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Green space and stroke: A scoping review of the evidence

Mina Whyte [a], Jeroen Douwes [b], Annemarei Ranta [a,*]

[a] Department of Medicine, University of Otago Wellington, PO Box 7343, Wellington 6242, New Zealand
[b] Research Centre for Hauora and Health, Massey University, Wellington, New Zealand

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ABSTRACT

Background: Global industrialisation and urbanisation has led to an increased interest in the link between the environment and health. Stroke is a major cause of morbidity and mortality, and there is increased evidence that environmental factors may affect both the incidence and severity of stroke. This review summarises the evidence for relationship between green space exposure and stroke incidence and outcomes.
Methods: We conducted a literature search in Medline and Scopus until 1 August 2023, and screened references of relevant articles. Selected articles were appraised for their relevance, and critically reviewed. The findings were thematically categorised.
Results: Of the 1342 papers identified, 27 were included. These involved a mix of study designs (cohort, cross-sectional, quasi-experimental, time stratified case crossover and ecological). There was consistent evidence indicating a protective association between green space exposure and disability and stroke-related death with mortality hazard ratios between 0.66 and 0.95. Most studies also showed that green space was inversely associated with stroke risk, with risk estimates from studies showing a protective effect ranging between 0.4 and 0.98; however, results were more mixed and some did not reach statistical significance. The moderating effects of green spaces on ambient temperatures, noise and air pollution, and psychosocial health plus greater enjoyment and opportunity for exercise and enrichment of the human microbiome may underly these associations.
Conclusion: There is likely some protective effect of green space on stroke, with the benefits most convincingly shown for post-stroke outcomes. More research is recommended to confirm the protective association between green space exposure and reduced stroke risk.

1. Introduction

There has long been an interest in the link between the environment and health, driven in part by extensive industrialisation, rapid urbanisation and associated environmental health hazards. These hazards include urban violence, traffic, the formation of heat islands, air and water pollution, increased access to, and consumption of, unhealthy foods and alcohol, accumulation of plastics, heavy metals and persistent organic pollutants, as well as noise and light pollution. Important in the context of this paper, rapid urbanisation has also resulted in the degradation and destruction of the natural environment and reduced access to biodiverse urban green space such as parks, town belts and tree greenery, for which there is emerging evidence that it may enhance health and protect against a wide range of mostly non-communicable diseases. [1]

The notion that green spaces may have health benefits is not new and was a major factor in the urban park movements of the 19th century in Europe and North America, [2] although empirical evidence was, until recently, largely lacking, [3]. Although green space in many studies is often not well defined, it generally refers to either urban vegetation or nature more generally. [4] For the purpose of this paper, and unless specified differently, we refer to it as urban vegetation. Considering that more than half of the world's population (56% in 2023) now live in urban areas with numbers only expected to rise, [5,6] there is an urgent need to improve understanding of the health benefits of urban green spaces (and the underlying biological mechanism), as this will likely contribute to novel and more effective interventions to reduce the increasing incidence of many non-communicable diseases, including stroke, observed in many high income (and increasingly low and middle) countries over the past few decades.

Exposure to green spaces is associated with improvements in a range of health outcomes across the life course, including greater sense of well-being, [7] improved perceived general health, improved mental health and reduced stress, [8] reduced obesity, [9] improved birth outcomes

* Corresponding author.
E-mail address: anna.ranta@otago.ac.nz (A. Ranta).

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including higher birth weight, [10] reduced cardiovascular and all-cause mortality, [8,11] reduced risk of immune diseases such as asthma and childhood leukaemia, [12,13] and improved developmental, behavioural, and academic outcomes. [14] In addition, physical activity outdoors, compared to indoors, has been associated with reduced negative emotions and fatigue, increased energy, improved attention, greater enjoyment, satisfaction and intent to repeat. [7,15]

Stroke is the second leading cause of death and the third leading cause of disability in all ages globally. [16] The past three decades has seen an increase in the total incidence of stroke, with a resultant increase in mortality and morbidity. [16] In addition to individual and behavioural risk factors, environmental factors also affect the incidence and severity of stroke. Air pollution, [17–20] ambient temperature (heat or cold), [21–24] and living closer to high-traffic roadways [25] have been reported to increase the risk of incident strokes and stroke-related mortality. On the other hand, studies have shown that access to green space can improve vascular health, which may reduce the risk of stroke. Residential greenness has been associated with reduced risk of cardiovascular disease including ischaemic heart disease, the most common cause of mortality worldwide, [26,27] and reduced cerebrovascular events. [28–30]

The mechanisms of how exposure to green spaces improve well-being are poorly understood, but are likely multi-factorial and have been summarised into reducing harm (e.g. reducing air and noise pollution), restoring capacities (e.g. attenuating the effects of fatigue and stress) and building capacities (e.g. encouraging social cohesion and physical activity). [31] Green space generally provides more opportunities for physical exercise. [32,33] Also, there is evidence that walking in nature, compared with urban locations or indoors, is specifically associated with reduced neuronal activity in the subgenual prefrontal cortex, which is associated with a feeling of well-being. [34] For instance, forest therapy, inspired by the Japanese “shinrin-yoku” (forest bathing), has been demonstrated as natural therapy for mental well-being and also cardiovascular health. [35–37] Other potential factors include greater opportunities for social interactions, [38] increased environmental exposure to more diverse microorganisms that may, through increased diversity of the human microbiota, enhance health-promoting immune responses, [39] cooling land surface temperature through shading and evapotranspiration, [40] and reducing air and noise pollution. [41,42]

Given the increasing evidence of the health benefits of the natural environment and urban green space, and the increased understanding of the importance of environmental factors on the burden of stroke, there is a need to assess whether green space reduces the risk and improves outcomes of stroke. While some reviews have included stroke as part of a wider range of health outcomes, or focused on one sub-type of stroke, none have reviewed the benefits of green space and all stroke types, as well as stroke-related outcomes. This scoping review summarises the evidence of the association between green space and stroke that may aid the development of urban interventions to reduce the increasing burden of stroke and potentially other non-communicable diseases. It will also identify future research priorities.

