GREENSPACE AND ADOLESCENT MENTAL HEALTH: UNDERSTANDING GREENSPACE METRICS AND SOCIO-DEMOGRAPHIC EFFECT MODIFIERS

A Thesis
by
SOPHIA CROWLEY RYAN

Submitted to the School of Graduate Studies
at Appalachian State University
in partial fulfillment of the requirements for the degree of
MASTER OF ARTS

May 2023
Department of Geography

GREENSPACE AND ADOLESCENT MENTAL HEALTH: UNDERSTANDING GREENSPACE METRICS AND SOCIO-DEMOGRAPHIC EFFECT MODIFIERS

A Thesis
by
SOPHIA CROWLEY RYAN
May 2023

APPROVED BY:

_____
Maggie Sugg, PhD
Chairperson, Thesis Committee

_____
Jennifer Runkle, PhD
Member, Thesis Committee

_____
Bhuwan Thapa, PhD
Member, Thesis Committee

_____
Saskia van de Gevel, PhD
Chairperson, Department of Geography and Planning

_____
Marie Hoepfl, Ed.D.
Interim Dean, Cratis D. Williams School of Graduate Studies

Abstract

GREENSPACE AND ADOLESCENT MENTAL HEALTH: UNDERSTANDING GREENSPACE METRICS AND SOCIO-DEMOGRAPHIC EFFECT MODIFIERS

Sophia C Ryan
B.A., University of Vermont
M.A., Appalachian State University

Chairperson: Maggie Sugg, PhD

Poor mental health outcomes among young people, including anxiety, self-harm, and suicide, have increased substantially in recent years. Given this concerning rise, more research into low-cost mental health interventions is needed. Research suggests that greenspace may be protective of mental health. This study aims to further understanding of the greenspace-mental health association among young people in five distinct urbanities (i.e. urban, suburban, micropolitan, small towns, rural/isolated). We apply publicly available greenspace datasets, which were used to derive greenspace quantity, quality, and accessibility metrics. Emergency department visits for young people (<24 years) for the following mental health disorders were examined: anxiety, depression, mood disorders, mental and behavioral disorders, suicide-related outcomes, and substance use disorders. Generalized linear models investigated the association between greenspace and community-level drivers of mental health burden in North Carolina. Results found the prevalence of suicide-

related outcomes was highest in communities with the least amount of public greenspace (PRR_{Urban}: 1.11, CI: 1.08-1.13; $PRR_{Suburban}$: 1.27, CI: 1.10-1.46; $PRR_{SmallTowns}$: 1.21, CI: 1.05-1.39). Mood disorders saw the highest increase in prevalence in urban communities with low greenspace quantity (PRR: 1.19, CI: 1.16-1.21), anxiety disorders were associated with the greatest increase in rural/isolated communities with poor greenspace quality (PRR: 1.61, CI: 1.43-1.82), and both substance use disorders (PRR: 2.38, CI: 2.19-2.58) and depression (PRR: 2.09, CI: 1.72-2.53) were associated with the greatest increase in prevalence in rural/isolated communities with poor greenspace accessibility. Greenspace quantity interventions may be most effective in urban and suburban areas, greenspace quality interventions may be most beneficial in small towns and rural/isolated communities, and greenspace accessibility interventions may be most useful in urban, micropolitan and rural/isolated communities. Our analysis provides community-specific findings to guide targeted greenspace-mental health interventions.

Acknowledgments

Thank you to my committee members: Drs. Maggie Sugg, Jennifer Runkle and Bhuwan Thapa. This work was supported by the Faculty Early Career Development Program (CAREER) award (grant #2044839) from the National Science Foundation and the Human Environment Geographical Sciences (HEGS) Program - Research Experience for Graduate Students (REG). The North Carolina Disease Event Tracking and Epidemiologic Collection Tool (NC DETECT) is an advanced, statewide public health surveillance system. NC DETECT is funded with federal funds by the North Carolina Division of Public Health (NC DPH), Public Health Emergency Preparedness Grant (PHEP), and managed through a collaboration between NC DPH and the University of North Carolina at Chapel Hill Department of Emergency Medicine's Carolina Center for Health Informatics (UNC CCHI). The findings and conclusions in this publication are those of the author(s) and do not necessarily represent the views of the North Carolina Department of Health and Human Services, Division of Public Health. Thank you to my fellow graduate students and lab mates. Last, but not least, thank you to my ever-supportive family - Mom, Dad, Emma & Taylor.

Table of Contents

Foreword

Chapter 2 of this thesis will be submitted to *Science of the Total Environment*, an international peer-reviewed journal owned by Elsevier and published by Elsevier; it has been formatted according to the style guide for that journal.

Chapter 1. Literature Review

Greenspace positively impacts mental health and is a low-cost health intervention which encourages physical activity and social cohesion. Neighborhood greenspace quantity has been associated with benefits to population-level mental health and well-being, including a reduction in depression, psychological stress levels, prescription rates, and improved emotional well-being (Astell-Burt and Feng, 2019; Collins et al., 2020; Roberts et al., 2021). The positive health benefits of greenspace have been most effective among low-income groups (Browning and Rigolon, 2018; Hoffimann et al., 2017) and the socially marginalized, like older adults (Brown et al., 2018; Lee and Lee, 2019).

Due to a lack of universal metrics and definitions regarding greenspace, the pathways and intricacies of the greenspace-mental health relationship remain understudied (Collins et al., 2020; Lachowycz and Jones, 2013). Given that greenspace can function as low-cost preventative care for mental health, a better understanding of these relationships, especially across different contextual and compositional factors (such as rurality and age) is critical (Lachowycz and Jones, 2013).

Greenspace Definitions

Greenspace is defined and identified in numerous ways. Past studies' identifications of greenspace have ranged from considering total greenness (Beyer et al., 2014; Sarkar et al., 2018), to only including public parks as greenspace (Houlden et al., 2019; Mears and Brindley, 2019). When defining greenspace, most studies do not differentiate between public

and private greenspaces. The lack of universal greenspace definitions is exhibited in the three main metrics that are typically used -- quantity, quality, and accessibility.

Mental Health Outcomes

Past greenspace mental health research has found greenspace benefits anxiety (Beyer et al., 2014; de Vries et al., 2016; Nutsford et al., 2013), depression (Beyer et al., 2014; McEachan et al., 2016), mood disorders (de Vries et al., 2016; Nutsford et al., 2013) and general mental health and wellbeing (mental illness) (Feng and Astell-Burt, 2017a; Houlden et al., 2019; Wheeler et al., 2015; Zhang et al., 2017). Additionally, increases in greenspace quantity may be beneficial for addiction treatments and for helping reduce addiction-related cravings (Berry et al., 2021; Martin et al., 2019).

Greenspace Metrics

When considering greenspace quantity as a metric, results suggest that the more greenspace, the better the community-level mental health outcomes (van Dillen et al., 2012; Wang et al., 2021; Wood et al., 2017). Greenspace quantity is directly linked to the greenspace definition used and subsequent identification technique employed. Techniques for determining quantity include participant surveys (Zhang et al., 2017), using street view data (Wang et al., 2021), using local databases (Houlden et al., 2019; Mears and Brindley, 2019), or using GIS technologies to determine what quantity of land cover is comprised of green vegetation (e.g., NDVI) (Beyer et al., 2014; Sarkar et al., 2018; Wang et al., 2021) and calculating total acreage. Regardless of greenspace definition, more greenspace is associated with better mental health outcomes. However, the lack of universal metrics means there is a failure in

the literature to understand what aspects of greenspace quantity benefit mental health. Specifically, it is unclear if more total greenness or public greenspace is the key in the greenspace mental health relationship.

Quality is another metric utilized when studying greenspace and mental health. However, very few studies have attempted to qualify greenspace due to the subjectivity involved, as what makes high-quality greenspace varies depending on the individual. Of the studies that have considered quality, the most common technique is the use of surveys, therefore allowing the researcher to assess self-reported high-quality greenspace and mental health outcomes (Wang et al. 2021). Other studies have qualified greenspace through consideration of the physical characteristics of the greenspace itself, such as land cover, conservation easements, land designations, species diversity and health, and presence of birds (Wheeler et al. 2015), in addition to water features and heavy tree cover to provide numerous options for shade in hot months (Mears et al., 2019a). The findings from these studies suggest quality of greenspace may be a crucial factor in the greenspace mental health relationship. However, the lack of universal metrics and qualifiers inhibits further understanding of how greenspace quality may influence mental health.

The third metric commonly used when evaluating greenspace is accessibility. In the literature, accessibility refers to how far an individual must travel to access greenspace. Buffers are commonly utilized to ascertain accessibility and can range from 100m to 3km, or larger (Mears and Brindley, 2019; Nutsford et al., 2013). When determining accessibility, most studies consider walkability, which translates to, at most, an 800m buffer (Ekkel and de

Vries, 2017; Houlden et al., 2019; Mears and Brindley, 2019). Findings from studies that have conducted accessibility analyses suggest that regardless of the accessibility buffer distance, more access translates to better mental health outcomes (Ekkel and de Vries, 2017; Nutsford et al., 2013). As such, this suggests that having ample easy access to greenspace benefits mental health.

Contextual and Compositional Factors

In addition to greenspace metrics, consideration of contextual factors, such as rurality and community-level socio economic status and racial/ethnic demographics, and compositional factors, including race, age and gender identity is necessary to better understand the greenspace mental health relationship.

Research shows that regardless of rurality greenspace benefits mental health (Beyer et al., 2014; van Dillen et al., 2012; Zhang et al., 2017). However, the intricacies of this relationship may be different in urban areas versus rural areas (Ekkel and de Vries 2017). Studies focusing on greenspace and mental health in urban areas suggest that quality and accessibility are especially important (Nordh et al., 2017; van Dillen et al., 2012; Wang et al., 2021). The quality of greenspace, specifically with regards to legal accessibility, becomes more important (Carter and Horwitz, 2014), potentially due to the lack of private yards in urban areas. In terms of accessibility, walkability is especially important in urban areas, as are walkable greenspaces, such as greenspaces that offer trail networks or parks that offer walking trails (Nordh et al., 2017). Furthermore, satisfaction of an individual's urban living

situation and with their community have been linked to quantity, quality and accessibility of nearby greenspace (Zhang et al., 2017).

The greenspace mental health relationship is slightly different in rural areas. This is likely due to the surrounding countryside greenness, prevalence of private greenspace and access to agricultural fields (Ekkel and de Vries, 2017). However, access to greenspace is still shown to be protective of mental health in rural areas (Beyer et al., 2014; Ryan et al., 2023). With this said, most research focuses on urban greenspace access and mental health, indicating future research needs to consider urbanity, or rurality, as a contributing factor to better understand the greenspace mental health relationship.

In addition to rurality, community-level socio economic status and racial/ethnic demographics may also influence the greenspace mental health relationship. It is well known that greenspace is not equitably or equally distributed (Mears and Brindley, 2019). High-income, predominantly White neighborhoods tend to have more access to greenspace and outdoor recreation opportunities (Hoffimann et al., 2017; Kimpton, 2017; Mears and Brindley, 2019; Rigolon et al., 2018a). Greenspace in low income, often minority neighborhoods, is typically further away, less well-maintained and may pose a safety risk for users (Hoffimann et al., 2017). Given that greenspace can be a low-cost preventative healthcare option, ensuring equitable access to greenspace is key. However, there is a long history of greening followed by gentrification, or greening occurring at the early stages of gentrification (Goossens et al., 2020; Rigolon et al., 2018a). Therefore, to ensure that access to greenspaces does not result in the gentrification of a neighborhood, intentional,

community-based greenspace development should be considered. With all this said, studies have shown that greenspace remains protective of mental health regardless of socio-economic status or race/ethnicity (Rigolon et al., 2018a).

