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Exposure to residential green space and semen quality among Chinese men

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ABSTRACT

Background: Residential greenness has been linked to various health benefits, but evidence on its association with sperm quality remains limited.
Methods: We enrolled 28,089 adult men from an infertility clinic in Hubei, China, from 2014 to 2020. Residential greenness was estimated using the Normalized Vegetation Index (NDVI) from satellite imagery, averaged within buffers of 250 m, 500 m and 1000 m around each participant's residential address. We employed multivariate linear regression analysis to evaluate the association between NDVI exposure and semen quality, while controlling for individual characteristics and semen collection season. Additionally, we performed subgroup analyses to investigate potential variations in the association based on individual characteristics.
Results: An interquartile range increase of 0.243 in NDVI within the 1000 m buffer was associated with increases of 1.68 % (95 % CI: 0.31 %, 3.06 %) in sperm concentration, 0.43 % (95 % CI: 0.08 %, 0.79 %) in progressive motility, and 0.50 % (95 % CI: 0.14 %, 0.87 %) in total motility. These associations were consistent across different buffer sizes. The associations were more pronounced during the 70–90 lag days prior to semen collection (spermatogenesis stage) and among men aged ≥ 40 years or those with lower education levels.
Conclusions: Our study demonstrated that exposure to residential greenness may act as an innovative protective factor for semen quality.

1. Introduction

The decline in semen quality contributing to human infertility has become a major public health concern (Levine et al., 2023). Recent studies reported significant reductions in male sperm quality across regions like North America, Europe, and Australia (Aitken, 2022; Levine et al., 2023; Skakkebæk et al., 2022). In China, a study conducted between April 2011 and June 2013 found a 31 % decrease in sperm concentration, a 38 % reduction in progressive motility, and a 66 % drop in the proportion of normal sperm (Sun et al., 2020).

Exposure to residential greenness has been linked to various health benefits, including reduced risk of neurological diseases, metabolic disorders, and adverse pregnancy outcomes (Zhu et al., 2023). Recent study suggested that residential greenness was also associated with improved sperm quality, including increased semen volume, total sperm number, sperm motility, and the proportion of morphologically normal sperm (Choe et al., 2021; Dai et al., 2024; Yang et al., 2021). These protective effects of greenness may through the promotion of physical activity and enhanced social well-being (Markevych et al., 2017). Thus, exposure to greenness may plausibly contribute to better sperm quality. However, the current evidence on the association between greenness and semen quality remains limited.

In this study, we aimed to assess the link between residential greenness exposure and semen quality in 32,773 males at an infertility

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clinic (2014–2022) in China. Furthermore, we investigated whether this association was influenced by variables such as age, body mass index (BMI), educational attainment, and the semen collection season.

2. Method

2.1. Study population

From April 2014 to December 2020, we recruited 32,777 males attending an infertility clinic in Wuhan, Hubei, China, who had complete outcome data and residential information (Zeng et al., 2014). We excluded 4684 individuals who reported azoospermia or reproductive dysfunction, such as vasectomy, epididymitis, vesiculitis, varicocele, testicular injury, and endocrine disorders, due to their potential impact on semen quality. Additionally, we excluded participants residing outside Hubei, China (n = 4), resulting in a final analytical cohort of 28, 089 participants (Table S1). We collected demographic information, including age, education level, fatherhood status, and health conditions, via a standardized and structured questionnaire. Clinical examinations were conducted by local registered nurses. The study received approval from the Ethics Committee of Tongji Medical College.

2.2. Study outcome

Sperm samples were collected and analyzed following the 2010 World Health Organization (WHO) guidelines (Yang et al., 2017). Each participant was instructed to ejaculate into a sterile plastic specimen cup in a designated private area near the semen analysis facility. The collected semen samples were then liquefied in a controlled heating chamber. Semen volume was measured using a serological pipette, and sperm concentration, progressive motility, and non-progressive motility were assessed using micro-cell slides and computer-assisted semen analysis. Total sperm motility was calculated by combining sperm progressive and non-progressive motility.

2.3. Environmental exposure data

NDVI data ranging from −1.0–1.0 were obtained from MODIS (MOD13Q1, spatial resolution: 250 m, temporal resolution: 16 days). We assumed that the daily NDVI values remain constant across each 16-day interval. Negative NDVI values, which do not represent vegetation, were converted to 0 (Yang et al., 2017). Participants' residential addresses were geocoded into geographic coordinates using Baidu map. To assess residential green exposure levels for each participant, we calculated the mean NDVI across three buffer distances: 250 m, 500 m, and 1000 m (Yu et al., 2024).

Daily air pollutant data for each participant, corresponding to their geographic locations from 2014 to 2020, were acquired utilizing the ChinaHighAirPollutant (CHAP) dataset, a gridded dataset with a resolution of 1 km × 1 km (Wei et al., 2023). This dataset includes data on fine particulate matter ($PM_{2.5}$), carbon monoxide (CO), nitrogen dioxide (NO_2), ozone (O_3), and sulfur dioxide (SO_2). The CHAP dataset has demonstrated good accuracy and reliability, with R^2 values ranging from 0.8 to 0.93 (Wei et al., 2022).

