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RESEARCH ARTICLE

Urban vegetation and well-being: A cross-sectional study in Montreal, Canada

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Abstract

1. As urbanisation continues to accelerate, urban green spaces are increasingly recognised as key elements for enhancing people's health and well-being. However, most research has used vegetation metrics that may not capture the specific associations between different types of vegetation and different mental health outcomes.
2. In this study, we investigate the cross-sectional associations between residential vegetation exposure and individual well-being in Montreal, Canada, using different vegetation and well-being measures: The proportion of grass cover, tree cover, and average NDVI value within buffers of various radii (100–1000 m) were linked to each participant's residence ($n = 1072$, aged 18 years or older), while well-being was assessed using subjective happiness, emotional well-being, and personal well-being scales. The associations were analysed using generalised additive regression models.
3. Our findings show that more vegetation was linked to enhanced well-being, although the effect sizes were relatively small. Irrespective of the buffer distance, the positive associations for grass and NDVI were more pronounced than those for trees, though these associations varied across the different well-being outcome measures. We also observed that increasing tree coverage has a stronger positive effect on the well-being of individuals who are dissatisfied with the current number of street trees.
4. *Synthesis and applications*. Everyday exposure to nearby nature is associated with better self-reported mental health, suggesting urban greening policies should focus on including more vegetation within built spaces, from individual street trees to small and large parks. Our study also highlights the importance of distinguishing between different types of vegetation (e.g. grass vs. trees) when studying the effects of vegetation on well-being or other health-related outcomes. Likewise, using different measures of well-being may provide a more nuanced and comprehensive understanding of how vegetation impacts people's well-being.

KEYWORDS

grass cover, health and well-being, mental health, NDVI, tree cover, urban green space, urban greening

1 | INTRODUCTION

With over half of the world's population living in cities and an additional two billion expected by 2030 (United Nations, 2019), urban vegetation has been widely recognised as a key urban element for ensuring residents' health and well-being (Frumkin et al., 2017). The term 'urban vegetation' encompasses various forms of greenery found within and around a city, such as street and park trees, grassy lawns, private gardens and backyards, and woodlands (Taylor & Hochuli, 2017). Exposure to vegetation has been linked to beneficial health outcomes such as improved general health (Dadvand et al., 2016) and mental health (Bratman et al., 2019; Gascon et al., 2015), better birth outcomes (Banay et al., 2017), better childhood behavioural development (Chawla, 2015), reduced chronic illness (Brown et al., 2016), reduced premature mortality (James et al., 2016), and a lower risk of cancer mortality (Demoury et al., 2017).

During the COVID-19 pandemic, access and exposure to vegetation gained even greater significance as studies reported a surge in people's use of green spaces (Derks et al., 2020; Soga et al., 2021; Venter et al., 2020) and found that contact with nature helped people to cope with lockdown measures (Mintz et al., 2021; Pouso et al., 2020; Soga et al., 2021). The benefits of exposure to nature for mental health have been studied in various contexts, ranging from window views of nature (e.g. Ulrich, 1984; Velarde et al., 2007) to urban parks (e.g. Larson et al., 2016; Wood et al., 2017) and large wilderness areas such as national parks (e.g. Li, Chen, et al., 2021; Thomsen et al., 2018). Although the mechanistic pathways behind these effects are not fully understood yet (Bratman et al., 2015; Hartig et al., 2014; Kuo, 2015; Marselle, Hartig, et al., 2021; Marselle, Lindley, et al., 2021; Shanahan et al., 2015), the Biophilia Hypothesis, Attention Restorative Theory, and Stress Reduction Theory provide the dominant theoretical frameworks explaining nature's effect on human mental health and well-being.

The Biophilia Hypothesis suggests a fundamental human need to connect with nature rooted in our evolutionary history (Wilson, 2007). This affinity, however, is shaped to a large extent by cultural factors (Barbiero & Berto, 2021). Complementary theories, such as the Attention Restoration and Stress Reduction Theories, support the stress-reducing benefits of natural environments (see (Bratman et al., 2019; Yao et al., 2021) for reviews). The Attention Restoration Theory suggests that natural environments help recover from mental fatigue by promoting feelings of 'being away' from routine activities and 'soft fascination' that attracts a person's attention without requiring any cognitive effort (Kaplan, 1995). Similarly, the Stress Reduction Theory argues that cities tend to have higher levels of arousal-increasing properties, such as complexity, intensity and movement, for instance, heavy traffic or places with many people, while nature may have a restorative influence on stress (Ulrich et al., 1991).

Mounting evidence supports these theories, showing that exposure to nature reduces both physiological and psychological stress (Bratman et al., 2019; Cox et al., 2017; Hartig et al., 2014; Yao et al., 2021). These benefits may be gained from intentionally choosing to engage with nature, for instance, by visiting a park (Larson et al., 2016; Pouso et al., 2020) or gardening (Soga et al., 2017), or even indirectly, such as viewing nature through a window (Soga et al., 2021; Ulrich, 1984; Velarde et al., 2007). The natural environment around residences is, therefore, the nature that most people will experience every day and that through all kinds of interactions, will significantly contribute to their well-being (Ekkel & de Vries, 2017; Marselle et al., 2020; Mintz et al., 2021; Pelgrims et al., 2021; Su et al., 2019).

Still, most research on associations between nature and health has estimated exposures using metrics that represent overall vegetation density (e.g. the normalised difference vegetation index, NDVI). The problem with such estimates is that different types of vegetation (e.g. grass vs. trees) may have different associations with health outcomes (e.g. Astell-Burt & Feng, 2019; Huang et al., 2020; Knobel et al., 2021; Reid et al., 2017). For example, trees offer more shade and improve thermal comfort more than grass or shrubs (Armson et al., 2012), which may encourage physical activities, such as walking, running, or cycling that are beneficial for mental health (Bedimo-Rung et al., 2005; Shanahan et al., 2016). Street trees may also have a greater impact on people's well-being, possibly because residents are more exposed to them in their daily routines (Kardan et al., 2015). Living near trees can also enhance restorative experiences by providing opportunities to enjoy nature in different ways, such as listening to birdsong, which, in turn, has stress-reducing benefits for people (Berman et al., 2008; Butler et al., 2024; Fuller et al., 2007; Nghiem et al., 2021; Ratcliffe et al., 2013).

In this study, we investigate the cross-sectional associations between neighbourhood vegetation and individual well-being in the adult population of the Montreal metropolitan area, Canada, using different well-being (subjective) measures and vegetation (objective) measures. Well-being is essential to an individual's general health and is considered a measure of societal progress (Stiglitz et al., 2009). Neighbourhood vegetation was measured as (i) the total area covered by shrubs and grasses, (ii) by tree crowns, and (iii) overall vegetation density (measured with NDVI) within buffers of various radii around each participant's residence. Mental well-being was measured using the (i) subjective happiness, (ii) emotional well-being, and (iii) personal well-being scales.