2. Methods

2.1. Search strategy

A literature search was carried out using MEDLINE and SCOPUS databases. Keywords and subject headings related to outdoor greenery (“green space*” OR “vegetation” OR “recreation*” OR “parks” OR “environment”) were combined with the keyword “stroke” in article titles and abstracts. The search was limited to the English language and the last search was conducted on 1 August 2023. The titles and abstracts were reviewed for relevance and selected full articles were accessed for further review. Details of the search strategy are in supplemental Table S1. Additional articles were sourced using references of relevant articles.

2.2. Inclusion criteria

For studies to be considered eligible for inclusion they were required to: (i) have assessed the use of at least one type of natural green space as an exposure; (ii) have included stroke of any type included among the health outcomes; (iii) be written in the English language, (iv) and represent original research. Studies which did not describe the type of green space, how it was measured, represented review articles or opinion pieces, or did not specifically measure stroke as a health outcome were excluded. No date limits were set, and all papers published before 1 August 2023 were considered. Discrepancies were resolved by discussion among the authors.

2.3. Data analysis

All screened records were imported into EndNote version 21 [43] reference management software. Data was then extracted by the following: author, year of publication, study location, study population, study type, green space exposure assessment, stroke or stroke-related outcome assessment, and estimates from the study. The studies were broadly categorised by the characteristic of stroke that was considered, either stroke incidence/prevalence or post-stroke outcomes, and compiled as a narrative synthesis. Where multiple regression models were used, the results of the main model identified by the authors are presented. If a main model was not stated, estimates are presented from the model(s) which included green space exposure or whose results were discussed and presented in the abstract.

3. Results

3.1. Literature retrieval and characteristics of studies

The search yielded 1334 articles and eight additional articles were identified through other sources (e.g., reference lists of relevant publications). After screening titles and abstracts, the full texts of 50 articles were assessed for further review. This resulted in a total of 27 articles that were included (Fig. 1). A full list of excluded articles is available in supplemental Table S2.

Of the 27 studies reviewed, 11 studies were conducted in Asia (41%), eight in North America (30%), seven studies (26%) in Europe, and one used data from multiple countries (3%). There were no studies from South America, Africa or Oceania but data from these continents were included in a multi-country ecological study. [27] All studies that specified the age of participants were conducted in adults aged 18 years and above, and study populations ranged from 374 participants [44] to a population-based cohort of 4.3 million. [45] Twenty studies were characterised as cohort ($n = 12$) or cross-sectional ($n = 8$) studies; four were ecological studies, two were quasi-experimental, and one study used a time-stratified case-crossover design. All included studies were published between 2008 and 2023. It is noteworthy that 25 of the 27 articles were published in the last 10 years, with almost half ($n = 13$) published since 2020.

3.2. Green space exposure measure

Green space exposure was measured using various parameters, but most of the studies ($n = 15$) measured green space as the Normalized Difference Vegetation Index (NDVI), reporting it as a continuous variable or a categorical variable, usually in quartiles, tertiles or comparing highest and lowest exposure groups. The NDVI is a measure of the amount of green vegetation in an area with values ranging from −1 to +1, and is obtained from satellite imagery. [2,46] However, while NDVI is a popular measure for greenness, it can only be used to measure greenness and does not specify the type of greenery e.g. grass or a tree

