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Branching out: Feasibility of examining the effects of greenspace on mental health after traumatic brain injury

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ABSTRACT

Aim: This pilot study's aim was to determine the feasibility of examining the effects of an environmental variable (i.e., tree canopy coverage) on mental health after sustaining a brain injury.
Methods: A secondary data analysis was conducted leveraging existing information on mental health after moderate to severe traumatic brain injury (TBI) from the TBI Model System. Mental health was measured using PHQ-9 (depression) and GAD-7 (anxiety) scores. The data were compared with data on tree canopy coverage in the state of Texas that was obtained from the Multi-Resolution Land Characteristics (MRLC) Consortium using GIS analysis. Tree canopy coverage as an indicator of neighborhood socioeconomic status was also examined using the Neighborhood SES Index.
Results: Tree canopy coverage had weak and non-significant correlations with anxiety and depression scores, as well as neighborhood socioeconomic status. Data analysis was limited by small sample size. However, there is a higher percentage (18.8%) of participants who reported moderate to severe depression symptoms in areas with less than 30% tree canopy coverage, compared with 6.6% of participants who endorsed moderate to severe depression symptoms and live in areas with more than 30% tree canopy coverage (there was no difference in anxiety scores).
Conclusion: Our work confirms the feasibility of measuring the effects of tree canopy coverage on mental health after brain injury and warrants further investigation into examining tree canopy coverage and depression after TBI. Future work will include nationwide analyses to potentially detect significant relationships, as well as examine differences in geographic location.

1. Introduction

The World Health Organization (WHO) recognizes that where people live, work, and recreate affects their health, naming environmental context (including the physical environment) as one of the main determinants of health and well-being in cities [1]. Neighborhood characteristics affect physical and mental health at the individual and community level through both the natural and built environment [2], social conditions and networks, and availability of resources (or lack thereof) [3]. One aspect of the physical environment that has received attention in recent years is greenspace or the presence of nature, such as vegetation and tree canopy [4–6]. Although definitions of greenspace in studies vary [7], research has demonstrated the physical and mental health benefits of living in proximity to natural areas and vegetation [4,5]. Greenspace has also been found to moderate the effects of stressful life events on health [6], and exposure to nature has been shown to reduce barriers to attention and decrease mental fatigue [8,9]. Tree canopy coverage (TCC), or the presence of trees and canopy cover, is one of the more widely studied indicators of greenspace and has been associated with better general health [10,11] and mental health in the general population [12,13]. TCC is also the green space variable that is best associated with public perception of greenspace [14]. Urban TCC has demonstrated associations with a lower likelihood of depressive

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symptoms [15], lower antidepressant prescription rates [16], and a better ability to control stress and feel calmer [11,17,18].

Mental health is one of the most studied outcomes related to greenspace [19], yet little is known about the influence of greenspace on the mental health of people with disabilities, many of whom are already at higher risk for mental health conditions than their non-disabled peers [20]. At a particularly high risk of experiencing adverse mental health symptoms, including anxiety and depression [21,22], are the estimated 3.2 to 5.3 million people in the United States (U.S.) living with disability resulting from traumatic brain injury (TBI) [23]. Every year, about 1.5 million Americans sustain a new TBI [24], and ~80 to 90 thousand of them will experience lifelong disability resulting from their injury [24]. Though much research demonstrates how individual and social characteristics contribute to mental health conditions after a TBI [25–30], there has been significantly less attention paid to the effects of geospatial context or a person's natural environment (including greenspace) on post-injury mental health. While there have been two studies examining the health benefits of greenspace in those with spinal cord injury [31] and in post-stroke populations [32], there have been no studies to date with individuals with TBI. Given that depression and anxiety, as well as symptoms like attention problems, mental fatigue, and aggression, are common after TBI [33,34] *and* known to benefit from access to greenspace [8,9,35], improving exposure to greenspace could prove beneficial to persons with TBI.

