Residential tree canopy configuration and mortality in 6 million Swiss adults: a longitudinal study

Dengkai Chi, Gabriele Manoli, Brenda Lin, Raf Aerts, Jun Yang, Amy Hahs, Daniel Richards, Naika Meili, Yue Zhu, Yeshan Qiu, Jing Wang, Paolo Burlando, Simone Fatichi, Puay Yok Tan

Summary

Background Residential exposure to trees has been associated with reduced mortality risks. We hypothesise that in addition to tree canopy cover, tree canopy configuration also plays a role in exposure–mortality relationships. As there is limited evidence on this hypothesis, especially longitudinal evidence, we performed a nationwide study to investigate the residential tree canopy configuration–mortality associations in the Swiss population.

Methods In this longitudinal study, the tree canopy cover and configuration metrics within 500 m of individuals' residences were quantified using high-resolution tree canopy data (1×1 m) from 2010 to 2019. We developed single-exposure and multi-exposure time-varying Cox regression models to estimate the associations between the different exposure metrics and natural-cause and cause-specific mortality in Swiss adults (aged from 20 years to 90 years). Mortality and census data were taken from the Swiss National Cohort (SNC). We estimated the hazard ratios (HRs) and corresponding 95% CIs per IQR increase in the metrics adjusting for personal sociodemographic and contextual covariates. We also explored the effect modification by tree canopy cover, PM_{10}, air temperature, urbanisation level, age, sex, and area-based local socioeconomic position.

Findings Our analyses included 6 215 073 individuals from the SNC between 2010 and 2019. In the fully adjusted single-exposure models, we observed protective associations between natural-cause mortality risk and tree canopy cover (IQR 12·4%, HR 0·979 [95% CI 0·975–0·983]) and configuration metrics describing the aggregation (6·3%, 0·831 [0·823–0·840]), and connectedness (2·9%, 0·946 [0·938–0·953]); and detrimental associations with two metrics describing the fragmentation (211 patches per 100 ha, 1·073 [1·066–1·080]) and shape complexity (1·9, 1·094 [1·089–1·100]) of patches. The associations were generally preserved with other common causes of death. According to the multi-exposure models, the HR (95% CI) for the combination of one IQR decrease in aggregation and one IQR increase in fragmentation and shape complexity was 1·366 (1·343–1·390). Analyses on modification effects suggested a stronger association in people living in areas with a higher level of tree canopy cover, PM_{10} concentration, air temperature, and urbanisation level.

Interpretation Aggregated, connected, and less fragmented forested greenspaces might offer stronger health benefits than isolated, fragmented ones, but are difficult to implement in cities. Our study provided valuable insights into optimising forested greenspaces and highlighted future directions for the planning and management of urban forests towards healthy and green cities.

Funding National Research Foundation, Prime Minister's Office, Singapore under its Campus for Research Excellence and Technological Enterprise programme and ETH Zurich.

Lancet Planet Health 2025; 9: e186–95

This online publication has been corrected. The corrected version first appeared at thelancet.com/planetary-health on April 1, 2025

Singapore–ETH Centre, Future Cities Laboratory Global, Singapore (D Chi PhD, N Meili PhD, Y Qiu MSc, J Wang MSc); Laboratory of Urban and Environmental Systems, École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland (G Manoli PhD); CSIRO Environment, Brisbane, QLD, Australia (B Lin PhD); Division of Ecology, Evolution and Biodiversity Conservation, University of Leuven, Leuven, Belgium (R Aerts PhD); Risk and Health Impact Assessment, Sciensano, Brussels, Belgium (R Aerts); Department of Earth System Science, Institute for Global Change Studies, Ministry of Education Ecological Field Station for East Asian Migratory Birds, Tsinghua University, Beijing, China (Prof J Yang PhD); School of Agriculture, Food and Ecosystem Sciences, Burnley Campus, The University of Melbourne, Richmond, Melbourne, VIC, Australia (A Hahs PhD); Manaaki Whenua – Landcare Research, Lincoln, New Zealand (D Richards PhD); Institute of Environmental Engineering, ETH Zurich, Zurich, Switzerland (Y Zhu PhD, Prof P Burlando PhD); Department of Architecture, College of Design and Engineering, National University of Singapore, Singapore (Y Qiu, Prof P Y Tan PhD); Department of Civil and Environmental Engineering, College of Design and Engineering, National University of Singapore, Singapore (Prof S Fatichi PhD)

Introduction

Exposure to greenspaces, including trees, is associated with reduced risks of mortality.[1–6] Studies have almost exclusively focused on the amount of greenspaces, employing indicators such as the Normalized Difference Vegetation Index, greenspace cover, tree density, and tree crown volume to quantify exposure.[1,3–7] Although these studies have provided the evidence base that contributed to the emergence of policy recommendations on urban greenspaces both globally[8] and regionally,[9] and on forested greenspaces specifically, such as the 3-3-300 rule (that everyone should see three trees from their home, have 30% tree canopy in their neighbourhood, and be within 300 m of a green space to maximise urban health benefits),[10] we contend that these exposure measures are inadequate to fully understand the value of greenspace in supporting human health.

The spatial configuration of vegetation plays a pivotal role in how effectively greenspaces can provide ecosystem services. By configuration, we refer to different quantitative features that describe greenspace distribution—eg, aggregation and connectedness, fragmentation and size, and shape complexity of greenspaces (appendix p 6). These metrics were originally developed in landscape ecology to investigate how landscape patterns influence

Correspondence to:
Dr Dengkai Chi, Singapore–ETH Centre, Future Cities Laboratory Global, Singapore 138602
dengkai.chi@sec.ethz.ch
or
Prof Puay Yok Tan, Department of Architecture, College of Design and Engineering, National University of Singapore, Singapore 117566
puay.yok.tan@nus.edu.sg

See **Online** for appendix

Research in context

Evidence before this study

We searched PubMed and Scopus for epidemiological studies on associations between exposure to greenspace and mortality using the terms "green space", "greenspace", "greenness", "Normalized Difference Vegetation Index", "NDVI", "nature", "parks", "trees", "tree cover", "tree canopy cover", "mortality", and "deaths". We included peer–reviewed studies published up to Jan 8, 2025, regardless of the location of the study. Only papers in English were considered. We also perused the bibliographies of relevant research articles and reviews. We identified 70 relevant articles with most of the studies using quantity measures (eg, the Normalized Difference Vegetation Index, greenspace cover, and density of greenspaces) to represent the exposure to greenspace. Only nine articles looked at the associations with greenspace configuration: seven cross-sectional or ecological studies and two longitudinal studies. However, both the longitudinal studies involved a relatively small population size (n=3949 and n=12 999), and the greenspace configuration was measured either at the census tract level or county level. Most of the seven studies focused on only one city and there was no national scope. None of the seven studies were conducted in European countries and they did not look at tree canopy configuration. The findings were inconsistent: six studies observed associations between one or more greenspace configuration metrics and mortality and two studies found no relationship.

