



Association Between Urban Greenspace and Mental Wellbeing During the COVID-19 Pandemic in a U.S. Cohort

Jeremy D. Wortzel¹, Douglas J. Wiebe², Grace E. DiDomenico^{1,3}, Elina Visoki^{1,3}, Eugena South^{4,5}, Vicky Tam^{2,6}, David M. Greenberg⁷, Lily A. Brown⁸, Ruben C. Gur^{3,8}, Raquel E. Gur^{3,8} and Ran Barzilay^{3,8,9*}

¹Perelman School of Medicine, University of Pennsylvania, Philadelphia, PA, United States, ²Department of Biostatistics, Epidemiology and Informatics, Perelman School of Medicine, University of Pennsylvania, Philadelphia, PA, United States, ³Lifespan Brain Institute, Children's Hospital of Philadelphia & Penn Medicine, Philadelphia, PA, United States, ⁴Department of Emergency Medicine, Perelman School of Medicine, University of Pennsylvania, Philadelphia, PA, United States, ⁵Urban Health Lab, Perelman School of Medicine, University of Pennsylvania, Philadelphia, PA, United States, ⁶Healthcare Analytics Unit, Department of Biomedical and Health Informatics, The Children's Hospital of Philadelphia, Philadelphia, PA, United States, ⁷Interdisciplinary Department of Social Sciences, Bar-Ilan University, Ramat Gan, Israel, ⁸Department of Psychiatry, Perelman School of Medicine, University of Pennsylvania, Philadelphia, PA, United States, ⁹Department of Child and Adolescent Psychiatry, Children's Hospital of Philadelphia, Philadelphia, PA, United States

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*Correspondence:

Ran Barzilay
barzilayr@chop.edu;
ran.barzilay@pennmedicine.upenn.edu

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The Coronavirus Disease 2019 (COVID-19) pandemic brought unprecedented socially isolating measures to mitigate the spread of disease, heightening the importance of public outdoor urban greenspace. Here, we investigated the association between tree-rich greenspace and mental health in a large opportunity sample surveyed using a crowdsourcing research website (www.covid19resilience.org) between April 6th and October 12th, 2020 during the pandemic in the United States. Participants living in the U.S. ($N = 2,089$, 83.1% females, mean age 42 years, age range 18–90 years) were mapped to 1,080 unique ZIP Codes and mean tree canopy density was calculated with a 250m buffer around each ZIP Code grouped by quartile as a proxy for nearby greenspace. Four mental health parameters were assessed: (1) COVID-19-related worries; (2) anxiety symptoms; (3) depression symptoms; and (4) a standardized and weighted composite mental health score of all three parameters. Multivariate regression analyses with multilevel models were used to study the association between nearby greenspace and the four mental health outcomes, controlling for participant demographics and ZIP Code urbanicity. In the entire cohort, increased nearby greenspace showed a significant protective effect for depression (Coef. = -0.27 ; $p = 0.0499$), and composite mental health scores (Coef. = -0.19 ; $p = 0.038$) when comparing ZIP Codes with the most greenspace to ZIP Codes with the least, with no observed effects on COVID-19 related worries or anxiety individually. Stratifying by age suggested protective trends of greenspace on mental health in older subsets of the population (top age quartile, over 65 years old) experiencing less depression (Coef. = -0.45 ; $p = 0.048$) and lower composite mental health scores (Coef. = -0.34 ; $p = 0.032$) as a function of nearby greenspace. Additionally, younger

subsets of the population (second youngest age quartile, 18–38 years) experienced lower COVID-19 related worries (Coef. = -1.34 ; $p = 0.022$) as a function of greenspace. These findings may indicate that tree-rich greenspace plays a protective role on mental health during the COVID-19 pandemic, specifically in certain age groups, supporting the use of greenspace-related strategies to help mitigate mental health burden during this challenging and isolating time.

Keywords: urban greenspace, COVID-19, nature-based solutions, personalized ecology, mental health

INTRODUCTION

Throughout the Coronavirus Disease 2019 (COVID-19) pandemic, actions were taken by countries around the world to limit the spread of the virus. These actions included requiring lockdown measures, social distancing precautions, and virtual school and work alternatives to limit human interactions. In the United States, the first mitigation strategies began in March 2020 (Moreland et al., 2020). While beneficial for disease prevention, these mitigation efforts have been associated with negative mental health outcomes as symptoms of depression and anxiety worsened in the general population over the course of this pandemic (Marchini et al., 2020; Panchal et al., 2020; Rossi et al., 2020; Vindegaard and Benros, 2020).

At the same time, individuals frequented greenspaces more readily. For example, a Norwegian study estimated that outdoor recreational activity increased by 91% during lockdown relative to the 3-year prior average for the same days (Venter et al., 2020). In some areas, increased greenspace utilization was used strategically in direct response to increased disease prevalence. For example, in several East Asian cities, greenspace utilization increased by 5.3% for every 100 additional new COVID-19 cases reported (Lu et al., 2021b). The cause of increased greenspace utilization is multifactorial. Not only did outdoor space provide an escape from home isolation (Naomi, 2020), but also outside spaces emerged as a relatively safe method to socialize with others, an activity which became restricted anywhere aside from the outdoors (Killgore et al., 2020; Marchini et al., 2020).