Based on the results of these previous studies and the demonstrated health benefits for the general population, there is a need to explore if there is a positive association between access to greenspace and mental health among persons with TBI. Therefore, our objective was to examine the feasibility of studying the potential relationship between TCC and mental health among persons with TBI, focusing on those living in the state of Texas. We leveraged the TBI Model Systems data, the largest longitudinal dataset of long-term post-TBI outcomes in the world [36], from two model systems centers in Texas to establish a feasible approach that could be scaled up and applied to the larger TBI Model Systems National Database in the future. We further explored whether TCC was associated with an indicator of neighborhood socioeconomic status among participants included in our analysis, as previous studies have shown less TCC in lower-income neighborhoods [37,38].

2. Materials and methods

2.1. Participants

Participants were adults (n = 185) enrolled in the Traumatic Brain Injury Model Systems (TBIMS) National Database [39,40] at the North Texas TBIMS site in Dallas, TX, or the Texas TBIMS at TIRR site in Houston, TX, and residing in the state of Texas at the time of their follow-up visit. Inclusion in the TBIMS requires a diagnosis of a moderate-severe TBI, determined by at least one of the following: 1) positive neuroimaging findings, 2) a loss of consciousness greater than 30 minutes, 3) post-traumatic amnesia greater than 24 hours after injury, or 4) a Glasgow Coma Scale score of less than 13. Additionally, TBIMS participants have to be ≥16 years old, be able to consent or have a legally authorized representative consent for them, be admitted to a TBIMS acute care facility within 72 hours of injury, and receive inpatient rehabilitation services at a TBIMS-designated facility. Follow-up data were collected at 1, 2, 5, or any subsequent 5 years, per TBIMS protocol. For the current study, we used the most recent follow-up data (i.e., data collected at 1, 2, 5, 10, and 15 years or more) collected after 2016 (the year the satellite imagery for TCC was taken). Census tracts were identified for all participants who consented to provide their address (~80% of the TBIMS sample) and linked to the percentage of TCC as described below.

2.2. TCC procedures

Data about TCC was taken from the Multi-Resolution Land Characteristics Consortium [41]. Mapped from satellite imagery, which captures images of greenness, the TCC data are a map of the percentage of TCC (0 to 100 %) for every 30-by-30 meter area of the continental United States (Figure 1) [42]. The mean error for the data was 9.7% at the national level [43].

Several geospatial processes were performed using ArcGIS Pro Software to link the TCC to the 6882 tracts in Texas. The greenness data are stored in a raster (grid) file, where each pixel (cell) in the raster represents a 30 by 30 m area. The tracts derived from the U.S. Census Bureau [44] are stored as polygons. The two datasets are merged using a spatial join (See Figure 2, where Houston census tracts were used to illustrate the process applied to the whole state of TX), creating a new map in which each census track is represented by the average TCC percentage of all pixels within its border.

To ensure that our results (based on imagery taken in 2016) reflect current TCC conditions, we compared the TCC of Houston obtained from our results to those obtained from another satellite imagery [45] of 0.3 to 0.5-meter resolution that was updated on April 27, 2022. The results showed similarity with satellite imagery, as shown in Figure 3. From this figure, we can see that even for tracts with 0% TCC, there would still be some greenery (for example, a few trees). This can be explained by the fact that the process involves averaging many pixels with different greenery percentages into one representative value, so those trees have a negligible effect on the overall result.

2.3. Measures

Demographic data were collected from participants upon enrollment and at each follow-up visit (see Table 1). All participants included in this analysis provided their addresses such that we were able to identify their census tract to link with TCC data.

2.4. Neighborhood SES index

We used 2015-2019 data from the U.S. Census Bureau's American Community Survey [46] to generate a Neighborhood SES Index score for each census tract. Briefly, the Neighborhood SES Index [47] was made up of a

