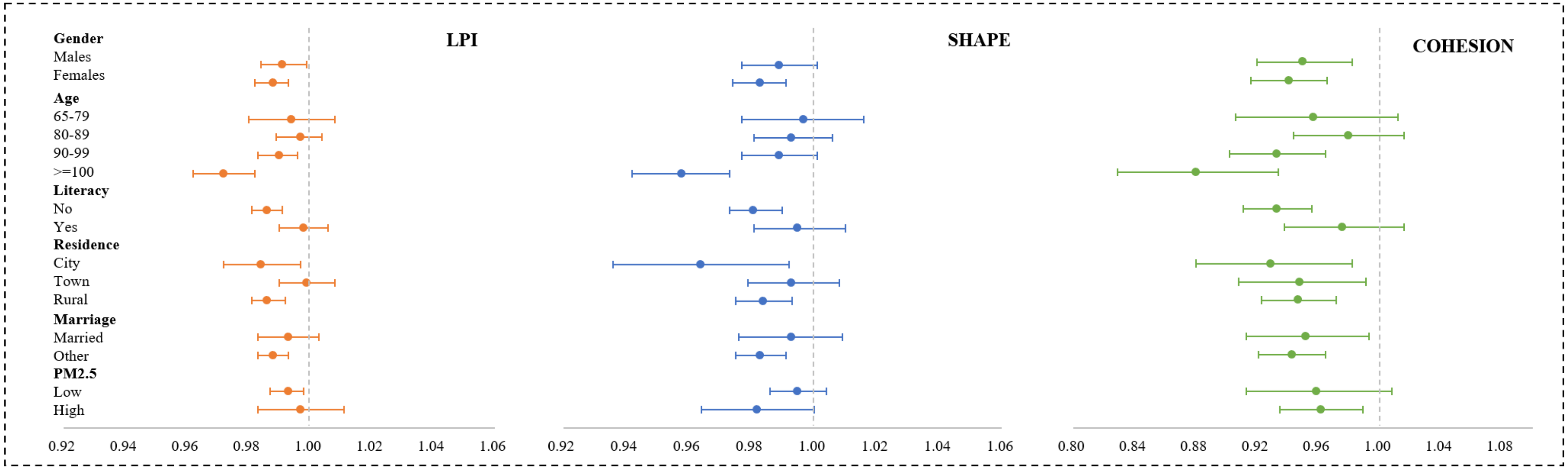

Figure 2. Subgroup analysis of the ORs (estimates with 95% CIs) of frailty and indices of greenspace structures according to (a) sex. (b) age. (c)literacy. (d) urban or rural residential location, (e) marital status, and (f) $PM_{2.5}$ (N = 8,776).

*Adjusted for age, sex, the study entrant year, marital status, geographic region, urban or rural residential location, literacy, annual household income, BMI, smoking status, alcohol consumption, exercise status, three-year average, PM2.5. LPI: largest patch index. SHAPE: shape index. COHESION: patch cohesion index.

Table S1. Formula and descriptions for the indices of greenspace structures.

Indices	Formula	Description
Area-Edge		
Largest Patch Index (LPI)	$\frac{\max_{j=1}^{a}(a_{ij})}{A}(100)$	LPI equals the area (m2) of the largest patch of the corresponding patch type divided by total landscape area (m2), multiplied by 100 (to convert to a percentage).
Edge Density (ED)	$\frac{E}{A}(10{,}000)$	ED equals the sum of the lengths (m) of all edge segments in the landscape, divided by the total landscape area (m^2), multiplied by 10,000.
Shape		
Shape Index (SHAPE)	$\frac{\sum_{i=1}^{m}\sum_{j=1}^{n}\frac{p_{ij}}{min\ p_{ij}}}{N}$	Shape Index equals the sum, across all patches in the landscape, of the SHAPE value for each patch, divided by the total number of patches.
Area-weighted mean fractal dimension index (FRAC)	$k * A^{D/2}$	Fractal analysis usually is applied to the entire landscape mosaic using the perimeter-area relationship. Area-weighted mean fractal dimension index was calculated by weighting patches according to their size.
Proximity		
Patch Cohesion Index (COHESION)	$[1-\frac{\sum_{i=1}^{n} p_{ij}}{\sum_{i=1}^{n} p_{ij}\sqrt{a_{ij}}}][1-\frac{1}{\sqrt{A}}]^{-1}\cdot(100)$	COHESION equals 1 minus the sum of patch perimeter divided by the sum of patch perimeter times the square root of patch area for patches of the corresponding patch type, divided by 1 minus 1 over the square root of the total number of cells in the landscape, multiplied by 100 to convert to a percentage.
Percentage of Like Adjacencies (PLADJ)	$\left[\frac{g_{ij}}{\sum_{k=1}^{m} g_{ik}}\right](100)$	PLADJ equals the number of like adjacencies involving the focal class, divided by the total number of cell adjacencies involving the focal class; multiplied by 100,