Additionally, spending more time in greenspace during the pandemic may have influenced emotional wellbeing, as growing body of pre-pandemic evidence suggests that living near and spending time in greenspace is associated with better mental health (Twohig-Bennett and Jones, 2018). Increased usable urban greenspace was associated with decreased anxiety and mood disorders (Nutsford et al., 2013) as well as lower risks of developing psychiatric disorders in adulthood (Engemann et al., 2019). Observational studies established similarly strong associations between greenspace and mental health in urban environments in the United States and abroad (Beyer et al., 2014; Ruijsbroek et al., 2017). A recent randomized control trial examining the impact of interventions to green vacant urban land found that self-reported feelings of depression and worthlessness were significantly increased in those living next to newly greened lots, compared to those living around lots that remained blighted (South et al., 2018). However, all greenspace does not impact mental health equally. Tree canopy, over other forms of urban

greenery such as open grass spaces, was most strongly associated with better mental health outcomes (Astell-Burt et al., 2014), as well as with perceptions of overall greenspace (Astell-Burt et al., 2014; Astell-Burt and Peng, 2019; Mazumdar et al., 2020).

While the association between greenspace and improved mental health is well-established, and greenspace utilization during COVID-19 increased, only a few studies have investigated the relationship of greenspace and mental health during the COVID-19 pandemic. Studies thus far found evidence to support that individuals with accessible outdoor spaces or with natural elements in window views while in quarantine experienced decreased symptoms of depression and anxiety with improved measures of mental health (Pouso et al., 2020; Slater et al., 2020; Soga et al., 2020). The current study aims to further this work to determine the association between nearby tree-rich greenspace and mental health during the COVID-19 pandemic in a U.S. cohort. We hypothesized that having trees located nearby an individual's home neighborhood positively influenced their emotional wellbeing during this pandemic.

MATERIALS AND METHODS

General Approach

This study explores the association between tree-rich greenspace in ZIP Codes and four measures of mental health during the COVID-19 pandemic: COVID-19-related worries, anxiety, depression, and a weighted composite score generated from all three measures. We analyzed data from 2,089 individuals surveyed through research crowd sourcing website (www.covid19resilience.org) between April 6th and October 12th, 2020. Participants were living in 1,080 unique ZIP Codes across the United States. Building on previous findings from this data source, we sought to disentangle the specific association between greenspace defined by tree canopy density and mental health during the pandemic from other factors related to mental health including age, race, sex, and education status (Barzilay et al., 2020); as well as stressors uniquely impacting mental health during this pandemic such as living alone (Gao and Bai, 2020), and recent job loss (Ziersch et al., 2014). Additionally, because COVID-19 has differentially impacted mental health according to age (Banerjee, 2020; Barzilay et al., 2020) we explored greenspace impacts at different ages across the lifespan.

Participants and Procedures

Participants for this study were sampled from an online survey (www.covid19resilience.org) launched in April 2020

to study resilience and mental health during the COVID-19 pandemic (Barzilay et al., 2020). In addition to providing data on demographics, COVID-19 exposures and mental health, participants living in the United States also indicated their ZIP Code. The survey collected demographic information including mental health history and factors influencing mental health during the pandemic (such as living alone and recent job loss), as well as three measures of current mental health. First, participants were asked to complete an interactive assessment of COVID-19-related stress (worries) regarding: (1) getting (contracting), (2) dying from, (3) currently having, (4) family member getting, (5) unknowingly infecting others with, and (6) experiencing significant financial burden following COVID-19. A 5-item rating scale (0—not at all; 1—a little; 2—a moderate amount; 3—a lot; 4—a great deal) was provided to allow participants to indicate how much each parameter concerned them. Next, participants were offered to take a second survey on their anxiety symptoms (generalized anxiety disorder 7 questionnaire (GAD7)) (Spitzer et al., 2006) and depression symptoms (patient health questionnaire (PHQ-2)) (Arroll et al., 2010). Participants received feedback on several components of their responses with personalized recommendations regarding stress management. The feedback was also meant to incentivize participants to complete the survey accurately. The study was advertised through: (1) the researchers' social networks, including emails to colleagues; (2) social media; (3) the University of Pennsylvania and Children's Hospital of Philadelphia internal notifications; and (4) organizational mailing lists. The results presented here are based on data collected from participants living in the United States. Participation required responders to provide online consent. The study was approved by the Institutional Review Board of the University of Pennsylvania. All data was processed and cleaned using R Studio version 1.453 (R Studio Team, 2020).

Measures of Mental Health

We used principal-components factor analysis (Jolliffe, 1992) to examine whether responses to the three mental health measures were unrelated and thus appropriate to consider in combination as a single mental health construct. The motivation to do so stems from the work of other researchers, who have described how external forms of stress, such as the COVID-19 pandemic can potentiate underlying anxiety and depression (Gobbi et al., 2020). Doing so revealed one distinguishable factor with an eigenvalue of 0.95 formed by COVID-19-Related Worries, GAD-7, and PHQ-2. The factors loadings for the three mental health measures were all over 0.6 (0.67, 0.89, 0.83, respectively). Finding this evidence of a single construct, we generated a new composite variable called Composite Mental Health Score, derived as the weighted sum of responses to the three measures in standardized form (mean = 0, SD = 1).