Individual age and gender identity have also been shown to have an effect (Astell-Burt et al., 2014). While neither of these factors are regularly considered, studies that have included these confounding factors have found that the greenspace mental health relationship may change with age and gender identity. Astell-Burt et al., (2014) found that middle-aged men and older women experience the greatest mental health benefits from greenspace. Interestingly, Feng and Astell-Burt (2017) suggest that the mental health benefits of greenspace for children become more prevalent as youth transition into adolescence and young adulthood, and that greenspace quality is especially important in this relationship. These findings suggest that community and individual-level factors may influence the greenspace mental health relationship. As such, additional focus on these potential influencing factors is necessary to better understand greenspace and mental health (Lachowycz and Jones 2013).

Causal Pathways

In addition to quantity, quality and accessibility, attention has been directed towards understanding the causal pathways through which greenspace benefits mental health. Four main pathways have been identified – stress reduction, social cohesion, pollution reduction and outdoor recreation (Lachowycz and Jones, 2013; Wang et al., 2021). Stress reduction occurs due to the restorative properties of nature, such as breathing fresh air, interacting with

other species or intentionally taking time to relax (Lachowycz and Jones 2013). Social cohesion occurs by interacting with community members, attending sporting events, or participating in outdoor group activities, to name a few (Lachowycz and Jones 2013). Pollution reduction occurs thanks to the physical properties of plants found in greenspaces, and people have reported that they appreciate having access to greenspace for this specific reason (Wang et al. 2021). Recreation opportunities are of particular interest due to their role as a causal pathway, by offering opportunities for physical exercise and social cohesion (Lachowycz and Jones 2013), and due to the additional mental health benefits physical activity offers (Thompson Coon et al., 2011).

Adolescent Mental Health

Poor mental health among adolescents, including depression (Keyes et al., 2019; Thorisdottir et al., 2017), anxiety (Duffy et al., 2019; Eisenberg, 2019; Thorisdottir et al., 2017), self-harm (Duffy et al., 2019; Eisenberg, 2019) and suicide (Duffy et al., 2019; Eisenberg, 2019) have increased substantially in recent years (Keyes et al., 2019). Observed increases in poor mental health outcomes among youth, adolescents, and young adults have been especially pronounced for females (Keyes et al., 2019; Mercado et al., 2017; Thorisdottir et al., 2017), LGBTQ+ individuals (Fish et al., 2020; Ormiston and Williams, 2022; Salerno et al., 2020), adolescents of color (Lindsey et al., 2019), and Hispanic individuals (Runkle et al., 2021).

Recent research suggests that increases in poor mental health outcomes among adolescents may be attributed to increased social media use (Odgers and Jensen, 2020) and exposure to

extreme events (Danese et al., 2020). Investigation into low-cost mental health interventions are needed for this population.

Adolescent Mental Health and Greenspace

Recent research has focused on investigating the associations between greenspace exposure and childhood attention and behavior. Findings suggest greenspace is associated with better attention among adolescents (ages 13-17) (Bijnens et al., 2022), and contact with greenspace may be beneficial for child neurological development (Luque-García et al., 2022). In addition to being associated with short-term improvements to behavior and attention among children, adolescents and young adults, prolonged exposure to greenspace in childhood and adolescence has been associated with lower risk of developing psychiatric disorders in adulthood (Engemann et al., 2019).

Among children, adolescents and young adults, greenspace quality (Feng et al., 2022; Feng and Astell-Burt, 2017a, 2017b; Lyons et al., 2022; Vanaken and Danckaerts, 2018), and accessibility (Markevych et al., 2014a; Zach et al., 2016) may be more important than neighborhood greenspace quantity. Findings further suggest that the relationship between greenspace and mental health may change as individuals age through adolescence and young adulthood. Feng and Astell-Burt (2017a) suggest that the mental health benefits of greenspace for children become more prevalent as youth transition into adolescence and young adulthood, and that greenspace quality is especially important in this relationship.

Despite an increase in greenspace-mental health research in recent years, gaps in understanding persist. First, past studies have relied primarily on self-reported, or parent-reported wellbeing questionnaires to quantify mental health (Vanaken and Danckaerts, 2018). Second, many studies do not consider multiple greenspace metrics (e.g. quality, quantity, accessibility), relying on NDVI to quantify greenspace (Vanaken and Danckaerts, 2018), or self-reported questionnaires relating to neighborhood greenspace quantity, quality and/or accessibility (Vanaken and Danckaerts, 2018). Third, there is a gap in the literature relating to mental health concerns, such as anxiety, depression or suicide-related outcomes, with more focus targeted at childhood and adolescent behavior, hyperactivity and attention (Vanaken and Danckaerts, 2018). Fourth, many studies focus on one stage of development (e.g., childhood), rather than considering multiple stages of development (e.g., childhood, adolescence, young adulthood) to see how the relationships between greenspace and mental health change as individuals age. Finally, research is most often conducted in urban settings, and those that consider rural neighborhoods tend to consider rurality as a binary (rural vs urban), rather than as a continuum. Consideration of rurality may provide needed insight into the childhood, adolescent and young adult greenspace-mental health relationship.

Chapter 2. Manuscript

Abstract

Poor mental health outcomes among young people, including anxiety, self-harm, and suicide, have increased substantially in recent years. Given this concerning rise, more research into low-cost mental health interventions is needed. Research suggests that greenspace may be protective of mental health. This study aims to further understanding of the greenspace-mental health association among young people in five distinct urbanities (i.e. urban, suburban, micropolitan, small towns, rural/isolated). We apply publicly available greenspace datasets, which were used to derive greenspace quantity, quality, and accessibility metrics. Emergency department visits for young people (<24 years) for the following mental health disorders were examined: anxiety, depression, mood disorders, mental and behavioral disorders, suicide-related outcomes, and substance use disorders. Generalized linear models investigated the association between greenspace and community-level drivers of mental health burden in North Carolina. Results found the prevalence of suicide-related outcomes was highest in communities with the least amount of public greenspace (PRR_{Urban}: 1.11, CI: 1.08-1.13; $PRR_{Suburban}$: 1.27, CI: 1.10-1.46; $PRR_{SmallTowns}$: 1.21, CI: 1.05-1.39). Mood disorders saw the highest increase in prevalence in urban communities with low greenspace quantity (PRR: 1.19, CI: 1.16-1.21), anxiety disorders were associated with the greatest increase in rural/isolated communities with poor greenspace quality (PRR: 1.61, CI: 1.43-1.82), and both substance use disorders (PRR: 2.38, CI: 2.19-2.58) and depression (PRR: 2.09, CI: 1.72-2.53) were associated with the greatest increase in prevalence in rural/isolated communities with poor greenspace accessibility. Greenspace quantity interventions may be most effective in urban and suburban areas, greenpace quality interventions may be most beneficial in small towns and rural/isolated communities, and greenspace accessibility interventions may be most useful in urban, micropolitan and rural/isolated communities. Our analysis provides community-specific findings to guide targeted greenspace-mental health interventions.

Keywords: children, young adults, suicide-related outcomes, green space, substance use

Introduction

Poor mental health among adolescents, including depression (Keyes et al., 2019; Martínez-Alés and Keyes, 2019; Thorisdottir et al., 2017), anxiety (Eisenberg, 2019; Thorisdottir et al., 2017), self-harm (Duffy et al., 2019; Eisenberg, 2019) and suicide (Duffy et al., 2019; Eisenberg, 2019) have increased substantially in recent years (Keyes et al., 2019). Observed

increases in poor mental health outcomes among children, adolescents, and young adults have been especially pronounced for females (Keyes et al., 2019; Mercado et al., 2017; Thorisdottir et al., 2017), individuals who identify as LGBTQ+ (Fish et al., 2021, 2020; Ormiston and Williams, 2022), adolescents of color (Lindsey et al., 2019), and Hispanic individuals (Runkle et al., 2021). To better inform targeted mental health interventions, additional research into low-cost mental health resources, such as greenspace, are needed for this population.

Recent research has focused on investigating the associations between greenspace exposure and childhood attention and behavior (Bijnens et al., 2022; Luque-García et al., 2022). Findings suggest greenspace is associated with better attention, both in terms of focusing on one specific task and the ability to continue focusing despite external distractions, among adolescents (ages 13-17) (Bijnens et al., 2022). Further research suggests that contact with greenspace may be beneficial for child neurological development (Luque-García et al., 2022).

Among children, adolescents, and young adults, greenspace quality (measured as user-perceived or parent perceived greenspace quality) (Feng and Astell-Burt, 2017b, 2017a; Feng et al., 2022; Lyons et al., 2022; Vanaken and Danckaerts, 2018), and accessibility (measured as availability or greenspace or distance from residence to nearest greenspace) (Markevych et al., 2014b; Zach et al., 2016) may be more important than neighborhood greenspace quantity. Findings further suggest that the association between greenspace and mental health may change as individuals age through adolescence and young adulthood. Feng and Astell-Burt

(2017a) suggest that the mental health benefits of greenspace for children become more prevalent as youth transition into adolescence and young adulthood, and that greenspace quality is especially important in this relationship. In addition to being associated with short-term improvements in behavior and attention, prolonged exposure to greenspace in childhood and adolescence is associated with a lower risk of developing psychiatric disorders in adulthood (Engemann et al., 2019).

Past greenspace mental health research among the general population has found greenspace is associated with population-level reductions in anxiety (Beyer et al., 2014; de Vries et al., 2016; Nutsford et al., 2013), depression (Beyer et al., 2014; McEachan et al., 2016), mood disorders (de Vries et al., 2016; Nutsford et al., 2013) and general mental health and wellbeing (mental illness) (Feng and Astell-Burt, 2017b; Houlden et al., 2019; Zhang et al., 2017). Additionally, increases in greenspace quantity may be beneficial for addiction treatments and helping reduce addiction-related cravings (Berry et al., 2021; Martin et al., 2019).

The greenspace-mental health association is typically investigated by looking at the quantity, quality and/or accessibility of greenspace. However, the identification of greenspace, and thus, greenspace quantity calculations, is highly variable, with past studies identifying greenspace using participant surveys (Zhang et al., 2017), street view data (Wang et al., 2021), local governmental databases (Houlden et al., 2019; Mears and Brindley, 2019), or through land use, land cover and Normalized Difference Vegetation Index (NDVI) datasets (Beyer et al., 2014; Sarkar et al., 2018; Wang et al., 2021).

Greenspace quality metrics are more subjective and are considered less frequently (Collins et al., 2020). Of the studies that have considered quality, the most common technique is the use of participant surveys, which provide self-reported greenspace quality (Feng and Astell-Burt, 2017a; Wang et al., 2021). However, participant surveys are not always available, and first order data collection may not be feasible on a large scale; thus other studies have qualified greenspace quality through consideration of the physical characteristics of the greenspace itself, such as land cover, conservation easements, land designations, species diversity and health, and presence of birds (Wheeler et al., 2015). Greenspace accessibility is often quantified using GIS buffer analysis (Ekkel and de Vries, 2017; Houlden et al., 2019). The lack of a universal consensus on a set of predefined greenspace metrics that best operationalize quantity, quality, and availability makes drawing conclusions and comparing results difficult.