Based on the above considerations, we formulated the following research questions (RQs):

(RQ1) Is there a positive association between vegetation exposure and well-being?
(RQ2) Does the association between neighbourhood vegetation and the well-being outcomes become more pronounced with the percentage of tree cover than with the shrub and grass cover and NDVI values?
(RQ3) Are these associations stronger for the immediate residential surrounding vegetation than for distant ones?

2 | MATERIALS AND METHODS

2.1 | Study design and sampling

Individual-level data comes from the INTErventions, Research, and Action in Cities Team (INTERACT) research programme. INTERACT is a pan-Canadian collaboration of scientists, urban planners, and public health decision-makers assessing the impacts of built environment interventions on health outcomes, including well-being (Fuller et al., 2023; Kestens et al., 2019). Data collection occurred in three waves of research in four Canadian cities (Montreal, Quebec; Saskatoon, Saskatchewan; Vancouver and Victoria, British Columbia). Our study is cross-sectional and focused on the first wave of INTERACT data collection for the Montreal metropolitan area, Quebec, which occurred between June 2018 and January 2019, with participants recruited on the Island of Montreal and in neighbouring cities of Laval, Longueuil, Brossard, and Saint-Lambert. The surveys were posted online using the Polygon Research SGNA platform (www.polygon.company); they were available for self-administration in both English and French and included questions on people's physical activity, social participation, and well-being (Kestens et al., 2019). In this study, we focus our analyses on the well-being questions from INTERACT's health survey.

Recruitment methods included social media, news media, partner communications, snowball recruitment, and in-person recruitment activities (Wasfi et al., 2021). Specific efforts were made to recruit underrepresented groups, including sending personalised invitations by mail, working with community organisations, and Facebook advertising in low-income postal codes (Wasfi et al., 2021). Inclusion criteria were being at least 18 years old, being able to read and write in English or French well enough to answer an online questionnaire, living on the Island of Montreal, Laval, or the South Shore, and not planning to move out of the city within the next 2 years (Wasfi et al., 2021). In Montreal, a total of 1155 participants (aged 18 and older) completed the online health survey (completion rate: 75.4%; Fuller et al., 2023; Wasfi et al., 2021). Participants provided informed consent by ticking a box indicating that they had read the relevant information and were willing to participate in the INTERACT study. Only those who ticked the box were permitted to proceed to the health survey. Ethical approval was obtained from the ethics committee of the Centre de Recherche du Centre hospitalier de l'Université de Montréal (CÉR CHUM 16.397).

2.2 | Well-being assessment

Participants provided self-reported information on three well-being dimensions: subjective happiness, emotional well-being, and personal well-being. The Subjective Happiness Scale is a four-item measure that assesses participants' sense of overall happiness on a 7-point Likert scale (Lyubomirsky & Lepper, 1999). Item one asks respondents to what extent they identify themselves as happy or unhappy individuals (1 = not a very happy person, 7 = a very happy person), whereas item two asks them to rate their level of happiness relative to their peers. The third and fourth items describe happy and unhappy individuals and ask respondents to what extent each characterisation describes them (1 = less happy, 7 = more happy). A composite score is calculated as the mean of the four items, with the fourth item reverse-coded, and higher scores reflecting greater perceived happiness.

Emotional well-being was measured using the Mental Component Summary (MCS) scores of the Short-Form 12 Health Survey (SF-12), which is widely used to assess health outcomes in clinical practice and public health research (Ware et al., 1996). The SF-12 consists of 12 questions: six related to physical health, five to mental health, and one combining both physical and mental health dimensions. The mental health component aggregates the scores of the six mental health-related items, including questions about vitality (energy and fatigue), social functioning, role limitations due to emotional health problems, and mental health (psychological distress and psychological well-being). These items, comprising binary and Likert scale answers, are weighted and summed to create the SF-12 mental component summary (MCS-12), ranging from 0 to 100, with higher scores indicating better mental health status.

The Personal Well-being Index (PWI) (International Well-being Group, 2013) is a measure designed to assess overall life satisfaction along seven specific life domains: standard of living, personal health, achievement in life, personal relationships, personal safety, sense of community, and future security. Possible responses are given on an 11-point scale, with 0 denoting 'no satisfaction at all' and 10 indicating 'completely satisfied', and the overall personal well-being score is a sum of each domain-specific score with higher scores reflecting greater life satisfaction.

For the main analyses, values for the three well-being measures were rescaled to range from 0 to 1 to ease the interpretation of the regression coefficients. A higher score indicates higher average levels of well-being.

2.3 | Vegetation exposure assessment

We used three different measures to assess surrounding vegetation: (i) proportion covered by shrubs and grasses (in % of total area), (ii) by tree crowns (in % of total area), and (iii) overall vegetation density (NDVI values from 0 to 1). Surrounding vegetation was assessed in buffers with radii of 100, 200, 300, 400, 500, and 1000 m around the participant's residential address (see Figure 1 for an example). This choice was informed by international recommendations of public accessibility to green space, suggesting a linear distance of 300–500 m as the maximum distance one should live from a green space, defined as any place where there is a natural surface or where trees are growing (WHO, 2016). Smaller buffers were included to test the hypothesis that they might better represent the restorative influences of vegetation on mental health and well-being (Markevych et al., 2017). A final distance of 1000 m was selected based on the green space-health literature (Crouse et al., 2021; Jarvis, Gergel, et al., 2020). We limited the buffers to the land mass of the Montreal metropolitan area. Participants' residential addresses were provided in longitude–latitude pairs using the WGS84 datum.

We used a high spatial resolution (1 m) land cover map of Greater Montreal's entire territory (http://observatoire.cmm.qc.ca/) to assess the proportion of vegetation within a buffer around each participant's residence. This map was created using a combination of airborne LiDAR images and colour-infrared orthophotos taken in 2018, wherein four mutually exclusive land cover classes were determined based on the normalised difference vegetation index (NDVI) and height: low mineral (NDVI < 0.3; height < 3 m), buildings (NDVI < 0.3; height > 3 m), low vegetation (hereafter referred to as 'grass cover') (NDVI > 0.3; height < 3 m) and tree canopy (hereafter referred to as 'tree cover') (NDVI > 0.3; height > 3 m). A fifth class corresponding to water was added from ancillary data. Percentages were defined as the total area covered by tree crowns, for tree canopy cover, or shrub and grass cover, for low vegetation cover, divided by the total land area in each buffer. The data were reprojected from the original NAD83 datum to WGS84 to keep it consistent with the other data sources.