Measure of Greenspace

Greenspace was measured through mean tree canopy density with a 500 m buffer around each ZIP Code divided into quartiles. This proxy was chosen because (1) tree canopy, over other forms of urban greenery, has been most strongly associated

with improved mental health outcomes (Astell-Burt et al., 2014); (2) other forms of urban greenery, such as grass spaces, have been associated with worse mental health outcomes (Astell-Burt and Feng, 2019); and (3) tree canopy density was shown to be the most accurate proxy for total perceived greenspace when compared to other common spatial measures including percent parks and Normalized Differential Vegetative Index (NDVI) (Mazumdar et al., 2020). Therefore, throughout this study the term greenspace will be used to refer to tree-rich greenspaces exclusively created by tree canopy as seen from aerial imaging. Additionally, buffers surrounding ZIP Codes have been utilized in other studies to depict the viewable and walkable neighborhood especially for individuals living on the boundaries of a particular ZIP Code (Cox et al., 2017; Soga et al., 2020). We selected a 500 m buffer as this is the distance considered to influence the experiences of a person in their daily life and has been shown to be the threshold distance for appreciable physical and mental benefits of greenspace around ZIP Code (Browning and Lee, 2017; Cox et al., 2017). Additionally, in preliminary analysis, several buffer sizes were considered (e.g., 100, 500, 1,000 m) which confirmed that the buffer size did not essentially affect the results of the study as described in Table A1.

Mean tree canopy density was calculated using the United States Department of Agriculture (USDA) Forest Service 2016 Tree Canopy Cover for the continuous United States (Bender et al., 2019). Tree Canopy included tree leaves, needles, and branches that provide tree coverage of the ground, viewed from an aerial perspective. This USDA product provided a raster image of the continuous United States broken down into individual pixels representing 30 × 30 m squares of land. Each pixel was identified with a tree canopy cover value, ranging from 0 to 100, reflecting the tree canopy density of that area. Using ArcMap version 0.8 (ESRI, 2011), all pixel values within a ZIP Code including a 500 m buffer were averaged creating a mean tree canopy density value used in this study as a proxy for greenspace. ZIP Codes were then stratified by quartiles from low to high mean tree canopy density: Q1 (< 6.90%), Q2 (6.91–18.61%), Q3 (18.62–32.12%), Q4 (> 32.13%). These greenspace quartiles acted as the primary independent variable throughout the analyses.

Statistical Analysis

Main Analysis

Descriptive statistics were used to summarize the data. Variance inflation factors (VIF) were calculated to explore the potential for multicollinearity, and found to be < 3, supporting the assumption that the variables were statistically independent and suitable to be modeled simultaneously as covariates. Multivariable regression was used to evaluate the association between greenspace in each ZIP Code and mental health. Due to the hierarchical nature of the data, with geographic nesting of survey participants, multilevel models with random intercepts for ZIP Codes was used to avoid the potential for bias (Bryk and Raudenbush, 1992). Doing so was supported by the intra-class correlation coefficients of the models (i.e., 0.016–0.032), showing that mental health measures in the same ZIP Codes were somewhat correlated.

The regression modeling included all participants and involved four multilevel models—one for each of the four mental health outcomes: (1) COVID-19-related worries (continuous scores ranging from 0 to 24 derived from an aggregate of all six worry questions rated on a 5-point scale from 0 to 4), (2) GAD-7 scores (continuous, ranging from 0 to 21), (3) PHQ-2 scores (continuous, ranging from 0 to 6), and (4) a Composite Mental Health Score (continuous weighted score comprised of all three mental health measures including COVID-19-related worries, GAD-7 and PHQ-2, ranging from -1.78 to 3.35). Greenspace divided by quartile was the independent variable of interest in each model, with the quartile with the least greenspace (Q1) treated as the reference group. Covariates in each model were participant gender, age, race, education status, prior mental health diagnosis, recent job loss, living alone, and urbanicity of the participant's ZIP Code of residence. All covariates were analyzed as categorical variables accounting for non-linear associations with each outcome. Prior mental health diagnosis was determined for participants who endorsed being diagnosed with mental health condition by a professional prior to the pandemic. Urbanicity was defined by the 2013 Rural-Urban Continuum Codes (RUCC) which form classification schemes for U.S. counties utilizing population size and adjacency to metro areas to determine urbanicity (scale from 1 to 9; most urban to most rural) (Rural-Urban Continuum Codes, 2013). Annual household income was included in all initial models, but excluded from final analyses for parsimony after finding no instances of being statistically associated with mental health. All regression analyses were conducted in Stata/IC version 16.1 (StataCorp, 2019).

Secondary Analysis

Given that the relation between mental health and greenspace may vary as a function of age, we stratified the cohort by age quartiles and ran the multilevel models as described above within each age-group quartile. Age quartiles, rather than small groupings, were used in an attempt to have sample sizes adequate and precision in the effect estimates. All regression analyses were conducted in Stata/IC version 16.1 (StataCorp, 2019).

RESULTS

Spatial Distribution of Study Participants

The survey data were comprised of 2,089 participants surveyed April 6th through October 12th, 2020 who provided ZIP Code of residence and completed the COVID-19-related worries screening questions. The majority of participants were female ($n = 1,736, 83.1\%$) and identified as White ($n = 1,802, 86.3\%$). Age ranged considerably, from 18 to 90 years (mean age = 42 years, standard deviation = 13.4). Full demographics are shown in Table 1.