Daily ambient temperature data were obtained from the China Meteorological Administration. We used inverse distance weighting to estimate the temperatures at participants' residences, utilizing data from the five closest monitoring stations (Zhang et al., 2023).

Spermatogenesis, the process of sperm production, spans 90 days and consists of three key stages: epididymal storage (0–9 days before ejaculation), sperm motility development (10–14 days before), and spermatogenesis (70–90 days before) (Zhang et al., 2023; Hansen et al., 2010). The average values of NDVI, air pollutants, and ambient temperature were used for participants during these critical periods of sperm development.

Table 1
Summary characteristics of the study participants (n=28,089).

Characteristics	N (%) Mean ± SD
Demographics	
Age, years	
≤30	8743 (31.1 %)
31–39	14981 (53.3 %)
≥40	4367 (15.5 %)
Unknown	1 (0.0 %)
BMI, kg/m^2	
<18.5	1109 (3.9 %)
18.5–23.9	12935 (46.0 %)
24.0–27.9	10501 (37.4 %)
≥28	3258 (11.6 %)
Unknown	289 (1.0 %)
Education	
College and higher	12521 (44.6 %)
High school	3397 (12.1 %)
Middle school and lower	12152 (43.3 %)
Unknown	22 (0.1 %)
Ever having fathered a child	
No	13518 (48.1 %)
Yes	4014 (14.3 %)
Unknown	10560 (37.6 %)
Season of semen collection	
Spring (March to May)	6470 (23.0 %)
Summer (June to August)	9165 (32.6 %)
Autumn (September to November)	7376 (26.3 %)
Winter (December to February)	5081 (18.1 %)
NDVI	
NDVI 250 m	0.383 ± 0.167
NDVI 500 m	0.383 ± 0.167
NDVI 1000 m	0.383 ± 0.167
Air pollutants (μg/m^3)	
CO	1.04 ± 0.20
NO_2	32.6 ± 13.2
O_3	101.0 ± 25.1
SO_2	15.1 ± 8.9
$PM_{2.5}$	47.8 ± 18.9
Ambient temperature (°C)	21.2 ± 7.7
Semen quality parameters	
Sperm concentration (millions/mL)	55.9 ± 31.7
Sperm count (millions)	56.1 ± 38.7
Progressive motility (%)	40.4 ± 17.2
Total motility (%)	45.1 ± 17.8

Note. N: number of counts; SD: Standard deviation; BMI: body mass index; NDVI: normalized difference vegetation index; carbon monoxide (CO); nitrogen dioxide (NO_2), ozone (O_3); and sulfur dioxide (SO_2); fine particulate matter ($PM_{2.5}$).

2.4. Statistical analysis

Natural logarithms were used to transform right-skewed sperm counts and sperm concentrations into distributions approximating normality. A multivariate linear regression model was used to examine the association between residential greenness and semen quality over the entire sperm development period, and each of the three key sperm development period, adjusting for age, BMI, education level, fatherhood status, and season of semen collection.

To examine the dose-response relationship between greenness and semen quality, we used a natural cubic spline with three degrees of freedom for the NDVI. We used the likelihood ratio test to assess whether the dose-response curve deviated from linearity. The selection of the number of knots for the restricted cubic spline was guided by minimizing the Akaike Information Criterion and Bayesian Information Criteria.

Subgroup analyses were conducted to evaluate whether the association differed according to age, body mass index (BMI), educational level, and the season of semen collection, with the aim of identifying susceptible subpopulations. A two-sample Z-test was employed to determine the homogeneity of the association across the different