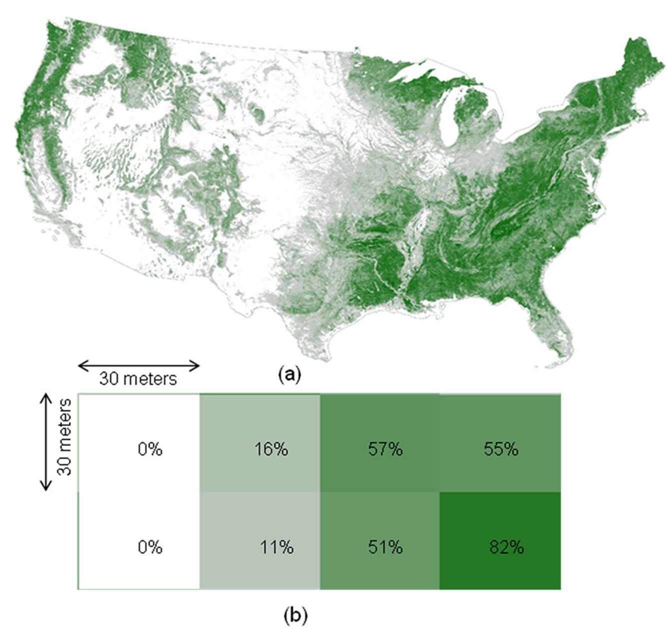

Fig. 1. Shows (a) the resulting raster (161190 columns X 104424 rows) of green canopy for the United States inland, as well as (b) the way that the data is stored (top left pixel contains 0% of green canopy, whereas bottom right pixel contains 82% of green canopy). In a raster, certain phenomena (here, green canopy) associated with a particular spatial location are represented as rows and columns of cells (or pixels), where each cell consists of a value representing information pertaining to that phenomenon.

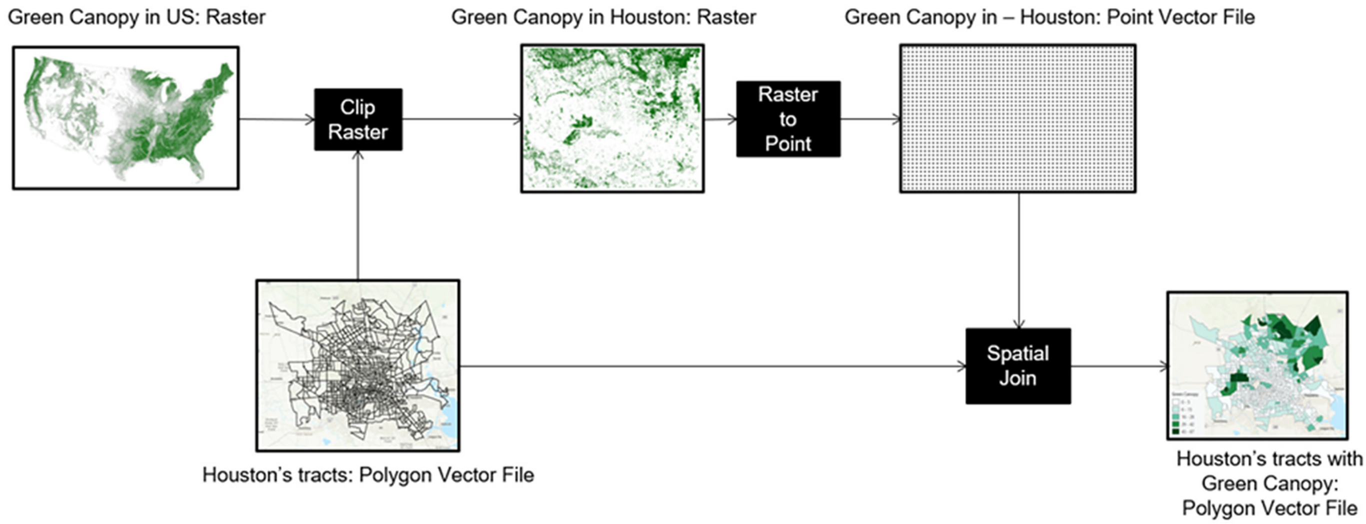

Fig. 2. Schematically displays all geospatial processes involved and their inputs and outputs.

composite of eight standardized neighborhood-level variables at the census tract level, including: percent unemployed, percent single parent-led households, percent no high school or GED, percent bachelor's degree or higher, percent below the poverty line, percent of households that were on food stamps/SNAP, median household income, and median family income. The Neighborhood SES index was created using Principal Components Analysis methods [48] and using the first principal component to represent the index. Neighborhood SES Index scores were z-scores, with a mean of 0 and a standard deviation of 1, with positive scores indicating greater neighborhood SES *dis*advantage.