Table S2. The list of items included in calculating the FI.

No.	Items
1	IADL: Unable to visit neighbors by oneself
2	IADL: Unable to shop by oneself if necessary
3	IADL: Unable to cook meals by oneself if necessary
4	IADL: Unable to wash clothing by oneself
5	IADL: Unable to walk continuously for 1 km
6	IADL: Unable to lift a weight of 5 kg (such as a heavy bag of groceries)
7	IADL: Unable to continuously crouch and stand up 3 times
8	IADL: Unable to use public transportation
9	Functional limitations: Unable to put hand behind neck
10	Functional limitations: Unable to put hand behind lower back
11	Functional limitations: Unable to raise arm upright
12	Functional limitations: Unable to stand up from sitting in a chair
13	Functional limitations: Unable to pick up a book from the floor
14	ADL: Needs assistance bathing
15	ADL: Needs assistance dressing
16	ADL: Needs assistance toileting
17	ADL: Needs assistance in indoor transferring
18	ADL: Needs assistance eating
19	ADL: Incontinence
20	Cognitively impaired (based on the MMSE)
21	Poor self-rated health
22	Health worsened in the past year
23	Poor interviewer-rated health
24	Hearing loss
25	Vision loss
26	Abnormal heart rhythm
27	Symptom of psychological distress (based on loneliness, fearfulness)
28	Number of serious illnesses in the past 2 years
29	Suffering from hypertension
30	Suffering from diabetes
31	Suffering from tuberculosis
32	Suffering from heart disease
33	Suffering from stroke/cerebrovascular disease
34	Suffering from bronchitis
35	Suffering from cancer
36	Suffering from arthritis
37	Suffering from bedsores
38	Suffering from gastric or duodenal ulcers
39	Suffering from Parkinson's disease

*IADLs, instrumental activities of daily living; ADL, activities of daily living. Item no. 28 was assigned a value of 2.

Table S3. Baseline NDVI, LPI, SHAPE, COHESION, and FI for the participants with or without follow-up surveys.

	All Participants (N = 8,776)	**Participants with Follow-up Surveys (N = 2,855)**	**Participants Without Follow-up Surveys**		
			All (N = 5,921)	Death (N = 4,318)	Lost to Follow-up (N = 1,603)
Baseline NDVI, mean ± SD	0.41 (0.20)	0.44 (0.19)	0.40 (0.21)	0.39 (0.20)	0.45 (0.20)
Baseline LPI, mean ± SD	7.93 (12.30)	8.64 (12.58)	8.85 (13.06)	9.43 (13.37)	7.36 (12.09)
Baseline SHAPE, mean ± SD	8.11 (7.58)	8.47 (7.49)	8.72 (8.05)	8.98 (8.15)	8.05 (7.78)
Baseline COHESION, mean ± SD	97.6 (2.69)	97.78 (2.62)	97.79 (2.63)	97.84 (2.67)	97.67 (2.53)
Baseline FI, mean ± SD	0.17 (0.15)	0.10 (0.09)	0.20 (0.15)	0.22 (0.16)	0.12 (0.12)

Table S4. Sensitivity analysis of frailty and other indices of greenspace structures in China.