Figure A shows a visualization of all U.S. ZIP Codes and ZIP Codes of all study participants, with a close-up of the number of surveyed participants in the greater Philadelphia area in Figure B. To show an example of the geographic specificity, the majority of participants were located in urban centers or immediate metro-adjacent ZIP Codes (RUCC 1 and 2; $n = 969,$

TABLE 1 Cohort Demographics^(N= 2089)

	n	%
Age bins, years^b		
18–30	468	22.4
31–38	422	20.2
39–51	506	24.2
51–90	478	22.9
Other demographics		
Gender, female	1,736	83.1
Gender, male	348	16.7
Race, white	1,797	86.7
Race, non-white	276	13.3
Income (annual per household)^c		
Under \$50,000	315	15.1
\$50,000 to \$74,999	304	14.6
\$75,000 to \$149,999	670	32.1
\$150,000 and above	652	31.2
Mental health risk factors		
Prior mental health diagnosis	1,168	35.5
Recent job loss	83	0.04
Lives alone	443	21.2

^aMissing demographic data for participants answering "don't know" or "rather not say" was lower than .8% for all variables except age and income.

^bMissing data for age = 10.3%.

^cMissing data for household income = 7.1%.

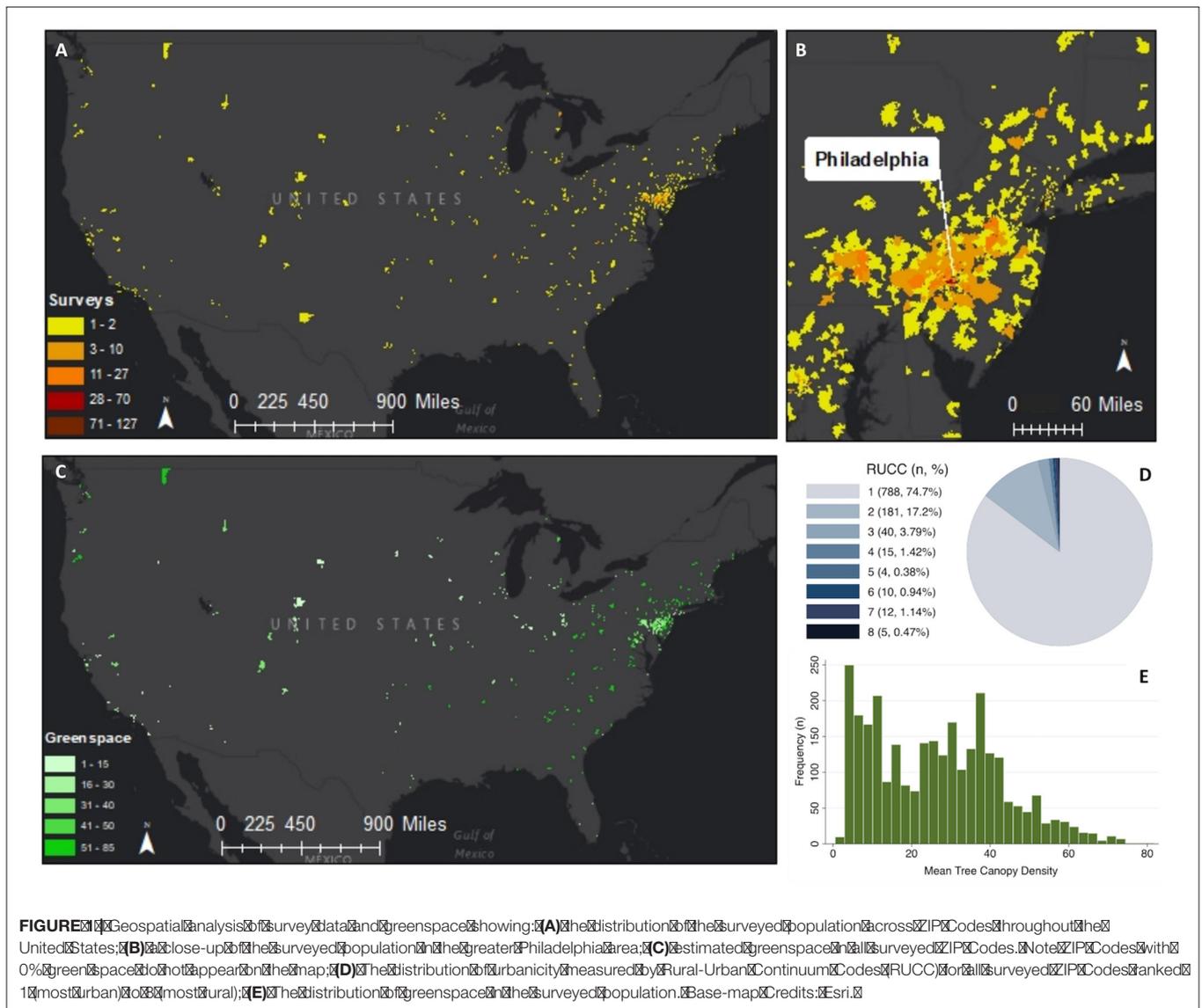
91.8%) as shown in Figure D. The distribution of greenspace for study participants across the U.S. is summarized in Figure C with the proportion of greenspace for each study participant represented in Figure E.

Factors Associated With Mental Health

When assessing the entire cohort, greenspace showed a significantly protective effect on clinical depression scores (PHQ-2 Coef. = -0.27; $p = 0.0499$) and Composite Mental Health Scores (Coef. = -0.19; $p = 0.038$) when comparing ZIP Codes with the most greenspace (Q4) to the ZIP Codes with the least greenspace (Q1). Greenspace was not associated with COVID-19-related worries (p -value > 0.097) or with anxiety (P -values > 0.064) when assessing the entire cohort. Details of the results of how greenspace related to the mental health variables in the entire cohort are reported in Table 2. Results on how the covariates including race, gender, education status, prior mental health diagnosis, living alone, and urbanicity related to the mental health outcomes are reported in Table 2, but are not discussed here given the results are consistent with findings that were presented previously in which their relation to the pandemic was the focus (Barzilay et al., 2020).