Overall vegetation density was measured as the average NDVI value within the defined buffers surrounding each participant's residence. The NDVI is a quantitative measure of vegetation density, ranging from −1 to +1, where higher values indicate more greenness. The principle underlying NDVI is that green vegetation absorbs more

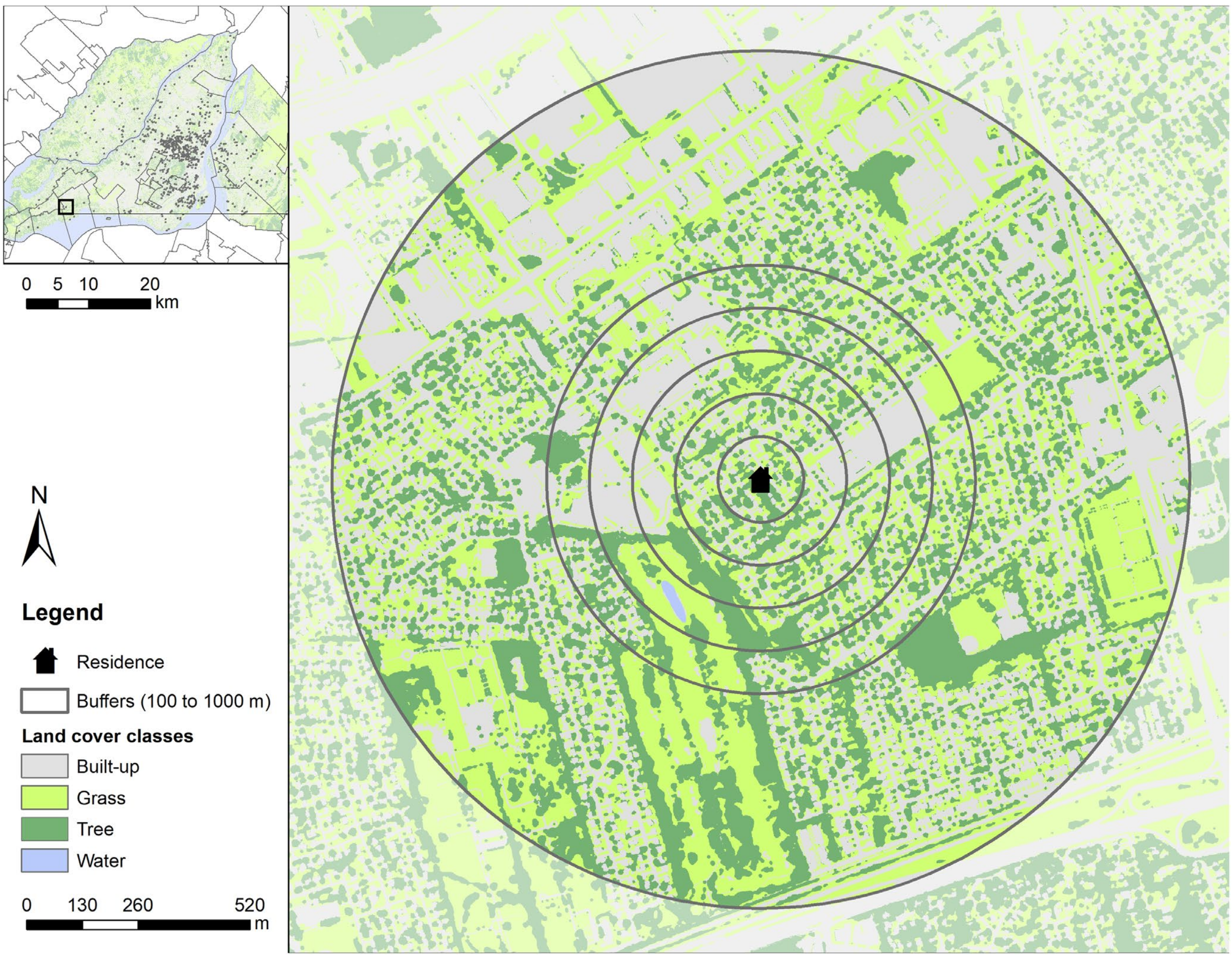

FIGURE 1 Sample residences with surrounding areas (including vegetation) and buffers of various sizes (a radius of 100, 200, 300, 400, 500, and 1000 m). Data were georeferenced and projected in WGS84.

visible light and reflects more near-infrared light than non-vegetated surfaces (Rhew et al., 2011). The NDVI was derived from Landsat images (30 m spatial resolution) for the 2015 growing season obtained from the Canadian Urban Environmental Health Research Consortium (www.canue.ca).

All spatial analyses were performed using ArcMap software (ArcGIS 10.7.1). All the input data were reprojected from their corresponding coordinate system to the WGS84 coordinate reference system.

2.4 | Covariates

To account for sociodemographic confounders, we selected a parsimonious set of variables that could confound or modify the associations between surrounding vegetation and mental health outcomes based on the literature (Markevych et al., 2017; van den Berg et al., 2015). We controlled for participants' age, gender, education, self-rated health, sense of community belonging, and perceived income adequacy, which were provided from the INTERACT's health survey. We also accounted for potential spatial dependencies in the analysis using a Gaussian process based on the geographic location of the participants' residential addresses, as detailed in Section 2.5.

Self-rated general health was assessed using the first question of the SF-12 health survey. Perceived income adequacy was assessed by asking: 'To what extent does your annual household income allow you to satisfy your household's needs?' with responses on a four-point scale ranging from 'very well' to 'not at all' (scale: high = 1, low = 4). We chose this subjective measure as subjective perceptions have been suggested to be a stronger predictor of mental health than objective financial circumstances (Asebedo & Wilmarth, 2017). Sense of belonging to the community was assessed by asking: 'How would you describe your sense of belonging to your local community?', with responses on a four-point scale ranging from 'very strong' to 'very weak' (scale: high = 1, low = 4). We also considered participants' satisfaction with street trees (taken from responses to the question, 'To what extent do you agree or disagree with the statement: In my neighbourhood, there are enough trees along the street.'). Responses were given on a 4-point scale (1 = completely agree, 4 = completely disagree) and were categorised as 'satisfied' (1 for responses 1 and 2) or 'dissatisfied' (0 for responses 3 and 4).

2.5 | Data analysis

Associations between the vegetation indicators and the well-being metrics were tested using generalised additive regression models (GAMs), including as predictors age, gender, education, self-rated health, sense of community belonging, perceived income adequacy, and geographic location. We fitted a separate regression model for each well-being measure (subjective happiness, emotional well-being, personal well-being), each vegetation measure (grass cover, tree cover, NDVI), and buffer distance (100, 200, 300, 400, 500, 1000 m), resulting in 36 models. In exploratory analysis, we also fitted models with the grass and tree cover predictors together, but the results were similar and were not reported. For the 100-m buffer, we also explored with stratified analyses interactions between the tree cover metric and participants' satisfaction with street trees to evaluate the potential effect modification of vegetation by satisfaction.

GAMs are a general class of models that allow for parametric and non-parametric forms of relationship between continuous and categorical exposure variables and non-normally distributed outcomes. For the current setting, we have an exposure variable (vegetation) and an outcome (well-being) bounded between 0 and 1. Outcomes are represented as beta-distributed random variables, employing the *logit* as a link function between the mean and the linear predictor. After ensuring convergence, we validated the models by inspecting residual graphics based on quantile residuals (Dunn & Smyth, 1996). The final models did not show any problematic residual patterns. See Supporting Informations S1 and S2 for the list of models used in this study and their goodness-of-fit, including adjusted R-squared and proportion of deviance explained.

GAMs also allow for non-linear relationships between the response variable and multiple explanatory variables. In sensitivity analyses, we replaced the linear effect of the vegetation variable (grass cover, tree cover, NDVI) with a smooth thin-plate regression spline to assess the potential non-linearity of the associations. Based on the AIC scores and the inspection of residuals of these non-parametric models with smoothing splines (not shown), smoothing splines did not improve the models. Therefore, we included only linear effects in the final models.