2.5. Mental health measures

Participants completed the Generalized Anxiety Disorder-7 (GAD-7) scale and the Patient Health Questionnaire-9 (PHQ-9) scale via a telephone interview at their follow-up TBIMS study visit.

The GAD-7 scale is a 7-item measure of anxiety symptoms over the last two weeks, using a scale that ranges from 0 (Not at All) to 3 (Nearly Every Day) [49]. Higher total scores represent more frequent anxiety symptoms. Scores of 5-9 represent mild anxiety, 10-14 represent moderate anxiety, and >15 represent severe anxiety.

The PHQ-9 is a nine-item screening measure for depression [50]. Participants rate how often they have experienced depressive symptoms over the last two weeks on a scale of 0 (Not at all) to 3 (Nearly Every Day). Total scores for the PHQ-9 range from 0-27, with higher scores representing more frequent depressive symptoms. Scores of 5-9 represent mild depression, 10-14 represent moderate, 15-19 represent moderately severe, and scores of >20 represent severe depression.

2.6. Analyses

We calculated summary statistics of the demographics and outcome variables. The independent variable was percent TCC, and dependent variables included mental health measurements (PHQ-9, GAD-7) and Neighborhood SES Index. However, these X-Y correlational relationships are not causal in nature, and we cannot rule out reverse causality in the instance of tree canopy and Neighborhood SES association. Continuous variables (PHQ-9, GAD-7, Neighborhood SES Index, Percent TCC) are reported with means

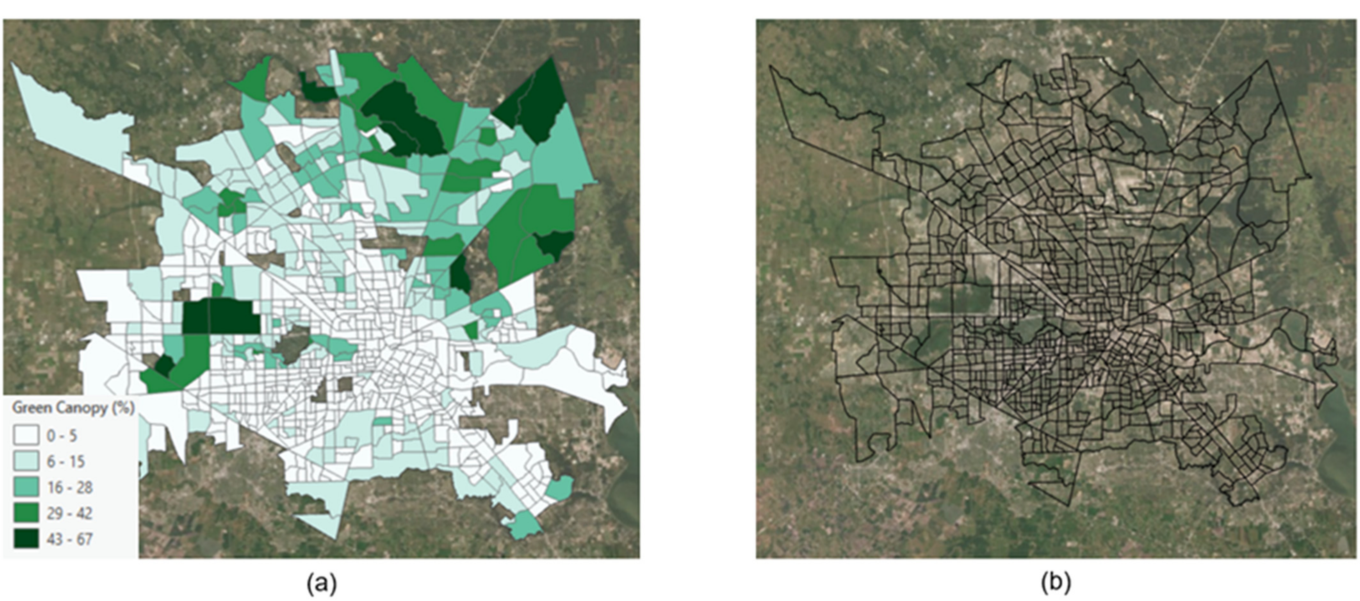

Fig. 3. (a) Green Canopy Percentage for the tracts in Houston (b) Satellite imagery of Houston and the tract polygons (in black).