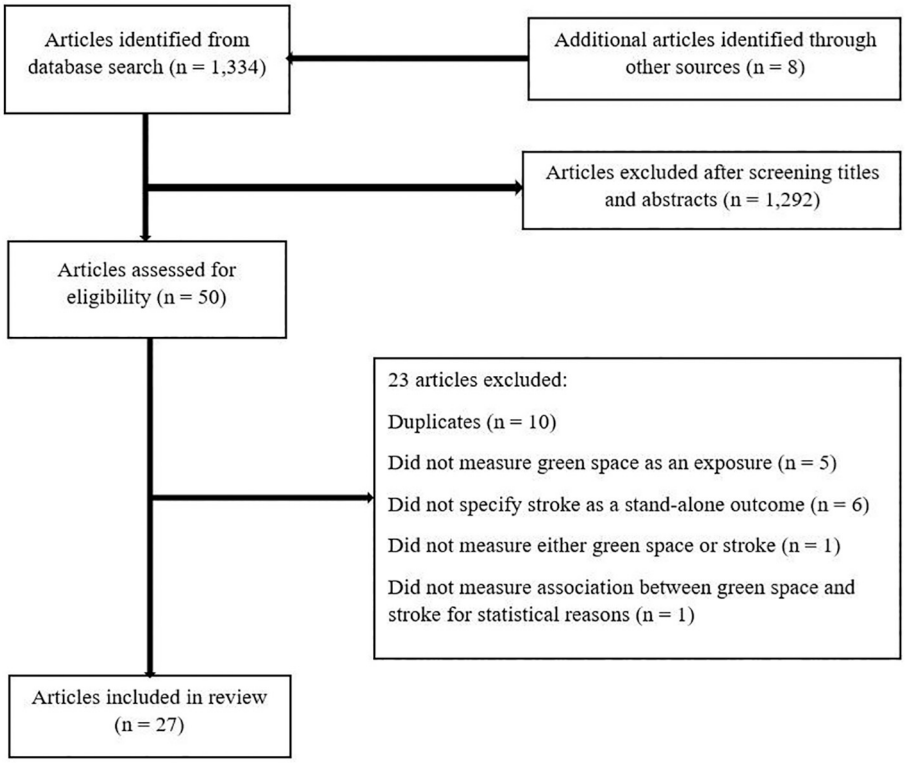

Fig. 1. Flow chart of selection process.

[2,47] The NDVI was measured at different times of the year, some targeting the seasons of expected maximum vegetation, while others took average annual values from different seasons. Percentage of green space in the study area was the next common parameter used, using detailed maps from cartographic databases of land parcels classified by land use e.g., agricultural land, parks, forests etc. Biodiversity, [48] leaf area index, [49] green space ratio and green view index [50] were other less common parameters used to measure green space in the reviewed studies.

3.3. Stroke or stroke-related outcome measure

Stroke or stroke-related outcome measurement was heterogenous between studies and stroke sub-types included in the broad definition of stroke also varied. The most common method was using a clinical classification, especially the International Classification of Diseases coding from patients' medical records, although the codes used were not uniform. Clinical diagnosis by experts on the study, government databases, registers, and participants' self-reported diagnoses were also used. While most of the studies viewed stroke in general, five studies specifically assessed ischaemic stroke, [51–55] one focused on haemorrhagic stroke, [56] and one study on stroke and its major sub-types. [57]

3.4. Summary of findings

Findings are presented separately for stroke incidence/prevalence (Table 1 and Table 2 and post-stroke-related outcomes, such as death (Table 3) or disability (Table 4).

3.4.1. Green space and stroke incidence/prevalence

A total of 16 studies assessed associations between green space and stroke incidence/prevalence, including eight cohort studies, [45,49,51,56–60] six cross-sectional studies, [50,54,61,62,64,65] and one ecological [63] and time-stratified case-crossover study [53] each. Mostly, stroke was evaluated in addition to other health outcomes with less than half assessing stroke only ($n = 6$). [51,54,56,60,59,64] Overall, ten studies found statistically significant positive or protective association between green space exposure and stroke incidence/prevalence, two found higher green space exposure was associated with higher risk of stroke, and four studies reported no clear association. Evidence for a positive association came from cohort studies ($n = 6$) and cross-sectional studies ($n = 4$), while an increased risk of stroke in association with green space exposure was reported in one cohort and an ecological study each. Neutral data came from one cohort, two cross-sectional, and one time series crossover study. Four studies reported lower incidence or prevalence of all stroke with higher green space exposure, [45,50,59,62] and Seo et al. found greater green space coverage to reduce the risk of total and ischaemic stroke, but not haemorrhagic stroke. [57]

Some articles assessed the modifying effect of green space on various other environmental risk factors for stroke, and vice versa providing insights into potential pathways for these associations. Bao et al. [64] and Li et al. [54] reported that higher levels of green space exposure reduced all stroke and ischaemic stroke respectively under unfavourable temperature conditions (cold and heat). Also, Gu et al. reported that green space modifies the effect of noise pollution on incident intracranial haemorrhage, and exposure to lower levels of green space percentage and long-term residential road traffic noise exposure increases the risk of incident intracranial haemorrhage. [56] The evidence is conflicting for air pollution reduction as a potential pathway linking green space and stroke. While Orioli et al. in a large cohort study found a small, but significant protective association between green space and stroke incidence, results from their mediation analysis showed no significant mediation on this association by reduced exposure to air pollution and road traffic noise. [49] Another study by Vivanco-Hidalgo et al. detected an association between the air pollutant, black carbon, and large-artery atherosclerosis ischemic stroke subtype, with no significant modifying effect of higher green space exposure on this association. [53] Poulsen et al. actually reported a harmful modification effect between green space, air pollution and stroke, as their findings

Table 1
Summary of articles describing associations between green space and stroke incidence/prevalence – Cohort studies.