To account for potential spatial dependencies in the response, the models also include a Gaussian process based on the geographic location of the participants' residential addresses. We followed the recommendations by Kammann and Wand (2003) and chose a Matérn covariance function with smoothness 1.5 for the Gaussian process. We also applied the double penalty approach of Marra and Wood (2011), which allows us to shrink the effect of location to zero if it is irrelevant. This approach properly accounts for all covariate effects, ensuring that any spatially structured variability that may influence the response variable is captured (Kammann & Wand, 2003; Rasmussen, 2004).

Regression results are reported as adjusted odds ratio (OR) and corresponding 95% confidence intervals (CI) expressing the change in odds for the well-being outcome variables for an interquartile range (IQR) increase in surrounding vegetation exposure. Although our outcome variables were treated as continuous variables (but not proportions), we can still interpret the regression parameters of the beta regression models as odds ratios due to the use of the *logit* link function (Ferrari & Cribari-Neto, 2004). We additionally computed the marginal effects at the mean for the model with an interaction between tree cover and participants' satisfaction with street trees. These marginal effects at the mean allow us to plot how the relationship between the predictor of interest (tree cover) and the outcome variable (well-being) changes as the value of a moderator variable (perceived tree cover) changes while holding all other predictors constant at their means (Arel-Bundock, 2024).

Finally, the statistical tools of regression diagnostics for verification of residual analysis, detection of influential cases, and check of multicollinearity were applied to discover any model or data problems (none found). Visual inspection of the residual plots (such as the Q-Q plot and residuals versus predicted response) did not indicate meaningful deviations from the theoretical expectations. The variance inflation factor was <4 for all covariates, indicating no severe or even moderate multicollinearity between the explanatory variables in any of our models.

All statistical analyses were performed in R v.4.1.1 (R Core Team, 2021) using RStudio; the R packages used were: *dplyr* v.1.1.4 (Wickham, François, et al., 2023), *tidyverse* v.2.0.0 (Wickham et al., 2019), *scales* v.1.3.0 (Wickham, Pedersen, & Seidel, 2023), *mgcv* v.1.9-1 (Wood, 2011), *mgcv.helper* v.0.1.9 (Clifford, 2024), *mgcViz* v.0.1.11 (Fasiolo et al., 2020), *DHARMa* v.0.4.6 (Hartig, 2022), *marginaleffects* v.0.20.1 (Arel-Bundock, 2024), and *ggplot2* v.3.5.1 (Wickham, 2016).

3 | RESULTS

3.1 | Study population characteristics

The INTERACT study in Montreal included 1155 participants at baseline (2018). Of these participants, we excluded 83 who did not provide answers to all the questions used in this analysis. A total of 1072 participants (92.8%) were included in the analysis. Participants' characteristics are shown in Table 1. The majority of participants were women, White, and university-educated. Participants scored on average 0.72 (SD=0.20) on subjective happiness, 0.47 (SD=0.11) on emotional well-being, and 0.74 (SD=0.15) on personal well-being (values for each variable were rescaled to range between 0 and 1), reflecting an overall sense of well-being across the full sample. The median vegetation exposures within 100 m of residence to grass cover, tree cover, and total vegetation cover (trees and grass combined) were 15.3% (8.1–20.8), 22.2% (15.2–27.9), and 37.5% (27.2–46.8), respectively (Table 1). The proportions of vegetation exposures were very similar across the different buffer sizes (Table S2).

3.2 | Associations between vegetation exposure and well-being

We observed that higher vegetation exposures (grass, trees, NDVI) were all associated with higher levels of self-reported well-being in our study population across all buffer radii (Figure 2). The measures of association are generally small, ranging from an OR of 0.99 (no effect on the outcome) to 1.10 (10% increase in the outcome measure) per IQR increase (Table 2). The associations were consistent across buffer sizes, as indicated by the similar trends and magnitudes in odds ratios, but did differ depending on which measure of vegetation and well-being was used: we found that associations with tree cover were always smaller than those with grass cover and NDVI.

The strongest association between vegetation exposure and well-being was found for overall vegetation cover (measured with the NDVI) on subjective happiness at the 100-m buffer, where an IQR increase in the NDVI (0.08) was associated with a 10% increase in the odds of reporting a high level of happiness (95% CI: 1.01–1.19; Table 2). Similarly, an IQR increase in grass cover was associated with a 9%–10% increase in the odds of reporting high happiness across all buffers (Table 2). This association between vegetation and subjective happiness also presented the largest variability (wider confidence intervals) across exposures and buffer radii (Figure 2). For emotional well-being, we observed a statistically significant positive association with grass exposure (OR: range from 1.05 to 1.06, 95% CI: range from 1.02–1.08 to 1.03–1.10; Table 2) and with NDVI exposure (OR: range from 1.04 to 1.05, 95% CI: range from 1.01–1.08 to 1.01–1.09; Table 2) for all buffer radii. Specifically, an IQR increment in grass cover (ranging from 12.7% at 100 m to 10.5% at 1000 m; Table S2) was associated with a 5%–6% increase in the odds of reporting high emotional well-being in our study population. The associations between vegetation exposure and personal well-being were also positive across all radii buffers, albeit not statistically significant, except for a borderline association with NDVI at a buffer distance of 1000 m (OR: 1.06, 95% CI: 1.01–1.13; Table 2).

Further analysis examining the influence on well-being outcomes of the interaction between the percentage of tree cover in the 100-m radius buffer and the satisfaction with the number of street trees revealed that, among those participants who were dissatisfied, increases in tree canopy cover were associated with higher odds of reporting better well-being (Figure 3). Although the confidence intervals are wider at higher tree cover percentages, the overall positive trend is clear. For those already satisfied with the number of street trees, additional tree cover led to smaller relative gains in well-being, starting from a higher baseline.

4 | DISCUSSION

4.1 | Key findings

Rapid urbanisation and the potential for future pandemics require a better understanding of the benefits of urban vegetation for mental health and well-being. This understanding can help decision-makers make better-informed public health decisions. From our study, which investigates the associations between different types of vegetation and individual well-being (subjective happiness, emotional well-being, and personal well-being), three major insights can be drawn: (i) higher vegetation exposure is associated with higher levels of well-being in our study population; (ii) the association between vegetation and

TABLE 1 Characteristics of the study population ($n = 1072$).

