Green space associations with mental health and cognitive function

Results from the Quebec CARTaGENE cohort

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Background: Urban green space may be important to mental health, but the association between long-term green space exposures and depression, anxiety, and cognitive function in adults remains unknown.

Methods: We examined 8,144 adults enrolled in the CARTaGENE cohort in Quebec Canada. Average green space and change in green space with residential mobility were assessed using satellite-derived normalized difference vegetation index from 5-year residential address histories. Outcomes included depression and anxiety determined through medical record linkages, self-reported doctor diagnosis of depression, and the Patient Health Questionnaire-9 and Generalized Anxiety Disorder-7scales. Cognitive function was available for 6,658 individuals from computerized tests of reaction time, working memory, and executive function. We used linear and logistic multivariate models to assess associations between green space and each mental health and cognitive function measure.

Results: In fully adjusted analyses, a 0.1 increase in residential normalized difference vegetation index within 500 m was associated with an odds ratio of 0.85 (95% CI: 0.76, 0.95) for a self-reported doctor diagnosis of depression and 0.81 (95% CI: 0.70, 0.93) for moderate anxiety assessed using the Generalized Anxiety Disorder 7 scale. Other models showed protective effects of urban green space on depression and anxiety but were not statistically significant, and the magnitude of association varied by green space exposure and mental health outcome assessment method. We did not observe any evidence of associations between green space and cognitive function.

Conclusions: We observed some evidence to support the hypothesis that urban green space is associated with decreased depression and anxiety but not cognitive function.

Keywords: Green space; Mental health; Depression; Anxiety; Cognitive function; Built environment

Background

The built environment is an important determinant of health,[1] and urban green space (also referred to as greenness or nature) may be one particularly beneficial component.[2] Exposure to urban green space has been associated with diverse beneficial health outcomes, ranging from positive birth outcomes[3] to reduced cardiovascular disease[4] and mortality.[5]

Mental health may be especially amenable to the effects of green space exposures, but there are limited studies examining the long-term effects of urban green space on adult depression, anxiety, and cognitive function. This is despite the fact that a 2010 meta-analysis demonstrated that individuals living in urban areas were 20% more likely to develop anxiety disorders and 40% more likely to develop mood disorders than individuals living in rural areas.[6] A review of 19 studies examining perceived mental health and green space concluded that there was strong evidence for a positive association with urban green space,[7] but that substantial uncertainty remained due to how mental health was assessed, green space exposure measures, and lack of information on pathways linking green space to mental health.

Few studies have specifically examined green space and cognitive function, although other aspects of the urban environment

What this study adds

We examined associations between exposure to urban green space and mental health outcomes, including depression and anxiety for 8,144 adults, and cognitive function for 6,658 adults with the CARTaGENE Cohort in Quebec, Canada. We leveraged multiple outcome assessments, including medical health linkage and validated scales for depression and anxiety, as well as comprehensive computerized tests for cognitive function. We examined unique green space exposure measures, including 5-year residential satellite derived green space metrics, as well as change in green space exposures with residential mobility. Overall, this study provides a better understanding of the links between urban green space and mental health outcomes.

(e.g. neighborhood deprivation) have been associated with cognitive function.[8] Individuals residing in urban environments may experience more cognitive fatigue and have less opportunities for mental restoration.[9] In a systematic review of green space exposure and cognition, only three studies were found that examine long-term exposure and cognitive function in adults, and these reported mixed findings.[10] Recently, the relationship between natural outdoor environments and cognitive function was explored using survey data from three European cities.[11] Here only residential distance to a natural outdoor environment was associated with cognitive function, with all other exposure measures and mediation analyses demonstrating null effects. Overall, there is little evidence for an association between adult cognitive function and urban green space exposure.

We examined associations between long-term exposure to urban green space and mental health, including depression and anxiety for 8,144 adults, and cognitive function for 6,658 adults within the Quebec CARTaGENE study,[12] located in four urban areas in the Province of Quebec, Canada. This large study leverages different mental health outcome assessments, comprehensive cognitive tests, and extensive exposure measures to add new information on the associations between urban green space and mental health.

Methods

CARTaGENE cohort

The CARTaGENE Cohort is a prospective cohort study in the province of Quebec, Canada, including over 43,000 adults aged 40–69 years of age enrolled from August 2009 to October 2014 from six metropolitan areas (Montreal, Quebec, Saguenay, Sherbrooke, Gatineau, and Trois-Rivieres). Participants were selected randomly to broadly represent these urban populations based on the provincial health insurance registry. A full description of the cohort and data collection has been published elsewhere.[12] Here, we use a subset of the cohort that were enrolled during the first phase of the project (Phase A: 2009–2010, n = 20,004 participants) who completed a detailed environmental and occupational questionnaire allowing the reconstruction of residential and occupational histories (n = 12,189). We further restrict to participants with at least 80% complete residential histories for the 5 years prior to study entry (n = 8,144). For the cognitive function analyses, we further restrict to the 6,658 adults that completed these computerized on-site tests.