Author/Year	Study location (Country/City)	N/study pop/study type	Green space exposure type	Green space measure/ classification	Stroke description[a]	Estimate type	Estimate provided by study	Association or no association[b]
Yitshak-Sade M. et al. (2017) [58]	Israel Negev	23,110 adults (>18 years) Cohort study	Neighbourhood greenness	NDVI (30 m buffer) Categorised as: - 0–0.1 - 0.1–0.2 - > 0.2	Stroke incidence (ICD9-CM: 432–435)	OR (95% CI)	NDVI = 0.1–0.2 vs. NDVI = 0–0.1: 0.92 (0.53, 1.25) NDVI ≥0.2 vs. NDVI = 0–0.1: 1.53 (0.50, 14.40)	No association found
Orioli et al. (2019) [49]	Italy Rome	1,263,721 adults (≥30 years) Cohort study	Residential greenness	NDVI (300 m and 1000 m buffer) Leaf Area Index (LAI) (300 m and 1000 m buffer)	Stroke incidence (ICD-9-CM)	HR (95% CI)	Using NDVI (300 m): 0.98 (0.96, 0.99)* Using LAI (300 m): 0.98 (0.96, 0.99)*	Association found
Seo et al. (2019) [57]	Republic of Korea 7 Korean metropolitan cities	351,409 adults (> 20 years) Cohort study	Urban green space - Artificially designed parks and green space	Urban green space coverage (% area) By quartiles: Q1 (lowest): 0.0–0.34 Q2: 0.34–0.92 Q3: 0.94–2.33 Q4 (highest): 2.38–15.3	Stroke incidence (ICD-10) - Total stroke (I60 – I69) - Haemorrhagic stroke (I60 – I62) - Ischaemic stroke (I63)	HR (95% CI)	Q4 (highest) v Q1 (lowest): Total stroke: 0.87 (0.82, 0.93)* Ischaemic stroke: Q4: 0.86 (0.80, 0.94)* Haemorrhagic stroke: Q4: 0.98 (0.86, 1.12)	Association found with total and ischaemic stroke, but not haemorrhagic stroke
Paul L. A. et al. (2020) [45]	Canada Ontario	4,300,000 adults (65–85 years) Cohort study	Residential greenness	NDVI (250 m buffer) - Increase in the IQR (0.12 unit) of NDVI	Incident stroke (ICD-9 or ICD-10)	HR (95% CI)	0.96 (0.95, 0.98)*	Association found
Avellaneda-Gómez et al. (2022) [51]	Spain Catalonia	3,521,274 adults Cohort study	Residential green space	NDVI (300 m buffer)	Incident ischaemic stroke (ICD-9 codes)	HR (95% CI)	0.84 (0.70, 1.00)	Association found[c]
Gu T. et al. (2023) [56]	UK Nation-wide	402,268 adults (40–69 years) Cohort study	Residential green space	Land use percentage coverage (300 m buffer) Low: < 29.9% High: ≥ 29.9%	Incident intracerebral haemorrhage	HR (95% CI)	High road traffic noise and low green space levels: 1.35 (1.08, 1.67)* High road traffic noise and high green space levels: 1.02 (0.83, 1.25)	Association found
Poulsen et al. (2023) [59]	Denmark Nation-wide	1,971,246 (≥50 years) Cohort study	Green space	Land use (150 m and 100 m buffer) - Non-green (150 m) - Non-green (1000 m)	Incident stroke (ICD-8: 431–434,436 & ICD-10: I61–I64)	HR (95% CI)	Single pollutant model Non-green (150 m): 1.012 (1.005, 1.019)* Non-green (1000 m): 1.014 (1.005, 1.022)* Two pollutant model Non-green (150 m): 1.010 (1.003, 1.017)* Non-green (1000 m): 1.011 (1.003, 1.020)*	Association found
Poulsen et al. (2023) [60]	Denmark Nation-wide, excluding Greenland and Faeroe Islands	1,964,702 (≥50 years) Cohort study	Green space - recreational areas - forests and open nature areas - private gardens - agricultural areas	Proportion of green space (150 m buffer) Categorised into tertiles: T1 (Low): <55.1% T2 (Medium): 55.1–63.5%	Incident stroke (ICD8: 431–434, 436, ICD10: I61-I64)	HR (95% CI)	By air pollutants and tertiles $PM_{2.5}$: T1 (Low): 1.20 (1.15, 1.26)* T2 (Medium): 1.27 (1.20, 1.35)* T3 (High): 1.36 (1.28, 1.44)* Ultra-fine	Association found, higher risk

(*continued on next page*)

Table 1 (*continued*)

Author/Year	Study location (Country/City)	N/study pop/study type	Green space exposure type	Green space measure/ classification	Stroke description[a]	Estimate type	Estimate provided by study	Association or no association[b]
				T3 (High): ≥63.6%			particles: T1 (Low): 1.06 (1.02, 1.09)* T2 (Med): 1.10 (1.05, 1.15)* T3 (High): 1.22 (1.16, 1.28)* Elemental Carbon: T1 (Low): 1.01 (0.97, 1.04) T2 (Med): 1.07 (1.01, 1.14)* T3 (High): 1.13 (1.08, 1.19)* NO_2: T1 (Low): 1.02 (1.00, 1.03) T2 (Med): 1.08 (1.05, 1.11)* T3 (High): 1.15 (1.11, 1.19)*	

β regression coefficient, *SE* standard error, *OR* odds ratio, *HR* hazards ratio, *RR* risk ratio, *CI* confidence interval, *NDVI* Normalized Difference Vegetation Index, *IQR* interquartile range, *Q* quartile, *T* tertile, *ICD-9-CM* International Classification of Diseases, Ninth Revision, Clinical Modification, *ICD-10* International Classification of Diseases, Tenth Revision.

Note: Estimates are presented at two decimal places, except where rounding may change the interpretation of the results.

* Denotes a statistically significant result.

[a] Method of case ascertainment reported where available.

[b] Presence or absence of a statistically significant association based on the study estimates. Associations denote a 'protective association', except otherwise stated.

[c] The authors report the study estimate as showing lower risk of IS, despite the upper limit of the confidence interval being 1.00; we assume this may be due to rounding.

showed that the association between air pollution and stroke was stronger among those living in areas with more green space. [60] Table 1 summarises these findings in more detail.