Characteristic	*n* (%)	Mean (SD)	Median (25th–75th)
Demographics			
Age (years)		45 (15)	43 (33–58)
Gender			
Women	733 (68.4)		
Men	338 (31.5)		
Genderqueer/gender non-conforming	1 (0.1)		
Racial groups			
White	986 (92.0)		
Arab	10 (0.9)		
Asian	51 (4.8)		
Black	10 (0.9)		
Latin American	25 (2.3)		
Indigenous	6 (0.6)		
Racial group not included above	26 (2.4)		
Prefer not to answer	12 (1.1)		
Level of education			
Primary/secondary schooling	40 (3.7)		
Vocational/technical schooling	159 (14.8)		
University degree	873 (81.4)		
Annual household income			
$0–$19,999	68 (6.3)		
$20,000–$49,999	205 (19.1)		
$50,000–$99,999	359 (33.5)		
$100,000–$200,000	295 (27.5)		
$200,000 and greater	68 (6.3)		
Prefer not to answer	77 (7.3)		
Perceived income adequacy			
Very well	392 (36.6)		
Well	528 (49.3)		
Not so well	129 (12.0)		
Not at all	23 (2.1)		
Perceived general health			
Excellent	186 (17.4)		
Very good	466 (43.5)		
Good	326 (30.4)		
Fair	77 (7.2)		
Poor	17 (1.6)		
Vegetation exposure, in the 100 m buffer			
Grass cover (%)		15.3 (9.6)	12.3 (8.1–20.8)
Tree cover (%)		22.2 (10.5)	20.9 (15.2–27.9)
NDVI (range 0–1)		0.18 (0.06)	0.18 (0.14–0.22)

Note: Percentages may not add up to 100% due to rounding. Participants were able to report multiple ethnic identities, therefore, the sum of ethnicities exceeds 100%, as each ethnic group represents people who identify alone or in combination with another ethnicity.

well-being is more pronounced for grass coverage and NDVI exposure values than tree coverage; and (iii) the strength of these associations remains relatively consistent across different buffer sizes representing the vegetation exposure around participants' homes, though it varies between the different well-being outcome measures. Additionally, we found that at the 100-m buffer, increasing tree coverage had a stronger

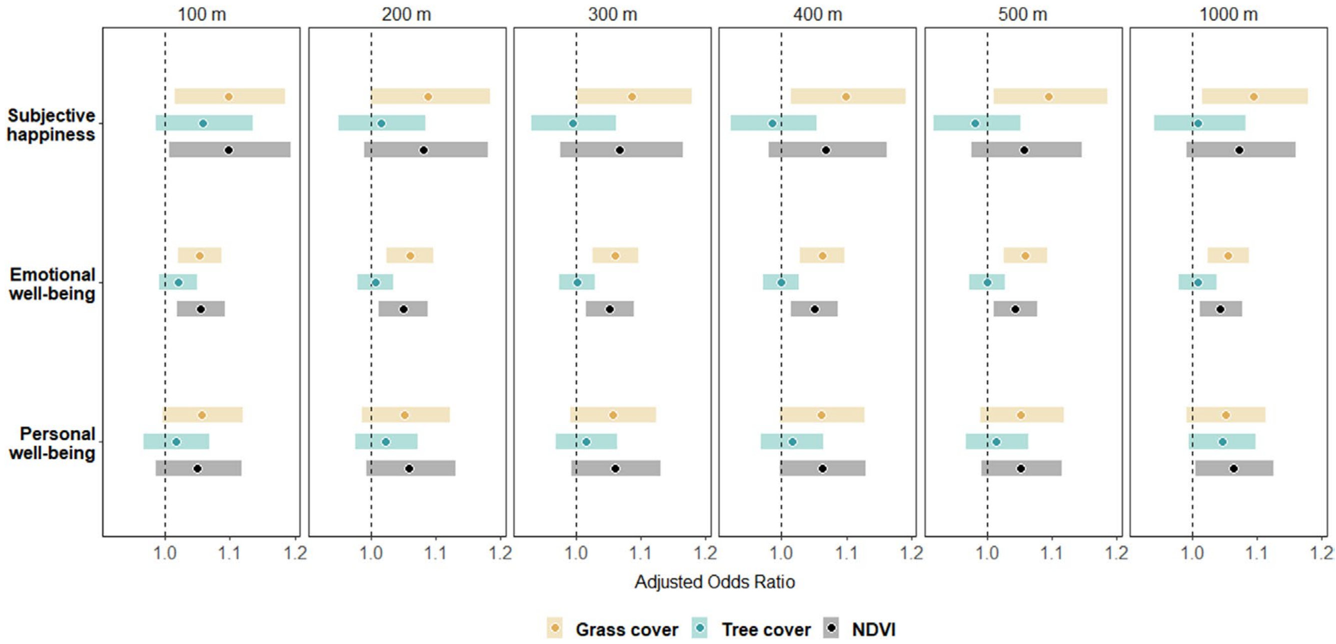

FIGURE 2 Odds ratios (and 95% confidence interval) per one interquartile range increase in vegetation levels for associations between subjective happiness, emotional well-being, and personal well-being and residential surrounding vegetation. Dots represent adjusted odds ratios and error bars, 95% confidence intervals. Exposure values were calculated as the proportion (in % of total area) covered by shrubs and grass ('grass cover'), tree crowns ('tree cover'), and the average NDVI value inside radii of 100, 200, 300, 400, 500 and 1000-m buffers around residential addresses in Greater Montreal (n = 1072). Models were adjusted for age, gender, education, self-rated health, perceived income adequacy, sense of community belonging, and spatial dependencies based on geographic location. For exact values, see Table 2.

positive association with well-being among individuals dissatisfied with the number of street trees than those who were satisfied.

4.2 | Comparisons with other studies

Our study joins a growing body of literature investigating the heterogeneity of associations between vegetation and well-being across different measures of vegetation and well-being and buffer sizes. Associations between more green cover and improved self-reported health, including better well-being, have been widely observed (e.g. Astell-Burt & Feng, 2019; Cottagiri et al., 2022; Liu et al., 2019; Lõhmus et al., 2021; Reyes-Riveros et al., 2021; Wood et al., 2017). Despite this, many studies still focus on exposures using indices such as NDVI that fail to discern different types of vegetation (e.g. grass vs. trees). Furthermore, the different ways exposure to vegetation has been conceptualised and measured, as well as the diversity of health outcome measures used to investigate impacts on well-being, make comparisons across studies difficult.

Overall, epidemiological studies suggest that vegetation exposure may have positive impacts on well-being (see for reviews, Bowler et al., 2010; Gascon et al., 2015; Houlden et al., 2018; Li, Menotti, et al., 2021; Yang et al., 2021). For instance, recent research investigating associations between residential vegetation and self-rated measures of mental health among participants in two different longitudinal surveys in Canada (the Canadian Community Health Survey and the Canadian Longitudinal Study of Aging), using the NDVI at a buffer distance of 500 m to characterise participants' exposure to vegetation, found that increases in surrounding vegetation were associated with improved perceptions of mental health: Crouse et al. (2021) reported 6% lower odds of poor self-rated mental health per increase in the IQR of NDVI (0.12; 500 m buffer), and Cottagiri et al. (2022) observed a 5% reduction in the prevalence of self-reported depression and a 7% reduction in the odds of having a 'fair/poor' perception of mental health rather than an 'excellent' perception per increase in the IQR of NDVI (0.06; 500 m buffer). Our odds ratios were of similar magnitude when restricting our analysis to NDVI at a 500 m buffer (ORs in the range of 1.04–1.05 for an IQR increase of 0.07).