Mental health measures

Depression

Depression was assessed using three different measures. First, we linked to administrative health data to identify diagnosed depression (hereafter referred to as health record depression diagnosis). We could only identify depression from hospitalizations and medical billing claim records for participants after 1998, thereby representing an approximate 10-year window before study baseline. Depression was classified based on the following International Classification of Diseases, Tenth Revision (ICD-10) codesidentified at any time in participant medical records after 1998: F32.0–32.9, F33.0–33.3, F33.8, F33.9, F34.1 & F41.2, representing a case definition with a positive predicted value of 91.01%.[13] Second, the Patient Health Questionnaire-9 (PHQ-9) was implemented at baseline, which asked nine questions from the Diagnostic and Statistical Manual of Mental Disorders with each question scored as "0" (not at all), "1" (several days), "2" (more than half the days), and "3" (nearly every day) covering the last 2 weeks. For example, "over the last 2 weeks, how often have you felt down, depressed, or hopeless?". The reliability of this scale is high for diagnosis of depression and as a measure of depression severity.[14] We examined the PHQ-9 as a linear

outcome (higher scores representing higher depression severity) as well as representing minor (defined as $10 \geq$ PHQ-9 scores ≥ 5) and moderate depression (defined as PHQ-9 scores ≥ 10). Third, individuals were also asked if they had ever had a doctor diagnosis of major depression (Has a doctor ever told you that you had depression?).

Anxiety

Similar to depression, we linked to administrative health data to identify diagnosed anxiety after 1998. Anxiety was classified according to the World Health Organization classification method, based on the following ICD-10 codes identified at any time in participant medical records after 1998: F40.00–F40.20, F41.00–F41.10, F42.00–F43.10. The Generalized Anxiety Disorder 7-item (GAD-7) scale was implemented at study baseline, with each of the seven questions scored as "0" (not at all), "1" (several days), "2" (more than half the days), and "3" (nearly every day). For example, over the last 2 weeks, how often have you felt nervous, anxious, or on edge. The GAD-7 has a high sensitivity and specificity for cut-points representing mild, moderate, and severe levels of anxiety and increasing scores on the scale are strongly associations with functional impartment.[15] We examined the GAD-7 as a linear outcome (higher scores representing higher anxiety severity) as well as representing minor (defined as $10 \geq$ GAD-7 scores ≥ 5) and moderate (defined as GAD-7 scores ≥ 10) anxiety. It has also been demonstrated the anxiety (assessed using the GAD-7) and depression (assessed using the PHQ-9) are distinct dimensions.[15] No self-reported measure of doctor diagnosed anxiety was available.

Cognitive function measures

Cognitive function was measured using a computerized touch-screen interface at the studies clinical site. Three tests were used to assess cognitive function using reaction time, paired associates learning (working memory), and verbal and numeric reasoning (executive function).[16] Briefly, *reaction time* (two choice) was assessed by participants pressing a button with their dominant hand as quickly as possible each time a symbol was presented on-screen. The test used 60 presentations divided into eight response-stimulus-interval groups. The mean time to correctly identify matches (milliseconds) was calculated among correct answers after removing times under 50 ms due to anticipation rather than reaction and times over 2000 ms. *Paired associates learning (working memory)* was assessed using seven targets presented on-screen, and participants were asked to memorize the positions. Targets were then removed, and participants were asked to identify their locations. The number of guesses needed to correctly identify all seven locations was modeled, with scores ranged from 7 (best) to 30 (worst—guesses over 30 were assigned a value of 30). *Verbal and numeric reasoning (executive function)* was assessed with up to 12 verbal and numeric reasoning problems conducted in a 2-minute time limit. The sum of the correct answers was modeled, with scores ranged from 0 (worst) to 12 (best). These cognitive function measures have been developed and used the U.K. BioBank study,[16] which had a mean age (56 years) similar to the CARTaGENE cohort (54 years).

Green space exposure measures

Green space measures were derived from reported residential histories between 2007 and 2011, representing an approximate 5-year green space exposure period prior to study enrollment. Addresses were geocoded using six-digit postal codes, which in an urban area correspond to one side of a city block or smaller (e.g. single apartment building). Only individuals with at least 4 years of complete residential history in the 2007–2011 period

were included in analyses. When individuals moved during the exposure period the time at each residential location was used to weight exposures corresponding to the number of days living in each residence.

The primary green space exposure measure was based on satellite-derived normalized difference vegetation index (NDVI) derived from Landsat 5 30 m retrievals. A long-term green space measure was assessed using the average NDVI between 2007 and 2011 and calculated for different buffer distances (i.e. 100, 250, 500, 750, and 1000 m) around residential postal codes. All areas of water were masked from the NDVI calculation, and pixels with >20% cloud or snow cover were removed. Because the study area has substantial snow cover during the winter months, the average NDVI primarily represents nonwinter NDVI levels. Summer maximum NDVI exposure values were highly correlated with the annual average (all buffer r >0.90).

Residential change in green space

The impact of change in residential green space was assessed using residential history data. Individuals who moved during the 5-year exposure window were classified as either moving to a higher green space area (determined as a change in NDVI within 500 m between the current and previous household greater than 0.1) or moving to a similar green space area (change in NDVI within 500 m between the current and previous household between –0.1 and 0.1). The difference of 0.1 in NDVI is large and meant to capture substantial changes in residential green space levels. Here, we compare individuals who moved to a higher green space neighborhood to individuals who moved to a similar green neighborhood, with the rationale that depression and anxiety is associated with nonmovers.

Other environmental exposures

We assessed air pollution exposures for each residential postal code as air pollution is a hypothesized mediator between green space and mental health. Traffic-related air pollution was assessed using a 2006 nitrogen dioxide land use regression model.[17] Fine particulate matter air pollution was assessed using 2005–2012 satellite data fused with a chemical transport model and available ground level monitoring data.[18] Finally, ozone was assessed using the 2002–2009 Canadian and Hemispheric Regional Ozone and NO_x System data.[19] Similar to NDVI, the time at each residential location was used to weight exposures.