3.4.2. Green space and stroke-related outcomes

Eleven papers investigated the association between green space and post-stroke outcomes including four cohort studies, [55,66–68] two cross-sectional studies, [44,52], two quasi-experimental studies, [69,70] and three ecological studies. [27,48,71] They assessed stroke-related outcomes like stroke severity, post-stroke disability and mortality.

3.4.2.1. Stroke-related mortality. Five studies assessed stroke-related mortality, and all of these reported significantly lower risk of mortality from stroke in general [48,66,67,71] and ischaemic stroke specifically [55] with exposure to higher levels of green space. These included three cohort, and two ecological studies.

3.4.2.2. Stroke-related disability. Two papers explored stroke related disability in relation to green space exposure. Asri et al. using data from the global burden of diseases study and satellite data on green space from 183 countries in their ecological study showed that increased NDVI exposure was associated with reduced stroke-related disability adjusted life years. [27] Similarly, Cao et al.'s cohort study reported a reduced risk of post-stroke disability based on the modified Ranking Scale with higher green land cover. [68]

3.4.2.3. Other stroke-related outcomes. Two quasi-experimental studies were conducted to investigate the impact of green therapy on the psychosocial health of chronic stroke patients, and both studies reported positive outcomes. Ho et al. grouped participants into two sets that carried out gardening activities one-hour a week for three months, and their findings showed that gardening had a significant impact on social role based on the Stroke Specific Quality of Life scale. [70] Chun et al. demonstrated that chronic stroke patients who participated in forest therapy had significantly lower depression and anxiety scores after the programme compared with their scores before the programme. [69] One cross-sectional study from Spain found that living in the highest quartile of green space cover was associated with less severe ischaemic stroke using the National Institute of Health Stroke Scale score compared to the lowest green space quartile. [52] Exploring a mechanistic link, Twardzik et al. reported no significant association between proportion of park area and either light or moderate-to-vigorous physical activity in stroke survivors in their cross-sectional study. [44]

4. Discussion

4.1. Key findings

This review included 27 articles from a literature search on green space and stroke, with the majority published quite recently. Few studies assessed green space and stroke specifically. For the relationship between green space and stroke incidence or prevalence, the evidence is strongly suggestive but not entirely conclusive. About two thirds of the studies indicated a positive association, and this was from mostly cohort ($n = 10$) and cross-sectional ($n = 5$) studies. The negative studies were generally of lower quality with one time-series cross over study, three cross-sectional studies and one cohort study reporting neutral, and one ecological and one cohort study finding a potential harmful effect of greenspaces. Almost all studies controlled for sociodemographic characteristics like age, sex and socioeconomic status, and various cardiovascular risk factors such as smoking, alcohol intake, hypertension etc. Some studies also reported a stronger, protective association in older age groups. [62,64] The demonstrated potential beneficial effect of green space is in keeping with studies that have shown green space to reduce the burden of diseases and improve health more generally. [7,8,15] Where there was no association, authors posited that it could be due to the whole population being exposed to low levels of greenness, [53] mediation by participants' comorbidities, [58] or that other

Table 2
Summary of articles describing associations between green space and stroke incidence/prevalence – other studies.

Author/ Year	Study location (Country/ City)	N/study pop/study type	Green space exposure type	Green space measure/ classification	Stroke description[a]	Estimate type	Estimate provided by study	Association or no association[b]
Akpinar A. (2017) [61]	The US Washington State	8976 adults Cross-sectional study	Urban green space, forest Rangeland, Agricultural land, wetland	Percentage of green spaces	Stroke incidence Self-reported physician-diagnosis	β (SE)	0.00 (0.00)	No association found
Jia X. et al. (2018) [62]	China Bengbu	1944 adults (≥ 40 years) Cross-sectional study	Residential greenness	NDVI (250 m buffer) Quartiles [moderate to high (Q2-Q4)] vs. lowest (Q1)]	Stroke prevalence (diagnosed by CT scan, MRI or medical records)	OR (95% CI)	Middle aged (40–59 years): 0.80 (0.51, 0.90)* Older (≥60 years): 0.81 (0.58, 0.94)*	Association found
Vivanco-Hidalgo et al. (2018) [53]	Spain Barcelona	2742 Time-stratified case-crossover	Neighbourhood green space	NDVI (100, 300, and 500 m buffer)	Ischaemic stroke Neurologist-diagnosed	OR (95% CI)	All IS – No significant results Large-artery atherosclerotic stroke (LAAS): At 24–47 h exposure levels to black carbon: 1.25 (1.00, 1.55)* Black carbon + Higher green space exposure (300 m): 1.30 (0.95,1.81)	No significant modifying effect of greenness on association between black carbon and LAAS
Servadio et al. (2019) [63]	The US Atlanta	4 cities Ecological study	Green space	Percent tree canopy cover and green space access	Stroke prevalence Self-reported	β (*p*-value)	0.20 ($p < 0.05$)*	Association found, higher prevalence
Leng H. et al. (2020) [50]	China Harbin	4155 adults (20 – 98y) Cross-sectional study	Green space	Green space Ratio, green view/vision index, presence of evergreen trees	Stroke risk assessed by doctors based on a Stroke Score Card (With stroke risk = 1, Without stroke risk = 0)	OR (95% CI)	Green Space ratio: 0.49 (0.37, 0.68)* Green View Index: 0.48 (0.38, 0.61)* Evergreen trees: 0.90 (0.62, 1.32)	Association found
Li K. et al. (2021) [54]	China Wuhan	3547 Cross-sectional study		NDVI Four levels: - Low: ≤0.25 - Medium-Low: >0.25–0.35 - Medium-High: >0.35–0.45 - High: >0.45	Ischaemic stroke incidence (ICD-10); Under the meteorological condition (K_{ssd}) classified as: Q1 – Cold & uncomfortable weather Q2 – Comfortable weather Q3 – Hot and uncomfortable)	Proportion of IS hospitalisations	By NDVI & K_{ssd}: Low: Q1:2.04; Q2: 1 Q3: 2.28 Medium-Low: Q1:1.08; Q2:1 Q3:0.65 Medium-High: Q1:0.79; Q2:1 Q3:0.77 High: Q1:0.90; Q2:1 Q3:1.03	Lower proportion of hospitalisations with higher NDVI[c]
Bao J. et al. (2021) [64]	China Shenzhen	22,424 Cross-ectional study	Green space	NDVI	Incident stroke (ICD-10)	OR (95% CI)	0.77 (0.69, 0.85)*	Association found
Wang R. (2022) [65]	China Shenyang, Anshan, and Jinzhou	24,799 adults (18 to 74 years) Cross-sectional study	Street-level green space	NDVI (800 m, 1000 m and 1500 m buffers) Street view-based green space (SVG) Categorised into quartiles – Q1 (low) to Q4 (high)	Stroke prevalence Self-reported physician-diagnosis	OR (95% CI)	By NDVI quartiles: Q1: Reference Q2: 1.03 (0.81, 1.31) Q3: 1.04 (0.81, 1.33) Q4: 1.07 (0.82, 1.38) *Similar results for SVG	No association found