Our findings align with previous studies on vegetation exposure and well-being (e.g. Ambrey, 2016a; Luck et al., 2011; Mavoa et al., 2019; Soga et al., 2021; Taylor et al., 2018), although the strength of these associations varies between studies. For instance, Luck et al. (2011) reported that the odds of recording a higher level of personal well-being increased by 55% with higher neighbourhood vegetation. In contrast, Soga et al. (2021) found that neighbourhood vegetation cover (NDVI) had no significant relationship with any of the reported mental health metrics, including subjective happiness—although the authors did find a positive association between the existence of green window views from home and improved mental health.

TABLE 2 Odds ratios (OR) and 95% confidence interval (CI) per one interquartile range increase in vegetation levels for associations between subjective happiness, emotional well-being, and personal well-being and residential surrounding vegetation.

		Buffer distance (m) from residential address centroid											
		100		200		300		400		500		1000	
	Exposure	OR (95% CI)	*p*-value	OR (95% CI)	*p*-value	OR (95% CI)	*p*-value	OR (95% CI)	*p*-value	OR (95% CI)	*p*-value	OR (95% CI)	*p*-value
Subjective happiness	Grass	1.10 (1.01, 1.18)	**0.02**	1.09 (1.00, 1.18)	**0.05**	1.09 (1.00, 1.18)	**0.05**	1.10 (1.01, 1.19)	**0.02**	1.09 (1.01, 1.19)	**0.03**	1.09 (1.02, 1.18)	**0.02**
	Trees	1.06 (0.99, 1.14)	0.12	1.02 (0.95, 1.08)	0.65	0.99 (0.93, 1.06)	0.89	0.99 (0.92, 1.06)	0.70	0.98 (0.92, 1.05)	0.62	1.01 (0.94, 1.08)	0.81
	NDVI	1.10 (1.01, 1.19)	**0.03**	1.08 (0.99, 1.18)	0.08	1.07 (0.98, 1.17)	0.15	1.07 (0.98, 1.16)	0.13	1.06 (0.98, 1.15)	0.17	1.07 (0.99, 1.16)	0.08
Emotional well-being	Grass	1.05 (1.02, 1.09)	**0.00**	1.06 (1.02, 1.10)	**0.00**	1.06 (1.03, 1.10)	**0.00**	1.06 (1.03, 1.10)	**0.00**	1.06 (1.03, 1.09)	**0.00**	1.06 (1.02, 1.09)	**0.00**
	Trees	1.02 (0.99, 1.05)	0.18	1.01 (0.98, 1.03)	0.61	1.00 (0.98, 1.03)	0.92	1.00 (0.97, 1.03)	0.99	1.00 (0.97, 1.03)	0.99	1.01 (0.98, 1.04)	0.57
	NDVI	1.05 (1.02, 1.09)	**0.00**	1.05 (1.01, 1.09)	**0.01**	1.05 (1.01, 1.09)	**0.01**	1.05 (1.01, 1.09)	**0.01**	1.04 (1.01, 1.08)	**0.01**	1.04 (1.01, 1.08)	**0.01**
Personal well-being	Grass	1.06 (1.00, 1.12)	0.06	1.05 (0.99, 1.12)	0.12	1.06 (0.99, 1.12)	0.09	1.06 (1.00, 1.13)	0.06	1.05 (0.99, 1.12)	0.10	1.05 (0.99, 1.11)	0.09
	Trees	1.02 (0.97, 1.07)	0.53	1.02 (0.98, 1.07)	0.33	1.02 (0.97, 1.06)	0.51	1.02 (0.97, 1.07)	0.53	1.02 (0.97, 1.07)	0.55	1.05 (1.00, 1.10)	0.08
	NDVI	1.05 (0.99, 1.12)	0.14	1.06 (0.99, 1.13)	0.08	1.06 (0.99, 1.13)	0.08	1.06 (1.00, 1.13)	0.06	1.05 (0.99, 1.12)	0.09	1.06 (1.01, 1.13)	**0.03**

Note: Exposure values were calculated as the proportion (in % of total area) covered by shrubs and grass ('grass'), tree crowns ('trees'), and the average NDVI value inside radii of 100, 200, 300, 400, 500 and 1000-m buffers around residential addresses in Greater Montreal. Models were adjusted for age, gender, education, self-rated health, perceived income adequacy, sense of community belonging, and spatial dependencies based on geographic location. All models were fitted using 1072 observations and a beta regression distribution with a logit link function. *p*-values < 0.05 are shown in bold.

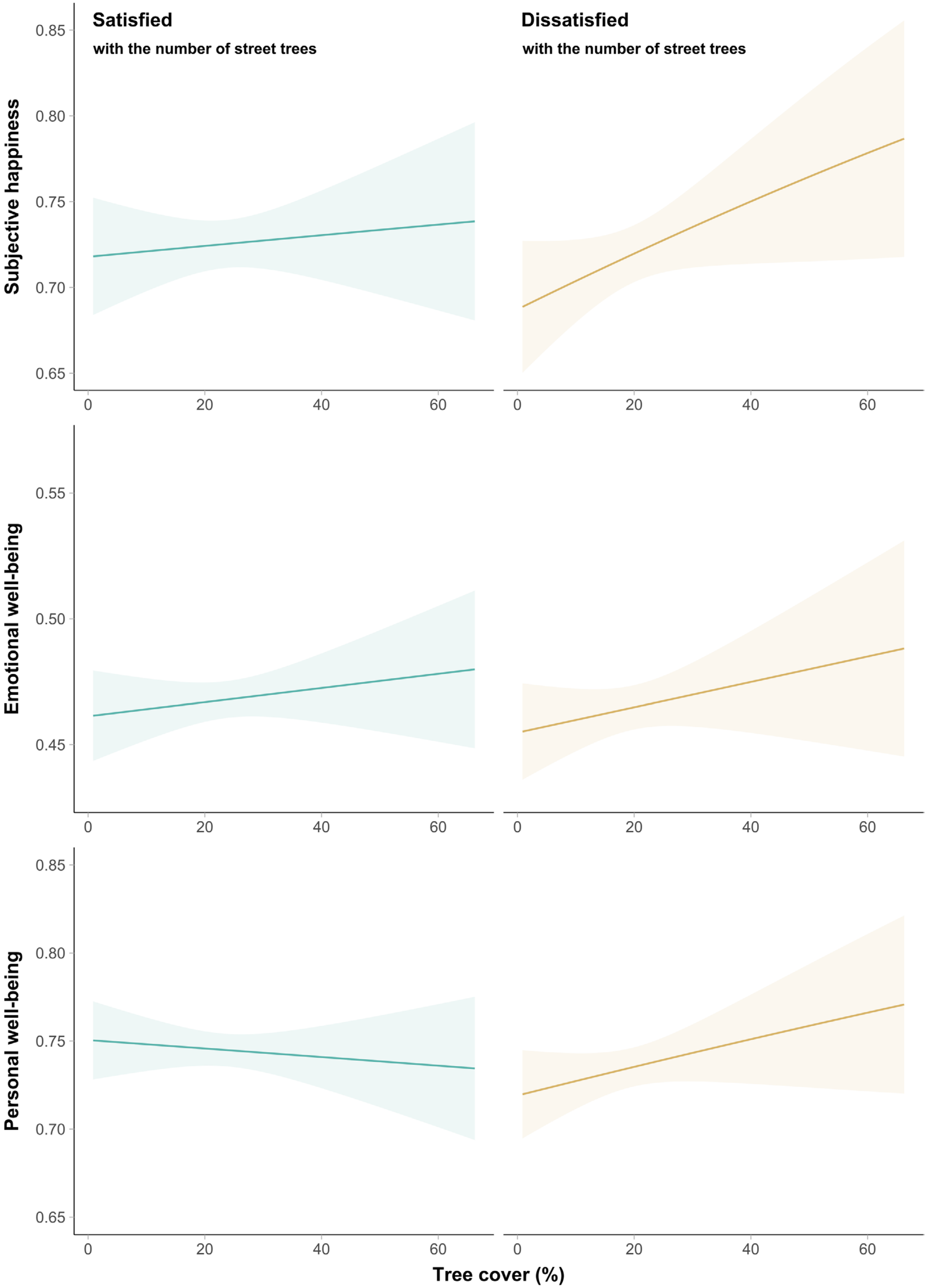
Satisfied
with the number of street trees
Dissatisfied
with the number of street trees
Subjective happiness
Emotional well-being
Personal well-being
Tree cover (%)
0.85
0.80
0.75
0.70
0.65
0.55
0.50
0.45
0
20
40
60