Table 1
Participant and neighborhood characteristics.

	Mean (SD)	n
Tree Canopy Coverage (percent)	13.9 (15.9)	185
SES index (z-score)	0.1 (0.94)	110
PHQ9	4.8 (5.5)	127
GAD7	3.8 (5.0)	128
Age at follow-up (years)	45.8 (16.7)	185
Time since injury (follow-up year)	8.0 (7.1)	185
	n (%)	
Sex		
Female	43 (23.2%)	
Male	141 (76.2%)	
Missing	1 (0.5%)	
Race/Ethnicity		
White	99 (53.5%)	
Black	33 (17.8%)	
Asian/ Pacific Islander	6 (3.2%)	
Native American	1 (0.5%)	
Hispanic	45 (24.3%)	
Missing	1 (0.5%)	
Education at follow-up		
below HS	31 (16.8%)	
HS or GED	48 (26.0%)	
above HS	104 (56.2%)	
Unknown/Others	1 (0.5%)	
Marital status		
Single	70 (37.8%)	
Married	67 (36.2%)	
Divorced/separated	44 (23.8%)	
Widowed	4 (2.2%)	
Employment status at follow-up		
Full-time student	4 (2.16%)	
Employed	75 (40.54%)	
Homemaker	3 (1.62%)	
Retired	78 (42.16%)	
Unemployed	21 (11.35%)	
Unknown/Others	4 (2.16%)	
SES		
Disadvantaged (index ≥ 0)	64 (34.6%)	
Advantaged (index < 0)	46 (24.9%)	
Missing	75 (40.5%)	
PHQ9		
< 10	105 (56.8%)	
≥ 10	22 (11.9%)	
Missing	58 (31.4%)	
GAD7		
< 10	111 (60.0%)	
≥ 10	17 (9.2%)	
Missing	57 (30.8%)	
Urbanicity at follow-up		
Rural	30 (17.0%)	
Suburban	75 (42.6%)	
Urban	71 (40.3%)	
Missing	9 (4.9%)	

and standard deviations. Categorical variables are reported with counts and percentages. We computed Spearman correlations for TCC versus PHQ-9 and GAD-7. Given the small sample size (n = 127 with PHQ-9, n = 128 with GAD-7, n = 110 with Neighborhood SES Index) and exploratory nature of the study, we plotted scatterplots of TCC by GAD-7, PHQ-9, and Neighborhood SES Index to visually examine potential relationships. For scatterplots, we identified meaningful cutoffs as follows: For TCC, we used a cutoff of 30% coverage, determined based on known differences in physical and mental health outcomes for those living in areas with TCC above versus below this threshold [12,51]. For both GAD-7 and PHQ-9, we used a cutoff of <10 vs. ≥10, differentiating those with moderate or worse anxiety and depressive symptom severity [49,52]. Using these cutoffs, we calculated how many participants met the criteria for moderate or worse depression and anxiety symptom severity among those above versus below our TCC threshold. For SES Index, we used <0 and ≥0, as this was a z-score with a mean of 0; positive scores indicated a greater disadvantage than the U.S. National mean.

3. Results

Summary statistics for participants and their neighborhood characteristics are reported in Table 1. Most participants were male, White, and more than high school educated. Sixty-four percent of participants with depression scores reported no depressive symptoms at follow-up (PHQ-9 ≤4), with 17.3% reporting moderate or worse depressive symptoms (PHQ-9≥10). Seventy percent of participants with anxiety scores reported no anxiety symptoms at follow-up (GAD-7≤4), with 13.3% reporting moderate or worse anxiety (GAD-7≥10). About 30% of participants did not have PHQ-9 or GAD-7 available; these may have been participants who were unable to complete the interview themselves, as PHQ-9 and GAD-7 could not be collected from a proxy.