β regression coefficient, *SE* standard error, *OR* odds ratio, *HR* hazards ratio, *RR* risk ratio, *CI* confidence interval, *NDVI* Normalized Difference Vegetation Index, *IQR* interquartile range, *Q* quartile, *T* tertile, *ICD-9-CM* International Classification of Diseases, Ninth Revision, Clinical Modification, *ICD-10* International Classification of Diseases, Tenth Revision.

Note: Estimates are presented at two decimal places, except where rounding may change the interpretation of the results.

* Denotes a statistically significant result.

[a] Method of case ascertainment reported where available.
[b] Presence or absence of a statistically significant association based on the study estimates. Associations denote a 'protective association', except otherwise stated.
[c] Estimates table not found in text to interpret statistical significance. Authors say higher NDVI were found to be associated with lower risks of ischemic stroke.

Table 3
Summary of articles describing associations between green space and stroke mortality.

Author/Year	Study location (Country/ City)	N/study pop/study type	Green space exposure type	Green space measure/ classification	Outcome description[a]	Estimate type	Estimate provided by study	Association or no association[b]
Hu Z. et al. (2008) [71]	The US Florida	2 counties Ecological study	Green and recreational areas	Greenness layer	Stroke mortality rate (Florida CHARTS)	95% credible sets	−0.29, −0.03*	Association found
Villeneuve P. (2012) [66]	Canada Ontario	574,840 adults (≥35 years) Cohort study	Urban green space	NDVI (30 m and 500 m buffer) Increase in the IQR of the NDVI	Stroke mortality rate (Canadian Mortality Database)	RR (95% CI)	0.95 (0.92, 0.97)*	Association found
Wilker et al. (2014) [55]	The US Boston	1645 adults (≥21 years) Cohort study	Residential green space	NDVI As quartiles: Q1 (lowest): 0.119–0.533 Q2: 0.534–0.647 Q3: 0.648–0.753 Q4 (highest): 0.754–0.893	Post-ischaemic stroke mortality (Social Security Death Index)	HR (95% CI)	Q4 (highest) v Q1 (lowest): 0.78 (0.63, 0.97)*	Association found
Wang D. et al. (2017) [67]	China Hong Kong	3544 adults (≥65 years) Cohort study	Green space	NDVI (300 m buffer)	Stroke-caused mortality (Government Death Registry)	HR (95% CI)	0.66 (0.52, 0.83)*	Association found
Giacinto J. J. et al. (2021) [48]	The US Los Angeles	1010 zip codes Ecological study	Green space - urban forest biodiversity	Shannon-Weiner Index at the genus level	Stroke mortality (California Department of Public Health)	Mortality rate per 100,00 Individuals (S.E.)	−12.40 (4.95)*	Association found; decrease in the stroke mortality 16% (7.7 per 100,000)

β regression coefficient, *OR* odds ratio, *HR* hazard ratio, *RR* rate ratio, *CI* confidence interval, *NDVI* Normalized Difference Vegetation Index, *Q* quartile, *SD* standard deviation, *SE* standard error.
Note: Estimates are presented at two decimal places, except where rounding may change the interpretation of the results.
* Denotes a statistically significant result.
[a] Source of case ascertainment reported where available.
[b] Presence or absence of a statistically significant association based on the study estimates. Associations denote a 'protective association', except otherwise stated.