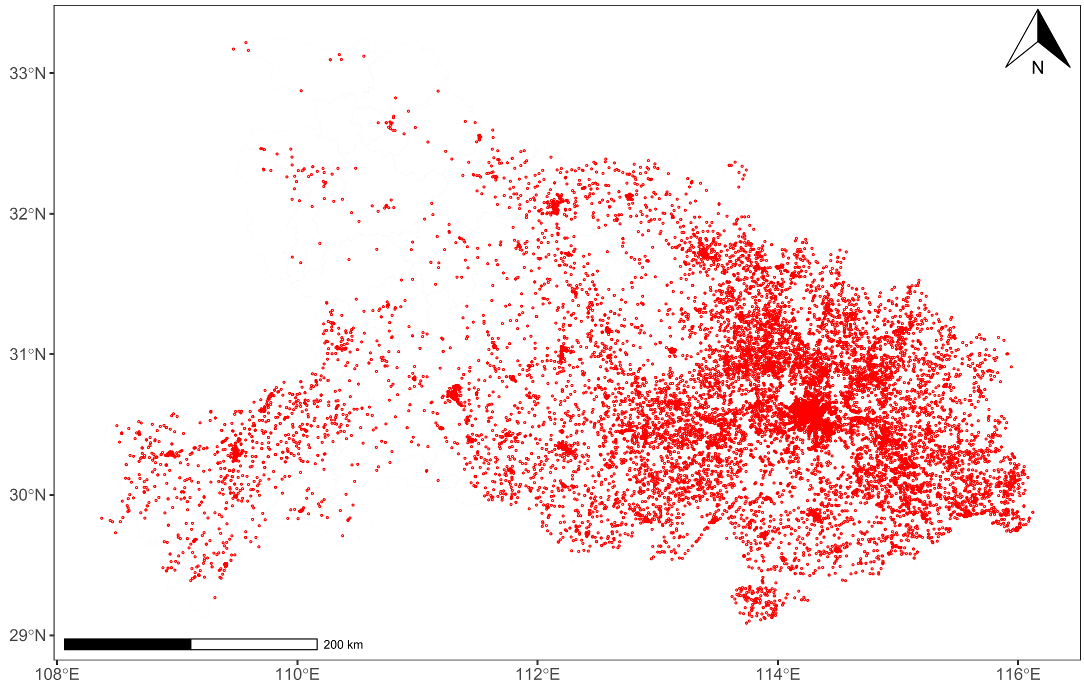

Fig. 1. The spatial distribution of the study participants (n=28,089).

Table 2
Associations between residential greenness exposure and semen quality at 0–90 days before semen sample collection.

Semen quality parameters[a]	NDVI 250 m[b]	NDVI 500 m[b]	NDVI 1000 m[b]
Sperm concentration (% changes in millions/mL)	1.69 (0.31, 3.06)	1.69 (0.31, 3.06)	1.68 (0.31, 3.06)
Sperm count (% changes in millions/sample)	1.97 (−0.59, 4.52)	1.96 (−0.60, 4.51)	1.95 (−0.60, 4.51)
Progressive motility (%)	0.43 (0.08, 0.78)	0.43 (0.08, 0.79)	0.43 (0.08, 0.79)
Total motility (%)	0.50 (0.14, 0.86)	0.50 (0.14, 0.87)	0.50 (0.14, 0.87)

Note. IQR: interquartile range; BMI: body mass index; NDVI: normalized difference vegetation index.
[a] An IQR increase in NDVI 250 m, NDVI 500 m, and NDVI 1000 m exposure at the residential address were 0.243.
[b] Models were adjusted for age, body mass index, education levels, fatherhood status, and season of semen collection.

subgroups.

The association between greenness and sperm quality may through the reduction of air pollution and ambient temperature (Dai et al., 2024; Yang et al., 2023). We conducted mediation analysis to investigate these potential mediating effects of air pollution and ambient temperature on the association between residential greenness and sperm quality.

In the sensitivity analysis, to determine whether the beneficial effects of greenness were similarly evident in males exhibiting normal semen quality. Our analysis was confined to participants whose semen parameters conformed to the World Health Organization (WHO) guidelines. According to the WHO (2010) reference values, normal semen quality was characterized by a sperm concentration exceeding 15×10^6/mL, a sperm count surpassing 39×10^6 per sample, progressive motility above 32 %, and total motility greater than 40 % (World Health Organization WHO, 2010).

The analyses used R version 4.2.2 and the Mediation package for median analysis (Zhu et al., 2023).

3. Results

3.1. Descriptive statistics

The final analysis included a cohort of 28,089 men from 2014 to 2020, with the majority (53.3 %) aged between 31 and 39 years (Table 1). Among them, 48.1 % had not previously fathered a child, 44.6 % had attained a college education or higher, and 46.0 % had a BMI between 18.5 and 24.0 kg/m^2 (Fig. 1, Fig S1). Additionally, residential greenness was negatively correlated with $PM_{2.5}$, CO, NO_2, and SO_2, but positively correlated with O_3 (Fig S2, Fig S3).

3.2. Residential exposure to green space and semen quality

Exposure to greater residential greenness was associated with improved semen quality (Table 2). The association was consistent across NDVI measurements with different buffers. Each interquartile range (IQR) increase of 0.243 in NDVI at a buffer of 1000 m was associated with a 1.68 % increase in sperm concentration (95 % CI: 0.31 %, 3.06 %), a 1.95 % increase in sperm count (95 % CI: −0.60 %, 4.51 %), a 0.43 % increase in progressive motility (95 % CI: 0.08 %, 0.79 %), and a 0.50 % increase in total motility (95 % CI: 0.14 %, 0.87 %). Among the three key sperm development periods, a more pronounced association was observed during spermatogenesis (lag 70–90 days) (Table 3). Specifically, each IQR increase in NDVI (1000 m buffer) was associated with a 1.08 % increase in sperm concentration (95 % CI: −0.20 %, 2.36 %) during the epididymal storage (lag 0–9 days), a 1.08 % increase (95 % CI: −0.18 %, 2.34 %) during the sperm motility development (lag 10–14 days), and a 1.78 % (95 % CI: 0.48 %, 3.08 %) during the spermatogenesis (lag 70–90 days).