Linear regression															
	ED					**FRAC**					**PLADJ**				
	N	Coef.	95% CI		P	N	Coef.	95% CI		P	N	Coef.	95% CI		P
Q1	2,191	Ref				2,193	Ref				2,180	Ref			
Q2	2,157	-0.009**	-0.016	-0.001	0.02	1,997	-0.009*	-0.016	-0.002	0.01	2,187	-0.005	-0.013	0.002	0.14
Q3	2,227	-0.002	-0.009	0.006	0.67	2,388	-0.020**	-0.027	-0.013	<.001	2,184	-0.009*	-0.016	-0.002	0.01
Q4	2,201	-0.024**	-0.031	-0.017	<.001	2,198	-0.027**	-0.034	-0.020	<.001	2,225	-0.014**	-0.021	-0.007	<.001
Logistic regression															
	ED					**FRAC**					**PLADJ**				
	N	OR	95% CI		P	N	OR	95% CI		P	N	OR	95% CI		P
Q1	2,191	Ref				2,193	Ref				2,180	Ref			
Q2	2,157	0.934	0.795	1.097	0.41	1,997	0.894	0.760	1.050	0.17	2,187	1.002	0.853	1.178	0.98
Q3	2,227	0.984	0.838	1.156	0.85	2,388	0.699**	0.596	0.819	<.001	2,184	0.883	0.755	1.031	0.12
Q4	2,201	0.733**	0.627	0.857	<.001	2,198	0.668**	0.571	0.781	<.001	2,225	0.808**	0.692	0.943	0.01
GEE-continuous															
	ED					**FRAC**					**PLADJ**				
	N	Coef.	95% CI		P	N	Coef.	95% CI		P	N	Coef.	95% CI		P
Q1	714					710					716				
Q2	713	-0.015	-0.044	0.014	0.32	716	-0.026	-0.054	0.002	0.07	713	-0.017	-0.045	0.011	0.22
Q3	715	-0.013	-0.041	0.015	0.36	714	-0.005	-0.036	0.026	0.75	714	0.004	-0.026	0.034	0.78
Q4	713	-0.022	-0.050	0.006	0.12	715	-0.014	-0.044	0.017	0.40	712	-0.013	-0.043	0.016	0.38
GEE-Binary															
	ED					**FRAC**					**PLADJ**				
	N	OR	95% CI		P	N	OR	95% CI		P	N	OR	95% CI		P
Q1	714					710					716				
Q2	713	0.879	0.570	1.354	0.56	716	0.902	0.594	1.370	0.63	713	0.806	0.526	1.237	0.32

Q3	715	0.855	0.565	1.295	0.46	714	1.023	0.650	1.611	0.92	714	1.178	0.746	1.860	0.48
Q4	713	0.832	0.541	1.281	0.40	715	1.083	0.686	1.708	0.73	712	0.714	0.460	1.108	0.13

*Adjusted for age, sex, the study entrant year, marital status, geographic region, urban or rural residential location, literacy, annual household income, BMI, smoking status, alcohol consumption, exercise status, $PM_{2.5}$. ED: edge density. FRAC: fractal dimension index. PLADJ: percentage of like adjacencies.