This study aims to further understanding of the greenspace-mental health association among young people in five distinct urbanities (i.e., urban, suburban, micropolitan, small towns, rural/isolated). We apply publicly available greenspace datasets, which were used to derive greenspace quantity, quality, and accessibility metrics. The exploration of multiple greenspace metrics, in addition to an administrative emergency-department mental health dataset, contributes new knowledge to the greenspace-mental health association. Furthermore, consideration of a suite of mental health outcomes (e.g., mood disorders, anxiety, suicide-related outcomes) and effect modification analyses investigating how rurality, age, and sex may influence the association provide important information for targeted health interventions. Given that greenspace may function as low-cost preventative

mental health care, a better understanding of these associations and how they vary with rurality is critical.

Methods

Health Data

Emergency department (ED) visit data were obtained from the North Carolina Disease Event Tracking and Epidemiologic Collection Tool (NC DETECT) (NC DETECT, 2021) for 2016-19. NC DETECT provides complete spatio-temporal coverage of ED visits in North Carolina (NC DETECT, 2021). For this analysis, data were restricted to ED visits of individuals aged 24 and younger, producing a dataset of 5,357,703 total ED visits between January 2016 and December 2019.

ED data were coded using the International Classification of Diseases 10-CM codes (ICD-10) (Supplemental Table 1) to isolate six mental health outcomes: (1) anxiety, (2) depression, (3) mental and behavioral disorders (an aggregated category including any mental health concern), (4) mood disorders, (5) suicide-related outcomes, and (6) substance use disorders. To identify suicide-related outcomes cases, ED visits were coded for intentional self-harm, self-poisoning and toxic effects, suicidal ideation, and asphyxiation (Ridout et al., 2021). Substance use disorders included any substance-related ED visit (e.g., alcohol, opioids).

The unit of analysis was the Zip Code Tabulation Area (ZCTA) level, with individual ED data converted from zip code to ZCTA when applicable (AAFP, 2022). ZCTAs are a US Census Bureau spatial geography relating to mailing postal codes (US Census Bureau, 2022)

and are considered one of the original categorizations of a neighborhood (Duncan and Kawachi, 2018). In NC, ZCTAs have a median area of 115km2. ZCTA is the finest spatial resolution available for the NC DETECT health dataset. Mental health outcomes were coded in RStudio, version 2022.07.1 (RStudio Team, 2022).

Greenspace Data

For this analysis, greenspace was identified using two publicly available greenspace datasets: the Protected Area Database of the United States (PAD-US) (USGS, 2020), and the Trust for Public Land's ParkServe dataset (TPL, 2021) (Figure 1). PAD-US is a spatial dataset of all government-managed greenspaces (e.g., wildlife refuges, national forest land, historical sites). Greenspace selection was restricted to remove any non-public greenspaces (e.g., military bases), to ensure selected greenspaces were publicly accessible (Browning et al., 2022; J. D. Runkle et al., 2022). ParkServe is a spatial dataset comprising all public parks (e.g., local and city parks) (TPL, 2021). No additional selection criteria were applied to the ParkServe dataset. ParkServe and PAD-US data were combined to create one spatial greenspace dataset in ArcGIS Pro 3.0.0 (ESRI, 2022) (Figure 1). This dataset was used to generate the following greenspace metrics for each neighborhood (i.e. ZCTA):

1.) Greenspace quantity considers the total amount of public greenspace per ZCTA. For this analysis, greenspace quantity was operationalized as two metrics: (a) Percent Greenspace and (b) Greenspace per person (Runkle et al., 2022) (Table 1). Calculations were made in ArcGIS Pro 3.0.0 (ESRI, 2022).

2.) Greenspace accessibility was operationalized as one metric: Greenspace distance (Table

Calculations were made in ArcGIS Pro 3.0.0 (ESRI, 2022).

3.) Greenspace quality was operationalized as three metrics: (a) Perimeter area ratio (PAR), (b) Average Google Review, and (c) Nearest Google Review (Table 1). The PAR was included to capture greenspace patchiness (Fonseca, 2008). Natural landscape patchiness is often a proxy for biodiversity; as patchier natural spaces tend to have higher edge effects which can harm flora and fauna (Helzer and Jelinski, 1999). ZCTAs with no public greenspace were categorized as poor quality. The average google review was calculated by averaging all available average greenspace google reviews for each ZCTA, producing one value for each ZCTA. The nearest google review was determined by identifying the nearest greenspace's average google review (see greenspace accessibility) (Table 1) (Supplemental Figure 3).

Covariates

Analyses were adjusted for ZCTA race and socio-economic status using the Index of the Concentration of Extremes (ICE) (Krieger et al., 2016). ICE considers extreme concentrations of economic and racial privilege and deprivation by analyzing the spatial distribution of income and race using US Census Data, producing community-level race and income metrics (Krieger et al., 2016). The first metric, ICE: Income, measures ZCTA income extremes by comparing how many households make over $100,000 per year to how many make under $25,000 per year. The second metric, ICE: Race, captures racial segregation of a community by comparing the number of Black residents to the number of White residents. For this analysis, ICE metrics were computed as tertiles. The use of tertiles was adapted to improve the interpretability of the regression results; where Tertile 1 corresponds to

predominately low income (ICE: Income) and predominately Black (ICE: Race); Tertile 2 corresponds to mixed income (ICE: Income) and mixed race (ICE: Race), and Tertile 3 corresponds to predominantly high income (ICE: Income) and predominantly White (ICE: Race) (Supplemental Figure 1).

Mental Health Professional Shortage Areas (MHPSA) (HRSA, 2023) data was included to adjust for community mental health care access. MHPSA data was included as a binary variable, where each ZCTA is either located in a MHPSA (1) or not (0) (Supplemental Figure 2).

Greenspace-mental health association may vary with rurality (Jiang et al., 2021; Ryan et al., 2023). Rurality was included using Rural-Urban Commuting Area (RUCA) codes at the ZCTA-level (USDA, 2020). RUCA codes range from 1-10. This analysis followed RUCA divisions and operationalized rurality with five classifications, where RUCA code 1 was considered urban, RUCA codes 2-3 were considered suburban, RUCA codes 4-6 were considered micropolitan, RUCA codes 7-9 were considered small towns, and RUCA code 10 was considered rural/isolated (USDA, 2020) (Figure 2).

Age categories were considered to see if the greenspace-mental health association changes with age (Feng and Astell-Burt, 2017a). Three age categories were created to capture childhood (ages 14 and under), adolescence (ages 15-17), and young adulthood (ages 18-24) (US Census Bureau, 2020).

Sex was included, where data were categorized as ED visits among males and ED visits among females to see if sex influences the greenspace-mental health association (Sillman et al., 2022).

Variable Importance

Machine learning was employed to quantify variable importance. Variable importance was determined using the GLM elastic net regression (GLMNET) function from the 'caret' package in RStudio version 2022.07.1 (RStudio Team, 2022). GLMNET models were run with a Poisson distribution and included greenspace area per person, distance to nearest greenspace, and the perimeter:area ratio; the tuneLength was set to three as there were three independent variables. Supplemental Figure 4 depicts GLMNET results.

Statistical Analysis

Generalized linear models (GLMs) with a poisson distribution were used to analyze the association between ZCTA mental health burden and greenspace quantity, quality, and accessibility in North Carolina. Stratified analyses were employed to investigate the presence of effect modification by (1) Rurality, (2) Age, and (3) Sex.

GLMs were run to assess if greenspace is associated with community-level mental health outcomes among individuals aged 24 and younger. All five greenspace metrics were considered in the state-wide analysis, and one model was run for each mental health outcome, producing six total models. Due to multicollinearity, percent greenspace was removed from these models in favor of greenspace per person. The google review-based

quality metrics were included in the initial analysis, but excluded from effect modification analyses as the availability of google review data was skewed to urban areas.

Stratified GLMs were run to investigate the effect modification of rurality. Age and sex-stratfied models were included as a supplemental analysis. Models were run for each rurality designation and each mental health outcome (30 models); each age group and each mental health outcome (18 models); and each sex and mental health outcome (12 models). For the stratified effect-modification analyses, Average google review and Nearest google review were removed in favor of the PAR metric, as it is a more standardized measure of greenspace quality.

All GLMs were adjusted for race, income, population, and MHPSA designation. All greenspace metrics and the ICE index metrics were included in the GLMs as tertiles to improve interpretation. Tertiles were calculated for each rurality. MHPSA data was included as a binary, and population was included as a continuous variable.

Multicollinearity was considered by calculating the Variance Inflation Factor (VIF) to identify the best model (Craney and Surles, 2002). The percent greenspace metric was removed for violating the assumption of independence. Models considering all greenspace metrics and sociodemographic factors had the lowest AIC values.

Results

Demographic Summary

Table 2 summarizes the demographic characteristics for all ED visits, and for each mental health-related ED visit. Overall, there were 5,357,703 total ED visits. ED visits for any mental health concern were highest among females (51.5-67.7%), White individuals (60.7-69.6%), and young adults aged 18-24 (48-92.2%). The most prevalent mental health outcome was substance use disorder followed by anxiety and depression.

Greenspace Metric Distribution

Figure 3 depicts the distribution of greenspace metrics in North Carolina. Greenspace quantity is highest in western and eastern North Carolina. Greenspace accessibility varies throughout the state; with southwestern NC and the urban centers of Charlotte, Durham and Greensboro having the best community-level greenspace access, and many ZCTAs in eastern NC having the worst greenspace access. Greenspace quality, operationalized as the perimeter:area ratio (PAR), is the best in eastern NC (smallest PAR values), and worst in western NC (highest PAR values).

Generalized Linear Models

Table 3 reports state-wide GLM results. All five greenspace metrics were included in the state-wide analyses. ZCTAs with low or moderate greenspace quantity (greenspace area/person: T1, T2) were associated with higher prevalence rate ratios (PRRs) for all mental health outcomes; suicide-related outcomes were associated with up to 1.73 (CI: 1.67-1.78, $p<0.001$) higher prevalence of suicide-related outcomes as compared to the ZCTAs with the

greatest quantity of public greenspace (T3). Living in ZCTAs with moderate greenspace accessibility (T2) were associated with higher prevalence of all mental health outcomes; this increase was highest for anxiety (PRR: 1.25, CI: 1.23-1.27, $p<0.001$). Moderate greenspace quality was significantly associated with population-level mental health benefits; this increase was largest for anxiety (PRR: 1.05, CI; 1.03-1.06) and suicide-related outcomes (PRR: 1.05, CI; 1.03-1.07). ZCTAs with lower reviews of the nearest greenspace were associated with higher PRRs across all mental health outcomes; substance use disorder had the largest PRR values (PRR: 1.27, CI: 1.25-1.28).

Rurality-Stratified

Table 4 reports GLM results for rurality-stratified models. In both urban and suburban ZCTAs, ZCTAs with less greenspace quantity were associated with higher PRRs for all mental health outcomes, as compared to ZCTAs with more greenspace quantity. In urban areas, suicide-related outcomes was the only health outcome that exhibited it's highest PRR in ZCTAs with least amount of public greenspace per person (T1); with suicide-related outcomes 11% higher (PRR: 1.11, CI: 1.08-1.13). However, for all other health outcomes, ZCTAs with moderate greenspace quantity (T2) were associated with the highest PRR estimates; this association was most substantial for mood disorders, with a 33% (CI: 1.30-1.35) higher prevalence of mood disorders in ZCTAs with moderate greenspace quantity as compared to ZCTAs with high greenspace quantity. Suburban areas indicate that as greenspace quantity decreases, mental health outcome prevalence increases. In suburban ZCTAs, the association with greenspace quantity was most pronounced for substance use disorders, with a 1.35 (CI:1.28-1.43) higher prevalence of substance use disorders.