Statistical analyses

We used linear and logistic regression models to assess the associations between each depression, anxiety, and cognitive function variable and green space exposure measure in main analyses. All analyses were conducted with SAS 9.4 (SAS Institute, Cary, NC, USA). Penalized regression splines were also used to assess the shape of the association between outcome measures and NDVI (R Statistical Software 3.5.1, For depression and anxiety outcomes, we modeled the PHQ-9 and GAD-7 scales as a linear outcome as well as binary outcome for each of moderate and minor depression/anxiety. For self-reported doctor diagnoses and health record depression diagnoses, we modeled whether an individual had major depression or anxiety (binary outcome). Cognitive function measures (reaction time, working memory, and executive function) were modeled as linear outcomes. We report changes in outcomes for a 0.1 unit increase in NDVI, while for the residential mobility analyses, we compare individuals who moved to a higher green space neighborhood with individuals who moved to a similar green space neighborhood. We used the Global Moran's I test (ESRI ArcGIS 10.6) to examine spatial clustering of model residuals at the neighborhood level (represented by census tracts).

Detailed individual data were available from CARTaGENE baseline questionnaire data, and the following specific covariates were selected a-priori and included in adjusted models: year and month of completion of baseline questionnaire, age (continuous), sex at birth (male/female), household income (quintiles), education level (less than high school, high school, college, university, graduation studies), white/non-white, marital status (single, married, divorced, widowed), city (Montreal, Quebec, Sherbrooke, Saguenay), and population density (quartiles). We further examined mediation for variables that may lie on the causal pathway between green space and mental health using incremental models. These include physical activity (assessed using the International Physical Activity Questionnaire and estimated metabolic equivalent of tasks); social connections (assessed using questions about having persons in one life that make you feel loved, have to share worries, and provide trust advise); and air pollution exposures.

Results

A total of 8,144 study participants met the study inclusion criteria for the depression and anxiety analyses. The mean (standard deviation) NDVI level within 250 m of residential postal codes was 0.40 (0.10). The correlation between NDVI measures at 100, 250, 500, 750, and 1,000 m ranged from 0.98 (NDVI in 1000 and 750 m) to 0.75 (NDVI in 100 and 1,000 m). Figure illustrates the pattern of NDVI for the cities examined; Montreal contained 74% of the total study population.

Table 1 summarizes descriptive statistics for the 8,144 study participants by NDVI (500 m) quartiles. Differences in depression, anxiety, and cognitive function measures were observed across the NDVI quartiles as well as important sociodemographic variables. For example, 40.6% of individuals in the lowest NDVI category were in the lowest-middle income (Q1 and Q2) categories compared with 18.9% in the highest NDVI category. Individuals within the lowest NDVI quartile were also more likely to be single and non-white. As expected, NDVI was highly correlated with population density (r = –0.54 for NDVI and population density with 500 m). Important differences between measures of depression and anxiety were also observed. For example, 807 individuals (9.9%) were diagnosed with depression through medical health records, while only 569 individuals (7%) reported ever being diagnosed by a doctor for depression. The correspondence between these two measures was low, with a 36% positive predictive value and a 93% negative predictive values using the standard 2×2 table calculations.[20]

Residential NDVI levels

Table 2 summarizes unadjusted and adjusted associations between residential NDVI within 500 m of residential locations and depression, anxiety, and cognitive function (results for all NDVI buffer distances are provided in the eAppendix eTable 1; http://links.lww.com/EE/A32). Unadjusted models demonstrated statistically significant protective effects for almost all NDVI distances and depression and anxiety outcomes, but no consistent associations with cognitive function measures. In adjusted models, protective associations were observed only between NDVI (for all buffer distances) and self-reported doctor diagnosis of depression and the GAD-7 scores ≥10 (moderate anxiety). The general direction of associations for green space was protective for the different classification of anxiety and depression as well as for each cognitive function outcomes (i.e. faster reaction time and increased working memory and executive function). eAppendix eFigure 1; http://links.lww.com/EE/A32 illustrates the dose-response associations in unadjusted and adjusted spline models for NDVI (500 m), which showed the strongest associations with the linear PHQ-9 depression and
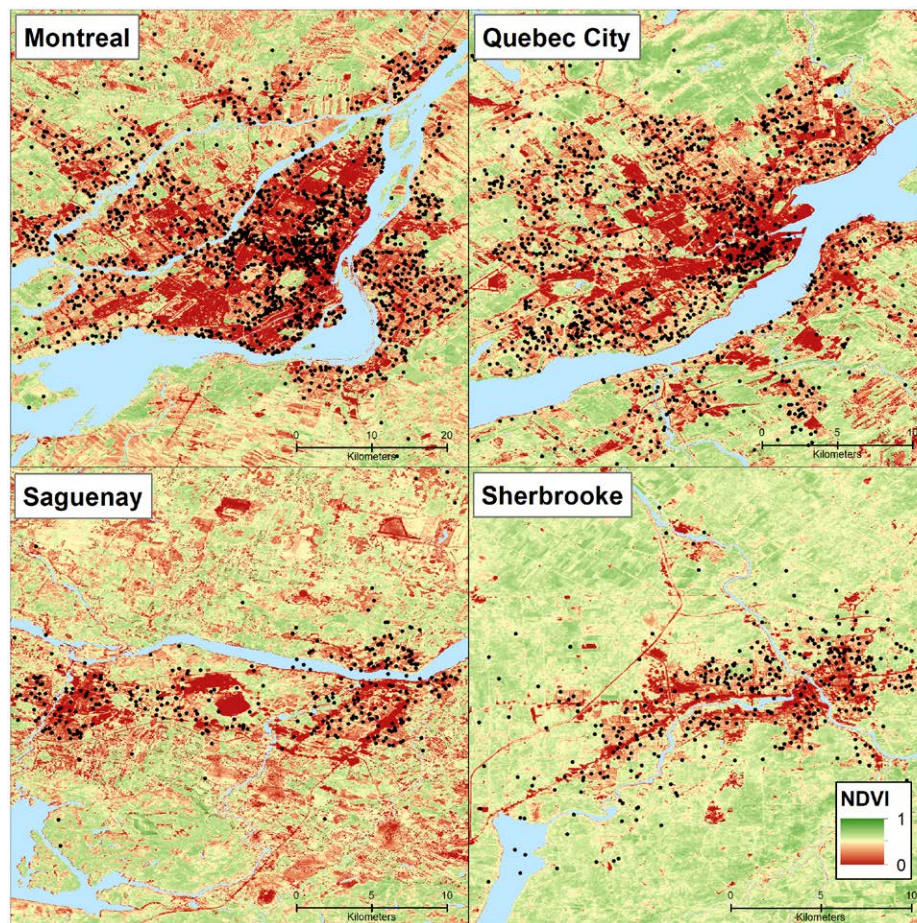
Figure. Maps of study cities with 30 m NDVI levels and general location of study participants (represented by random locations within neighborhood areas to visually represent locations).