A restricted cubic spline was employed for NDVI to investigate the association between residential green space and semen quality. The association was monotonic, with higher levels of NDVI linked to improved sperm parameters (Fig. 2).

3.3. Stratified analyses

Subgroup analysis was utilized to determine which subpopulations

Table 3
The association between residential greenness and semen quality during three critical exposure windows of sperm development.

Exposure time window, lag days[a]	Effect estimates (95 % CI)				
	NDVI level	Sperm concentration (% changes in millions/mL)	Sperm count (% changes in millions/sample)	Progressive motility (%)	Total motility (%)
0 ~ 9[b]	250 m	1.07 (−0.21, 2.35)	1.25 (−1.10, 3.60)	0.11 (−0.21, 0.44)	0.24 (−0.10, 0.58)
	500 m	1.07 (−0.21, 2.35)	1.25 (−1.10, 3.59)	0.11 (−0.21, 0.44)	0.24 (−0.10, 0.58)
	1000 m	1.08 (−0.20, 2.36)	1.25 (−1.10, 3.60)	0.12 (−0.21, 0.45)	0.24 (−0.09, 0.58)
10 ~ 14[c]	250 m	1.07 (−0.19, 2.33)	1.33 (−0.99, 3.64)	0.18 (−0.14, 0.50)	0.28 (−0.05, 0.61)
	500 m	1.07 (−0.19, 2.33)	1.32 (−0.99, 3.63)	0.18 (−0.14, 0.50)	0.28 (−0.05, 0.61)
	1000 m	1.08 (−0.18, 2.34)	1.33 (−0.99, 3.64)	0.18 (−0.14, 0.51)	0.28 (−0.05, 0.61)
70 ~ 90[d]	250 m	1.78 (0.48, 3.08)	1.96 (−0.45, 4.38)	0.19 (−0.14, 0.52)	0.29 (−0.05, 0.63)
	500 m	1.78 (0.48, 3.08)	1.96 (−0.45, 4.37)	0.19 (−0.14, 0.52)	0.29 (−0.05, 0.63)
	1000 m	1.78 (0.48, 3.08)	1.95 (−0.46, 4.37)	0.19 (−0.14, 0.52)	0.29 (−0.05, 0.63)

Note. CI: confidence interval; BMI: body mass index; NDVI: normalized difference vegetation index.
[a]Models were adjusted for age, BMI, education levels, fatherhood status, and season of semen collection.
[b,c]An IQR increase in NDVI 250 m, NDVI 500 m, and NDVI 1000 m exposure at the residential address were 0.261 during epididymal storage (0–9 days prior to ejaculation) or sperm motility development (10–14 days prior to ejaculation) stages.
[d]During spermatogenesis (70–90 days prior to ejaculation) stage, an IQR increase in NDVI 250 m, NDVI 500 m, and NDVI 1000 m exposure at the residential address were 0.251.