Added value of this study

We showed associations between the residential tree canopy configuration and natural-cause and cause-specific mortality risks, after controlling for tree canopy cover and a set of personal sociodemographic and contextual covariates. Our findings highlighted that the associations were stronger in areas with a higher tree canopy cover, PM_{10} concentration, air temperature, and urbanisation level. Other key strengths of our study are the study design (a nationwide longitudinal study), large population size (6 215 073 individuals), use of multitemporal very-high-resolution tree canopy cover data, and examination of the joint effect sizes of multiple configuration metrics on mortality.

Implications of all the available evidence

The development of future health-sensitive cities can greatly benefit from optimising residential forested greenspaces. Our findings suggest that these spaces should prioritise configurations that feature high levels of aggregation, minimal fragmentation, and simpler shapes—a configuration that typically also harbours elevated levels of biodiversity. Such configurations might offer substantial health advantages, particularly for urban populations exposed to more severe environmental challenges such as air pollution and heat.

species richness, ecological processes, and ecosystem services.[11]

Studies have shown that greenspace configuration can affect capability of greenspaces to mitigate environmental harms. For instance, more aggregated and connected, less fragmented, and geometrically simpler greenspaces have been associated with lower land surface or air temperatures in cities.[12–14] Furthermore, the configuration of increased aggregation, connectedness, mean area, and shape complexity, and reduced fragmentation of greenspaces is correlated with lower pollutant concentrations (eg, $PM_{2·5}$, NO_2, and O_3).[15,16] Heat and air pollution are well-documented risk factors that negatively impact a wide range of health outcomes.[17] Greenspace configuration might also impact human behaviour. Larger greenspaces complete with well-designed paths are more likely to encourage physical activities and increase social cohesion.[18] Aggregated greenspaces and connected greenspaces by street trees or other linear-shaped greenspaces might increase residents' usage frequency and duration, leading to increased social cohesion and physical activities such as walking, biking, and jogging. The duration and frequency of contact with greenspaces are associated with improved cardiovascular health,[19] mental health,[19] and general health.[20] Large, less fragmented, and connected greenspaces also form crucial habitats and corridors that permit the movement of species and thereby contribute to biodiversity conservation, which is fundamental to many ecosystem services vital to human health.[21,22] The complexity of greenspace shapes might also influence their capacity to support biodiversity, with greater complexity and longer edges often leading to diminished habitat core areas,[23] and to provide a broader array of recreational opportunities.

For more on the **Swiss National Cohort** see https://www.swissnationalcohort.ch/

Tree clusters are the major component of greenspaces. Therefore, we hypothesise that tree canopies characterised by greater aggregation and connectedness, lower fragmentation and larger sizes, and simpler shapes are likely to deliver ecosystem services more efficiently, thereby offering enhanced health benefits to humans, including reduced risks of mortality (appendix p 6). Until now, no nationwide longitudinal studies have been done to examine the associations between the residential tree canopy configuration and mortality. We therefore aimed to address this knowledge gap in a large, national cohort study—ie, the Swiss National Cohort (SNC) between 2010 and 2019. Specifically, we aimed to assess whether tree canopy configuration is associated with natural-cause and cause-specific mortality risks in Swiss adults, while controlling for a range of personal and contextual covariates. Furthermore, we aimed to investigate whether the associations were modified by biological sex, age, local socioeconomic position, tree canopy cover, PM_{10}, air temperature, and urbanisation level.

Methods

Study design and participants

The SNC is a longitudinal, population-based research database. The current version of the SNC links census data from 1990, 2000, and annual register-based census data from 2010 to 2019 with data on mortality, livebirths, and emigration records. The compulsory census participation ensures a high coverage of the Swiss population in the SNC database (eg, 98·6% in the 2000 census[24]). The SNC was approved by the ethics committees of the cantons of Zurich and Berne.

In the present study, we used the data between Jan 1, 2010 and Dec 31, 2019, during which all annual movements were registered for 10·4 million individuals. For privacy protection, the coordinates (x and y in m) of individuals' home locations were rounded up to the nearest 50 m using the formula of $[\mathrm{int}(x/100)]\times100+50$ and $[\mathrm{int}(y/100)]\times100+50$ by the data provider. This rounding means that there could be a deviation of up to 71 m from the actual coordinates of the home locations. We included individuals who were followed up for at least 4 consecutive years until death or censoring (ie, emigration) or end of the follow-up period on Dec 31, 2019, were aged between 20 years and 90 years in 2010, and had complete and valid information on exposure, covariates, and building locations during the consecutive follow-up period for further analysis (appendix p 7). A 4-year duration offered an adequate timeframe to capture variability in exposure and health outcomes, while maintaining sufficient statistical power and ensured the representativeness of the study population.

Health outcomes

The cause of death in the SNC is coded by ICD-10. We considered all natural causes of death (ICD-10 codes A00–R99), and endocrine, nutritional, and metabolic diseases (E00–E90), mental and behavioural disorders (F00–F99), diseases of the nervous system (G00–G99), diseases of the circulatory system (I00–I99), and diseases of the respiratory system (J00–J99) that were identified as the definitive primary cause of death. We also considered ischaemic heart diseases (I20–I25), stroke (I60–I64), and hypertensive diseases (I10–I15) of the circulatory system.

Tree exposure metrics

In this study, tree exposure referred to the tree canopy cover and its configuration, which were quantified using the countrywide tree canopy cover data in 2012, 2016, and 2019 with a spatial resolution of 1 m (appendix p 5).[25] We calculated five configuration metrics within a 500 m buffer of the individual's approximated home location to quantify the aggregation (aggregation index), connectedness (cohesion index), fragmentation (patch density), size (mean patch area), and shape complexity (area-weighted mean shape index; hereafter referred to as the shape index) of tree canopies (appendix pp 6, 8). The exposure analysis was performed on the 2012, 2016, and 2019 tree canopy cover datasets separately in Fragstats (version 4.2.64), employing the 8-cell neighbour rule. The calculated exposure metrics were assigned to the period of 2010–13 for the 2012 dataset, 2014–16 for the 2016 dataset, and 2017–19 for the 2019 dataset, after accounting for the changes in individuals' locations.

For more on **Fragstats** see https://www.fragstats.org/index.php

Covariates

We considered the following confounding factors (all covariates were time varying unless otherwise indicated): demographic (fixed sex [taken from census data included in the SNC with the options of female and male], civil status, and nationality), socioeconomic (local socioeconomic position; appendix p 5), contextual (urbanisation level, linguistic region, PM_{10} concentration, and air temperature), and fixed period (2010–13, 2014–16, and 2017–19). These variables are available in the SNC, except for the local socioeconomic position (appendix p 5), PM_{10}, and air temperature data. Civil status, urbanisation level, nationality, and linguistic region were updated annually. The urbanisation level for every community was defined by the Swiss Federal Office for statistics based on morphological criteria such as population number and density as well as functional criteria such as commuter flows.