GAD-7 anxiety scales and binary self-reported doctor diagnosis of depression. All Global Moran's I tests of model residuals were not statistically significant (*P* > 0.05), indicating no spatial clustering of our model errors.

Exploratory stratified models were conducted by individual and contextual variables (Table 3). For the PHQ-9 and GAD-7 scores, there were stronger associations observed for low-income individuals [–0.18 (0.10) and –0.25 (0.09), respectively], white individuals [–0.13 (0.05) and –0.12 (0.05), respectively], and nonmarried individuals [–0.18 (0.09) and –0.29 (0.09), respectively] and living outside Montreal [–0.13 (0.08) and –0.14 (0.08), respectively]. For self-reported doctor diagnosed depression, there were consistent results across stratifications, with slightly stronger associations observed for individuals < 50 years of age [odds ratio (OR) = 0.78 (95% CI: 0.64, 0.95)]. For depression classified from health record data, we also observed stronger but not significant associations for individuals <50, but other patterns were inconsistent with those observed for self-reported doctor diagnosis of depression. For anxiety assessed through medical records linkage, we observed strong associations for individuals who have resided in their current address for over 10 years. For cognitive function, the strongest associations with NDVI were between reasoning and individuals with high school or lower education [0.11 (0.05)], visual memory errors and females [–0.26 (0.12)], males [–4.29 (2.23), and reaction time and individuals under 50 (–7.88 (2.88)].

Change in green space with residential mobility

Model results examining changes in green space exposure due to residential mobility are summarized in Table 4. Individuals

who moved to higher green space areas compared with individuals who moved to similar green space levels had lower PHQ-9 and GAD-7 scores, as well as reduced odds of depression, but results were not statistically significant. Here, the strongest associations were observed for depression assessed through medical record linkages and not participant reported. For example, the odds of a health record depression diagnosis was 0.77 (95% CI: 0.55, 1.06) for individuals moving to greener neighborhoods compared with those moving to similar green space neighborhoods. A strong association was observed for GAD-7 scores ≥10 (moderate anxiety) with OR = 0.39 (95% CI: 0.20, 0.76), but this included a very small sample in the moving to a greener neighborhood exposure category. For cognitive function measures, there were inconsistent associations, with a decrease in reasoning and an increase in visual memory pair errors (opposite to hypothesized directions) and a decrease in reaction time.

Mediation of green space associations

We assessed pathways between residential green space and mental health and cognitive function outcomes through incremental models (eAppendix eTable 2; http://links.lww.com/EE/A32). We conducted analyses for the PHQ-9 and GAD-7 linear scores as well as self-reported doctor diagnosis of depression as these outcomes demonstrated the most robust associations with green space in our main analysis and stratified models. Overall, the inclusion of physical activity, air pollution, and social support attenuated the associations between NDVI in 500 m and PHQ-9 (by 50%), GAD-7 (by 12.5%), and self-reported doctor diagnosis of depression (by 7%). Air pollution was responsible

Table 1

Descriptive statistics by average residential green space (NDVI within 500 m) derived from 5 years of residential histories for 8,144 study participants