Stratified Exploratory Analyses

Table 3 reports results of the models stratified by age groups to explore the association between greenspace and mental health across the lifespan. In the oldest age group of individuals between 52 and 90 years old, greenspace was associated with lower



depression scores (PHQ-2, $\text{Coef.} = -0.45; p = 0.048$) and lower Composite Mental Health Scores ($\text{Coef.} = -0.34; p = 0.032$) when comparing ZIP Codes with the most greenspace to the ZIP Codes with the least greenspace (Q4 vs. Q1). Additionally, higher greenspace was associated with lower COVID-related worries ($\text{Coef.} = -1.34; p = 0.022$) in individuals in the second youngest age group (ages 1–38 yo) when comparing individuals who lived in ZIP Codes with the second largest amount of greenspace to those with the least (Q3 vs. Q1). Clinical measures of anxiety (GAD-7) were not statistically associated with greenspace (P -values > 0.068).

DISCUSSION

In this cross-sectional analysis of an opportunity sample conducted in the U.S. during the first six-months of the COVID-19 pandemic, we found that greenspace showed

significant protective effects on both depression and composite mental health scores of the entire cohort. Exploratory analysis showed that in older populations, proximity to tree-rich greenspace was associated with decreased depression and Composite Mental Health Scores and in younger populations greenspace was associated with lower COVID-19 related worries. The fast spread of COVID-19 and the unique socially isolating precautions that were implemented, creates an opportunity to evaluate the impact that greenspace has on mental health. Here, we leverage a resource that collected data on COVID-19 stress and mental health and enables ZIP Code-based estimation of greenspace, allowing us to explore the impact of greenspace on several measures of mental health during this pandemic. Our findings support the prior literature on the benefits of greenspace on mental health, and expand on the scarce data on this topic during the pandemic.

TABLE 2 Greenspace and COVID-19-related worries, anxiety, depression, and composite mental health scores among all surveyed participants, multivariate regression analysis with multilevel models.

Study population	Greenspace quartiles	COVID-19 related worries	GAD-7	PHQ-2	Composite mental health score
		(n = 1,874 ^a)	(n = 1,129 ^a)	(n = 1,129 ^a)	(n = 1,129 ^a)
		Coef. [95% CI]	Coef. [95% CI]	Coef. [95% CI]	Coef. [95% CI]
Entire cohort	Q2 vs. Q1	-0.18 (-0.79, 0.44)	-0.41 (-1.31, 0.49)	-0.077 (-0.34, 0.19)	-0.077 (-0.25, 0.095)
	Q3 vs. Q1	-0.53 [†] (-1.16, 0.095)	-0.79 [†] (-1.69, 0.12)	-0.033 (-0.29, 0.23)	-0.13 (-0.31, 0.038)
	Q4 vs. Q1	-0.33 (-0.96, 0.29)	-0.85 [†] (-1.75, 0.05)	-0.27 (-0.53, -0.0001)	-0.19 (-0.36, -0.017)

GAD-7, Generalized Anxiety Disorder Questionnaire-7 item; PHQ-2, Patient Health Questionnaire-2 item; CI, confidence interval.
^a The number of participants in each group is lower than multilevel model relative to Table 1 as only those participants who responded to all variables were included in the analysis.
[†] P < 0.1, *p < 0.05.

A major finding in this study is that increased greenspace was associated with lower depression symptoms and lower composite mental health scores. These findings are in line with well-established, pre-pandemic protective associations between greenspace and clinical measures of depression (Nutsford et al., 2013; Ruijsbroek et al., 2017; Engemann et al., 2019; Hedblom et al., 2019) as well as with findings of recent studies on this topic conducted during COVID-19 (Pouso et al., 2020; Soga et al., 2020). This study supports that in times of isolation and quarantine, greenspaces, specifically those with tree canopy, become important factors at maintaining mental health. The pandemic may have increased the importance of greenspaces, as they not only provide respite from urban streetscapes, but also uniquely serve as social gathering locations for those observing social distancing precautions. Therefore, we echo the growing recommendations for making parks and greenspace more accessible in order to preserve mental health, now and in future pandemics (Slater et al., 2020). While this association was not statistically seen with anxiety or COVID-19-related worries within the entire cohort of our study, some effect estimates were trending toward significance and more research is required to understand the nuance of these trends.

Another finding of this study is that age may play a role in how individuals benefit from greenspace. Both sides of the age spectrum seem to show some benefit, while similar trends in middle-aged individuals were not observed. There are several possible explanations for these findings. First, prior studies have shown some age discrepancy regarding how greenspace is appreciated over a life course, with increased benefits of greenspace later in life (Astell-Burt et al., 2014). This finding may be attributed to several factors including generational differences in nature appreciation or the quality of greenspace itself. Prior studies showed that while greenspace in and of itself has been beneficial to mental health (Hedblom et al., 2019), the quality of greenspace is also a substantial factor in the perceived enjoyment (Francis et al., 2012). Older individuals may have more resources like time, transportation, and better living arrangements relative to younger individuals and therefore may have access to private or better-quality greenspaces. Perhaps the

quality of greenspace including the landscaping, maintenance, aesthetic values, biodiversity levels, and tranquility of green spaces are all important to consider in future studies and in future urban greening interventions.