Maps of annual mean NO_2 and PM_{10} concentrations with a spatial resolution of 200 m and average daily maximum air temperature in July and August with a spatial resolution of 250 m were provided by Meteotest.[26] We used PM_{10} data in the main analyses only because there is a high correlation between NO_2 and PM_{10} concentrations (r=0·73) and because PM_{10} is representative of a broad range of air pollution sources. Following a previous study,[27] we calculated the 3-year moving average of past PM_{10} and NO_2 concentrations and assigned the values to the individuals' locations.

Statistical analysis

We used time-varying Cox regression models to estimate the hazard ratios (HRs) and 95% CIs for associations between tree exposure and mortality, with age as the time scale. We adjusted our models for the previously mentioned covariates. Sex and period were added as strata. The inclusion of the period variable (ie, calendar time) was to adjust for time trends in tree exposure.[28] We estimated the HRs per IQR increase in the tree exposure metrics.

We developed a single-exposure model for each exposure metric, adjusting for the same covariates. In the models that evaluated the statistical effects of configuration metrics, the tree canopy cover was also included as a covariate to adjust the models. These single-exposure models were developed for each of the health outcomes.

Each configuration metric describes one aspect of the greenspace configuration but overlapping information is

	Number of individuals
All individuals	6 215 073 (100%)
Age, years	
20–64	5 107 072 (82·2%)
≥65	1 108 001 (17·8%)
Sex	
Female	3 168 558 (51·0%)
Male	3 046 515 (49·0%)
Linguistic region	
German and Rhaeto-Romansh	4 443 734 (71·5%)
French	1 487 292 (23·9%)
Italian	284 047 (4·6%)
Civil status	
Single	1 806 847 (29·1%)
Married	3 392 597 (54·6%)
Widowed	309 081 (5·0%)
Divorced	706 548 (11·3%)
Nationality	
Swiss	4 587 309 (73·8%)
Non-Swiss	1 627 764 (26·2%)
Urbanisation	
Urban	1 831 050 (29·5%)
Periurban	2 796 444 (45·0%)
Rural	1 587 579 (25·5%)

Data are n (%).

***Table 1:* Characteristics of the studied population at the time of entering the censuses**

contained in these metrics, as illustrated by the high correlations in the appendix (p 9). Therefore, we also developed multi-exposure models with aggregation index, patch density, and shape index together or in pairs combined in a single model to estimate the joint associations with natural-cause mortality, adjusted for tree canopy cover and all other covariates identical to the single-exposure models. Mean patch area and cohesion index were excluded from the multi-exposure models because the mean patch area was mathematically determined by tree canopy cover and patch density within buffers and the cohesion index was highly correlated with the aggregation index (r=0·92; appendix p 9). We adopted the variance inflation factor (VIF) approach to examine the multicollinearity between the tree exposure metrics in the same model. Values of VIF lower than four in all the multi-exposure models suggested minimal evidence of multicollinearity. We determined the joint association using the Cumulative Risk Index (CRI) approach. This approach assumes additive effects of multiple risk factors, which has been used to estimate the cumulative risk of exposure to multiple air pollutants on mortality[29] and the joint associations of exposure to air pollution, traffic noise, and greenspaces with mental health.[30] In the multi-exposure models, the HR for each configuration metric was estimated independently of other configuration metrics. The CRI and associated HR are defined as:

$$\mathrm{CRI}=\exp[\textstyle\sum_{i=1}^{p}\hat{\beta}_i x_i]$$

$$\mathrm{HR}_{\mathrm{CRI}}=\textstyle\prod_{i=1}^{p}\exp(\hat{\beta}_i)$$

where p indicates the number of configuration metrics; $\hat{\beta}i$ indicates the estimated coefficient for the ith metric in a multi-exposure model; and x_i indicates the values of the ith metric at which $\hat{\beta}i$ is estimated. Because CRI was designed for risk effect estimation and not all the configuration metrics were detrimentally associated with mortality, CRI in this study was determined as the combination of a 1 IQR increase in the metrics positively associated with mortality and a 1 IQR decrease in the metrics negatively associated with mortality.[30] That is, when estimating $\mathrm{HR}_{\mathrm{CRI}}$, we reversed the coefficient direction for the configuration metrics that demonstrated a negative association with mortality. This will lead to the $\mathrm{HR}_{\mathrm{CRI}}$ values always being higher than 1. $\mathrm{HR}_{\mathrm{CRI}}$ represents the relative hazard for a 1 IQR change in aggregation index, patch density, and shape index or their pairs, compared with no changes in any of them. A higher value indicates a larger protective effect size when the configuration metrics are optimised simultaneously. Comparing $\mathrm{HR}_{\mathrm{CRI}}$ with the effect sizes of individual metrics from single-exposure models helps to understand the impacts of interventions involving multiple configuration metrics on mortality.

We conducted five sensitivity analyses to assess the robustness of our findings in single-exposure models. First, we restricted our analyses to tree canopy patches larger than 100 m² and repeated the analyses. Second, to investigate the scale effects, we recalculated the six metrics within a 250 m and an 800 m buffer of the individual's location and estimated the HRs and 95% CIs for the metrics. Third, we developed models including a frailty term for cantons (n=26) to adjust for potential spatial autocorrelation. Fourth, we replaced PM_{10} with NO_2. Fifth, we included non-tree vegetation cover (appendix p 5) as a covariate to further adjust the models.

Furthermore, based on the multi-exposure models, we tested for effect modification by sex, age (<65 years and ≥65 years), tree canopy cover (tertiles), local socio-economic position (quartiles), urbanisation level (urban, periurban, and rural), air temperature (tertiles), and PM_{10} concentration (tertiles) in stratified multi-exposure models with the covariates identical to the main multi-exposure models.

Finally, we replaced the linear term of the exposure metrics with a B-spline with two degrees of freedom in each single-exposure model to allow a non-linear relationship with natural-cause mortality. Subsequently, we plotted the resulting HRs and 95% CIs to examine the