	Residential green space (measured by NDVI within 500 m)			
	Q1 (<0.33)	Q2 (0.33–0.41)	Q3 (0.41–0.46)	Q4 (>0.46)
Study population, n	2,031	2,176	1,828	2,109
Depression outcomes				
Health record diagnosis, n(%)	234 (11.5)	231 (10.6)	159 (8.7)	183 (8.7)
Self-reported doctor diagnosed, n (%)	192 (9.6)	161 (7.5)	105 (5.8)	111 (5.4)
PHQ-9 score, ($\bar{x}, sd$)	3.0 (3.7)	2.5 (3.2)	2.3 (3.2)	2.2 (3.0)
PHQ-9 score ≥10, n (%)	130 (6.4)	92 (4.2)	72 (3.9)	70 (3.3)
PHQ-9 scores ≥5, n (%)	467 (23.0)	402 (18.5)	309 (16.9)	339 (16.1)
Anxiety outcomes				
Health record diagnosis, n (%)	383 (18.9)	379 (17.4)	301 (16.5)	334 (15.8)
GAD-7 score, ($\bar{x}, sd$)	2.6 (3.6)	2.3 (3.2)	2.3 (3.2)	2.3 (3.2)
GAD-7 scores ≥10, n (%)	110 (5.4)	83 (3.8)	73 (4.0)	60 (2.8)
GAD-7 scores ≥5, n (%)	403 (19.8)	361 (16.6)	316 (17.3)	328 (15.6)
Cognitive function measures[a] (N)	1,764	1,494	1,797	1,603
Reasoning, ($\bar{x}, sd$)	3.53 (1.72)	3.40 (1.76)	3.37 (1.73)	3.50 (1.71)
Visual memory, ($\bar{x}, sd$)	8.86 (5.74)	9.01 (5.98)	9.30 (6.02)	9.08 (5.95)
Reaction time, ($\bar{x}, sd$)	498 (113)	509 (118)	506 (124)	511 (127)
Age, ($\bar{x}, sd$)	54.7 (7.8)	55.0 (7.6)	55.1 (7.8)	55.1 (8.0)
Female, n (%)	1,119 (55.1)	1,157 (53.7)	931 (50.9)	1,093 (51.8)
Household income, n (%)				
Q1 (lowest)	308 (15.2)	152 (7.0)	80 (4.4)	71 (3.4)
Q2	516 (25.4)	470 (21.6)	347 (19.0)	327 (15.5)
Q3	439 (21.6)	499 (22.9)	419 (22.9)	451 (21.4)
Q4	537 (26.4)	724 (33.3)	671 (36.7)	842 (39.9)
Q5 (highest)	147 (7.2)	237 (10.9)	224 (12.3)	328 (15.5)
Missing,	84 (4.2)	94 (4.3)	88 (4.9)	93 (4.4)
Educational attainment, n (%)				
Less than high school	36 (1.8)	33 (1.5)	22 (1.2)	10 (0.5)
High school	427 (21.0)	470 (21.6)	420 (23.0)	365 (17.3)
College	627 (30.9)	712 (32.7)	570 (31.2)	685 (32.4)
University	633 (31.2)	688 (31.6)	570 (31.2)	735 (34.8)
Graduate studies	306 (15.1)	265 (12.2)	244 (13.3)	307 (14.5)
Missing	2 (0.1)	8 (0.7)	3 (0.16)	10 (0.5)
White	1,644 (81.0)	1,826 (83.9)	1,539 (84.1)	1,854 (87.8)
Marital status, n (%)				
Single	502 (24.7)	244 (11.2)	139 (7.6)	129 (6.1)
Married	1,064 (52.4)	1,502 (69.0)	1,399 (76.5)	1,680 (80.0)
Divorced, separated	387 (19.1)	371 (17.1)	233 (12.7)	252 (11.9)
Widowed	74 (3.6)	50 (2.3)	56 (3.1)	43 (2.0)
Other	4 (0.2)	9 (0.4)	2 (0.1)	8 (0.4)
Change in residential NDVI (% of column), n (%)				
Did not move	1194 (58.8)	1329 (61.1)	1163 (63.6)	1333 (63.2)
Moved, similar green space	567 (27.09)	599 (27.5)	449 (24.6)	447 (21.2)
Moved, lower green space	212 (10.4)	114 (5.2)	50 (2.7)	32 (1.5)
Moved, higher green space	58 (2.9)	134 (6.2)	166 (9.1)	297 (14.1)
Population density[b], ($\bar{x}, sd$)	9,585 (7,067)	5,254 (4,805)	3,534 (2,721)	2,139 (1,754)
City, n (%)				
Montreal	1,685 (83.0)	1,723 (79.2)	1,314 (71.9)	1,312 (62.2)
Quebec	241 (11.9)	266 (12.2)	341 (18.7)	483 (22.9)
Saguenay	66 (3.3)	128 (5.9)	77 (4.2)	87 (4.1)
Sherbrooke	39 (1.9)	59 (2.7)	96 (5.3)	227 (10.8)

[a]Reasoning (0–12, higher is better executive function); visual memory (7–30, lower is better visual memory); reaction time (ms, lower is quicker reaction times).
[b]Population per square kilometer of dissemination area of residence.

for most of the attenuation in the PHQ-9 and GAD-7 models, but not for self-reported doctor diagnosis of depression.

Discussion

We examined associations between long-term urban green space exposure and different assessments of depression, anxiety, and cognitive function. We observed mixed evidence to support the hypothesis that urban green space is associated with decreased depression and anxiety, as the magnitude of association varied by exposure and health assessment method. For the three cognitive function tests examined (reasoning, visual memory, and reaction time), no consistent associations were observed with residential NDVI or moving-based exposures.