In urban, micropolitan and rural/isolated areas, increasing distance to nearest greenspace was associated with higher PRRs across all mental health outcomes. For urban and rural/isolated neighborhoods, this relationship was most pronounced for substance use disorders, with a 1.35 (CI:1.28-1.43) higher prevalence in urban areas and a 2.38 (CI: 2.19-2.58) higher prevalence in rural/isolated areas. In micropolitan areas, moderate greenspace accessibility (T2) was associated with higher PRRs; this association was greatest for mood disorders, with a 1.53 (CI: 1.48-1.58) higher prevalence of mood disorders, as compared to those with the best greenspace accessibility (T1) (Table 4). In contrast to the other mental health outcomes, both mental and behavioral disorders, and substance use disorders were associated with higher PRRs in ZCTAs with worse greenspace accessibility, this association was most substantial for substance use disorders (PRR: 1.47, CI: 1.43-1.51).

Both small towns and rural/isolated ZCTAs with worse greenspace quality (higher PAR values: T2 & T3) were significantly associated with higher PRRs for all mental health outcomes, except for suicide-related outcomes, as compared to ZCTAs with better greenspace quality (T1). In small towns this relationship was most substantial for substance use disorders, with 1.4 (CI:1.33-1.47) higher PRR of substance use disorders in ZCTAs with worse greenspace quality. In rural/isolated ZCTAs, this relationship was most pronounced for anxiety, with a 1.61 (CI: 1.53-1.82) higher prevalence of anxiety in ZCTAs with worse greenspace quality, as compared to ZCTAs with better greenspace quality (Table 4).

Age and Sex-Stratified

Supplemental Table 1 reports age-stratified GLM results for the entire state of NC. Across all three age groups (14 and under, 15-17, and 18-24), ZCTAs with less public greenspace quantity (greenspace area per person: T1 & T2) were significantly associated with higher prevalence of all mental health outcomes, compared to ZCTAs with more greenspace quantity (T3). Supplemental Table 2 reports sex-stratified GLM results for the entire state of NC. No substantial differences in the greenspace-mental health association were noted between males and females. A detailed explanation of age and sex results can be found in Supplemental Materials (Appendix A).

Discussion

This study investigated the association between three distinct greenspace metrics: greenspace quantity, quality, and accessibility, and population-level mental health outcomes among children, adolescents, and young adults in North Carolina. Results reveal that suicide-related outcomes, a behavioral mental health outcome, were significantly associated with a higher prevalence in communities with low to moderate quantities of greenspace, compared to those with higher quantities of greenspace. Other mental health outcomes (e.g., anxiety, depression, mood disorders, mental and behavioral disorders, and substance use disorders) were also significantly associated with greenspace metrics, though the association varied substantially with rurality.

Suicide-Related Outcomes Findings

Despite escalating rates of suicide-related outcomes (Keyes et al., 2019; Martínez-Alés and Keyes, 2019), few studies have considered the association between neighborhood greenspace quantity and suicide-related outcomes among adolescents. Our results suggest that increasing greenspace quantity may be protective for suicide-related outcomes, and this association remained robust for urban, suburban, small town, and rural/isolated neighborhoods. These findings support previous work, which found that greenspaces were associated with protective effects for suicide-related outcomes (Ryan et al., 2023), and suicides (Jiang et al., 2021; Ryan et al., 2023) in both urban and rural communities. Our findings also corroborate past research which found higher quantities of greenspace were associated with lower odds of serious psychological distress (Wang et al., 2019) and depression (Bezold et al., 2018) among adolescents, and exposure to high quantities of greenspace in childhood and adolescence may reduce the likelihood of developing psychiatric disorders in young adulthood (Engemann et al., 2019).

Our analysis found that greenspace accessibility can also function as a low-cost mental health intervention for suicide-related outcomes; specifically in urban, micropolitan, and rural/isolated areas. To the author's knowledge, this is one of the first analyses to investigate greenspace accessibility in non-urban settings (i.e., micropolitan, rural). Our results indicate that in addition to increasing greenspace quantity, many communities benefit from having better access to public greenspaces. In urban and micropolitan areas, better access to greenspace can make the beneficial aspects of greenspace, such as stress reduction and social cohesion (Liu et al., 2022; Wang et al., 2021) more readily available. In rural areas, better

access to greenspaces may provide opportunities for social cohesion, a pathway through which greenspace benefits mental health (Liu et al., 2022; Wang et al., 2021), and could be indicative of economic opportunities through recreation tourism. Recent research further indicates that better access to greenspaces during the pandemic was associated with higher prevalence of mental health resilience (Lee et al., 2023). Our findings add to the growing body of research linking greenspace accessibility to population-level mental health benefits. These compelling findings highlight the importance of developing equitable and accessible greenspaces.

Our analysis did not find suicide-related outcomes to be significantly associated with mental health benefits from greenspace quality, when operationalized as the PAR. Recent research has focused on assessing greenspace quality with surveys to understand user-perceived greenspace quality and safety of access (Feng and Astell-Burt, 2017a; Wang et al., 2021). Results from these analyses suggest that users who perceive their neighborhood greenspace to be safe to use and of high quality, are often associated with lower self-reported poor mental health (Feng and Astell-Burt, 2017a; Wang et al., 2021). Further research suggests that the type of greenspace (i.e sports complex, nature path) may mediate the association between greenspace quality and mental health (Mueller et al., 2023). Our analysis relied on emergency department visit data and state-wide greenspace metrics; collecting survey data on this scale is not feasible. As such, we recommend future research investigate additional greenspace quality metrics to better understand what characteristics and types of greenspaces are most beneficial for reducing suicide-related outcomes prevalence at the community level.

Suite of Five Mental Health Outcomes

Most greenspace-mental health research among children, adolescents, and young adults has focused on behavioral and attention problems; with less focus directed at additional mental health outcomes (Vanaken and Danckaerts, 2018). Most mental disorders develop between the ages of 14 and 24 (American Psychiatric Association, 2023), stressing the need for a better understanding of place-based, low-cost mental health interventions for this population. Our analysis found greenspace quantity was protective of poor mental health (i.e., anxiety, depression, mood disorders, substance use disorders and mental and behavioral disorders) in urban and suburban neighborhoods. Whereas, greenspace accessibility was protective in urban, micropolitan and rural/isolated areas, and greenspace quality was protective in small towns and rural/isolated communities. Our findings indicate that greenspace is protective of a wide suite of mental health outcomes among young people, and this association varies substantially with rurality. Our findings can help guide targeted, place-based greenspace interventions.

Past research indicates that greenspace quantity is protective for mental health (including neurocognitive development) in urban areas (Bezold et al., 2018; Bijnens et al., 2022; Engemann et al., 2019; Houlden et al., 2019; Islam et al., 2020; Madzia et al., 2019; Wang et al., 2019, 2021). Our analysis corroborates these findings, where all six mental health outcomes included in this analysis were more prevalent in urban communities with lower quantities of greenspace. Furthermore, we contribute new knowledge that this association remains true in suburban areas. In urban areas, mood disorders were 19% higher in communities with poor greenspace quantities; in suburban areas, substance use disorders

were 35% higher in communities with poor greenspace quantities. Untreated mood disorders may be a precursor of adolescent suicide (Runkle et al., 2022), and suicide-related outcomes related ED visits are often associated with mood disorders (Bježančević et al., 2019; Kim et al., 2020); emphasizing the importance of mood disorder interventions among adolescents.

Recent research corroborates our substance use disorder findings; suggesting greenspace may be associated with lower rates of binge drinking and tobacco-use among adolescents and young adults (Wiley et al., 2022), and the general public (Berry et al., 2021; Ryan et al., 2023). Our analysis highlights the protective role of greenspace quantity for young people's mental health in urban and suburban neighborhoods. Higher quantities of greenspace can contribute to lower community mental health burdens as greenspace can provide opportunities for physical recreation, social cohesion, and pollution reduction (Liu et al., 2022; Wang et al., 2021). Our analysis highlights that higher quantities of public greenspaces are protective of mental health among young people in both urban and suburban neighborhoods.

Better greenspace accessibility was associated with a lower prevalence of poor mental health outcomes in urban, micropolitan, and rural and isolated neighborhoods. Our results corroborate past research, which found greenspace accessibility was significantly associated with lower mental health burdens among young people in urban communities (Zach et al., 2016; Markevych et al., 2020), and contribute new knowledge that this association is also present in micropolitan and rural communities. For all three ruralities, this association was most pronounced for substance use disorders, which were 31% more prevalent in urban

neighborhoods with the worst greenspace access, 47% more prevalent in micropolitan neighborhoods with the worst greenspace access, and 138% more prevalence in rural communities with the worst greenspace access. Greenspace accessibility may indicate better opportunities for social cohesion (Dimitrova et al., 2017; Jennings and Bamkole, 2019). Community, family, and social cohesion may be a protective factor against adolescent and young adult substance use (Cleveland et al., 2008; Maclin-Akinyemi et al., 2021; Pei et al., 2020). Our findings add evidence that greenspace interventions, both quantity and accessibility, may reduce community substance use burdens (Berry et al., 2021; Wiley et al., 2022).

In both small towns and rural and isolated areas, worse greenspace quality, when operationalized as the PAR, was associated with a higher prevalence of poor mental health outcomes. This association was particularly pronounced for substance use disorders, which were 40% more prevalent in small towns with poor greenspace quality, and anxiety disorders, which were 61% more prevalent in rural communities with poor greenspace quality. As substance use disorders were also significantly associated with greenspace quantity and accessibility, these findings highlight that greenspace interventions, whether in the form of increasing greenspace quantity, accessibility, or quality, may be beneficial for reducing the community substance use disorder burden; these associations are dependent on place. Our findings regarding a higher prevalence of anxiety in rural communities with poor greenspace quality corroborate other analysis, which suggests that one of the main pathways through which greenspaces benefits mental health is via restorative experiences which promote stress reduction (Liu et al., 2022; Wang et al., 2021). Our quality metric (PAR) is

used as a proxy for habitat fragmentation and biodiversity (Helzer and Jelinski, 1999). Access to more biodiverse greenspaces can aid in promoting overall wellbeing (Carrus et al., 2015; Mavoa et al., 2019). Based on our findings, greenspace interventions in rural areas and small towns should emphasize development of high-quality greenspaces.

Implications

Our results indicate that greenspace interventions for child, adolescent, and young adult mental health in urban areas should focus on improving equitable greenspace accessibility, and community-level interventions aimed at reducing population-level suicide-related outcomes rates should also consider increasing greenspace quantity. Both of these interventions could involve development of greenspaces in neighborhoods with poor accessibility. Greenspace interventions in suburban neighborhoods should focus on increasing greenspace quantity, especially for substance use disorders. In micropolitan areas, our results suggest that greenspace-mental health interventions should focus on improving greenspace accessibility, specifically for interventions aimed at reducing mood disorders and substance use disorders. In small towns, mental health interventions should consider improving the quality of existing greenspaces, specifically for substance use disorders. Finally, in rural communities, greenspace interventions should focus on improving greenspace accessibility and greenspace quality to alleviate community burdens of substance use disorders and anxiety disorders in particular.

suicide-related outcomes, a behavioral mental health outcome (NAMI, 2023), was consistently associated with a higher prevalence in communities with low quantities of

greenspace. Past analyses in North Carolina indicate that suicide-related outcomes exhibits a different spatial clustering pattern, as compared to anxiety, depression, mood disorders, and general mental wellbeing (Ryan et al., 2022; Sugg et al., 2022). Our results further suggest that greenspace mental health interventions for suicide-related outcomes may vary from other mental health outcomes, with greenspace quantity indicating the strongest protective association, particularly in urban areas.