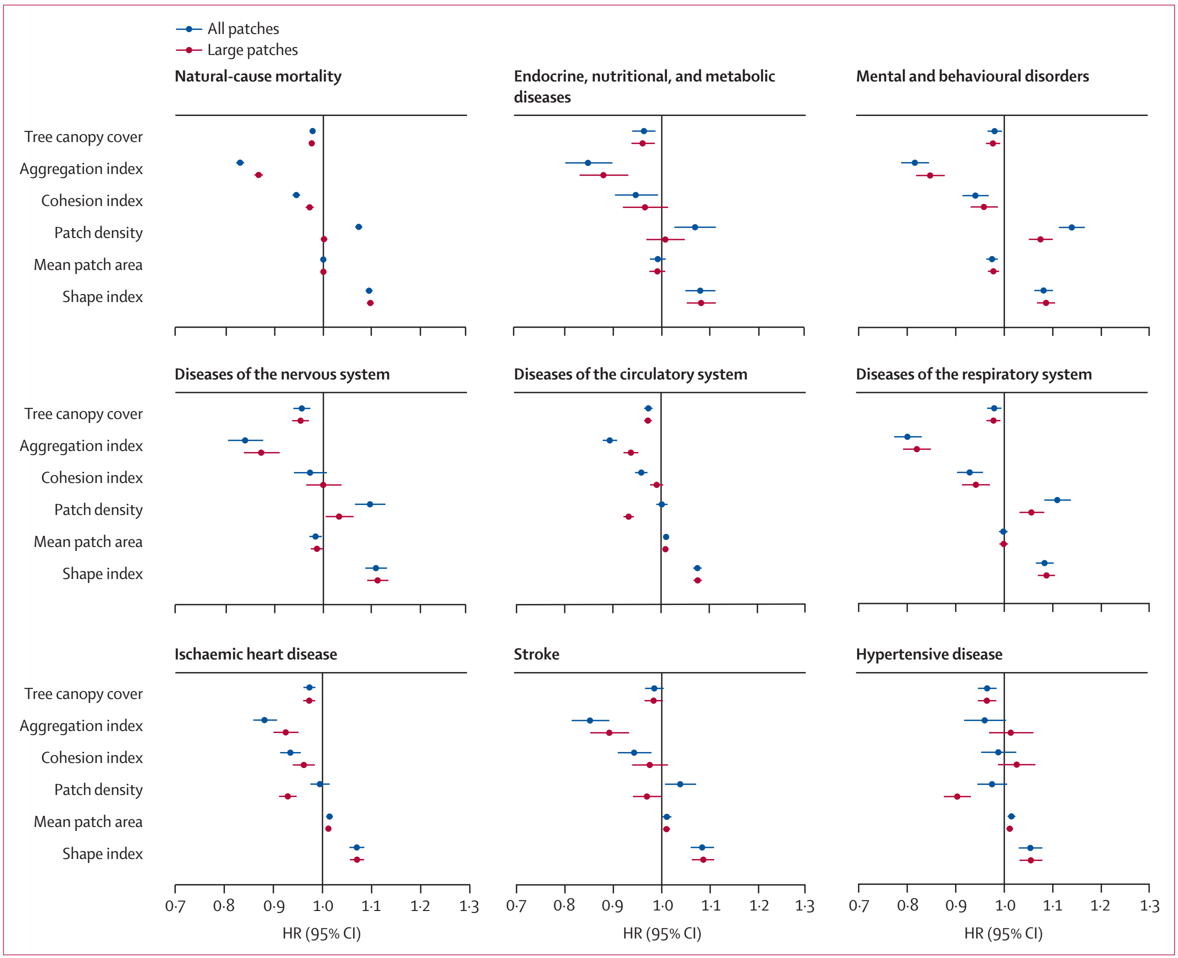

***Figure 1:* HRs and 95% CIs for associations between tree exposure metrics within a 500 m buffer of the individual's approximated home location and different causes of mortality in single-exposure models**

The HRs and 95% CIs were estimated for a 1 IQR increase in the exposure metrics using all patches (tree canopy cover=12·4%, aggregation index=6·3%, cohesion index=2·9%, patch density=211 per 100 ha, mean patch area=476 m^2, and area-weighted mean shape index=1·9) and patches larger than 100 m^2 (tree canopy cover=12·5%, aggregation index=5·1%, cohesion index=2·2%, patch density=97 per 100 ha, mean patch area=1186 m^2, and area-weighted mean shape index=1·9). Models were adjusted for sex, civil status, urbanisation level, nationality, linguistic region, local socioeconomic position, calendar time, PM_{10} concentration, air temperature, and tree canopy cover (for configuration metrics only). HR=hazard ratio.

shapes of the exposure–response curves. Note that we excluded individuals who had an extreme exposure score of less than 0·1% or more than 99·9% percentile values of any exposure metrics to eliminate the impacts of extreme values on the shapes of curves. All the statistical analyses in this study were conducted in R (version 4.3.1) using the survival package (version 3.5–7).

Role of the funding source

The funders of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

Results

Our analyses included 6 215 073 individuals who contributed a total of 58 665 486 person-years in the SNC between 2010 and 2019 (table 1; appendix p 7). Among the eligible individuals, 320 436 (5·2%) died during the 10 years of follow-up with 103 679 (32·4%) deaths related to circulatory diseases and 24 354 (7·6%) deaths caused by mental and behavioural disorders. The characteristics of the tree exposure metrics for the entire population and subgroups are in the appendix (pp 10–12). Among the exposure metrics, patch density showed the weakest negative correlations with other exposure metrics. For patch density, the lowest correlation was with tree canopy cover (*r*=–0·12) and the highest with aggregation index (*r*=–0·49). In contrast, other metrics were positively correlated with each other, among which the highest correlation was found in aggregation index with cohesion index (*r*=0·92) and tree canopy cover (*r*=0·71) and the lowest correlation in mean patch area with cohesion index (*r*=0·46) and shape index (*r*=0·47; appendix p 9).

	Aggregation index plus patch density plus SHAPE_AM	Aggregation index plus patch density	Aggregation index plus SHAPE_AM	Patch density plus SHAPE_AM
Aggregation index				
All patches	0·835 (0·826–0·845)	0·839 (0·830–0·849)	0·817 (0·809–0·825)	NA
Large patches	0·844 (0·834–0·853)	0·838 (0·828–0·847)	0·866 (0·858–0·875)	NA
Patch density				
All patches	1·033 (1·025–1·041)	1·014 (1·006–1·021)	NA	1·096 (1·088–1·103)
Large patches	0·962 (0·955–0·97)	0·947 (0·940–0·955)	NA	1·017 (1·011–1·024)
SHAPE_AM				
All patches	1·105 (1·100–1·110)	NA	1·102 (1·097–1·107)	1·105 (1·100–1·11)
Large patches	1·094 (1·089–1·099)	NA	1·097 (1·092–1·102)	1·098 (1·093–1·103)
CRI				
All patches	1·366 (1·343–1·390)	1·208 (1·189–1·228)	1·349 (1·334–1·363)	1·211 (1·200–1·222)
Large patches	1·347 (1·324–1·370)	1·260 (1·240–1·281)	1·266 (1·252–1·280)	1·117 (1·108–1·127)

Data are HR (95% CI). The HRs and 95% CIs for the cumulative risks were estimated for the combination of a 1 IQR change in aggregation index, patch density, and SHAPE_AM together or in pairs in the multi-exposure models. Models were adjusted for sex, civil status, urbanisation level, nationality, linguistic region, local socioeconomic position, calendar time, PM_{10} concentration, air temperature, and tree canopy cover. CRI=Cumulative Risk Index. HR=hazard ratio. NA=not applicable. SHAPE_AM=area-weighted mean shape index.