Our findings of some evidence for positive associations between green space and depression and anxiety are in line with the existing literature (see[21,22] for a review). Direct comparisons of results are difficult due to differing assessments of both green space exposure as well as depression and anxiety outcomes. A strength of our study is that we used various assessment methods to capture depression and anxiety, including self-reported ever having a doctor diagnosis of depression, the 10 years of

Table 2

Unadjusted and adjusted regression model results for residential green space in 500 meters (per 0.1 increase in NDVI) and depression, anxiety, and cognitive function outcomes

	n	Unadjusted	Adjusted
Unadjusted models			
Depression outcomes			
Health record depression diagnosis	8,144	0.90 (0.84, 0.97)	0.97 (0.88, 1.06)
Self-reported doctor diagnosed depression	8,144	0.78 (0.71, 0.85)	0.85 (0.76, 0.95)
PHQ-9 linear, β (SE)	8,144	−0.30 (0.04)	−0.06 (0.05)
≥5 (minor depression)	8,144	0.84 (0.79, 0.89)	0.96 (0.89, 1.03)
≥10 (moderate depression)	8,144	0.72 (0.65, 0.80)	0.92 (0.80, 1.06)
Anxiety outcomes			
Health record anxiety diagnosis	8,144	0.91 (0.86, 0.97)	0.97 (0.90, 1.05)
GAD-7 score, linear, β (SE)	8,144	−0.21 (0.04)	−0.08 (0.05)
GAD-7 scores ≥5 (minor anxiety)	8,144	0.88 (0.83, 0.93)	0.94 (0.88, 1.02)
GAD-7 scores ≥10 (moderate anxiety)	8,144	0.75 (0.67, 0.84)	0.81 (0.70, 0.93)
Cognitive function measures[a]			
Reasoning, β (SE)	6,658	−0.01 (0.02)	0.01 (0.03)
Visual memory, β (SE)	6,832	−0.13 (0.07)	−0.10 (0.09)
Reaction time, β (SE)	6,855	−3.86 (1.50)	−0.94 (1.78)

Adjusted: age, sex, city, year and month of baseline questions/cognitive tests, household income, education, white, marital status, population density. Model estimates reported are OR and 95% CIs for binary outcomes and β coefficients and standard errors (SE) for linear outcomes representing a 0.1 increase in mean NDVI within 500 meters.

[a]Reasoning (0–12, higher is better executive function); visual memory (7–30, lower is better visual memory); reaction time (ms, lower is quicker reaction times).

outcome assessment from linkage to medical records, and the 2-week assessment using the PHQ-9 and GAD-7 assessment scales. It is important to note the low correspondence between the different measures, which is in line with other reported associated between self-reported and electronic records agreement for depression.[20] In our study, the dissimilarity may be due to the differing time periods of assessment or reporting bias. Overall, we tended to observe larger associations with the self-reported doctor diagnosed depression outcomes and the PHQ-9 and GAD-7 outcomes compared with the health record diagnosis. These self-reported measures may be representing more acute measures of depression and anxiety or may represent a different construct of depression and anxiety more relevant to green space exposure. Self-reported measures are also more susceptible to reporting bias. Nevertheless, it is important to highlight that we observed protective associations (most not statistically significant) for all depression and anxiety outcomes for increasing green space exposures.

Most studies of green space and adult mental health have used self-reported depression, anxiety, and general health measurement scales, such as versions of the general health questionnaire[23–28] or patient health questionnaire[29] to assess mental health status, while only a small number have used linkages to health records,[30,31] which is a major strength of our study. For example, Maas et al[31] examined electronic medical records for 345,143 individuals from 96 Dutch general practices and observed ORs of 0.96 (95% CI: 0.95, 0.98) and 0.95 (95% CI: 0.94, 0.97) for depression and anxiety with a 10% increase in green land use within 1 km of residential locations. In our unadjusted model, we observed an OR of 0.92 (95% CI: 0.87, 0.98) for a 0.1 increase in NDVI within 1 km, but in fully adjusted models, this was completely attenuated. Other studies have

Table 3

Stratified analyses of adjusted models of NDVI within 500 m and depression, anxiety, and cognitive function measures