Furthermore, substance use disorders were often associated with the greatest increase in prevalence in communities with poor greenspace accessibility (urban, micropolitan and rural/isolated), quantity (suburban) and quality (small towns). These compelling findings indicate that greenspace interventions, regardless of urbanity, may help alleviate the community mental health burden of substance use.

Research indicates that greenspace development is not equitable; with primarily white and primarily high income communities (Mears et al., 2019b) and cities (Rigolon et al., 2018b) often seeing the greatest quantity, accessibility and/or quality of public greenspaces. Historically, development of greenspaces in minority neighborhoods has often led to gentrification (Kim and Wu, 2022; Triguero-Mas et al., 2022). Furthermore, some research cautions that in gentrifying neighborhoods, greenspace benefits the most affluent and may result in social exclusion for low-income and minority residents (Cole et al., 2019). Planning efforts need to be aware of these realities and ensure active participation of all residents when it comes to greenspace development, to guarantee the planning process is equitably beneficial for all residents.

Strengths & Limitations

Our study has numerous strengths. First, while past studies have relied primarily on self-reported, or parent-reported well-being questionnaires to quantify mental health (Vanaken & Danckaerts, 2018), our analysis employed an objective mental health dataset with state-wide coverage, allowing for analysis at the neighborhood scale (ZCTA). Second, many studies do not consider multiple greenspace metrics (i.e., quality, quantity, accessibility); relying on NDVI to quantify greenspace (Vanaken & Danckaerts, 2018; Collins et al., 2020), or self-reported questionnaires relating to neighborhood greenspace quantity, quality and/or accessibility (Vanaken & Danckaerts, 2018). This analysis considered multiple public greenspace metrics, investigating greenspace quantity, quality and accessibility, contributing important knowledge for future greenspace-mental health interventions. Third, there is less focus on mental health concerns, such as mood disorders, substance use or suicide-related outcomes, with more attention targeted at childhood and adolescent behavior, hyperactivity and attention (Vanaken & Danckaerts, 2018). This analysis considered a suite of six mental health outcomes, ranging from mental illnesses (e.g., mood disorder, anxiety, depression) to behavioral mental health outcomes (e.g., suicide-related outcomes) mental health outcomes. Fourth, our analysis considered the greenspace-mental health association among three age groups; our results help inform targeted care for these vulnerable sub-populations. Finally, greenspace-health research is most often conducted in urban settings, consideration of rurality on a spectrum, including suburban, micropolitan and small town designations, provides location-specific results that can guide future mental health interventions.

Our study is also limited. First, we did not consider the interaction between greenspace metrics; future research should consider the interplay between greenspace metrics to further understanding of the greenspace mental health relationship. Second, we conducted this analysis at the neighborhood-level. Neighborhood scale analyses can result in inflated relationships (Kwan, 2021). Furthermore, mental health data was derived from patients' ZCTA of residence, residential location doesn't necessarily reflect activity patterns, and we were unable to account for additional greenspace exposure opportunities (e.g., school); this may lead to exposure misclassification (Kwan, 2021). Third, greenspace metrics were collected cross-sectionally in 2019 (PAD_US) and 2020 (ParkServe), whereas mental health outcome data spans 2016-2019; greenspace exposure may have changed during this period. However, the authors are not aware of any major greenspace developments during the study period. Fourth, our mental health data is ED administrative data; we only captured one cohort of individuals, which may not be representative of the entire state. However, our cohort of mental health data is for the most vulnerable residents. Therefore, our results depict the association between greenspace and mental health among North Carolina's most vulnerable children, adolescents, and young adults. Finally, this analysis did not consider how the greenspace mental health association varies with race; future studies should consider how race modifies the greenspace mental health association.

Conclusions

This analysis investigated the association between greenspace quantity, quality, and accessibility, and population-level mental health outcomes among children, adolescents, and young adults in North Carolina. Results reveal that greenspace metrics, most notably

greenspace quantity and greenspace accessibility, are associated with population-level mental health benefits. This association varied substantially with rurality. Often, substance use disorders were associated with the greatest increase in prevalence. These compelling findings indicate that greenspace interventions, regardless of urbanity, may help alleviate the community mental health burden of substance use. Furthermore, increasing greenspace quantity in urban areas may serve as a low-cost intervention for suicide-related outcomes, which was 58% higher in urban communities with poor greenspace quantity. Our analysis found that greenspace is associated with population-level mental health benefits. Location and age-specific analyses provide important information for targeted mental health interventions.

References

AAFP. (2022). *ZIP Code to ZCTA Crosswalk*. UDS-Mapper. https://udsmapper.org/zip-code-to-zcta-crosswalk/

American Psychiatric Association. (2023). *Warning Signs of Mental Illness* [American Psychiatric Association Warning Signs of Mental Illness]. https://www.psychiatry.org:443/patients-families/warning-signs-of-mental-illness

Berry, M. S., Rung, J. M., Crawford, M. C., Yurasek, A. M., Ferreiro, A. V., & Almog, S. (2021). Using greenspace and nature exposure as an adjunctive treatment for opioid and substance use disorders: Preliminary evidence and potential mechanisms. *Behavioural Processes*, *186*, 104344. https://doi.org/10.1016/j.beproc.2021.104344

Beyer, K. M. M., Kaltenbach, A., Szabo, A., Bogar, S., Nieto, F. J., & Malecki, K. M. (2014). Exposure to neighborhood green space and mental health: Evidence from the survey of the health of Wisconsin. *International Journal of Environmental Research and Public Health*, *11*(3), 3453–3472. https://doi.org/10.3390/ijerph110303453

Bezold, C. P., Banay, R. F., Coull, B. A., Hart, J. E., James, P., Kubzansky, L. D., Missmer, S. A., & Laden, F. (2018). The Association Between Natural Environments and Depressive Symptoms in Adolescents Living in the United States. *Journal of Adolescent Health*, *62*(4), 488–495. https://doi.org/10.1016/j.jadohealth.2017.10.008

Bijnens, E. M., Vos, S., Verheyen, V. V., Bruckers, L., Covaci, A., De Henauw, S., Den Hond, E., Loots, I., Nelen, V., Plusquin, M., Schoeters, G., & Nawrot, T. S. (2022). Higher surrounding green space is associated with better attention in Flemish adolescents. *Environment International*, *159*, 107016. https://doi.org/10.1016/j.envint.2021.107016

Bježančević, M., Groznica Hržić, I., & Dodig-Ćurković, K. (2019). suicide-related outcomes in Adolescents: A Five-Year Study of Characteristics and Trends. *Psychiatria Danubina*, *31*(4), 413–420. https://doi.org/10.24869/psyd.2019.413

Browning, M. H. E. M., Rigolon, A., Ogletree, S., Wang, R., Klompmaker, J. O., Bailey, C., Gagnon, R., & James, P. (2022). *Curation of new green space indicator for the U.S.: Accessible & recreational park cover (PAD-US-AR)*. EcoEvoRxiv. https://doi.org/10.32942/osf.io/pydqe

Carrus, G., Scopelliti, M., Lafortezza, R., Colangelo, G., Ferrini, F., Salbitano, F., Agrimi, M., Portoghesi, L., Semenzato, P., & Sanesi, G. (2015). Go greener, feel better? The positive effects of biodiversity on the well-being of individuals visiting urban and peri-urban green areas. *Landscape and Urban Planning*, *134*, 221–228. https://doi.org/10.1016/j.landurbplan.2014.10.022

Cleveland, M. J., Feinberg, M. E., Bontempo, D. E., & Greenberg, M. T. (2008). The Role of Risk and Protective Factors in Substance Use Across Adolescence. *Journal of Adolescent Health*, *43*(2), 157–164. https://doi.org/10.1016/j.jadohealth.2008.01.015

Cole, H. V. S., Triguero-Mas, M., Connolly, J. J. T., & Anguelovski, I. (2019). Determining the health benefits of green space: Does gentrification matter? *Health & Place*, *57*, 1–11. https://doi.org/10.1016/j.healthplace.2019.02.001

Collins, R., Spake, R., Brown, K. A., Ogutu, B., Smith, D., & Eigenbrod, F. (2020, May 11). *A systematic map of research exploring the effect of greenspace on mental health* [Review]. Landscape and Urban Planning. https://doi.org/10.1016/j.landurbplan.2020.103823

Craney, T. A., & Surles, J. G. (2002). Model-Dependent Variance Inflation Factor Cutoff Values. *Quality Engineering*, *14*(3), 391–403. https://doi.org/10.1081/QEN-120001878

de Vries, S., ten Have, M., van Dorsselaer, S., van Wezep, M., Hermans, T., & de Graaf, R. (2016). Local availability of green and blue space and prevalence of common mental disorders in the Netherlands. *BJPsych Open*, *2*(6), 366–372. https://doi.org/10.1192/bjpo.bp.115.002469

Dimitrova, D., Tilov, B., & Dzhambov, A. (2017). Social cohesion mediates the association between urban greenspace and mental health in youth: Donka Dimitrova. *European Journal of Public Health*, *27*(suppl_3), ckx189.123. https://doi.org/10.1093/eurpub/ckx189.123

Duffy, M. E., Twenge, J. M., & Joiner, T. E. (2019). Trends in Mood and Anxiety Symptoms and suicide-related outcomes Among U.S. Undergraduates, 2007-2018: Evidence From Two National Surveys. *The Journal of Adolescent Health: Official Publication of the Society for Adolescent Medicine*, *65*(5), 590–598. https://doi.org/10.1016/j.jadohealth.2019.04.033

Duncan, D. T., & Kawachi, I. (Eds.). (2018). *Neighborhoods and Health* (2nd ed.). Oxford University Press. https://doi.org/10.1093/oso/9780190843496.001.0001

Eisenberg, D. (2019). Countering the Troubling Increase in Mental Health Symptoms Among U.S. College Students. *Journal of Adolescent Health*, *65*(5), 573–574. https://doi.org/10.1016/j.jadohealth.2019.08.003

Ekkel, E. D., & de Vries, S. (2017). Nearby green space and human health: Evaluating accessibility metrics. *Landscape and Urban Planning*, *157*, 214–220. https://doi.org/10.1016/j.landurbplan.2016.06.008

Engemann, K., Pedersen, C. B., Arge, L., Tsirogiannis, C., Mortensen, P. B., & Svenning, J.-C. (2019). Residential green space in childhood is associated with lower risk of psychiatric

disorders from adolescence into adulthood. *Proceedings of the National Academy of Sciences*, *116*(11), 5188–5193. https://doi.org/10.1073/pnas.1807504116

ESRI. (2022). *ArcGIS Pro 2.9.0*. https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview

Feng, X., & Astell-Burt, T. (2017a). The Relationship between Neighbourhood Green Space and Child Mental Wellbeing Depends upon Whom You Ask: Multilevel Evidence from 3083 Children Aged 12–13 Years. *International Journal of Environmental Research and Public Health*, *14*(3), Article 3. https://doi.org/10.3390/ijerph14030235