Table 2: **HRs and 95% CIs for the associations between tree canopy configuration metrics within a 500 m buffer of the individual's approximated home location and natural-cause mortality in multi-exposure models**

Except for mean patch area, associations were observed between all the other exposure metrics and natural-cause mortality within 500 m in the single-exposure models (figure 1; appendix p 13). Specifically, a 1 IQR increase in tree canopy cover was associated with a 2·1% reduction in the natural-cause mortality risk (IQR 12·4%, HR 0·979 [95% CI 0·975–0·983]), a 16·9% reduction for aggregation index (6·3%, 0·831 [0·823–0·840]), and a 5·4% reduction for cohesion index (2·9%, 0·946 [0·938–0·953]). In contrast, a 1 IQR increase in patch density was associated with a 7·3% increase in the natural-cause mortality risk (211 per 100 ha, 1·073 [1·066–1·080]) and a 9·4% increase for shape index (1·9, 1·094 [1·089–1·100]). For cause-specific mortality risks, the protective association with the tree canopy cover was consistent across the investigated causes (HRs ranging from 0·957 to 0·980), with the exception of stroke (0·985 [0·966–1·004], not significant). Among the configuration metrics, aggregation index showed the strongest protective associations with specific causes of death (HRs between 0·800 and 0·895). Mean patch area showed inconsistent associations with different causes of mortality, where a strong protective association was observed with mental and behavioural disorders (0·975 [0·963–0·987]) and diseases of the nervous system (0·985 [0·972–0·998]) but a detrimental association with diseases of the circulatory system (1·012 [1·009–1·015]) and the three specific circulatory diseases.

The directions of the associations were generally conserved when restricting the analyses to tree canopy clusters larger than 100 m², but a moderate to high attenuation in the magnitude of associations was noted for the aggregation index, cohesion index, and patch density. For example, the association with patch density disappeared in mortality from natural causes and endocrine, nutritional and metabolic diseases and reversed in circulatory diseases (figure 1; appendix p 13). The associations were also observed at the 250 m and 800 m buffer scales, where the magnitude of associations enhanced for tree canopy cover, aggregation index, cohesion index, and shape index with increasing buffer sizes. Mean patch area exhibited a scale-dependent relationship, showing a detrimental association at 250 m, but a protective association at 800 m (appendix pp 14–15). After adjusting for the spatial autocorrelation, slight changes in the magnitude of the associations were observed (appendix p 16). Replacing PM_{10} with NO_2 resulted in attenuated association magnitudes for most of the exposure metrics, although the association directions remained consistent for the configuration metrics (appendix p 17). When non-tree vegetation cover was included as an additional covariate, associations between natural-cause mortality and most of the tree configuration metrics were strengthened, and the associations with tree canopy cover were slightly weakened (appendix p 18).

In the multi-exposure models, each of the three examined metrics (aggregation index, patch density, and shape index) were still associated with natural-cause mortality when adjusted for the other metrics (table 2). The HR for the cumulative risk of a 1 IQR decrease in aggregation index and a 1 IQR increase in both patch density and shape index was 1·366 (95% CI 1·343–1·390), which was higher than that for any pairwise combinations. This finding suggests that interventions leading to a 1 IQR increase in aggregation index (higher aggregation), combined with a 1 IQR decrease in patch density and shape index (lower fragmentation and shape complexity), would be associated with a 36·6% reduction in natural-cause mortality risks. However, it is worth noting that patch density showed a protective association with natural-cause mortality when only larger patches (ie, ≥100 m²) were considered. According to the effect modification analysis on cumulative risks, generally, residents who lived in areas with a higher tree canopy cover, PM_{10} concentration, air temperature, and urbanisation level might experience more health benefits from an optimised tree canopy configuration, as indicated by the higher HRs (figure 2A; appendix pp 19–20). Similar patterns were observed when only larger tree clusters (≥100 m²) were considered (figure 2B; appendix pp 21–22).

The exposure–mortality relationships appeared approximately linear for tree canopy cover, aggregation index, and shape index (figure 3). For cohesion index, the relationship remained linear until it reached around 97%. Patch density exhibited a nearly linear shape starting at around 300 patches per 100 ha. The relationship for mean patch area became approximately linear only after reaching a very large size—ie, around 6000 m².

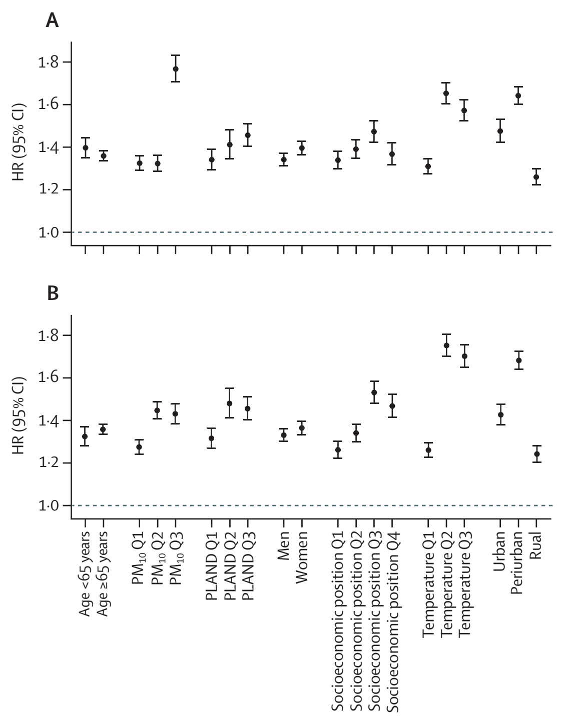

Figure 2: **Effect modification for the associations between tree canopy configuration within a 500 m buffer of the individual's approximated home location and natural-cause mortality by PLAND, PM_{10} concentration, air temperature, local socioeconomic position, sex, age, and urbanisation**
The HRs and 95% CIs were estimated for the cumulative risk (1 IQR change in aggregation index, patch density, and area-weighted mean shape index) in the stratified multi-exposure models. (A) All tree canopy clusters. (B) Tree canopy clusters that are 100 m² or more only. Q represents quartiles for socioeconomic position and tertiles for PM_{10}, PLAND, and air temperature. HR=hazard ratio. PLAND=tree canopy cover.

Discussion

Using a large, longitudinal, and nationwide cohort and multitemporal very-high-resolution tree canopy cover data, we determined the associations between residential tree canopy configuration, in addition to tree canopy cover, and mortality risk. Our study adds valuable evidence to the existing findings mostly from cross-sectional or ecological studies on this topic.[31–37] Our results indicated that living in neighbourhoods with more aggregated and connected, less fragmented, and geometrically simpler tree canopy clusters might reduce the risk of natural-cause mortality and mortality related to several common causes. The observed configuration–mortality relationships were independent of the tree canopy cover for which the models were adjusted. Despite the correlations between the configuration metrics, a combined intervention involving increased aggregation, reduced patch density, and simpler shapes was suggested to achieve a greater reduction in natural-cause mortality risks in Switzerland. Finally, our stratified analyses suggested stronger configuration–mortality associations in individuals who lived in more urbanised areas and in areas with a higher tree canopy cover and air temperature, and worse air quality.