TCC had weak and non-significant positive correlations with PHQ-9 (r = .10), GAD-7 (r = .09), and SES index (r = .07) scores. Scatterplots of TCC by PHQ-9 and GAD-7 are presented in Fig. 4. The mean TCC for neighborhoods in our sample was 13.9% (SD = 15.9), lower than the 30% or higher associated with positive health outcomes [12,51], with only 24 participants (13% of the sample) living in areas with ≥30% TCC.

The percentage of participants living in areas *below* the 30% TCC cutoff who reported moderate or worse depression symptoms was 18.8%, and for anxiety symptoms was 13.3%. In comparison, only 6.6% of participants living in areas above the 30% TCC cutoff reported moderate or worse depression symptoms, and 13.3% reported moderate or worse anxiety symptoms (Table 2).

4. Discussion

This study was the first investigation into the effects of natural environmental determinants of health on mental health after TBI. Given our small sample of individuals with TBI in Texas, we did not find statistically significant relationships between greenspace density [i.e., tree canopy coverage; TCC] and mental health outcomes (i.e., depression and anxiety). However, we did find that a larger percentage of those living in areas with low TCC had symptoms of moderate or worse depression (18.8%) compared to those living in areas with high TCC (only 6.6% with moderate or worse depression), aligning with previous research [15] and warranting further investigation in a larger sample. We did not, however, see a similar pattern for anxiety. It is unclear how this aligns with previous literature, as studies tend to focus on psychological distress as opposed to anxiety specifically [12,13]; however, Tiako et al. (2021) note that although there were no direct associations found between tree canopy coverage and perceived stress in pregnant women, individuals who had a *history* of anxiety or depression reported lower perceived stress for each standard deviation increase of tree canopy coverage in the 100 meters around their homes [53]. Future study should consider mental health history to see if this effect is seen in individuals with TBI.

Also potentially notable was the very low percentage (13%) of our participants who lived in areas with ≥30% TCC, with an average TCC across our participants' neighborhoods of only 13.9%. This is, however, comparable to the average TCC across TX, which is 12.2% (see Fig. 4, Panel A). The U.S. National map of TCC, presented in Fig. 1, clearly demonstrates vast differences in TCC by geographic location. It remains unclear whether the benefits of greenspace for mental health, demonstrated in the literature, are consistent or vary across different geographic environments and climates. For example, in states where temperatures remain relatively high year-round and the percent of the day where sunlight reaches the ground is much higher, could a lower TCC percentage still have some positive effects? Or conversely, in states with more seasonal variation in temperature and more days of cloud cover, is a higher TCC percentage necessary to confer notable benefit? These questions will be important to explore in a