FIGURE 3 Marginal effects at the mean of models examining the association between well-being outcomes (subjective happiness, emotional well-being, personal well-being) and the tree coverage in the 100-m radius buffer testing the interaction between tree cover and satisfaction with the number of street trees. Solid lines indicate the adjusted predictions, and dashed areas indicate 95% confidence intervals. Models were adjusted for age, gender, education, self-rated health, perceived income adequacy, sense of community belonging and spatial dependencies based on geographic location.

4.2.1 | Well-being measures and vegetation exposure

One strength of our study is the use of several well-being measures. Subjective happiness, emotional well-being, and personal well-being are related but distinct constructs that capture different aspects of an individual's psychological state. Subjective happiness centres on overall life satisfaction, emotional well-being on the experience of emotions, and personal well-being on multiple aspects of life satisfaction and fulfilment. Since subjective happiness reflects a person's overall assessment of their life satisfaction rather than their moment-to-moment emotional experiences (as in the emotional well-being scale) or specific aspects of their life (as in the personal well-being scale), this broader perspective may make it more sensitive to the everyday presence of vegetation closer to one's home, including the presence of trees or the greenness of vegetation (NDVI). Despite these differences, we found consistent positive associations between higher vegetation exposure and improved well-being outcomes regardless of the well-being measure used and the size of the buffers. These findings also align with previous reviews on green space and mental health (e.g. Beute et al., 2023; Gascon et al., 2015; Houlden et al., 2018). Interestingly, we identified positive associations between emotional well-being and both grass cover and NDVI across all buffer radii, suggesting that emotional well-being may be more influenced by the presence of grassy areas through opportunities for social interaction and physical activity (Liu et al., 2017; Maas et al., 2009).

4.2.2 | Influence of different types of vegetation exposure on well-being

We observed that associations between vegetation and well-being were stronger for grass than for tree cover. While others have also found grass to be associated with better mental health—for instance, Huang et al. (2020) reported that grassy environments were more strongly related to psychological well-being than tree and concrete environments, and Tsai et al. (2018) and Jarvis, Koehoorn, et al. (2020) found that exposure to shrubs and grasslands reduced the odds of poor mental health and common mental disorders—more studies have reported that trees matter more for mental health than the mere presence of grass (e.g. Astell-Burt & Feng, 2019; Beyer et al., 2014; Kardan et al., 2015; Reid et al., 2017).

To some extent, the explanation for these differences may lie in the characteristics of the populations studied. Despite adjusting for socioeconomic confounders, the benefits of vegetation for mental health may still be influenced by contextual factors at the individual, community, or city levels. For instance, our sample included more women (almost 70%), and previous research suggested that open grassy areas, such as parks, may be more attractive for social interaction (Maas et al., 2009), which is one possible mechanism behind the relationship between urban vegetation and health, and that women are more likely to visit green spaces to socialise than men (Peschardt et al., 2012). Open grassy areas may also be more attractive for walking and biking, as well as for different outdoor activities, including playing with a child or pet and recreational sports, which are important forms of social and physical recreation for adults (Liu et al., 2017). Further, the realisation of the well-being benefits associated with the use of green spaces may be contingent on individual and social environmental conditions, such as fear of crime in the neighbourhood (Ambrey, 2016b; Sreetheran & van den Bosch, 2014). Dense vegetation, including shrubs and trees, is often linked to concerns about crime, as it may provide hiding places for perpetrators (Sreetheran & van den Bosch, 2014; Wolfe & Mennis, 2012). However, given that Montreal is generally considered a safe city with low crime rates (Statistics Canada, 2019), fear of crime may not play a significant role in our study.

Another possible mechanism is the restorative benefits of exposure to nature. Attention Restoration Theory holds that environments that encourage effortless attention or 'soft fascination' and a sense of 'being away' are more likely to restore mental fatigue (Kaplan, 1995). Grassy areas may better fulfil these criteria by providing open, unobstructed views, which may be more conducive to soft fascination compared with denser, more enclosed tree-covered areas. This is consistent with results from previous studies that found environments with grass had a higher likelihood of restoration than those with trees (Huang et al., 2020; Nordh & Østby, 2013).

4.2.3 | The effect of closer versus farther-away vegetation on well-being

In our analysis, the associations between vegetation exposure and well-being were consistent across buffer distances (100–1000 m), contradicting our expectation that vegetation in one's immediate surroundings might have a greater impact. Instead, we observed a consistent, although relatively small, positive association across the six buffer sizes. In the literature, different findings by buffer size have been reported. For example, some found the benefits of vegetation peak at small buffer sizes (100 m; Su et al., 2019), while others found significant benefits within further distances from one's home (e.g. between 1000 m (White et al., 2021) and 3000 m (van den Berg et al., 2010)). These differences may reflect different mechanisms:

smaller buffers may better represent the restoring capacities of natural environments (e.g. attention restoration and physiological stress recovery), while larger buffers may better represent opportunities for building capacities (e.g. via physical activity and social engagement) (Hartig et al., 2014; Jarvis, Koehoorn, et al., 2020; Markevych et al., 2017). For instance, nature close to the home might increase opportunities to experience nature throughout the day, such as when viewing trees through a window or watching and listening to birds in a domestic garden (Soga & Gaston, 2020), which in turn might improve people's mental health as listening to birdsongs has been shown to contribute towards attention restoration and stress recovery (Cox et al., 2017; Ratcliffe et al., 2013). On the other hand, larger buffers may better represent overall activity spaces where people actually spend more time (Reid et al., 2017), but we did not have data to test this assumption.