The aggregation of tree clusters reflects how spatially clumped together forested greenspaces are within a neighbourhood. In our study, the aggregation index consistently showed the strongest protective associations with natural-cause mortality as well as with cause-specific mortality across different buffer sizes. A study published in 2019 by Wang and Tassinary showed that more aggregated greenspace was linked to lower all-cause and cause-specific mortality.[35] In this study, the authors examined the associations between mortality and one-unit changes in the same configuration metrics used in our study, at the census tract level (n=369) in Philadelphia, USA, employing a cross-sectional design. The cohesion index quantifies the connectedness of forested greenspaces, which was highly correlated with the aggregation index (r=0·92). Similar to aggregation, a protective association between connectedness and mortality risks has been documented in previous studies. Jaafari and colleagues reported a link between connectedness and reduced mortality related to respiratory diseases at the hexagonal region level (n=87 hexagons) in Tehran.[32] Our results also confirmed this protective relationship in multiple causes of death.

Patch density describes the fragmentation level of tree clusters within a neighbourhood. The detrimental association with natural-cause and respiratory mortality risks observed in this study aligns with the findings by Wang and Tassinary[35] and Shen and Lung[33,34] at the district level (n=48) in Taipei. By using the very-high-resolution tree canopy cover data, a high patch density in our data typically indicates a landscape with many

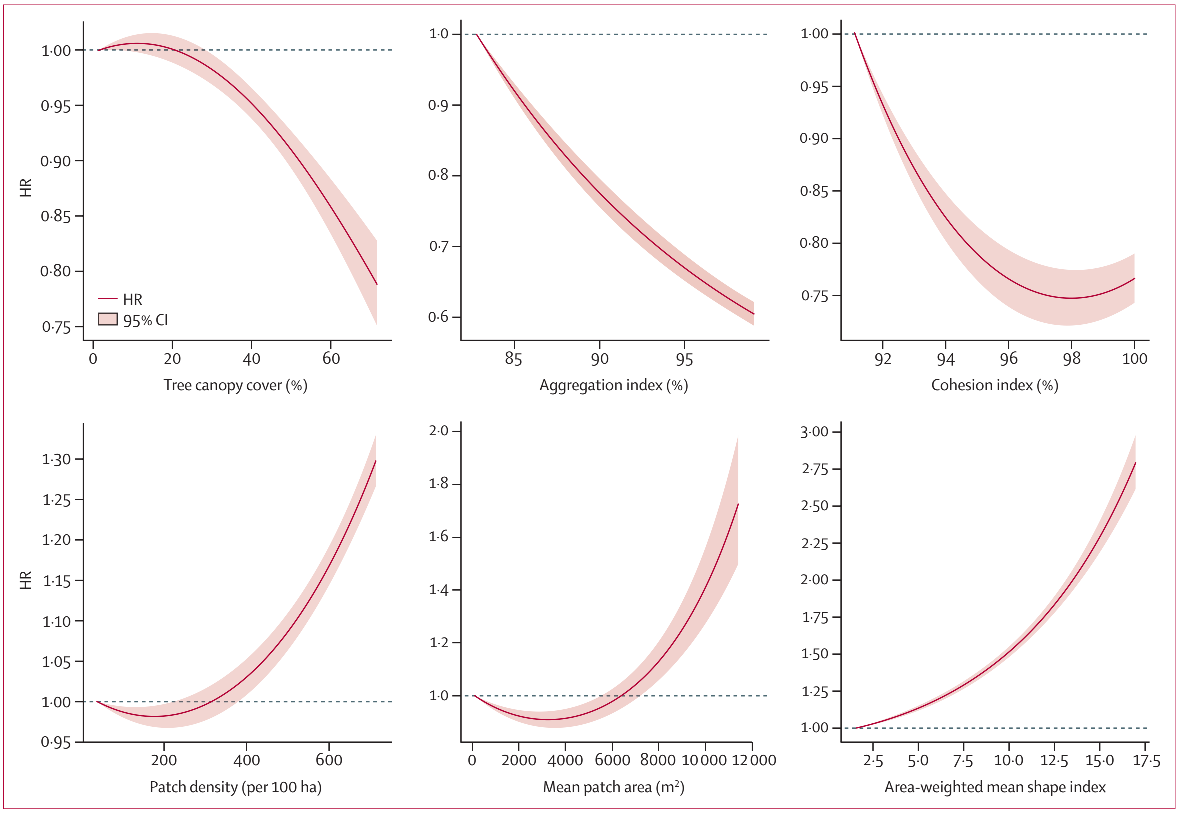

***Figure 3:* The exposure–response relationships between tree exposure metrics within a 500 m buffer of the individual's approximated home location and natural-cause mortality**

Models were adjusted for sex, civil status, urbanisation level, nationality, linguistic region, local socioeconomic position, calendar time, PM_{10} concentration, air temperature, and tree canopy cover (for configuration metrics only). HR=hazard ratio.

scattered, small individual trees or tree clusters, often found in neighbourhoods lacking large, contiguous forested parks. Such fragmented tree clusters have a weaker capacity to mitigate both air pollution and heat, compared with larger and more aggregated forested greenspaces.[12–16] However, when the analyses were restricted to larger patches (>100 m²) only, we found that the associations with patch density varied across different causes of death, with circulatory mortality being protectively affected. Larger tree canopy patches, even if fragmented, might still be effective in delivering ecological and health benefits. Consequently, an increase in the number of larger patches could have a positive impact on health. Similarly, we also observed complex relationships between mean patch area and mortality, varying by cause of death and buffer size. This complexity suggests that while forested greenspaces with a higher mean patch area might benefit mental health and neurological conditions, they might not always provide the same protective effects for cardiovascular health. This finding might indicate different pathways through which tree canopy configuration affects different diseases.

The area-weighted mean shape index compares the shape of the tree canopy cluster with a regular shape (eg, a square). We observed a detrimental association of shape complexity with mortality, which is contradictory to Wang and Tassinary's findings.[35] In their study, the configuration was quantified for all vegetation types collectively, and the authors attributed the negative association to the potentially increased number of access points offered by those shape-complex greenspaces. However, our data imply that such complexity might reduce the health advantages that forested greenspaces provide, potentially by limiting the core areas that sustain biodiversity,[23] human engagement, and the cooling capacity of tree canopies.[12] Further studies are needed to clarify the mixed evidence on the relationship between shape complexity and mortality.