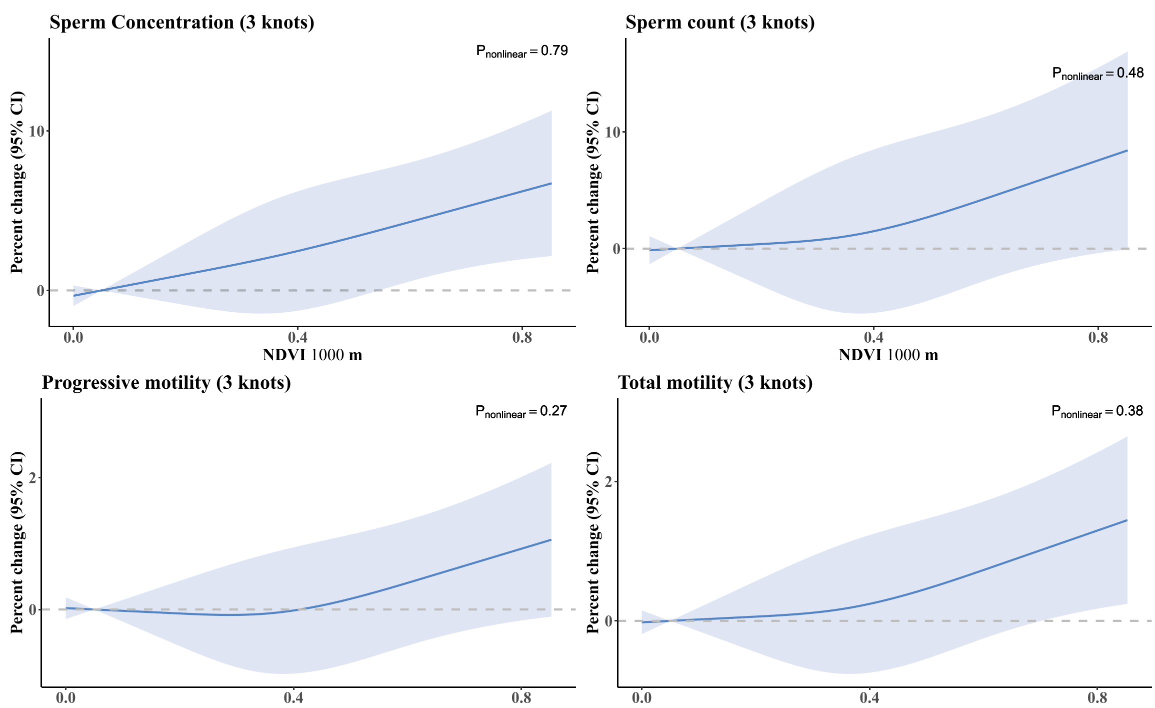

Fig. 2. The dose-response relationship for the association between residential greenness and sperm quality during the entire sperm development (0–90 days). Models were adjusted for age, body mass index, education levels, fatherhood status, and season of semen collection.

were more susceptible to the beneficial effects of residential greenness (Table 4). The association was more significant among men aged ≥ 40 years, those with a BMI of 18.5–23.9 kg/m^2, men with middle school or lower education levels, and those whose semen was collected during the spring season. For example, an IQR change in the NDVI was associated with a 5.29 % (95 % CI: 2.00 %, 8.57 %) increase in sperm concentration among men aged 40 years and older, compared to 0.71 % (95 % CI: −1.20 %, 2.61 %) increase among men aged 31–39 years.

3.4. Mediation analysis and sensitivity analysis

We conducted mediation analysis to examine the potential mediating effects of air pollution and ambient temperature on the association between residential greenness and semen quality. The results showed that neither air pollutants nor ambient temperature mediated the association between greenness and semen quality (Table S2). When we restricted the analysis to males with normal semen quality, NDVI was not

Table 4
Subgroup analysis for the associations of NDVI 1000 m with sperm quality at 0–90 days before semen collection.

Semen quality	**Subgroup**	Effect estimates (95 % CI)	*P* for heterogeneity
Sperm concentration (% changes in millions/mL)	Age, years		
	≤30	1.58 (−0.93, 4.08)	[Reference]
	31–39	0.71 (−1.20, 2.61)	0.59
	≥40	5.29 (2.00, 8.57)	0.08
	Education Attainment		
	Middle school and lower	3.40 (1.42, 5.38)	0.03
	High school	−1.16 (−4.83, 2.51)	[Reference]
	College and higher	0.44 (−1.81, 2.69)	0.47
	BMI, kg/m^2		
	< 18.5	2.70 (−4.17, 9.58)	0.58
	18.5–23.9	2.28 (0.27, 4.29)	0.29
	24.0–27.9	0.66 (−1.59, 2.91)	[Reference]
	≥ 28.0	2.09 (−1.94, 6.11)	0.54
	Season		
	Spring	2.45 (−0.97, 5.86)	0.91
	Summer	2.21 (−0.09, 4.51)	[Reference]
	Autumn	0.90 (−1.54, 3.33)	0.44
	Winter	−0.34 (−4.05, 3.36)	0.25
Sperm count (% changes in millions/sample)	Age, years		
	≤30	3.00 (−1.36, 7.36)	[Reference]
	31–39	1.05 (−2.51, 4.61)	0.50
	≥40	1.70 (−5.20, 8.61)	0.76
	Education Attainment		
	Middle school and lower	3.25 (−0.66, 7.17)	0.94
	High school	3.54 (−3.75, 10.83)	[Reference]
	College and higher	−0.15 (−4.00, 3.71)	0.38
	BMI, kg/m^2		
	< 18.5	−5.12 (−18.70, 8.47)	0.37
	18.5–23.9	2.63 (−1.14, 6.40)	0.67
	24.0–27.9	1.41 (−2.73, 5.54)	[Reference]
	≥ 28.0	2.80 (−4.49, 10.10)	0.75
	Season		
	Spring	8.83 (1.51, 16.14)	0.14
	Summer	2.51 (−1.63, 6.64)	[Reference]
	Autumn	−0.63 (−5.12, 3.87)	0.31
	Winter	−2.70 (−9.23, 3.83)	0.19
Progressive motility (%)	Age, years		
	≤30	0.42 (−0.21, 1.05)	[Reference]
	31–39	0.07 (−0.42, 0.55)	0.39
	≥40	1.58 (0.70, 2.46)	0.04
	Education Attainment		
	Middle school and lower	0.87 (0.35, 1.38)	0.41
	High school	0.42 (−0.52, 1.36)	[Reference]
	College and higher	−0.17 (−0.74, 0.39)	0.29
	BMI, kg/m^2		
	< 18.5	−0.52 (−2.26, 1.23)	0.48
	18.5–23.9	0.74 (0.22, 1.25)	0.13
	24.0–27.9	0.15 (−0.42, 0.73)	[Reference]
	≥ 28.0	0.45 (−0.57, 1.47)	0.62
	Season		
	Spring	0.79 (−0.09, 1.68)	0.39
	Summer	0.33 (−0.24, 0.90)	[Reference]
	Autumn	−0.13 (−0.75, 0.48)	0.28
	Winter	0.76 (−0.20, 1.72)	0.45
Total motility (%)	Age, years		
	≤30	0.45 (−0.20, 1.10)	[Reference]
	31–39	0.19 (−0.31, 0.69)	0.54
	≥40	1.56 (0.65, 2.46)	0.05
	Education Attainment		
	Middle school and lower	0.95 (0.42, 1.48)	0.50
	High school	0.57 (−0.41, 1.55)	[Reference]
	College and higher	−0.13 (−0.72, 0.45)	0.23
	BMI, kg/m^2		
	< 18.5	−0.89 (−2.69, 0.91)	0.26
	18.5–23.9	0.84 (0.30, 1.37)	0.11
	24.0–27.9	0.19 (−0.40, 0.78)	[Reference]
	≥ 28.0	0.69 (−0.36, 1.75)	0.42
	Season		
	Spring	0.89 (−0.02, 1.80)	0.42
	Summer	0.44 (−0.15, 1.04)	[Reference]
	Autumn	−0.14 (−0.77, 0.50)	0.19
	Winter	0.69 (−0.31, 1.68)	0.67