Feng, X., & Astell-Burt, T. (2017b). Residential Green Space Quantity and Quality and Child Well-being: A Longitudinal Study. *American Journal of Preventive Medicine*, *53*(5), 616–624. https://doi.org/10.1016/j.amepre.2017.06.035

Feng, X., Astell-Burt, T., Standl, M., Flexeder, C., Heinrich, J., & Markevych, I. (2022). Green space quality and adolescent mental health: Do personality traits matter? *Environmental Research*, *206*, 112591. https://doi.org/10.1016/j.envres.2021.112591

Fish, J. N., McInroy, L. B., Paceley, M. S., Williams, N. D., Henderson, S., Levine, D. S., & Edsall, R. N. (2020). "I'm Kinda Stuck at Home With Unsupportive Parents Right Now": LGBTQ Youths' Experiences With COVID-19 and the Importance of Online Support. *Journal of Adolescent Health*, *67*(3), 450–452. https://doi.org/10.1016/j.jadohealth.2020.06.002

Fish, J. N., Salerno, J., Williams, N. D., Rinderknecht, R. G., Drotning, K. J., Sayer, L., & Doan, L. (2021). Sexual Minority Disparities in Health and Well-Being as a Consequence of the COVID-19 Pandemic Differ by Sexual Identity. *LGBT Health*, *8*(4), 263–272. https://doi.org/10.1089/lgbt.2020.0489

Fonseca, M. S. (2008). Edge Effect. In S. E. Jørgensen & B. D. Fath (Eds.), *Encyclopedia of Ecology* (pp. 1207–1211). Academic Press. https://doi.org/10.1016/B978-008045405-4.00486-9

Helzer, C. J., & Jelinski, D. E. (1999). The Relative Importance of Patch Area and Perimeter-Area Ratio to Grassland Breeding Birds. *Ecological Applications*, *9*(4), 1448–1458. https://doi.org/10.2307/2641409

Houlden, V., Porto de Albuquerque, J., Weich, S., & Jarvis, S. (2019). A spatial analysis of proximate greenspace and mental wellbeing in London. *Applied Geography*, *109*, 102036. https://doi.org/10.1016/j.apgeog.2019.102036

HRSA. (2023). *Shortage Areas*. Health Workforce Shortage Areas. https://data.hrsa.gov/topics/health-workforce/shortage-areas

Islam, M. Z., Johnston, J., & Sly, P. D. (2020). Green space and early childhood development: A systematic review. *Reviews on Environmental Health*, *35*(2), 189–200. https://doi.org/10.1515/reveh-2019-0046

Jennings, V., & Bamkole, O. (2019). The Relationship between Social Cohesion and Urban Green Space: An Avenue for Health Promotion. *International Journal of Environmental Research and Public Health*, *16*(3), Article 3. https://doi.org/10.3390/ijerph16030452

Jiang, W., Stickley, A., & Ueda, M. (2021). Green space and suicide mortality in Japan: An ecological study. *Social Science & Medicine*, *282*, 114137. https://doi.org/10.1016/j.socscimed.2021.114137

Keyes, K. M., Gary, D., O'Malley, P. M., Hamilton, A., & Schulenberg, J. (2019). Recent increases in depressive symptoms among US adolescents: Trends from 1991 to 2018. *Social Psychiatry and Psychiatric Epidemiology*, *54*(8), 987–996. https://doi.org/10.1007/s00127-019-01697-8

Kim, H., Ryu, J. M., & Kim, H.-W. (2020). Characteristics and Trends of Suicide Attempt or Non-suicidal suicide-related outcomes in Children and Adolescents Visiting Emergency Department. *Journal of Korean Medical Science*, *35*(33). https://doi.org/10.3346/jkms.2020.35.e276

Kim, S. K., & Wu, L. (2022). Do the characteristics of new green space contribute to gentrification? *Urban Studies*, *59*(2), 360–380. https://doi.org/10.1177/0042098021989951

Krieger, N., Waterman, P. D., Spasojevic, J., Li, W., Maduro, G., & Van Wye, G. (2016). Public Health Monitoring of Privilege and Deprivation With the Index of Concentration at the Extremes. *American Journal of Public Health*, *106*(2), 256–263. https://doi.org/10.2105/AJPH.2015.302955

Kwan, M.-P. (2021). The Neighborhood Effect Averaging Problem. In *International Encyclopedia of Geography* (pp. 1–5). John Wiley & Sons, Ltd. https://doi.org/10.1002/9781118786352.wbieg2076

Lindsey, M. A., Sheftall, A. H., Xiao, Y., & Joe, S. (2019). Trends of Suicidal Behaviors Among High School Students in the United States: 1991–2017. *Pediatrics*, *144*(5), e20191187. https://doi.org/10.1542/peds.2019-1187

Liu, Y., Xiao, T., & Wu, W. (2022). Can multiple pathways link urban residential greenspace to subjective well-being among middle-aged and older Chinese adults? *Landscape and Urban Planning*, *223*, 104405. https://doi.org/10.1016/j.landurbplan.2022.104405

Luque-García, L., Corrales, A., Lertxundi, A., Díaz, S., & Ibarluzea, J. (2022). Does exposure to greenness improve children's neuropsychological development and mental health? A Navigation Guide systematic review of observational evidence for associations. *Environmental Research*, *206*, 112599. https://doi.org/10.1016/j.envres.2021.112599

Lyons, R., Colbert, A., Browning, M., & Jakub, K. (2022). Urban greenspace use among adolescents and young adults: An integrative review. *Public Health Nursing*, *39*(3), 700–718. https://doi.org/10.1111/phn.13010

Maclin-Akinyemi, C., Thurston, I. B., Howell, K. H., Jamison, L. E., & Anderson, M. B. (2021). The protective roles of ethnic identity and community cohesion on substance use among Black women experiencing adversity. *Journal of Ethnicity in Substance Abuse*, *20*(2), 225–240. https://doi.org/10.1080/15332640.2019.1622477

Madzia, J., Ryan, P., Yolton, K., Percy, Z., Newman, N., LeMasters, G., & Brokamp, C. (2019). Residential Greenspace Association with Childhood Behavioral Outcomes. *The Journal of Pediatrics*, *207*, 233–240. https://doi.org/10.1016/j.jpeds.2018.10.061

Markevych, I., Tiesler, C. M. T., Fuertes, E., Romanos, M., Dadvand, P., Nieuwenhuijsen, M. J., Berdel, D., Koletzko, S., & Heinrich, J. (2014). Access to urban green spaces and behavioural problems in children: Results from the GINIplus and LISAplus studies. *Environment International*, *71*, 29–35. https://doi.org/10.1016/j.envint.2014.06.002

Martin, L., Pahl, S., White, M. P., & May, J. (2019). Natural environments and craving: The mediating role of negative affect. *Health & Place*, *58*, 102160. https://doi.org/10.1016/j.healthplace.2019.102160

Martínez-Alés, G., & Keyes, K. M. (2019). Fatal and Non-fatal suicide-related outcomes in the USA: Critical Review of Current Trends and Innovations in Prevention. *Current Psychiatry Reports*, *21*(10), 104. https://doi.org/10.1007/s11920-019-1080-6

Mavoa, S., Davern, M., Breed, M., & Hahs, A. (2019). Higher levels of greenness and biodiversity associate with greater subjective wellbeing in adults living in Melbourne, Australia. *Health & Place*, *57*, 321–329. https://doi.org/10.1016/j.healthplace.2019.05.006

McEachan, R. R. C., Prady, S. L., Smith, G., Fairley, L., Cabieses, B., Gidlow, C., Wright, J., Dadvand, P., van Gent, D., & Nieuwenhuijsen, M. J. (2016). The association between green space and depressive symptoms in pregnant women: Moderating roles of socioeconomic

status and physical activity. *Journal of Epidemiology and Community Health*, *70*(3), 253–259. https://doi.org/10.1136/jech-2015-205954

Mears, M., & Brindley, P. (2019). Measuring Urban Greenspace Distribution Equity: The Importance of Appropriate Methodological Approaches. *ISPRS International Journal of Geo-Information*, *8*(6), Article 6. https://doi.org/10.3390/ijgi8060286

Mears, M., Brindley, P., Maheswaran, R., & Jorgensen, A. (2019). Understanding the socioeconomic equity of publicly accessible greenspace distribution: The example of Sheffield, UK. *Geoforum*, *103*, 126–137. https://doi.org/10.1016/j.geoforum.2019.04.016

Mercado, M. C., Holland, K., Leemis, R. W., Stone, D. M., & Wang, J. (2017). Trends in Emergency Department Visits for Nonfatal Self-inflicted Injuries Among Youth Aged 10 to 24 Years in the United States, 2001-2015. *JAMA*, *318*(19), 1931–1933. https://doi.org/10.1001/jama.2017.13317

Mueller, M. A. E., Midouhas, E., & Flouri, E. (2023). Types of greenspace and adolescent mental health and well-being in metropolitan London. *Cities & Health*, 1–20. https://doi.org/10.1080/23748834.2023.2175410

NAMI. (2023). *Self-harm | NAMI: National Alliance on Mental Illness*. Self-Harm | NAMI: National Alliance on Mental Illness. https://www.nami.org/About-Mental-Illness/Common-with-Mental-Illness/Self-harm

NC DETECT. (2021). *NC DETECT*. https://ncdetect.org/

Nutsford, D., Pearson, A., & Kingham, S. (2013). An ecological study investigating the association between access to urban green space and mental health. *Public Health*, *127*. https://doi.org/10.1016/j.puhe.2013.08.016

Ormiston, C. K., & Williams, F. (2022). LGBTQ youth mental health during COVID-19: Unmet needs in public health and policy. *Lancet (London, England)*, *399*(10324), 501–503. https://doi.org/10.1016/S0140-6736(21)02872-5

Pei, F., Wang, Y., Wu, Q., Shockley McCarthy, K., & Wu, S. (2020). The roles of neighborhood social cohesion, peer substance use, and adolescent depression in adolescent substance use. *Children and Youth Services Review*, *112*, 104931. https://doi.org/10.1016/j.childyouth.2020.104931

Ridout, K. K., Alavi, M., Ridout, S. J., Koshy, M. T., Awsare, S., Harris, B., Vinson, D. R., Weisner, C. M., Sterling, S., & Iturralde, E. (2021). Emergency Department Encounters Among Youth With Suicidal Thoughts or Behaviors During the COVID-19 Pandemic. *JAMA Psychiatry*, *78*(12), 1319–1328. https://doi.org/10.1001/jamapsychiatry.2021.2457

Rigolon, A., Browning, M., & Jennings, V. (2018). Inequities in the quality of urban park systems: An environmental justice investigation of cities in the United States. *Landscape and Urban Planning*, *178*, 156–169. https://doi.org/10.1016/j.landurbplan.2018.05.026

RStudio Team. (2022). *RStudio: Integrated Development Environment for R* [PBC]. RStudio. https://www.rstudio.com/

Runkle, J. D., Matthews, J. L., Sparks, L., McNicholas, L., & Sugg, M. M. (2022). Racial and ethnic disparities in pregnancy complications and the protective role of greenspace: A retrospective birth cohort study. *Science of The Total Environment*, *808*, 152145. https://doi.org/10.1016/j.scitotenv.2021.152145

Runkle, J. D., Sugg, M. M., Yadav, S., Harden, S., Weiser, J., & Michael, K. (2021). Real-Time Mental Health Crisis Response in the United States to COVID-19. *Crisis*. https://doi.org/10.1027/0227-5910/a000826