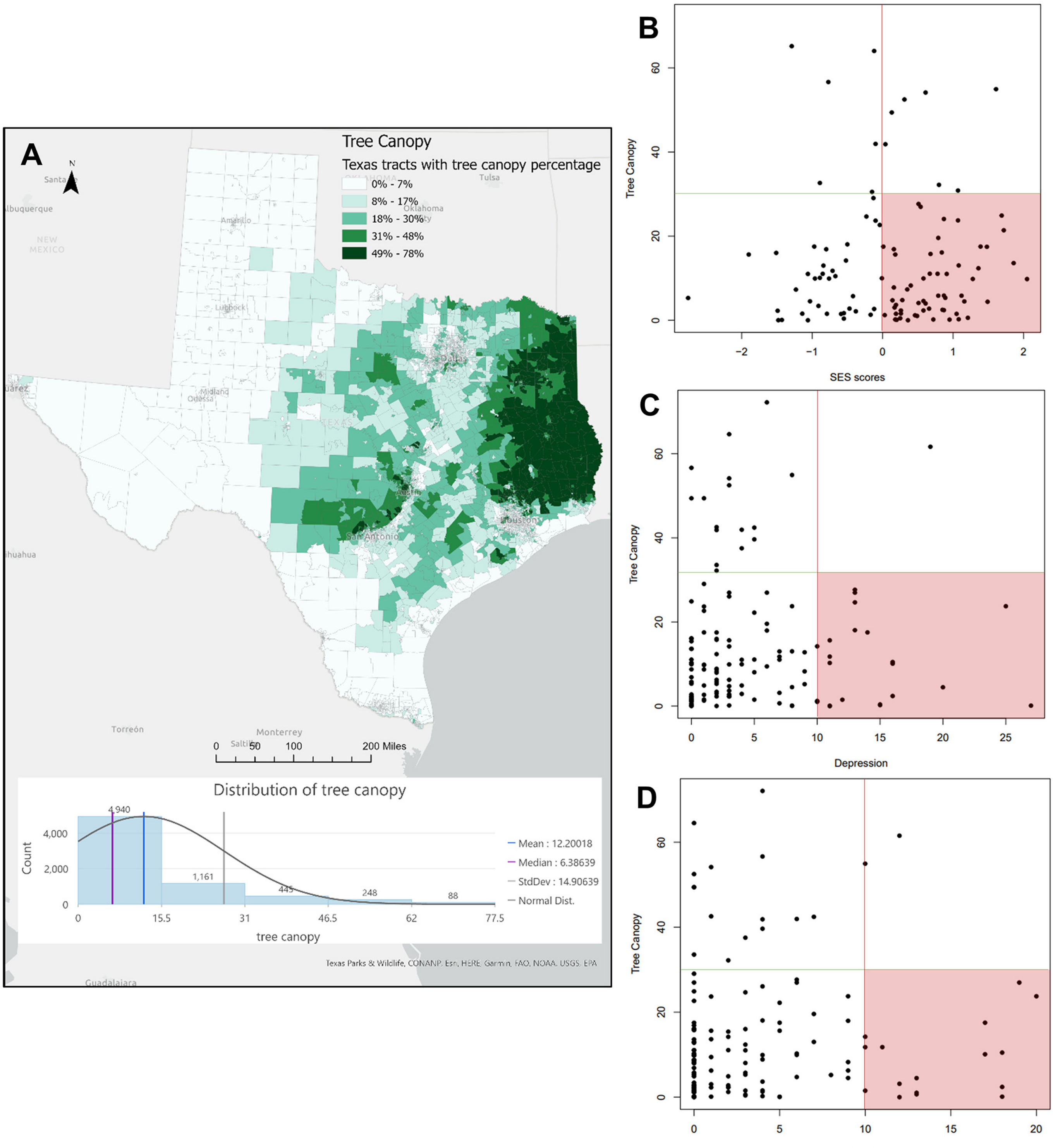

Fig. 4. [A] Percent Tree Canopy Coverage (TCC) for the census tracts in Texas; [B] Percent TCC by Neighborhood Socioeconomic Status (higher scores = greater socioeconomic disadvantage); [C] Percent TCC by Depression (PHQ9 scores); [D] Percent TCC by Anxiety (GAD7 scores). Red lines in panels B-D indicate 30% TCC, mean SES for neighborhoods in the U.S., and cutoffs for moderate or worse depression and anxiety.

nationwide sample to inform policy and health behavior recommendations more meaningfully. (See Fig. 2.)

4.1. Limitations

Several limitations are important to contextualize our results. First, neighborhoods in Texas are good candidates for a contribution of TCC to mental health, given the high temperatures almost year-round and the consequent benefits of shaded areas. However, as seen in Fig. 3, TCC in Houston (TX's largest city) is disproportionally prevalent in the city's outskirts, while the population is denser closer to the center. The very small number of participants in our sample living in areas where TCC ≥ 30%, especially among those with available mental health outcomes, likely weakened the sensitivity of our analyses. Consistently, comparing the scores of those

Table 2
TCC by mental health and SES index.