associated with improvement in semen quality (Table S3).

4. Discussion

Among 28,089 Chinese men, we found that residential greenness was associated with improved semen quality. The association was more significant among men aged ≥ 40 years, those with a BMI of 18.5–23.9 kg/m^2, individual with education levels of middle school or lower, or when semen was collected in the spring season.

Our study demonstrates the beneficial effects of green space on semen quality. Consistent with our study findings, other studies have also identified an association between green space exposure and improved semen quality (Yang et al., 2021; Dai et al., 2024). The mechanisms by which residential green space improved semen quality have not yet fully understood. Potential explanations include the promotion of physical activity, improved social well-being (Dadvand et al., 2014; Markevych et al., 2017; McMorris et al., 2015; Yu et al., 2023), or the reduction of air pollution and ambient heat. However, in our mediation analysis, we found no evidence that air pollution or ambient temperature mediated the association between greenness and semen quality.

The beneficial effects of residential greenness on semen quality were most significant during the spermatogenesis stage. Although studies on critical exposure windows for residential greenness are limited, potentially due to the low temporal resolution of NDVI, our study identified that greenness during the 70–90 days before semen quality (spermatogenesis stage) was more likely to improve semen quality, despite the relatively stable nature of greenness over short periods. Future studies are warranted to further investigate the critical exposure windows for residentially greenness.

We found that the beneficial effects of greenness were more pronounced among older men, which was consistent with findings from the Seniors-ENRICA-2 cohort involving 3273 individuals aged 65 years and older (Scheer et al., 2024). The pronounced beneficial effects may be due to increased engagement with greenness and reduced psychological stress in older individuals. For example, older adults are more likely to participate in recreational activities in parks, leading to greater exposure to natural green spaces (Yang et al., 2021). Additionally, exposure to residential greenness has been linked to reduced psychological stress and improved sperm quality (Dadvand et al., 2014; McMorris et al., 2015; Yu et al., 2023).

Studies have shown that green spaces provide greater health benefits to individuals with lower levels of education (Dadvand et al., 2012, Willis et al., 2023). In line with these findings, our study also found that men with lower levels of education were more likely to experience greater beneficial effects of greenness compared to their counterparts. Education level is a key indicator of socioeconomic status, which influences health outcomes. Several hypotheses have been proposed to explain the potential benefits of NDVI for populations with lower socioeconomic status. For example, individuals in lower socioeconomic positions are more likely to reside in rural areas, leading to greater exposure to greenness in China (Zhu et al., 2022). Additionally, those in lower socioeconomic conditions often spend more time commuting, which results in prolonged exposure to green spaces (Willis et al., 2023).

This study has several potential limitations. First, the satellite data utilized in this study could not provide detailed information on the type or quality of vegetation, which might reduce the specificity and accuracy in evaluating residential greenness. However, NDVI remains a widely validated and globally recognized vegetation index, offering valuable insights for most geographical regions in China. Second, we relied solely on residential addresses to estimate greenness exposure, which may not fully capture participants personal exposure during commuting or work, leading to potential exposure misclassification. Third, despite adjusting for a wide range of confounders, residual confounding by unmeasured confounders cannot be entirely ruled out. Fourth, the participants in the study are exclusively from Hubei Province, China, limiting the generalizability of our findings to other regions or countries. Future studies should be conducted across diverse geographic areas and population subgroups to enhance external validity.