Stratification variable	Health record depression diagnosis	PHQ-9 score, linear	Self-reported doctor diagnosed depression	Health record anxiety diagnosis	PHQ-9 score, linear	Reasoning	Visual memory	Reaction time
	Depression measures			**Anxiety measures**		**Cognitive function measures[a]**		
Overall model	0.97 (0.88, 1.06)	−0.06 (0.05)	0.85 (0.76, 0.95)	0.97 (0.91, 1.06)	−0.06 (0.05)	0.01 (0.03)	−0.11 (0.09)	−0.31 (1.81)
Sex								
Male	0.97 (0.84, 1.14)	−0.02 (0.06)	0.84 (0.70, 1.00)	0.96 (0.85, 1.09)	−0.02 (0.06)	0.00 (0.04)	0.16 (0.13)	−4.29 (2.23)
Female	0.96 (0.85, 1.09)	−0.06 (0.06)	0.86 (0.75, 0.99)	0.98 (0.89, 1.08)	−0.06 (0.06)	0.04 (0.03)	−0.26 (0.12)	0.04 (2.51)
Age								
<50	0.88 (0.75, 1.03)	0.01 (0.08)	0.78 (0.64, 0.95)	0.92 (0.80, 1.05)	0.01 (0.08)	0.04 (0.05)	−0.07 (0.14)	−7.88 (2.88)
≥50	1.01 (0.90, 1.14)	−0.07 (0.05)	0.87 (0.76, 1.00)	0.99 (0.90, 1.09)	−0.07 (0.05)	0.01 (0.03)	−0.05 (0.11)	1.03 (2.16)
Household income								
Low	1.00 (0.85, 1.19)	−0.18 (0.10)	0.76 (0.64, 0.91)	0.90 (0.78, 1.03)	−0.18 (0.10)	−0.05 (0.05)	0.03 (0.18)	0.38 (3.98)
High	0.95 (0.85, 1.08)	−0.04 (0.05)	0.89 (0.77, 1.02)	1.02 (0.92, 1.12)	−0.04 (0.05)	0.04 (0.03)	−0.16 (0.11)	−2.58 (1.98)
Education								
≤ High school	0.89 (0.72, 1.10)	0.00 (0.12)	0.90 (0.71, 1.14)	0.97 (0.82, 1.14)	0.00 (0.12)	0.11 (0.05)	0.00 (0.21)	−5.03 (4.39)
> High school	0.99 (0.89, 1.10)	−0.09 (0.05)	0.83 (0.72, 0.94)	0.98 (0.89, 1.06)	−0.09 (0.05)	0.00 (0.03)	−0.15 (0.10)	0.03 (1.94)
Race								
White	0.97 (0.87, 1.07)	−0.13 (0.05)	0.88 (0.78, 0.99)	0.97 (0.89, 1.05)	−0.13 (0.05)	0.01 (0.03)	−0.09 (0.09)	−0.05 (1.85)
Non–white	0.98 (0.78, 1.23)	0.28 (0.15)	0.73 (0.57, 0.95)	1.00 (0.84, 1.21)	0.28 (0.15)	0.01 (0.06)	−0.22 (0.25)	−6.94 (5.62)
Marital status								
Married	0.99 (0.88, 1.13)	−0.00 (0.05)	0.88 (0.76, 1.03)	0.98 (0.89, 1.08)	−0.00 (0.05)	0.02 (0.03)	−0.10 (0.11)	0.63 (2.07)
Other	0.92 (0.79, 1.07)	−0.18 (0.09)	0.82 (0.70, 0.97)	0.94 (0.83, 1.07)	−0.18 (0.09)	−0.02 (0.05)	−0.11 (0.16)	−4.34 (3.46)
Years in current residence								
<10	1.02 (0.88, 1.18)	−0.10 (0.07)	0.82 (0.70, 0.97)	1.10 (0.98, 1.24)	−0.10 (0.07)	0.04 (0.04)	−0.02 (0.13)	−3.30 (2.75)
≥10	0.94 (0.82, 1.07)	−0.02 (0.06)	0.91 (0.75, 1.06)	0.89 (0.81, 0.99)	−0.02 (0.06)	0.01 (0.03)	−0.18 (0.12)	0.42 (2.38)
City								
Montreal	0.94 (0.84, 1.05)	−0.06 (0.06)	0.82 (0.72, 0.94)	0.93 (0.85, 1.02)	−0.06 (0.06)	0.04 (0.03)	−0.08 (0.11)	0.63 (2.11)
Other	1.06 (0.88, 1.28)	−0.13 (0.08)	0.87 (0.70, 1.08)	1.06 (0.92, 1.23)	−0.13 (0.08)	−0.05 (0.05)	−0.14 (0.17)	−0.97 (2.96)

Model estimates reported are OR and 95% CIs for binary outcomes and β coefficients and standard errors (SE) for linear outcomes.

[a]Reasoning (0–12, higher is better executive function); visual memory (7–30, lower is better visual memory); reaction time (ms, lower is quicker reaction times).

Table 4

Regression model results for residential moves (during a 5-year period) and resulting changes in green space (individuals who moved to higher green space compared to individuals that moved to similar green space levels) and depression, anxiety, and cognitive function measures

	N[b]	Unadjusted	Adjusted
Depression outcomes			
Health record depression diagnosis	2,717	0.75 (0.54, 1.03)	0.77 (0.55, 1.06)
Self-reported doctor diagnosis of depression	2,717	0.83 (0.58, 1.19)	0.89 (0.57, 1.34)
PHQ-9 score, linear, β (SE)	2,717	−0.37 (0.15)	−0.26 (0.15)
PHQ-9 scores ≥5 (minor depression)	2,717	0.80 (0.63, 1.01)	0.85 (0.66, 1.08)
PHQ-9 scores ≥10 (moderate depression)	2,717	0.68 (0.40, 1.15)	0.78 (0.46, 1.35)
Anxiety outcomes			
Health record anxiety diagnosis	2,717	0.98 (0.78, 1.24)	1.02 (0.80, 1.29)
GAD-7 score, linear, β (SE)	2,717	−0.30 (0.15)	−0.24 (0.14)
GAD-7 scores ≥5 (minor anxiety)	2,717	0.92 (0.72, 1.18)	0.95 (0.74, 1.22)
GAD-7 scores ≥10 (moderate anxiety)	2,717	0.37 (0.19, 0.73)	0.39 (0.20, 0.76)
Cognitive function measures[a]			
Reasoning, β (SE)	2,237	−0.20 (0.09)	−0.22 (0.08)
Visual memory, β (SE)	2,237	−0.01 (0.29)	0.06 (0.35)
Reaction time, β (SE)	2,237	−5.29 (5.93)	−1.41 (5.58)

Adjusted: Age, sex, city, year and month of baseline questions/cognitive tests, household income, education, white, marital status, population density. Model estimates reported are OR and 95% CIs for binary outcomes and β coefficients and standard errors (SE) for linear outcomes for moving to a greener area (>0.1 NDVI change) compared to moving to a similar green area.
[a]Reasoning (0–12, higher is better executive function); visual memory (7–30, lower is better visual memory); reaction time (ms, lower is quicker reaction times).
[b]N included individuals who moved to a similar green space area and those that moved to a higher green space area (NDVI increase of >0.1 from last residence).

observed inverse associations between antidepressant prescriptions and green space, with nonlinear associations.[32] We were unable to examine prescription use but also observed minor differences in the shape of the dose-response relationship between green space and mental health outcomes. This could be due to small sample sizes at very low and high NDVI levels or complex interactions with other urbanicity measures, primarily population density. We did observe associations in fully adjusted models with self-reported doctor diagnosis of major depression and for anxiety with the GAD-7 Score ≥10 (moderate anxiety). A study in Catalonia Spain[27] also examined self-reported depression and/or anxiety and observed an OR of 0.81 (95% CI: 0.75, 0.88) for an interquartile range increase in NDVI within 300 m. A large study within the U.K. Biobank also examined life-time experience of major depression and observed an OR of 0.96 (95% CI: 0.93, 0.99) for an interquartile range increase in NDVI within 500 m catchment areas around residences.