	PHQ-9			GAD-7			SES		
TCC	<10	≥10	Total	<10	≥10	Total	<0	≥0	Total
≥30%	14	1	15	13	2	15	6	6	12
<30%	91	21	112	98	15	113	40	58	98
Total:	105	22	127	111	17	128	46	64	110

who lived above vs. below 30% TCC would also be underpowered (particularly if the effect is rather small); our sample size, derived from TBIMS participants in Texas, was adequately powered to identify medium but not small effect sizes in our primary correlation analysis.

Another limitation lies in the retrospective nature of this study. While we were able to measure the available TCC in the vicinities of participants' living areas, we did not measure their actual time spent in or around greenspace. It is possible that individuals either stay at home most of the day, thereby bypassing the potential benefits of living in a TCC-dense environment, or avoiding the drawbacks of low TCC availability. Although these are hard to quantify, self-report measures have been previously used for estimating time in nature [7,54], attitudes toward spending time in nature [55], and the cognitive, emotional, and experiential connection to nature [56]. Our mental health measures covered depression and anxiety, but several other aspects of well-being are often impacted during TBI recovery (e.g., sleep, neurobehavioral symptoms, and potential trauma). While depression and anxiety represent a substantial cause for mental health detriments, capturing a broader spectrum of symptoms and conditions could provide a more comprehensive view of environmental contribution to long-term outcomes after TBI.

Furthermore, TBI is an umbrella term describing a traumatic injury that often results in neural damage; however, we did not control for the type or severity of the injury nor the neural networks negatively impacted by the injury. Emotional well-being may be more sensitive to changes in greenspace and shading in certain forms of TBI than others. Moreover, several factors may contribute to variation in levels of distress post-injury, such as disparities in discharge placement, post-TBI mortality rate, and functionality consequences [57]. In addition, limited financial resources, insurance status, and socioeconomic status can affect the availability and accessibility of care and how individuals seek and participate in care post-injury [57–59]. Adjusting for these important factors would better reveal the specific effects of TCC on post-TBI mental health.

4.2. Implications and future directions

These limitations highlight considerations for several points of intervention for future studies to strengthen the investigative approach and provide a more comprehensive characterization of the environmental impact on post-TBI outcomes. Given uneven distributions of individuals with TBI in urban areas, investigations of larger areas (and, thereby, larger sample sizes) are needed. When using broader ranges of geospatial areas, TCC might need to be taken in the context of seasonal temperatures, as alongside its added greenery benefits [60], greenspace density provides even more protection from sun exposure than building shade [61,62]. This opportunity is available by leveraging the full TBIMS National Database cohort, representing patients from model systems of TBI care from around the U.S. [40] Larger sample sizes would also allow for stratifying based on injury severity, indicating the real-world application of greenspace allocation or recommendations for environmental alterations during recovery from brain injury. Additionally, measures of actual exposure to nature can further contextualize the impact of environmental greenspace on the primary outcomes. Prospective studies using validated self-report measures mentioned above – or leveraging the ever-increasing capacity of mobile technologies to collect environment-specific data – could answer these questions.

Public health and other policies must have a strong backing in research in order to ensure beneficial and effective health interventions. Without this research, public health interventions can be costly and ineffective, or even cause harm. In addition, due to the diverse nature of disease and injury, what is beneficial for one group may be less so for other groups. As public health research further reveals the influence of geospatial context on mental and physical health, it is critical that this influence is also examined in specific patient populations, like those with TBI. In doing so, we can better understand what public policies, such as those related to changing an area's environmental context, will benefit those patients, and use this to shape public health work in the future.

5. Conclusion

Our current feasibility study supports further investigation into the potential relationship between neighborhood greenspace and depression among persons with TBI. We established the feasibility of our methods for calculating the percent TCC per census tract in the U.S. and pairing it with longitudinal outcome data from the TBI Model Systems. Future work will attempt to scale this approach up to investigate the relationship between percent TCC and long-term mental health outcomes in the full TBIMS National Database, providing the opportunity to examine potentially important relationships with sufficient power and in a sample that would allow for adjustment for relevant covariates and geographic location.

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