Our multi-exposure models with the CRI approach enabled us to assess the combined effects of multiple configuration metrics. The higher HR for the CRI, which incorporates the aggregation index, patch density, and shape complexity, compared with individual metrics or their pairwise combinations, underscores the cumulative impacts of these metrics. In practice, high values of the aggregation index and cohesion index for tree canopies typically reflect spatially clustered and connected forested greenspaces, such as parks or large groups of trees in residential areas. An example of a potential intervention leading to improved configuration for health would involve reconnecting isolated forest fragments by establishing ecological corridors, complemented by the restoration of the edges of these fragments. This strategy not only increases the aggregation and connectedness of forested greenspaces but also reduces fragmentation. Notably, such an intervention is also anticipated to enhance biodiversity conservation.[21] However, merging tree clusters to increase aggregation might lead to more irregular shapes due to the influence of natural or human-made boundaries (eg, roads and buildings) that contribute to increased shape complexity. It is theoretically possible to enhance aggregation while minimising shape complexity. Achieving this would require more deliberate urban planning, ensuring that newly developed tree clusters are compact and regular in shape. Interventions such as redesigning the boundaries of forested greenspaces during redevelopment projects can facilitate an increase in aggregation without necessarily increasing shape complexity, especially if efforts are made to simplify the edges of forested greenspaces.

Relying on the CRI approach, we found that people living in highly air polluted, hot, periurban, and urban areas might benefit more from interventions aiming at creating well-structured forested greenspaces than those living in areas with good air quality, moderate air temperature, or rural areas. Urban and periurban areas usually offer limited space for greenspace development, and residents suffer more from the adverse effects of air pollution and heat. When optimising multiple aspects of tree canopy configuration is not feasible, increasing aggregation should be the priority. Our results indicate that aggregation index was the primary driver of variations in HRs for CRI. Moreover, urban planners should carefully consider the spatial configuration of tree canopies when planting trees in low-coverage areas to achieve medium-to-high canopy coverage, as suggested by our results that people living in such areas might benefit more from an optimised tree canopy configuration.

We acknowledge that some important limitations should be noted when interpreting our findings. First, the SNC dataset does not include crucial lifestyle information, such as smoking status and physical activity levels. Smoking and BMI frequently present a high association with socioeconomic position, which has been included in the models to adjust the tree canopy configuration–mortality associations.[38,39] However, the absence of direct measures might still leave some residual confounding, especially for diseases such as respiratory diseases. Second, our dataset did not have information on family disease history, preventing us from accounting for genetic predispositions in our models. Despite this limitation, we conducted cause-specific mortality analyses and found that, for diseases less influenced by genetic factors, such as mental and behaviour disorders, the associations with tree canopy configuration persisted. Third, we did not have behavioural information of the individuals, such as the frequency and duration of people using forested greenspaces, to more accurately quantify the real tree exposure. This missing information was a barrier to us being able to explore whether tree canopy configuration affects mortality through the pathway of increasing physical activities and nature exposure time. Fourth, we did not consider individuals' daily routine and exposures beyond their residential area such as at workplaces or during transport due to the lack of such information. Fifth, exposure to trees can vary across seasons due to both changes in trees and differences in outdoor activity levels. Similarly, exposure to trees can vary with species composition, because different species have different traits that could lead to temporal differences in exposure, such as trees being deciduous or evergreen. However, we do not have the same time-varying tree canopy cover data for winter months, species composition data, and behavioural data to account for seasonal variations in forested greenspace usage or their characteristics. Finally, Switzerland is a relatively green country. As suggested by the results, the tree canopy configuration might be more important in neighbourhoods with medium-to-high tree canopy cover. Therefore, the effect sizes of the configuration metrics observed in this study might be higher than in other countries or cities with relatively low tree canopy cover.

In conclusion, this observational study unveils that in addition to the mere presence of tree canopies, their spatial configuration seems to modify the risk of natural-cause mortality and several common causes of death. The magnitude of the associations might vary depending on tree canopy cover, air quality and temperature, and urbanisation level. Our findings suggest that high levels of aggregation, minimal fragmentation, and simpler shapes should be a priority in health-oriented forested greenspaces. Interventions targeting the combined optimisation of these aspects of configuration, such as reconnecting isolated forest fragments, could yield greater health benefits. Findings from this study should be of interest to policy makers and designers of urban greenspaces.

Contributors

DC and PYT conceived and designed the study. DC, YQ, and JW accessed and verified the underlying data with the assistance of GM. DC derived the greenspace exposure metrics, conducted the statistical analyses with the assistance of JY and DR, and wrote the first draft of the manuscript. PYT, PB, SF, GM, BL, JY, DR, and AH contributed to funding acquisition. PYT, PB, SF, GM, and BL supervised the study. All the authors contributed to the revision of the manuscript, interpretation of the results, and approval of the final manuscript.

Declaration of interests

We declare no competing interests.

Data sharing

The greenspace exposure metrics were derived from data provided by Christian Ginzler (Swiss Federal Research Institute WSL, Birmensdorf, Switzerland). The derived metrics will be shared on reasonable request to the corresponding authors. The mortality data were obtained from the Swiss Federal Statistical Office (FSO). The authors are unable to provide access to these data, but interested parties are advised to contact the FSO directly at https://www.bfs.admin.ch/bfs/en/home/statistics/population/surveys/snc.html.

Acknowledgments

This work was supported and funded by the National Research Foundation, Prime Minister's Office, Singapore under its Campus for Research Excellence and Technological Enterprise programme and ETH Zurich, with additional contributions from the National University of Singapore, Nanyang Technological University, Singapore, and the Singapore University of Technology and Design. GM acknowledges support from the SNSF Weave Lead Agency funding scheme (grant number 213995). We thank the FSO for providing mortality and census data, the Swiss Federal Office for the Environment and Meteotest for providing the air pollution and temperature data, and the cantons of Appenzell Ausserrhoden, Jura, Luzern, Nidwalden, Obwalden, Neuchâtel, and Vaud for providing the cadastral survey data that made this study possible. We thank Mathias Lerch for help and discussions at the beginning of this research.

References

1 Crouse DL, Pinault L, Balram A, et al. Urban greenness and mortality in Canada's largest cities: a national cohort study. *Lancet Planet Health* 2017; **1:** e289–97.

2 Hajna S, Nafilyan V, Cummins S. Associations between residential greenspace exposure and mortality in 4645 581 adults living in London, UK: a longitudinal study. *Lancet Planet Health* 2023; **7:** e459–68.

3 James P, Hart JE, Banay RF, Laden F. Exposure to greenness and mortality in a nationwide prospective cohort study of women. *Environ Health Perspect* 2016; **124:** 1344–52.

4 Donovan GH, Prestemon JP, Gatziolis D, Michael YL, Kaminski AR, Dadvand P. The association between tree planting and mortality: a natural experiment and cost-benefit analysis. *Environ Int* 2022; **170:** 107609.

5 Roscoe C, Mackay C, Gulliver J, et al. Associations of private residential gardens versus other greenspace types with cardiovascular and respiratory disease mortality: observational evidence from UK Biobank. *Environ Int* 2022; **167:** 107427.

6 Vienneau D, de Hoogh K, Faeh D, et al. More than clean air and tranquillity: residential green is independently associated with decreasing mortality. *Environ Int* 2017; **108:** 176–84.