Runkle, J. R., Harden, S., Hart, L., Moreno, C., Michael, K., & Sugg, M. M. (2022). Socioenvironmental drivers of adolescent suicide in the United States: A scoping review. *Journal of Rural Mental Health*, No Pagination Specified-No Pagination Specified. https://doi.org/10.1037/rmh0000208

Ryan, S. C., Runkle, J. D., Andersen, L. M., & Sugg, M. M. (2022). Spatial analysis of mental health and suicide clustering among older adults in North Carolina: An exploratory analysis. *SSupplemental - Mental Health*, *2*, 100162. https://doi.org/10.1016/j.ssmmh.2022.100162

Sarkar, C., Webster, C., & Gallacher, J. (2018). Residential greenness and prevalence of major depressive disorders: A cross-sectional, observational, associational study of 94 879 adult UK Biobank participants. *The Lancet. Planetary Health*, *2*(4), e162–e173. https://doi.org/10.1016/S2542-5196(18)30051-2

Sillman, D., Rigolon, A., Browning, M. H. E. M., Yoon, H. (Violet), & McAnirlin, O. (2022). Do sex and gender modify the association between green space and physical health? A systematic review. *Environmental Research*, *209*, 112869. https://doi.org/10.1016/j.envres.2022.112869

Sugg, M. M., Runkle, J. D., Andersen, L. M., & Desjardins, M. R. (2022). Exploring Place-Based Differences in Suicide and suicide-related outcomes Among North Carolina Adolescents and Young Adults. *Journal of Adolescent Health*. https://doi.org/10.1016/j.jadohealth.2022.06.013

The Trust for Public Land. (2021). *ParkServe Data Downloads*. The Trust for Public Land. https://www.tpl.org/parkserve/downloads

Thorisdottir, I. E., Asgeirsdottir, B. B., Sigurvinsdottir, R., Allegrante, J. P., & Sigfusdottir, I. D. (2017). The increase in symptoms of anxiety and depressed mood among Icelandic adolescents: Time trend between 2006 and 2016. *European Journal of Public Health*, *27*(5), 856–861. https://doi.org/10.1093/eurpub/ckx111

Triguero-Mas, M., Anguelovski, I., Connolly, J. J. T., Martin, N., Matheney, A., Cole, H. V. S., Pérez-Del-Pulgar, C., García-Lamarca, M., Shokry, G., Argüelles, L., Conesa, D., Gallez, E., Sarzo, B., Beltrán, M. A., López Máñez, J., Martínez-Minaya, J., Oscilowicz, E., Arcaya, M. C., & Baró, F. (2022). Exploring green gentrification in 28 global North cities: The role of urban parks and other types of greenspaces. *Environmental Research Letters*, *17*(10), 104035. https://doi.org/10.1088/1748-9326/ac9325

US Census Bureau. (2020). *Census.gov*. Census.Gov. https://www.census.gov/en.html

US Census Bureau. (2022). *ZIP Code Tabulation Areas (ZCTAs)*. Census.Gov. https://www.census.gov/programs-surveys/geography/guidance/geo-areas/zctas.html

U.S. Geological Survey (USGS) Gap Analysis Project (GAP). (2020). *Protected Areas Database of the United States (PAD-US) 2.0* [Map]. U.S. Geological Survey. https://doi.org/10.5066/P955KPLE

USDA. (2020). *Rural-Urban Commuting Area Codes*. https://www.ers.usda.gov/data-products/rural-urban-commuting-area-codes/

Vanaken, G.-J., & Danckaerts, M. (2018). Impact of Green Space Exposure on Children's and Adolescents' Mental Health: A Systematic Review. *International Journal of Environmental Research and Public Health*, *15*(12), E2668. https://doi.org/10.3390/ijerph15122668

Wang, P., Meng, Y.-Y., Lam, V., & Ponce, N. (2019). Green space and serious psychological distress among adults and teens: A population-based study in California. *Health & Place*, *56*, 184–190. https://doi.org/10.1016/j.healthplace.2019.02.002

Wang, R., Feng, Z., Pearce, J., Liu, Y., & Dong, G. (2021). Are greenspace quantity and quality associated with mental health through different mechanisms in Guangzhou, China: A comparison study using street view data. *Environmental Pollution*, *290*, 117976. https://doi.org/10.1016/j.envpol.2021.117976

Wheeler, B. W., Lovell, R., Higgins, S. L., White, M. P., Alcock, I., Osborne, N. J., Husk, K., Sabel, C. E., & Depledge, M. H. (2015). Beyond greenspace: An ecological study of population general health and indicators of natural environment type and quality. *International Journal of Health Geographics*, *14*(1), 17. https://doi.org/10.1186/s12942-015-0009-5

Wiley, E. R., Stranges, S., Gilliland, J. A., Anderson, K. K., & Seabrook, J. A. (2022). Residential greenness and substance use among youth and young adults: Associations with alcohol, tobacco, and marijuana use. *Environmental Research*, *212*, 113124. https://doi.org/10.1016/j.envres.2022.113124

Zach, A., Meyer, N., Hendrowarsito, L., Kolb, S., Bolte, G., Nennstiel-Ratzel, U., Stilianakis, N. I., & Herr, C. (2016). Association of sociodemographic and environmental factors with the mental health status among preschool children—Results from a cross-sectional study in Bavaria, Germany. *International Journal of Hygiene and Environmental Health*, *219*(4), 458–467. https://doi.org/10.1016/j.ijheh.2016.04.012

Zhang, Y., Van den Berg, A. E., Van Dijk, T., & Weitkamp, G. (2017). Quality over Quantity: Contribution of Urban Green Space to Neighborhood Satisfaction. *International Journal of Environmental Research and Public Health*, *14*(5), 535. https://doi.org/10.3390/ijerph14050535

Tables

Table 1. Summary of greenspace metrics considered in this analysis.

Greenspace Metric	Operationalized at ZCTA[1]	Calculated Using	Data Source(s)	Exclusion Criteria	Hypothesized Association
Greenspace Quantity					
Percent Greenspace	Percent greenspace land cover	Tabulate Intersection	PAD-US and ParkServe	Excluded due to multicollinearity with Greenspace per Person	
Greenspace per Person	Greenspace area/individual 24 and younger	Tabulate Intersection; total area of greenspace divided by total population (24 and younger)	PAD-US and ParkServe		Higher quantities of greenspace per person will be associated with a lower incidence of poor mental health
Greenspace Accessibility					
Greenspace Distance	Distance to nearest greenspace from population weighted mean center	Euclidean Distance	PAD-US and ParkServe		Shorter distances to greenspace will be associated with a lower incidence of poor mental health
Greenspace Quality					
Average Google Review	Average of available google reviews (0-5) of greenspaces	Reviews manually retrieved from google.com; averaged	Google	Included in state-wide model, excluded from stratified, effect modification analyses; not standardized	Higher average google reviews will be associated with a lower incidence of poor mental health
Nearest Google Review	Google review (0-5) of nearest greenspace from population weighted centroid	Reviews manually retrieved from google.com	Google, PAD-US and ParkServe	Included in state-wide model, excluded from stratified, effect modification analyses; not standardized	Higher near google reviews will be associated with a lower incidence of poor mental health
Perimeter Area Ratio (PAR)	Ratio of total greenspace perimeter to total greenspace area	Determined the perimeter using Summarize Within, divided the perimeter by the area of public greenspace	PAD-US and ParkServe		Lower PAR values (higher quality) will be associated with a lower incidence of poor mental health

ZCTA: All operationalized metrics are calculated for each ZCTA

Table 2. Demographic characteristics of all Emergency Department (ED) visits and mental health-related ED visits among individuals ages 24 and younger who visited a North Carolina ED (2016-2019). Data is from NC DETECT.

	All ED Visits n(%)	Anxiety n(%)	Depression n(%)	Mental and Behavioral Disorder n(%)	Mood Disorder n(%)	suicide-related outcomes n(%)	Substance Use Disorder n(%)
ED Visits	5,357,703 (100%)	97,447 (1.82)	86,924 (1.62)	575,536 (10.7)	119,434 (2.23)	59,999 (1.12)	350,277 (6.54)
Average Age (SD)	12.49 (8.19)	19.02 (3.96)	18.43 (3.78)	19.13 (4.5)	18.56 (3.89)	17.35 (4.1)	21.03 (2.54)
Year							
2016	1,378,846 (25.7)	22,864 (23.5)	19,572 (22.5)	124,878 (21.7)	27,280 (22.8)	11,256 (18.8)	72,254 (20.6)
2017	1,371,847 (25.6)	24,300 (24.9)	22,512 (25.9)	150,371 (26.1)	30,745 (25.7)	14,239 (23.7)	94,530 (27.0)
2018	1,300,575 (24.3)	25,441 (26.1)	22,496 (25.9)	154,648 (26.9)	30,750 (25.7)	16,826 (28.0)	95,531 (27.3)
2019	1,306,435 (24.4)	24,842 (25.5)	22,344 (25.7)	145,639 (25.3)	30,659 (25.7)	17,678 (29.5)	87,962 (25.1)
Sex							
Male	2,427,180 (45.3)	31,962 (32.8)	28,581 (32.9)	270,723 (47.0)	42,711 (35.8)	25,461 (42.4)	169,465 (48.4)
Female	2,922,642 (54.6)	65,359 (67.1)	58,237 (67.7)	303,969 (52.8)	76,583 (66.7)	34,435 (57.4)	180,323 (51.5)
Other/Unknown	7,881 (0.1)	126 (0.1)	106 (0.1)	58 (0.0)	140 (0.1)	103 (0.2)	488 (0.2)
Race							
Indigenous American	74,586 (1.5)	1,104 (1.2)	869 (1.0)	7,524 (1.4)	1,693 (1.5)	726 (1.3)	5,073 (1.5)
Asian/Pacific Islander	46,042 (0.9)	683 (0.7)	677 (0.8)	3,195 (0.6)	881 (0.8)	563 (1.0)	1,551 (0.5)
Black	1,902,890 (37.3)	21,098 (22.5)	20,305 (24.3)	175,678 (31.7)	29,168 (25.4)	15,003 (25.9)	111,377 (33.0)
White	2,556,293 (50.1)	65,187 (69.6)	56,585 (67.7)	338,448 (61.1)	76,668 (66.7)	37,422 (64.5)	204,927 (60.7)
Other	523,995 (10.3)	5,538 (5.9)	5,196 (6.2)	29,214 (5.3)	6,568 (5.7)	4,317 (7.4)	14,706 (4.4)
Age Group							
Under 15	2,796,174 (52.2)	13,196 (13.5)	14,949 (17.2)	84,031 (14.6)	19,948 (16.7)	15,813 (26.4)	4,365 (1.2)
15-17	529,510 (9.9)	16,808 (17.2)	20,215 (23.3)	69,161 (12.0)	25,401 (21.3)	15,374 (25.6)	22,943 (6.5)
18-24	2,032,019 (37.9)	67,443 (69.2)	51,760 (59.5)	422,344 (73.4)	74,085 (62.0)	28,812 (48.0)	322,969 (92.2)

Table 3 - State-wide GLM results investigating the relationship between greenspace quantity, quality and accessibility, and mental health outcomes among individuals ages 24 and under.