5. Conclusion

Among adult men attending an infertility clinic, our study provides evidence that exposure to residential greenness is associated with improved semen quality, contributing to the growing body of knowledge on the health benefits of greenness.

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CRediT authorship contribution statement

Shengzhi Sun: Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Yufeng Li:** Writing – review & editing, Supervision, Conceptualization. **Qiang Zeng:** Writing – review & editing, Supervision, Conceptualization. **Wangnan Cao:** Writing – review & editing. **Tian Liang:** Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Yangchang Zhang:** Writing – review & editing, Validation.

Declaration of Competing Interest

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

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ecoenv.2024.117309.

Data Availability

Data will be made available on request.

References

Aitken, R.J., 2022. The changing tide of human fertility. Hum. Reprod. 37 (4), 629–638. https://doi.org/10.1093/humrep/deac011.

Choe, S.A., Kim, S., Im, C., Kim, S.Y., Wellenius, G., Kim, Y.S., Yoon, T.K., Kim, D.K., 2021. Land use and semen quality: a fertility center cohort study. PLoS One 16 (8), e0255985. https://doi.org/10.1371/journal.pone.0255985.

Dadvand, P., Wright, J., Martinez, D., Basagaña, X., McEachan, R.R., Cirach, M., Gidlow, C.J., de Hoogh, K., Gražulevičienė, R., Nieuwenhuijsen, M.J., 2014. Inequality, green spaces, and pregnant women: roles of ethnicity and individual and neighbourhood socioeconomic status. Environ. Int. 71, 101–108. https://doi.org/10.1016/j.envint.2014.06.010.

Dai, T., Li, W., Wang, L., Zhou, J., Zhong, K., Yao, Y., Cai, X., Tian, L., Wu, H., Xu, T., Xiao, L., Ni, H., Song, C., Li, Y., Li, F., Meng, T., Sheng, H., Lv, Z., Guo, P., Wang, Q., Zhang, X., 2024. Beneficial effect of residential greenness on sperm quality and the role of air pollution: a multicenter population-based study. Sci. Total. Environ. 10 (946), 174038. https://doi.org/10.1016/j.scitotenv.2024.174038.

Hansen, C., Luben, T.J., Sacks, J.D., Olshan, A., Jeffay, S., Strader, L., Perreault, S.D., 2010. The effect of ambient air pollution on sperm quality. Environ. Health Perspect. 118 (2), 203–209. https://doi.org/10.1289/ehp.0901022.

Levine, H., Jørgensen, N., Martino-Andrade, A., Mendiola, J., Weksler-Derri, D., Jolles, M., Pinotti, R., Swan, S.H., 2023. Temporal trends in sperm count: a systematic review and meta-regression analysis of samples collected globally in the 20th and 21st centuries. Hum. Reprod. Update 29 (2), 157–176. https://doi.org/10.1093/humupd/dmac035.

Markevych, I., Schoierer, J., Hartig, T., Chudnovsky, A., Hystad, P., Dzhambov, A.M., de Vries, S., Triguero-Mas, M., Brauer, M., Nieuwenhuijsen, M.J., Lupp, G., Richardson, E.A., Astell-Burt, T., Dimitrova, D., Feng, X., Sadeh, M., Standl, M., Heinrich, J., Fuertes, E., 2017. Exploring pathways linking greenspace to health: theoretical and methodological guidance. Environ. Res. 158, 301–317. https://doi.org/10.1016/j.envres.2017.06.028.

McMorris, O., Villeneuve, P.J., Su, J., Jerrett, M., 2015. Urban greenness and physical activity in a national survey of Canadians. Environ. Res. 137, 94–100. https://doi.org/10.1016/j.envres.2014.11.010.

Scheer, C., Plans-Beriso, E., Pastor-Barriuso, R., Ortolá, R., Sotos-Prieto, M., Cabañas-Sánchez, V., Gullón, P., Ojeda Sánchez, C., Ramis, R., Fernández-Navarro, P., Rodríguez-Artalejo, F., García-Esquinas, E., 2024. Exposure to green spaces, cardiovascular risk biomarkers and incident cardiovascular disease in older adults: the Seniors-Enrica II cohort. Environ. Res. 185, 108570. https://doi.org/10.1016/j.envint.2024.108570.

Skakkebæk, N.E., Lindahl-Jacobsen, R., Levine, H., Andersson, A.-M., Jørgensen, N., Main, K.M., Lidegaard, Ø., Priskorn, L., Holmboe, S.A., Bräuner, E.V., Almstrup, K., Franca, L.R., Znaor, A., Kortenkamp, A., Hart, R.J., Juul, A., 2022. Environmental factors in declining human fertility. Nat. Rev. Endocrinol. 18 (3), 139–157. https://doi.org/10.1038/s41574-021-00598-8.