We also found that the mental health of the second youngest age group (ages 31–38 yo) was more impacted by greenspace relative to the mental health of the youngest age group (18–30 yo) and that of the second oldest age group (39–51 yo). There are several COVID-19 specific considerations that may explain this unique trend. For example, prior studies noted that having school-aged children during this pandemic has negatively impacted measures of mental health in the parents because school closures led to more stress at home and higher pressures while working remotely (Hiraoka and Tomoda, 2020). This may be especially true for the parent who takes on primary caregiver responsibilities. Therefore, working adults with school-aged children, as opposed to younger adults without children or older non-working/retired adults, may have had added stressors and reported more worries during this time. These stressors may also contribute to the amount of time a person has to engage with the outdoors and with greenspaces in their area thereby impacting the influence of greenspaces on their mental wellbeing.

Additionally, even though COVID-19 was disproportionately impacting the health of older individuals who therefore may have had a higher perceived knowledge of their vulnerability and overall threat of COVID-19 (Banerjee, 2020), adolescents and middle-aged adults had worse mental health outcomes during the pandemic (Barzilay et al., 2020; Ueda et al., 2020). Though little research has been done to examine this discrepancy, financial and job instability (Witteveen and Velthorst, 2020) in the working-age population and decreased social support structures for younger individuals (Cowie and Myers, 2021) are possible explanations. Adolescents have been singled out as a group particularly impacted by isolation due to the inherent lack of independence during quarantine. However, young adults who have already established their independence and social supports, yet do not have the responsibilities of school-aged children, may potentially be less affected and contribute to our findings (Ravens-Sieberer et al., 2021). Although we controlled for some

TABLE 2 | Greenspace and COVID-19-related worries, anxiety, depression, and composite mental health: stratification, multivariate regression analysis with multilevel models.

Study population (Age quartiles)	Greenspace quartiles	COVID-19 related worries	GAD-7	PHQ-2	Composite mental health score
		Coef. (95% CI)	Coef. (95% CI)	Coef. (95% CI)	Coef. (95% CI)
Age quartile 1 (18–30 years) N = 468	Q2 vs. Q1	0.33 (-0.64, .31)	-0.001 (-1.75, .74)	0.24 (-0.27, .75)	0.094 (-0.21, .39)
	Q3 vs. Q1	0.41 (-0.70, .53)	-0.59 (-2.51, .32)	0.23 (-0.35, -0.80)	0.018 (-0.33, .37)
	Q4 vs. Q1	0.89 (-0.28, 2.06)	0.066 (-1.96, 2.09)	0.25 (-0.36, 0.85)	0.12 (-0.25, 0.48)
Age quartile 2 (31–38 years) N = 422	Q2 vs. Q1	-0.65 (-1.74, .44)	-1.09 (-2.77, .59)	-0.38 (-0.92, .15)	-0.21 (-0.53, .097)
	Q3 vs. Q1	-1.34 (-2.48, -0.19)	-0.92 (-2.63, .78)	-0.013 (-0.68, .64)	-0.19 (-0.51, .13)
	Q4 vs. Q1	-0.47 (-1.69, .75)	-1.77 [†] (-3.67, .13)	-0.46 (-1.06, .13)	-0.27 (-0.62, .086)
Age quartile 3 (39–51 years) N = 506	Q2 vs. Q1	-0.43 (-1.78, .93)	0.49 (-1.25, 2.24)	0.024 (-0.49, .54)	-0.039 (-0.37, .29)
	Q3 vs. Q1	-0.83 (-2.15, .49)	-0.21 (-1.91, .48)	0.12 (-0.38, .62)	-0.094 (-0.42, .23)
	Q4 vs. Q1	-0.48 (-1.79, .83)	0.78 (-0.94, 2.51)	-0.067 (-0.58, .44)	-0.023 (-0.35, .31)
Age quartile 4 (52–90 years) N = 478	Q2 vs. Q1	0.20 (-1.21, .61)	-0.025 (-1.69, .64)	0.023 (-0.47, .51)	0.019 (-0.32, .36)
	Q3 vs. Q1	-0.31 (-1.66, .04)	-0.69 (-2.27, .88)	-0.12 (-0.59, .34)	-0.15 (-0.47, .18)
	Q4 vs. Q1	-0.62 (-1.92, .67)	-1.29 (-2.82, .22)	-0.45 (-0.90, -0.004)	-0.34 (-0.65, -0.029)

GAD-7, Generalized Anxiety Disorder Questionnaire-7; PHQ-2, Patient Health Questionnaire-2; CI, confidence interval.

^aThe number of participants in each group is lower than multilevel model relative to Table 1 as only those participants who responded to all variables were included in the analysis.

[†]P < 0.1, *p < 0.05.

confounders that disproportionately affect younger adults during the pandemic like recent job loss and living alone, we did not control for participants having school-aged children. The nuances of these specific age groups could be studied further with larger populations and child-age could be included in future versions of the survey.