characteristics of green spaces might be more important than just presence or type of greenery e.g., size, distribution, quality etc. [61] Few studies evaluated the association by stroke subtypes. Four of the six studies that assessed the association between green space and ischaemic stroke found that green space exposure was protective against ischaemic stroke risk, severity, and mortality. Only two studies reported results for haemorrhagic stroke, and while one found that low green space in conjunction with noise pollution increased the risk for incident intracranial haemorrhage, the other found no association between urban greenery and haemorrhagic stroke. [56,57]

The evidence around the relationship between green space and stroke-related outcomes is more consistent where the majority of studies showed a reduced risk of poor outcomes with exposure to higher levels of greenness. All studies on stroke-related mortality showed a significantly lower risk of death from stroke in areas with increased residential proximity to green space. This aligns with studies that have shown that increased greenery is associated with reduced cardiovascular and all-cause mortality. [8,11,46] Increased green space was also associated with reduced risk of stroke severity, post-stroke disability, and better psychosocial health outcomes. However, additional evidence is desirable to further increase confidence about these positive associations.

4.2. Potential mechanisms through which green space affects stroke

Some of the mechanisms posited by which green space can improve health include cooling of ambient air by providing shade, increased physical activity by providing opportunity and enjoyment, improved mental well-being and reduced stress, and reduced air and noise pollution by absorbing or displacing these irritants. [32–34,37,40–42] A meta-analysis found that greater greenspace exposure was associated with lower salivary cortisol, heart rate, diastolic blood pressure, and type 2 diabetes, [72] all potentially contributing to reduced stroke risk. Studies in this review support the argument that increased green space may modify the effect of heat and noise pollution on stroke. [54,56,64] There was also reported favourable improvement in mental health and social cohesion. [69,70] In respect to physical activity, one study found that the association between green space and the cardiovascular outcomes measured (including stroke) was partially mediated by physical exercise in middle aged and older adults, [62] while another study found no significant association between proportion of park areas and any type of physical activity suggesting this may not be the main or only factor. [44]

Consistent with the biodiversity hypothesis that posits that contact with natural environments promotes good heath through enriching the human microbiome, [1] a reduced risk of stroke incidence and improved outcomes post stroke may be explained by changes in the gut microbiome. Although there is no direct evidence that this may play a role in the observed associations with green space, several studies have shown that the gut microbiome may affect stroke, stroke prognosis and recovery, [73–75] suggesting that this could be a plausible mechanism that warrants further investigation.

A further consideration is the interplay between especially urban green spaces and certain population sub-demographics including ethnic minorities and those of low socioeconomic status. Both characteristics have been associated with greater stroke risk and while most studies controlled for socioeconomic deprivation and other patient

Table 4
Summary of articles describing associations between green space and stroke severity, post-stroke-disability and quality of life.

Author/Year	Study location (Country/ City)	N/study pop/ study type	Green space exposure type	Green space measure/ classification	Outcome description[a]	Estimate type	Estimate provided by study	Association or no association[b]
Ho et al. (2016) [70]	Taiwan Taipei	6 adults Quasi-experimental study	Gardening Long-term plants vs short-term plants		Post-stroke quality of life (using Stroke Specific Quality of Life scale) Social role, family role	β (SE)	Social role 0.72 (0.25)* Family role −0.07 (0.14)	Association found Gardening short-term plants improved social role
Chun et al. (2016) [69]	Republic of Korea Gyenggi-do	59 adults Quasi-experimental study	Forest therapy (mainly Korean pine trees) Before vs After program		Post-stroke depression and anxiety Beck Depression Inventory (BDI) Hamilton Depression Rating Scale (HAM—D17) Spielberger State-Trait Anxiety Inventory (STAI)	Mean (SD)	BDI 14.2 (11.3) v 1.2 (2.1)* HAM-D17 7.1 (4.1) v 1.6 (1.6)* STAI 38.1 (11.0) v 27.6 (6.1)*	Association found Significantly lower depression and anxiety scores in forest group
Vivanco-Hidalgo R. M. et al. (2019) [52]	Spain Barcelona	2761 Cross-sectional study	Residential green space	NDVI (300 m buffer) NDVI Q4 (highest) compared to Q1 (lowest)	Ischemic stroke severity using National Institute of Health Stroke Scale score (BASICMAR database) • Not severe (≤ 5) • Severe (>5)	OR (95% CI) β (95% CI)	0.75 (0.60, 0.95)* −0.11 (−0.21, −0.01)*	Association found
Asri A. K. et al. (2020) [27]	183 countries	Ecological study	Country greenness	NDVI	Stroke-related disability-adjusted life year (DALY) (Global Burden of Disease study database)	β (95% CI)	−4.39 (−7.93, −0.09)*	Association found
Cao M. et al. (2022) [68]	China All of mainland China	28,085 adults (≥ 40 years) Cohort study	Green space - Forests - Savannas - Grasslands - Croplands	NDVI	Post-stroke disability (China National Stroke Screening Survey) modified Ranking Scale: • Normal: ≤2 • Disability: >2	OR (95% CI)	0.53 (0.32, 0.90)*	Association found
Twardzik et al. (2022) [44]	The US Nation-wide	374 adults (≥ 45 years) Cross-sectional study	Park area	Proportion of park area (1000 m buffer)	Post-stroke physical activity (REGARDS study) • Light • Moderate-to-vigorous	β (95% CI)	Light: −8.48 (−103.40, 86.45) Moderate-to-vigorous: 5.30 (−12.97, 23.58)	No association found

β regression coefficient, *OR* odds ratio, *HR* hazard ratio, *RR* rate ratio, *CI* confidence interval, *NDVI* Normalized Difference Vegetation Index, *Q* quartile, *SD* standard deviation, *SE* standard error.
Note: Estimates are presented at two decimal places, except where rounding may change the interpretation of the results.
* Denotes a statistically significant result.
[a] Source of case ascertainment reported where available.
[b] Presence or absence of a statistically significant association based on the study estimates. Associations denote a 'protective association', except otherwise stated.

demographics, it is conceivable that the negative impact of reduced access to green space, may further contribute to inequities. However, care must be taken when adding greenness to such urban areas as there may be a risk of 'eco-gentrification' resulting in increasing housing prices and displacement of already underprivileged populations requiring detailed forward planning.