Sun, S., Zhao, J., Cao, W., Lu, W., Zheng, T., Zeng, Q., 2020. Identifying critical exposure windows for ambient air pollution and semen quality in Chinese men. Environ. Res. 189, 109894. https://doi.org/10.1016/j.envres.2020.109894.

Wei, J., Li, Z., Wang, J., Li, C., Gupta, P., Cribb, M., 2023. Ground-level gaseous pollutants (NO_2, SO_2, and CO) in China: daily seamless mapping and spatiotemporal variations. Atmos. Chem. Phys. 23, 1511–1532. https://doi.org/10.5194/acp-23-1511-2023.

Wei, J., Liu, S., Li, Z., Liu, C., Qin, K., Liu, X., Pinker, R.T., Dickerson, R.R., Lin, J., Boersma, K.F., Sun, L., Li, R., Xue, W., Cui, Y., Zhang, C., Wang, J., 2022. Ground-Level NO_2 surveillance from space across china for high resolution using interpretable spatiotemporally weighted artificial intelligence. Environ. Sci. Technol. 56 (14), 9988–9998. https://doi.org/10.1021/acs.est.2c03834.

Willis, M.D., Wesselink, A.K., Hystad, P., Pescador Jimenez, M., Coleman, C.M., Kirwa, K., Hatch, E.E., Wise, L.A., 2023. Associations between residential greenspace and fecundability in a north american preconception cohort study. Environ. Health Perspect. 131 (4), 47012. https://doi.org/10.1289/EHP10648.

World Health Organization (WHO), 2010. Laboratory Manual for the Examination and Processing of Human Semen, fifth edn. WHO, Geneva.

Yang, T., Gu, T., Xu, Z., He, T., Li, G., Huang, J., 2023. Associations of residential green space with incident type 2 diabetes and the role of air pollution: a prospective analysis in UK Biobank. Sci. Total. Environ. 866, 161396. https://doi.org/10.1016/j.scitotenv.2023.161396.

Yang, P., Wang, Y.X., Chen, Y.J., Sun, L., Li, J., Liu, C., Huang, Z., Lu, W.Q., Zeng, Q., 2017. Urinary polycyclic aromatic hydrocarbon metabolites and human semen quality in China. Environ. Sci. Technol. 51 (2), 958–967. https://doi.org/10.1021/acs.est.6b04810.

Yang, Z., Xu, R., Wang, Q., Fan, Z., Wang, Y., Liu, T., Xu, L., Shi, C., Duan, Y., Zhang, X., Liu, Y., 2021. Association of exposure to residential greenness with semen quality: a retrospective longitudinal study of sperm donation volunteers in Guangdong province, China. Ecotoxicol. Environ. Saf. 220, 112396. https://doi.org/10.1016/j.ecoenv.2021.112396.

Yu, Y., Lin, H., Liu, Q., Ma, Y., Zhao, L., Li, W., Zhou, Y., Byun, H.M., Li, P., Li, C., Sun, C., Chen, X., Liu, Z., Dong, W., Chen, L., Deng, F., Wu, S., Hou, S., Guo, L., 2024. Association of residential greenness, air pollution with adverse birth outcomes: results from 61,762 mother-neonatal pairs in project ELEFANT (2011-2021). Sci. Total. Environ. 912, 169549. https://doi.org/10.1016/j.scitotenv.2023.169549.

Yu, W., Liu, Z., La, Y., Feng, C., Yu, B., Wang, Q., Liu, M., Li, Z., Feng, Y., Ciren, L., Zeng, Q., Zhou, J., Zhao, X., Jia, P., Yang, S., 2023. Associations between residential greenness and the predicted 10-year risk for atherosclerosis cardiovascular disease among Chinese adults. Sci. Total. Environ. 868, 161643. https://doi.org/10.1016/j.scitotenv.2023.161643.

Zeng, Q., Wang, Y.X., Xie, S.H., Xu, L., Chen, Y.Z., Li, M., Yue, J., Li, Y.F., Liu, A.L., Lu, W.Q., 2014. Drinking-water disinfection by-products and semen quality: a cross-sectional study in China. Environ. Health Perspect. 122 (7), 741–746. https://doi.org/10.1289/ehp.1307067.

Zhang, Y., Wei, J., Liu, C., Cao, W., Zhang, Z., Li, Y., Zeng, Q., Sun, S., 2023. Association between ambient PM_1 and semen quality: a cross-sectional study of 27,854 men in China. Environ. Int. 175, 107919. https://doi.org/10.1016/j.envint.2023.107919.

Zhu, Z., Yang, Z., Yu, L., Xu, L., Wu, Y., Zhang, X., Shen, P., Lin, H., Shui, L., Tang, M., Jin, M., Wang, J., Chen, K., 2023. Residential greenness, air pollution and incident neurodegenerative disease: a cohort study in China. Sci. Total. Environ. 878, 163173. https://doi.org/10.1016/j.scitotenv.2023.163173.