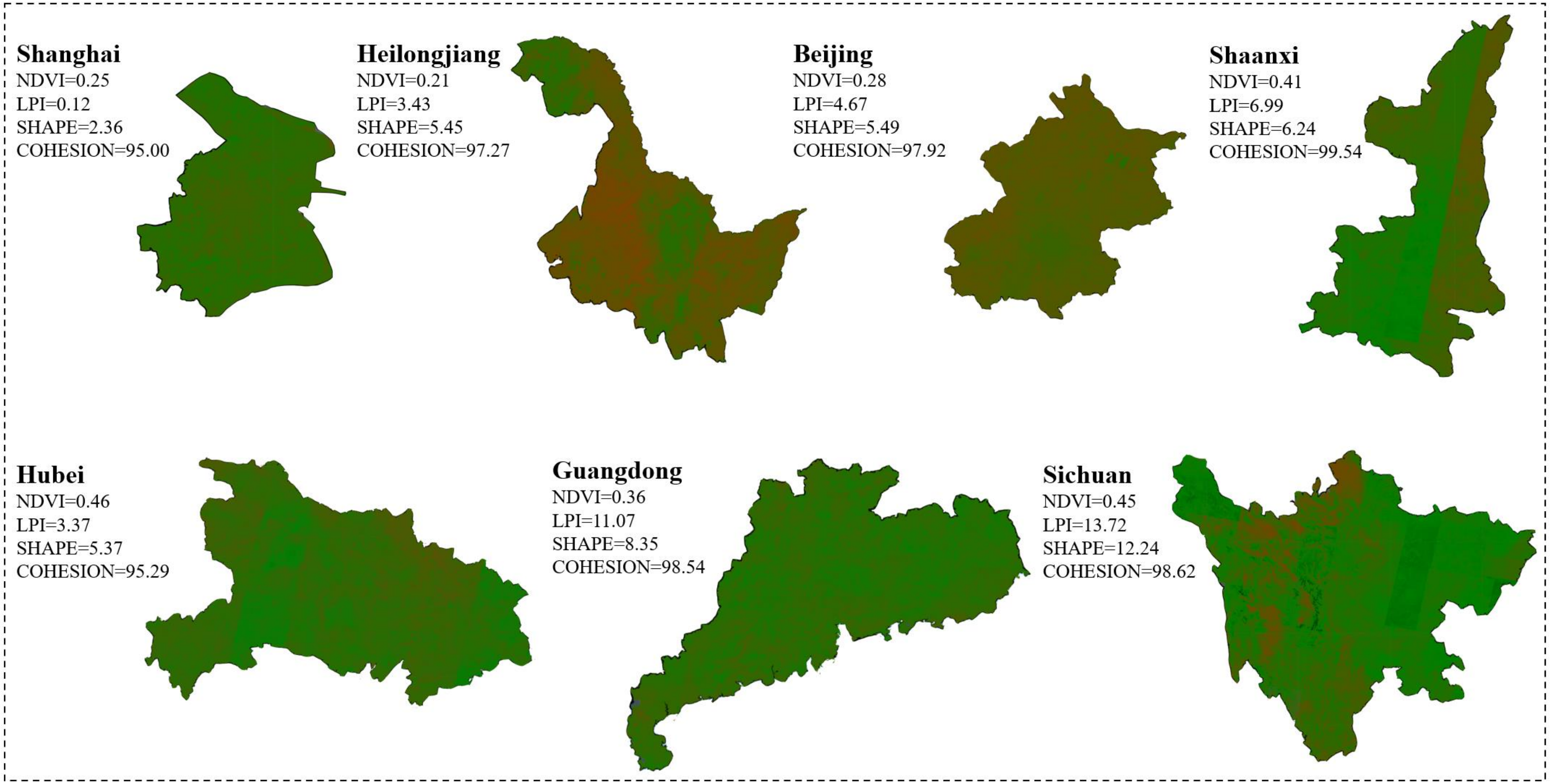

Figure S1. The mean value of 2008-baseline NDVI, LPI, SHAPE, and COHESION of seven representative provinces of Eastern, Northeastern, Northern, Northwestern, Central, Southern, and Southwestern China. LPI: largest patch index. SHAPE: shape index. COHESION: patch cohesion index.

Box S1. Official overview of the ALOS dataset

Global 25m resolutions PALSAR-2/PALSAR mosaic and forest/non-forest map are free and open dataset generated by applying JAXA's powerful processing and sophisticated analysis method/techniques to a lot of images obtained with Japanese L-band Synthetic Aperture Radars (PALSAR and PALSAR-2) on Advanced Land Observing Satellite (ALOS) and Advanced Land Observing Satellite-2 (ALOS-2). For understanding and responding to global environmental changes such as global warming and loss of biodiversity, timely assessment of deforestation and forest degradation is essential. Global monitoring with satellite remote sensing is one of the most effective approaches to detect land surface changes because satellites can provide wall-to-wall images covering wide areas periodically. L-band Synthetic Aperture Radars (SAR) on ALOS and ALOS-2 can observe the land surface even under clouds, and therefore the L-band SAR data have been providing useful information about forest changes in tropical region. The global 25m resolutions PALSAR/PALSAR-2 mosaic is a global SAR image created by mosaicking the SAR images in backscattering coefficients measured by PALSAR/PALSAR-2. Correction of geometric distortion specific to SAR (ortho-rectification) and topographic effects on image intensity (slope correction) are applied to make forest classification easy. The size of one pixel is approximately 25 meters by 25 meters. The temporal interval of the mosaic is generally 1 year. Global 25m resolution JERS-1 (Japanese Earth Resources Satellite-1) SAR mosaic dataset has been added since October 31, 2016. The original data of the mosaic were mainly acquired in 1996. The mosaic was generated with the same method as the PALSAR-2/PALSAR mosaic.