7 Chi D, Aerts R, Van Nieuwenhuyse A, et al. Residential exposure to urban trees and medication sales for mood disorders and cardiovascular disease in Brussels, Belgium: an ecological study. *Environ Health Perspect* 2022; **130:** 57003.

8 WHO. Urban green spaces and health. 2016. https://www.who.int/europe/publications/i/item/WHO-EURO-2016-3352-43111-60341 (accessed June 20, 2024).

9 European Environment Agency. Who benefits from nature in cities? Social inequalities in access to urban green and blue spaces across Europe. 2022. https://www.eea.europa.eu/publications/who-benefits-from-nature-in (accessed June 1, 2024).

10 Konijnendijk CC. Evidence-based guidelines for greener, healthier, more resilient neighbourhoods: introducing the 3-30-300 rule. *J For Res* 2023; **34:** 821–30.

11 McGarigal K, Marks BJ. FRAGSTATS: spatial pattern analysis program for quantifying landscape structure. Department of Agriculture, Forest Service, Pacific Northwest Research Station, 1995.

12 Masoudi M, Tan PY. Multi–year comparison of the effects of spatial pattern of urban green spaces on urban land surface temperature. *Landsc Urban Plan* 2019; **184:** 44–58.

13 Beele E, Aerts R, Reyniers M, Somers B. Spatial configuration of green space matters: associations between urban land cover and air temperature. *Landsc Urban Plan* 2024; **249:** 105121.

14 Lin J, Qiu S, Tan X, Zhuang Y. Measuring the relationship between morphological spatial pattern of green space and urban heat island using machine learning methods. *Build Environ* 2023; **228:** 109910.

15 Cai L, Zhuang M, Ren Y. Spatiotemporal characteristics of NO_2, $PM_{2.5}$ and O_3 in a coastal region of southeastern China and their removal by green spaces. *Int J Environ Health Res* 2022; **32:** 1–17.

16 Lei Y, Duan Y, He D, et al. Effects of urban greenspace patterns on particulate matter pollution in metropolitan Zhengzhou in Henan, China. *Atmosphere (Basel)* 2018; **9:** 199.

17 Markevych I, Schoierer J, Hartig T, et al. Exploring pathways linking greenspace to health: theoretical and methodological guidance. *Environ Res* 2017; **158:** 301–17.

18 Giles-Corti B, Broomhall MH, Knuiman M, et al. Increasing walking: how important is distance to, attractiveness, and size of public open space? *Am J Prev Med* 2005; **28** (suppl 2)**:** 169–76.

19 Grilli G, Mohan G, Curtis J. Public park attributes, park visits, and associated health status. *Landsc Urban Plan* 2020; **199:** 103814.

20 White MP, Alcock I, Grellier J, et al. Spending at least 120 minutes a week in nature is associated with good health and wellbeing. *Sci Rep* 2019; **9:** 7730.

21 Kong F, Yin H, Nakagoshi N, Zong Y. Urban green space network development for biodiversity conservation: identification based on graph theory and gravity modeling. *Landsc Urban Plan* 2010; **95:** 16–27.

22 Aerts R, Honnay O, Van Nieuwenhuyse A. Biodiversity and human health: mechanisms and evidence of the positive health effects of diversity in nature and green spaces. *Br Med Bull* 2018; **127:** 5–22.

23 Laurance WF, Yensen E. Predicting the impacts of edge effects in fragmented habitats. *Biol Conserv* 1991; **55:** 77–92.

24 Renaud AS. Coverage estimation for the Swiss population census 2000. 2004. https://www.bfs.admin.ch/bfsstatic/dam/assets/341896/master (accessed June 1, 2023).

25 Ginzler C, Hobi ML. Countrywide stereo-image matching for updating digital surface models in the framework of the Swiss National Forest Inventory. *Remote Sens (Basel)* 2015; **7:** 4343–70.

26 Künzle T. Karten von Jahreswerten der Luftbelastung in der Schweiz. 2022. https://www.bafu.admin.ch/dam/bafu/de/dokumente/luft/fachinfo-daten/karten_der_luftbelastunginderschweiz-dokumentation.pdf (accessed June 1, 2024).

27 Ji JS, Zhu A, Lv Y, Shi X. Interaction between residential greenness and air pollution mortality: analysis of the Chinese Longitudinal Healthy Longevity Survey. *Lancet Planet Health* 2020; **4:** e107–15.

28 Shaffer RM, Blanco MN, Li G, et al. Fine particulate matter and dementia incidence in the Adult Changes in Thought Study. *Environ Health Perspect* 2021; **129:** 87001.

29 Crouse DL, Peters PA, Hystad P, et al. Ambient PM2.5, O_3, and NO_2 exposures and associations with mortality over 16 years of follow-up in the Canadian Census Health and Environment Cohort (CanCHEC). *Environ Health Perspect* 2015; **123:** 1180–86.

30 Klompmaker JO, Hoek G, Bloemsma LD, et al. Associations of combined exposures to surrounding green, air pollution and traffic noise on mental health. *Environ Int* 2019; **129:** 525–37.

31 He Q, Liu L, Chang H-T, Wu C-D, Ji JS. Residential green space structures and mortality in an elderly prospective longitudinal cohort in China. *Environ Res Lett* 2021; **16:** 094003.

32 Jaafari S, Shabani AA, Moeinaddini M, Danehkar A, Sakieh Y. Applying landscape metrics and structural equation modeling to predict the effect of urban green space on air pollution and respiratory mortality in Tehran. *Environ Monit Assess* 2020; **192:** 412.

33 Shen Y-S, Lung S-CC. Can green structure reduce the mortality of cardiovascular diseases? *Sci Total Environ* 2016; **566–567:** 1159–67.

34 Shen Y-S, Lung S-CC. Mediation pathways and effects of green structures on respiratory mortality via reducing air pollution. *Sci Rep* 2017; **7:** 42854.

35 Wang H, Tassinary LG. Effects of greenspace morphology on mortality at the neighbourhood level: a cross-sectional ecological study. *Lancet Planet Health* 2019; **3:** e460–68.

36 Wiese D, Stroup AM, Maiti A, et al. Measuring neighborhood landscapes: associations between a neighborhood's landscape characteristics and colon cancer survival. *Int J Environ Res Public Health* 2021; **18:** 4728.

37 Zhou Y, Lu Y. Health effects of greenspace morphology: large, irregular-shaped, well-connected, and close-clustered greenspaces may reduce mortality risks, especially for neighborhoods with higher aging levels. *Environ Res* 2024; **263:** 120095.

38 Faeh D, Braun J, Bopp M. Prevalence of obesity in Switzerland 1992-2007: the impact of education, income and occupational class. *Obes Rev* 2011; **12:** 151–66.

39 Lohse T, Rohrmann S, Bopp M, Faeh D. Heavy smoking is more strongly associated with general unhealthy lifestyle than obesity and underweight. *PLoS One* 2016; **11:** e0148563.