This study's main strength is the unique timing of the data collection. The surveyed population was living during a global pandemic with either lockdown precautions in place or social distancing recommendations put forth by global and national health organizations. These unusual conditions are likely to have a major impact on mental health (Brooks et al., 2020), and due to the social distancing precautions, the importance of greenspace is likely to be heightened. Additionally, we controlled for several demographic, mental health, and COVID-19 specific factors that allowed more precise assessment of the impact that greenspace provided. Finally, this study applied a robust assessment of free-rich greenspaces based on the data collected and adequately accounted for tree canopy variation across the United States.

Several study limitations should be considered. These include a self-selection bias and a corresponding lack of diversity in our study population. The surveyed cohort consisted of an older, predominantly white, female, wealthy, more highly educated, professional population that is enriched with

healthcare providers and academics who decided to fill out a survey about mental health during this pandemic (Barzilay et al., 2020). COVID-19 has disproportionately impacted black communities and other communities of color enhancing our need to prioritize studies of greenspace and mental health in these populations (Yaya et al., 2020). This limitation is especially important as race was shown to moderate relationships between greenspace and mental health (Browning and Rigolon, 2018) and the racial disparity of COVID-19 infection was lower in areas with more greenspace (Lu et al., 2021a), which could be explained by historical redlining leaving neighborhoods segregated and with unequal investments over time including access to greenspace (Nardone et al., 2021). Therefore, while we controlled for race as one of the covariates used in this analysis, more data is required from more racially and socioeconomically diverse cohort to better understand the impact of greenspace on mental health during COVID-19 for these populations. Another key limitation is the inherent ascertainment bias in crowdsourcing data collection (Behrend et al., 2011), as this survey primarily reached academic populations in urban centers across the northeastern United States (Barzilay et al., 2020). These biases lessen the overall generalizability of this study and future work should be aimed at diversifying the population surveyed.

With regard to our mental health outcomes, only brief screening measures of anxiety and depression were used in this study and more comprehensive measures could be considered in the future. With regard to the conceptualization of greenspace, we could only estimate available greenspace but could not account for the accessibility to, the quality of, or individual interactions with these places. Additionally, the spatial resolution of the analysis was limited to the ZIP Code by the identifiers gathered in the survey. Furthermore, the nature of using tree canopy data as a proxy for all greenspace in this study has several limitations including not accounting for other forms of urban greenery including grass, lawns and shrubbery that may be common in yards and residential settings important during this pandemic. The 30×30 m resolution of our tree canopy analysis also presents limitations in accounting for smaller clusters of trees that may be important for defining urban greenery. Another limitation is that we do not account for temporal changes in COVID-19 spread, severity or variation in mitigation restrictions on social gatherings across ZIP Codes and along the course of data collection.

Additionally, the multiple comparisons made in the analyses should be interpreted with caution. Throughout the results we refer to effect estimates with P -values < 0.05 as being statistically significant. It is important to note, however, that several additional effect estimates had P -values < 0.10 and were considerable in magnitude. Here, we briefly draw attention to these results, which should be given some consideration to be consistent with the exploratory nature of this study given that greenspace has only minimally been investigated as potentially related to COVID-19-related mental health in the fashion done here. However, we present this data merely as exploratory to encourage future hypothesis-driven research on the effects of greenspace on mental health during COVID-19. Lastly, the cross-sectional design and exploratory nature of this analysis limits the ability to draw causal inference, which can be addressed in future longitudinal studies with added measures of greenspace utilization.

We present data from a large opportunity sample collected during the first 6 months of the COVID-19 pandemic within the United States—a time when the majority of those sampled were restricted by social distancing precautions. We found a significant protective trend for greenspace on mental health, with exploratory analyses suggesting that mental health of certain age groups benefit more from proximity to greenspace than others. Longitudinal studies with more diverse cohorts and specific geographic identifiers are required to assess the causal relationship between greenspace and mental health during the COVID-19 pandemic. Nevertheless, it is apparent that now,

more than ever, greenspace plays a unique role in preserving mental health.

DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available because this study includes individual participants' data. Data cannot be publicly accessible due to Institutional Review Board guidelines. We are open to collaborations with other researchers upon contacting us. Requests to access the datasets should be directed to barzilayr@chop.edu.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Institutional Review Board of the University of Pennsylvania. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

Conceptualization: JW, RB, ES, VT, GD, EV, and DW. Methodology, Investigation, Resources, and Writing—review and editing: JW, RB, ES, VT, GD, EV, DG, LB, RCG, REG, and DW. Software: JW, RB, ES, VT, GD, EV, DG, and DW. Validation: JW, DW, RB, and EV. Formal analysis: JW, DW, RB, ES, and EV. Data curation: RB, GD, EV, DG, LB, RCG, and REG. Writing—original draft preparation: JW. Visualization: JW, RB, and VT. Supervision: VT, DW, ES, and RB. Project administration and funding acquisition: RB. All authors have read and agreed to the published version of the manuscript.

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APPENDIX

TABLE 1 Preliminary Greenspace Buffer Analysis to Determine Optimal Buffer Size.