Finally, the influence of vegetation exposure on well-being may also be mediated by perceptions of the surrounding environment. Our results suggest that for participants dissatisfied with the number of street trees in their neighbourhood, increasing tree cover is associated with improvements in subjective happiness, emotional well-being, and personal well-being. However, for those already satisfied, additional tree cover does not substantially change their well-being, possibly because their baseline satisfaction is already high. This suggests that individuals who are dissatisfied might experience unmet needs for greenery (Stoltz & Grahn, 2021; Wilson, 2007). Increasing tree cover directly addresses this deficit, and their well-being improves as these needs are met, while satisfied individuals, starting from a higher baseline of well-being, experience smaller relative gains from the same increase in tree cover. This aligns with the findings of Sugiyama et al. (2008), who found that adults perceiving their neighbourhood as highly green had higher odds of better mental health. The importance of how people perceive their surrounding environment should thus not be underestimated.

4.3 | Limitations and avenues for future research

Some limitations should be considered when interpreting our findings. First, our sample was not representative of the Montreal metropolitan area's general population; it reflects the experiences of white, well-educated individuals who do not face the same structural barriers as equity-deserving populations like racialised people, Indigenous people, and people with low income. Second, self-selection bias may have occurred, with healthier individuals living in greener areas more likely to participate. Moreover, individuals (who are able) can choose to move to the neighbourhoods they perceive as more liveable, aligning with Tiebout's (1956) 'vote with their feet' model. However, our study did not ask direct questions about vegetation exposure, reducing the risk of bias due to participants' interest in green space.

Furthermore, we accounted for multiple contextual factors (e.g. self-rated health, income needs, sense of community belonging, geographic location), which could have confounded or modified the effects of vegetation on well-being. We also made significant efforts during the recruitment process to reach a greater diversity of participants, including working with community partners to reach priority populations and targeting underrepresented or low-income neighbourhoods in social media campaigns (Wasfi et al., 2021). Still, our study population was drawn from a specific geographic area, and our findings may not necessarily generalise to other populations with different sociodemographic and environmental contexts. We could also not determine how much vegetation was part of the participants' private properties, such as spaces for gardening or relaxing, which may have played a role in well-being (de Bell et al., 2020; Krols et al., 2022).

Future research could explore how frequent or how long exposures to nature need to be and what types of nature are needed using longitudinal studies with tracking technologies (Heikinheimo et al., 2020) or studies of brain activity and function during exposure to nature (Bratman et al., 2015). Future studies may also focus on the potential synergistic benefits of greenspace and physical activity on well-being (Ambrey, 2016b), which we did not have data to explore, by accounting whether the activity took place in a green space.

Another potential limitation is that we used straight-line distances to measure vegetation exposure. While buffer distances are commonly used to assess exposures, particularly exposures that require contact, such as nature views from a window or trees along the roads near their home (Markevych et al., 2017), future studies could consider exploring a combination of approaches, including network distances that account for actual travel paths and would offer a more accurate measure of accessibility (Wolff, 2021).

4.4 | Broader implications

This study aimed to assess the associations between vegetation exposure and well-being outcomes. Including various objective vegetation measures is a particularly important contribution to the literature exploring how different types of vegetation—specifically trees and grass—and distances impact mental health (e.g. Astell-Burt & Feng, 2019; Beute et al., 2023; Jarvis, Koehoorn, et al., 2020; Nishigaki et al., 2020; Reid et al., 2017; Su et al., 2019). Our results highlight the importance of distinguishing between vegetation types (e.g. grass and trees) when studying their well-being benefits. Furthermore, we found that NDVI may not reflect the nuanced effects of different vegetation types on well-being, as evidenced by the similar estimates of association for NDVI and grass cover but somewhat different for tree cover. This is an example of the information that could be leveraged when quantifying vegetation separately versus grouped together (as with NDVI), and such results are important for urban greening policies and practice interventions for better health outcomes (Martinez & Labib, 2023; Wheeler et al., 2015).

In our study, nature near home contributed to higher levels of well-being, supporting other studies in which daily contact with nearby nature has been shown to be beneficial for mental health and well-being (e.g. Ekkel & de Vries, 2017; Kaplan, 2001; Marselle et al., 2020; Mintz et al., 2021; Sugiyama et al., 2008). If viewing trees through a window, smelling wildflowers, or listening to birdsong are themselves drivers of the health benefits that flow from nearby nature (Soga et al., 2021; Soga & Gaston, 2020), urban greening policies should prioritise adding vegetation to built spaces. Since space for large green areas in a city can be difficult and challenging, small green spaces, such as pocket parks, street trees, flower beds, or green roofs, can still provide ample opportunities for more contact with nature in cities (Kerishnan & Maruthaveeran, 2021; Peschardt et al., 2012). Moreover, we encourage future research to investigate the characteristics of vegetation in parks (e.g. lower ground vegetation, more trees, flowering plants), as well as specific street tree features (e.g. size, height, species), that are more likely to enhance mental health and well-being. Finally, understanding the importance of shared, public, highly accessible green spaces and exploring how people use both public and private green spaces becomes particularly relevant, especially in situations where individuals do not have access to their 'own' private gardens (de Bell et al., 2020; Poortinga et al., 2021).

5 | CONCLUSIONS

This study brings into focus the well-being benefits of nearby nature, with higher levels of residential vegetation linked to better well-being outcomes. We also found that associations between vegetation and well-being were strongest for grass cover. As such, incorporating different forms of nature in cities in ways that promote people's contact with nearby nature in daily life could positively impact the mental health and well-being of urban populations. Planting trees along with understory vegetation in the streets, developing small urban green spaces, and making nature more accessible, safe, inclusive, and useable are some of the means urban planners, public health officials, and policymakers should promote and foster.

In closing, our results add evidence to our knowledge that surrounding residential vegetation is associated with better mental health, and different types of vegetation may play different roles. Future research may explore the mechanisms behind these associations, ideally examining the effects of urban interventions (e.g. new green spaces or upgrading existing parks) on health outcomes to examine the causal relationship between nearby nature and improved mental health.

AUTHOR CONTRIBUTIONS

Rita Sousa-Silva, Yan Kestens, Zoé Poirier Stephens, Benoit Thierry, and Audrey Smargiassi conceived the ideas and designed methodology; Yan Kestens, Zoé Poirier Stephens, and Benoit Thierry collected the data; Rita Sousa-Silva analysed the data with the support of Daniel Schoenig; Rita Sousa-Silva led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

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

DATA AVAILABILITY STATEMENT

The vegetation cover data used in this study are open and can be freely downloaded from the Montreal Metropolitan Community website (http://observatoire.cmm.qc.ca/). NDVI data are also available to researchers through request to the Canadian Urban Environmental Health Research Consortium (www.canue.ca). The well-being datasets analysed in this study are not publicly available due to privacy and confidentiality concerns.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Data S1: Coefficients of the generalized additive models testing the associations between subjective happiness, emotional well-being, and personal well-being and residential surrounding vegetation.

Table S1: Adjusted -squared and deviance explained for the 36 generalized additive models testing the associations between subjective happiness, emotional well-being, and personal well-being and residential surrounding vegetation.

Table S2: Vegetation exposure estimates.

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