4.3. Future perspectives

Substantial knowledge gaps remain, including limited understanding of what aspects of green space are protective. This is perhaps not surprising because, despite the long-standing recognition of the importance of green space for health, this field is still in its infancy. Although the number of publications assessing associations between green space and stroke is increasing (see Tables 1 to 4) it is unlikely that this knowledge gap will be fully addressed until we develop more refined exposure-assessment approaches. Currently, exposure assessment of green space often involves the use of the NDVI, a greenness index derived from satellite imagery, land-use data, or both. However, they provide, at best, a crude exposure index, with little ability to differentiate among vegetation types or among species/genera/families within the same vegetation type. [47] Remote sensing, including Light Detection and Ranging (LiDAR), the use of leaf area index and green view index measures, combined with other measures of ecological diversity is likely to reduce measurement error and improve accuracy [47] but this has not been tested in large scale population studies. Thus, improved exposure assessment methods are urgently needed as this will aid the identification of what types of green space are linked with health benefits, thus

informing future intervention studies, urban planning, and potentially clinical guidelines.

As mentioned in the introduction, the mechanisms through which green space affects health in general, and stroke in particular, are likely multifactorial, acting contemporarily and interdependently. Therefore, it is critical that researchers consider as many contributing factors as possible in future study design. However, it may also be the case that isolating these mediators individually in any single study could prove impossible thereby demanding a more holistic approach to assessing environmental health impacts and designing future interventions. Generally, speaking more information on the characteristics of green spaces such as location, proximity, size, biodiversity, indicators on accessibility and usage need to be consistently included in future studies to make them more useful in understanding the mechanisms through which green space can affect stroke, and health in general. In addition, environmental measures of potential intermediate factors such as temperature, air pollution, the outdoor and indoor microbiota, etc., will improve understanding of potential causal exposures and may point towards specific immune, endocrine, neural or other mechanisms. Finally, measurement of potential biomarkers including for example inflammatory or endocrine mediators, may provide more direct evidence of underlying pathophysiological pathways.

Although green space may help mitigate the health effects of climate change, climate change itself may adversely affect the quality and access of green space in urban environments, thus increasing the risk of stroke and other associated adverse health outcomes. Climate change may also more directly affect Stroke risk, particularly through increasing ambient temperature and air pollution, both known risk factors for stroke. [76–78] Future research may therefore consider taking this into account.

4.4. Strengths and limitations

This review has several strengths. To the best of our knowledge, this is the first comprehensive literature review that summarises the evidence between green spaces, all stroke types, and stroke-related outcomes. We used a comprehensive and systematic approach to search two high quality databases to identify and review relevant articles. The heterogeneity of green space measures used by the included articles also provides more information on any underlying associations between the exposures and outcomes. Finally, the studies were not limited to any continent or time period to offer a more generalised application of the findings across different jurisdictions.

There are also several limitations. This review did not quite meet the criteria for being wholly systematic. The aim was to avoid excluding any relevant articles that may add important information to this budding subject area. However, as a result we cannot exclude a degree of selection bias. It also excluded non-English language papers again risking bias. Additionally, very few papers considered the effect of urban versus rural green space as a factor in the associations between green space and stroke, to clarify if geographical location has a mediating effect on this relationship. Furthermore, the variability of measurement of green space exposures and stroke outcomes limits comparability between studies, however, the review primarily aims to provide scoping information and guidance on future research and policy decisions, not at establishing causal relationships.

5. Conclusion and recommendations

This review found that there is likely some protective effect of green space on stroke, with the benefits most convincingly demonstrated for post-stroke health outcomes. As the majority of the world's population continues to shift from rural to urban areas, policy makers should also view city planning with adequate provisions for urban green spaces as preventive medicine. More research is recommended to investigate especially the association between green space and incident stroke and by stroke sub-type. In addition, more epidemiological and intervention studies assessing the impact of green space exposure during post-stroke recovery are also warranted. This will help better guide what type of spaces and level of exposure is associated with optimal outcomes. The indicators with which green space exposure is measured may need to be expanded in order to clarify the underlying mechanisms for any potential association and researchers should take care to consider and measure potential co-variates and clearly specify characteristics and accessibility of the green spaces and stroke sub-types assessed.

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Ethical approval

All reported studies with human subjects performed by the authors have been previously published and complied with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Informed consent

We confirm that the present study is based on the analysis of other studies which had obtained informed consent for all included individuals.

CRediT authorship contribution statement

Mina Whyte: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft. **Jeroen Douwes:** Formal analysis, Supervision, Writing – review & editing. **Annemarei Ranta:** Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Resources, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare no competing interests.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jns.2024.122870.

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