	No buffer Coef. (95% CI)	100m buffer Coef. (95% CI)	250m buffer Coef. (95% CI)	500m buffer Coef. (95% CI)	1,000m buffer Coef. (95% CI)
COVID-19 worries	-0.0098 (-0.023, 0.005)	-0.011 (-0.025, 0.003)	-0.011 (-0.03, 0.003)	-0.012 (-0.026, 0.002)	-0.009 (-0.024, 0.005)
GAD-7	-0.005 (-0.03, 0.017)	-0.008 (-0.029, 0.013)	-0.009 (-0.03, 0.013)	-0.009 (-0.03, 0.012)	-0.008 (-0.03, 0.013)
PHQ-2	-0.0015 (-0.008, 0.005)	-0.003 (-0.009, 0.004)	-0.003 (-0.009, 0.003)	-0.003 (-0.009, 0.004)	-0.002 (-0.009, 0.004)
Composite stress score	-0.058 (-0.14, 0.025)	-0.081 (-0.16, -0.001)	-0.081 [†] (-0.016, -0.0002)	-0.081 [†] (-0.016, 0.0004)	-0.077 (-0.016, 0.004)

GAD-7, Generalized Anxiety Disorder Questionnaire-7 item; PHQ2, Patient Health Questionnaire-2 item; CI, Confidence Interval. Greenspace was defined as a continuous variable. Subsequent analysis stratified greenspace by quartiles.
[†] $p < 0.1$.

TABLE 2 Full Multivariate Regression Analysis with Multilevel Models for All Covariates.

Covariates	Categorical breakdown	COVID-19 related worries	GAD-7	PHQ-2	Composite mental health score
		Coef. (95% CI)	Coef. (95% CI)	Coef. (95% CI)	Coef. (95% CI)
		(n = 1,874) ^a	(n = 1,129) ^a	(n = 1,129) ^a	(n = 1,129) ^a
Sex		-1.11** (-1.66, -0.57)	-0.76 [†] (-1.56, 0.04)	0.07 (-0.17, 0.31)	-0.12 (-0.19, 0.20)
Age	1	0.41 (-0.27, 1.09)	-0.13 (-1.14, 0.87)	-0.11 (-0.42, 0.19)	0.001 (-0.19, 0.21)
	2	0.44 (-0.23, 1.13)	-0.26 (-1.30, 0.78)	-0.11 (-0.42, 0.21)	0.01 (-0.19, 0.21)
	3	0.79* (0.12, 1.45)	-0.37 (-1.35, 0.62)	0.01 (-0.28, 0.31)	0.06 (-0.13, 0.25)
	4	0.11 (-0.55, 0.77)	-1.93* (-2.90, -0.96)	-0.25 [†] (-0.54, 0.04)	-0.22* (-0.40, -0.03)
Edu	2	8.89* (2.65, 5.12)	-9.54 [†] (-19.2, 0.11)	-2.64 [†] (-5.56, 0.29)	-0.51 (-2.38, 1.36)
	3	7.39* (1.26, 3.5)	-11.1* (-20.6, -1.58)	-3.66* (-6.53, -0.78)	-1.05 (-2.89, 0.79)
	4	7.36* (1.25, 3.4)	-11.8* (-20.9, -2.02)	-4.04* (-6.91, -1.18)	-1.22 (-3.05, 0.61)
	5	6.55* (0.44, 2.7)	-11.8* (-21.2, -2.35)	-4.25* (-7.11, -1.38)	-1.35 (-3.19, 0.48)
	6	6.29* (-0.55, 0.78)	-12.5* (-21.9, -3.03)	-4.51* (-7.38, -1.64)	-1.51 (-3.35, 0.32)
	7	0.63* (0.05, 1.21)	-0.53 (-1.39, 0.33)	-0.18 (-0.44, 0.08)	-0.04 (-0.21, 0.13)
Race (non-white)		0.63* (0.21, 1.05)	2.08** (1.49, 2.68)	0.74** (0.56, 0.92)	0.44** (0.32, 0.55)
Prior mental health diagnosis		1.56* (0.51, 2.60)	-0.43 (-2.03, 1.17)	0.81* (0.33, 1.29)	0.31 (-0.002, 0.62)
Lives alone		-0.38 (-0.89, 0.13)	-0.09 (-0.83, 0.64)	0.29* (0.07, 0.52)	0.03 (-0.11, 0.18)
Urbanicity	2	-0.15 (-0.78, 0.48)	0.30 (-0.59, 1.19)	0.11 (-0.16, 0.38)	0.04 (-0.14, 0.21)
	3	-1.59* (-2.90, -0.28)	-0.68 (-2.55, 1.20)	0.11 (-0.45, 0.68)	-0.17 (-0.53, 0.19)
	4	-0.05 (-2.89, 2.8)	-0.02 (-3.41, 3.37)	0.45 (-0.58, 1.47)	0.12 (-0.53, 0.78)
	5	-0.43 (-1.89, 0.76)	6.63* (1.12, 12.12)	2.10* (0.45, 3.76)	1.48* (0.51, 2.45)
	6	1.45 (-1.62, 4.51)	2.52 (-1.78, 6.83)	0.09 (-1.21, 1.38)	0.32 (-0.51, 1.15)
	7	-2.73* (-5.25, -0.21)	-0.98 (-4.38, 2.42)	-0.03 (-1.05, 0.99)	-0.22 (-0.87, 0.44)
	8	2.47 (-1.39, 6.34)	3.14 (-2.37, 8.65)	0.95 (-0.71, 2.61)	0.65 (-0.42, 1.71)

GAD-7, Generalized Anxiety Disorder Questionnaire-7 item; PHQ2, Patient Health Questionnaire-2 item; CI, Confidence Interval. Greenspace was defined as a continuous variable. Subsequent analysis stratified greenspace by quartiles.

^a The number of participants in each group is lower in multilevel model relative to Table 1 as only those participants who responded to all variables were included in the analysis.

[†] $p < 0.1$, * $p < 0.05$, ** $p < 0.0001$.