We did not observe associations between residential green space exposure and cognitive function using the tests given to the participants. Associations were generally in the hypothesized direction (increases in reasons, decreases in visual memory pair errors, and decreases in reaction time with increased green space exposures), but were very small in magnitude, varied by green space exposure metric, and did not demonstrate consistent patterns in exploratory stratified analyses. Recently, a study of three European cities examined associations between green space and cognitive function (assessed using the color trails test) and observed associations with distance to a natural outdoor environment but not with NDVI in 100, 300, and 500 m buffers.[11] Wu et al[33] also examined green space and cognitive function (assessed using the Mini-Mental State Examination) in the Cognitive Function and Ageing Study II and observed a u-shape

association between natural environment availability and cognitive impairment, with increasing risk for individuals in the highest compared with the lowest quintile of natural environment availability. They also observed varying associations by urban/rural categories, with no protective associations of natural environments in urban locations, similar to what we observed in our analyses.

Exploratory stratified models did not reveal clear differences in the associations between green space and depression, anxiety, and cognitive function. It is hypothesized that green space may be more beneficial to low socioeconomic status (SES) and minority populations,[34] but the empirical evidence for this is limited for mental health outcomes. In stratified models, we did observe stronger associations between low-income and minority individuals and the self-reported doctor diagnosis of depression and anxiety measures, but not with the diagnoses from medical record linkages. Importantly, there were marked differences in the prevalence of depression, anxiety, and cognitive function scores (as well as SES measures) across green space levels. For example, in the lowest versus the highest quartile of residential green space exposure (defined using NDVI within 250 m), 9.6% vs. 5.4% of individuals had self-reported a doctor diagnosis of major depression and 11.5% vs. 8.7% of individuals had depression assessed using health record linkages. Similar differences were observed across other depression and anxiety measures as well as the three cognitive function assessments. This presents an important environmental injustice issue in terms of the distribution of green space and mental health outcomes with urban areas.

We also examined change in green space with residential mobility to further explore potential green space associations with mental health. Comparing individuals who moved to greener neighborhoods (defined as an increase in NDVI > 0.1) with individuals who moved (but to a similar NDVI measure) showed protective associates for a range of depression and anxiety outcomes, but not for cognitive function. A study using the British Household Panel Survey examined individuals who moved and changes in repeated mental health scores over a 5-year period.[23] Compared with premove mental health scores, individuals who moved to greener areas had better mental health outcomes, as compared to individuals who moved to less green areas, who initially demonstrated worse mental health scores but later returned to baseline. In our analysis, we did not have longitudinal repeated measures nor were we able to control for why individuals chose to move to certain neighborhoods, although we did adjust for several SES factors and compared with individuals who moved but to neighborhoods with similar levels of green space.

How green space may influence mental health outcomes in unclear, and we conducted analyses to assess whether observed green space and mental health associations may be operating through physical activity, air pollution exposures, or social connections. Evaluating such pathways has been highlighted as an important research need,[34] as few studies have these types of data available to assess mediation. For depression and anxiety, we found little mediation by physical activity or social connections and moderate mediation by air pollution exposures for the PHQ-9 and GAD-7 scores, but not for participant-reported medical depression. The robustness of the green space association, particularly with self-reported doctor diagnosed depression, suggests psychological pathways (such as the stress recovery and attention restoration[35]) may be responsible for the associations observed, although we did not have measures to directly evaluate these pathways.

Limitations

Several limitations of our analyses should be highlighted. First, we used cross-sectional data and reverse causation cannot be

ruled out, especially for our moving based analyses (i.e. individuals with depression and anxiety may be less likely to move or selectively move). However, we compared movers to other movers and included a comprehensive set of SES variables. Second, we did not have access to medication use through data linkages, and our depression and anxiety classification is based off having a diagnosis of depression or anxiety in the 10-year period. Third, the cognitive function testing was designed to identify early dementia and may not be sensitive enough to measure green space related declines thus explaining our null findings, although the tests have been used in the U.K. BioBank Study,[16] which has a similar age structure to the CARTaGENE cohort. Fourth, our green space exposure measure was based on NDVI, and while this is the most common exposure measure used in the literature, it does not necessarily capture exposure, use, accessibility or quality of green space. Finally, unmeasured and residual confounding by SES cannot be ruled out, especially since we observed strong protective effects of green space on most outcomes in unadjusted analyses, highlighting a potentially important environment injustice issue. However, we controlled for many potential confounding factors and observed consistent trends across strata of potential confounding factors.

Conclusions

We observed some evidence to support the hypothesis that residential urban green space is associated with decreased depression and anxiety, although the magnitude of association varied by green space exposure and depression and anxiety assessment methods. We did not observe any evidence for an association with cognitive function in this adult population using three computerized tests of reasoning, visual memory, and reaction time.

Conflicts of interest statement

The authors declare that they have no conflicts of interest with regard to the content of this report.

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