	Anxiety		Depression		Mood		Mental and Behavioral Disorders		suicide-related outcomes		Substance Use Disorder	
	PRR	CI	PRR	CI	PRR	CI	PRR	CI	PRR	CI	PRR	CI
Area/Person												
T1 (0 - 45.38m2)	**1.24**	1.22-1.27	**1.31**	1.28-1.34	**1.32**	0.94-0.99	**1.27**	1.26-1.29	**1.56**	1.51-1.61	**1.21**	1.20-1.22
T2 (45.92-1,129 m2)	**1.32**	1.29-1.35	**1.41**	1.38-1.44	**1.39**	1.36-1.41	**1.40**	1.39-1.42	**1.73**	1.67-1.78	**1.35**	1.34-1.37
Reference: T3 (1,147 - 2,249,938m2)												
Distance												
T2 (1.23-4.06km)	**1.25**	1.23-1.27	**1.17**	1.16-1.19	**1.2**	1.18-1.22	**1.20**	1.19-1.20	**1.12**	1.10-1.14	**1.19**	1.18-1.20
T3 (4.09-21.6km)	0.90	0.88-0.92	0.81	0.80-0.83	0.96	0.94-0.98	0.96	0.95-0.96	0.76	0.74-0.78	0.99	0.98-1.00
Reference T1 (0-1.22km)												
Perimeter:Area Ratio												
T2 (0.01-0.035)	**1.05**	1.03-1.06	**1.03**	1.01-1.04	**1.01**	0.99-1.02	0.99	0.99-1.00	**1.05**	1.03-1.07	**1.02**	1.01-1.03
T3 (0.035-1.13)*	0.68	0.67-0.70	0.71	0.70-0.73	0.69	0.67-0.70	0.68	0.67-0.69	0.77	0.75-0.79	0.68	0.67-0.69
Reference: T1 (0-0.01)												
Near Review												
T1 (0-4.6)	**1.12**	1.10-1.14	**1.13**	1.10-1.15	**1.12**	1.07-1.10	**1.19**	1.18-1.20	**1.11**	1.09-1.14	**1.27**	1.25-1.28
T2 (4.6-4.8)	0.96	0.94-0.98	1.01	0.99-1.03	1.00	0.92-0.95	0.97	0.96-0.97	1.05	1.02-1.07	0.98	0.97-0.99
Reference: T3 (4.8-5)												
Average Review												
T1 (0-4.05)	**1.06**	1.04-1.07	**1.08**	1.06-1.10	**1.05**	1.04-1.07	**1.05**	1.05-1.06	**1.06**	1.04-1.09	**1.06**	1.05-1.07
T2 (4.06-4.55)	**1.23**	1.21-1.25	**1.21**	1.19-1.23	**1.23**	1.21-1.25	**1.20**	1.20-1.21	**1.05**	1.03-1.07	**1.26**	1.25-1.27
Reference: T3 (4.56-5)												
ICE:Income												
T1: Low Income	1.44	1.42-1.47	1.35	1.32-1.38	1.47	1.44-1.49	1.82	1.80-1.83	1.25	1.22-1.28	2.07	2.05-2.10
T2: Mixed Income	1.42	1.40-1.44	1.38	1.36-1.40	1.43	1.41-1.45	1.69	1.68-1.70	1.31	1.28-1.34	1.90	1.88-1.92
Reference: T3 (High Income)												
ICE:Race												
T1: Predominately Black	0.81	0.80-0.83	0.89	0.87-0.91	0.96	0.95-0.98	1.04	1.03-1.05	1.07	1.04-1.10	0.96	0.95-0.97
T2: Mixed Race	1.06	1.04-1.08	1.10	1.08-1.12	1.13	1.11-1.15	1.15	1.14-1.16	1.19	1.16-1.25	1.08	1.07-1.09

Reference: T3 (Predominately White)												
MHPSA	1.23	1.16-1.29	1.25	1.18-1.32	1.26	1.20-1.32	1.29	1.26-1.33	1.07	1.01-1.13	1.40	1.35-1.44
Observations: 808												

*Includes ZCTAs with no public greenspace

Table 4 - Rurality-stratified GLM results investigating the relationship between greenspace quantity, quality and accessibility, and mental health-related ED visits among individuals ages 24 and under with consideration of urban, suburban, micropolitan, small towns, and rural/isolated communities in NC (2016-2019). Ruralities were determined using USDA Rural Urban Commuting Area (RUCA) Codes.

Urban

	Anxiety		Depression		Mood		Mental and Behavioral Disorders		suicide-related outcomes		Substance Use Disorder	
	PRR	CI	PRR	CI	PRR	CI	PRR	CI	PRR	CI	PRR	CI
Area/Person												
T1 (0-3.33m2)	1.13	1.10-1.15	1.17	1.14-1.19	1.19	1.16-1.21	1.14	1.13-1.15	1.11	1.08-1.13	1.17	1.16-1.18
T2 (4.49 - 136.9m2)	1.29	1.26-1.32	1.24	1.21-1.27	1.33	1.30-1.35	1.24	1.23-1.25	1.08	1.05-1.11	1.3	1.29-1.32
Reference: T3 (137 - 285,182.7m2)												
Distance												
T2 (0.56 - 1.82km)	1.01	0.99-1.03	0.98	0.96-1.00	0.98	0.97-1.00	1.11	1.11-1.12	0.97	0.94-0.99	1.12	1.11-1.13
T3 (1.89 - 10.7km)	1.15	1.13-1.17	1.08	1.06-1.10	1.09	1.07-1.11	1.28	1.27-1.29	1.07	1.04-1.10	1.31	1.29-1.32
Reference T1(0-0.53km)												
Perimeter:Area Ratio												
T2 (0.025 - 0.064)	1	0.99-1.02	0.97	0.95-0.99	0.99	0.98-1.01	1.04	1.03-1.04	0.98	0.95-1.00	1.08	1.07-1.09
T3 (0.066 - 1.02)	0.8	0.79-0.82	0.77	0.76-0.79	0.77	0.76-0.79	0.82	0.81-0.83	0.83	0.80-0.85	0.83	0.82-0.84
Reference: T1 (0-0.02)												
ICE:Income												
T1: Low Income	1.72	1.68-1.76	1.64	1.60-1.68	1.75	1.71-1.78	2.23	2.20-2.25	1.47	1.43-1.51	2.71	2.67-2.75
T2: Mixed Income	1.25	1.22-1.28	1.19	1.16-1.22	1.26	1.24-1.29	1.45	1.44-1.47	1.09	1.06-1.12	1.68	1.66-1.70
Reference: T3 (High Income)												
ICE:Race												
T1: Predom Black	0.79	0.78-0.81	0.95	0.93-0.98	1	0.98-1.02	1.16	1.15-1.18	1.19	1.16-1.23	1.11	1.10-1.13
T2: Mixed Race	0.85	0.83-0.87	0.95	0.92-0.97	0.96	0.94-0.98	0.99	0.98-1.00	1.11	1.08-1.15	0.97	0.96-0.98
Reference: T3 (Predom White)												
MHPSA	1.08	1.02-1.14	1.15	1.08-1.22	1.17	1.11-1.23	1.08	1.06-1.11	0.93	0.87-0.99	1.12	1.08-1.16
Observations: 254												

Suburban

	Anxiety		Depression		Mood		Mental and Behavioral Disorders		suicide-related outcomes		Substance Use Disorder	
	PRR	CI	PRR	CI	PRR	CI	PRR	CI	PRR	CI	PRR	CI
Area/Person												
T1 0m2	1.28	1.15-1.43	1.23	1.09-1.38	1.27	1.15-1.40	1.29	1.23-1.34	1.27	1.10-1.46	1.35	1.28-1.43
T2 (0 - 1,280.6m2)	1.01	0.97-1.06	1.05	1.00-1.10	1.06	1.02-1.11	1.21	1.19-1.23	1.21	1.14-1.29	1.22	1.19-1.25
Reference: T3 (1,340.8 - 508,778.6m2)												
Distance												
T2 (2.52km - 6.49km)	0.76	0.73-0.79	0.72	0.69-0.76	0.73	0.70-0.76	0.79	0.78-0.80	0.77	0.73-0.82	0.81	0.79-0.83
T3 (6.56 - 17.19km)	0.66	0.63-0.70	0.67	0.63-0.71	0.7	0.66-0.73	0.74	0.73-0.76	0.83	0.77-0.88	0.74	0.72-0.76
Reference: T1 (0-2.5km)												
Perimeter:Area Ratio												
T2 (0-0.021)	1.11	1.06-1.15	1.08	1.03-1.12	1.11	1.07-1.15	1.03	1.02-1.05	1.05	0.99-1.11	1.04	1.02-1.06
T3 (0.022-1.13)	0.78	0.70-0.86	0.77	0.69-0.86	0.74	0.67-0.81	0.81	0.78-0.84	0.74	0.65-0.84	0.78	0.75-0.83
Reference: T1 (0)												
ICE:Income												
T1: Low Income	1.38	1.31-1.45	1.25	1.18-1.32	1.4	1.33-1.46	1.61	1.57-1.64	1.08	1.01-1.16	1.82	1.77-1.87
T2: Mixed Income	1.53	1.46-1.60	1.5	1.43-1.57	1.49	1.43-1.56	1.55	1.52-1.58	1.22	1.15-1.29	1.62	1.58-1.67
Reference: T3 (High Income)												
ICE:Race												
T1: Predom Black	0.59	0.56-0.62	0.63	0.60-0.66	0.68	0.65-0.71	0.77	0.76-0.79	0.81	0.76-0.87	0.71	0.69-0.73
T2: Mixed Race	0.62	0.59-0.65	0.67	0.64-0.70	0.7	0.67-0.73	0.71	0.70-0.73	0.78	0.74-0.83	0.67	0.65-0.69
Reference: T3 (Predom White)												
MHPSA												
Observations: 202												

Micropolitan

	Anxiety		Depression		Mood		Mental and Behavioral Disorders		suicide-related outcomes		Substance Use Disorder	
	PRR	CI	PRR	CI	PRR	CI	PRR	CI	PRR	CI	PRR	CI
Area/Person												
T1 (0-12.4m2)	0.67	0.62-0.73	0.54	0.50-0.60	0.5	0.51-0.59	0.55	0.54-0.57	0.72	0.65-0.81	0.48	0.46-0.50
T2 (19.1 - 1,050.7m2)	0.98	0.94-1.02	0.89	0.85-0.93	0.9	0.87-0.94	0.92	0.91-0.94	1.01	0.95-1.06	0.88	0.86-0.89
Reference: T3 (1,091.7 - 357,933m2)												
Distance												
T2 (1.78km - 5.09km)	1.48	1.43-1.54	1.49	1.43-1.55	1.53	1.48-1.58	1.39	1.37-1.41	1.15	1.09-1.21	1.37	1.34-1.40
T3 (5.09 - 20.2km)	1.35	1.28-1.42	1.32	1.25-1.39	1.36	1.30-1.43	1.4	1.37-1.43	0.95	0.88-1.02	1.47	1.43-1.51
Reference T1 (0-1.78km)												
Perimeter:Area Ratio												
T2 (0.008 - 0.025)	0.78	0.75-0.82	0.74	0.71-0.77	0.73	0.70-0.76	0.66	0.65-0.67	0.72	0.68-0.76	0.6	0.59-0.61
T3 (0.025 - 0.56)	0.52	0.48-0.57	0.53	0.48-0.58	0.55	0.51-0.60	0.6	0.58-0.62	0.51	0.46-0.58	0.64	0.61-0.67
Reference: T1 (0-0.006)												
ICE:Income												
T1: Low Income	1.71	1.63-1.79	1.45	1.38-1.52	1.52	1.46-1.59	1.58	1.55-1.61	1.28	1.20-1.36	1.77	1.73-1.81
T2: Mixed Income	1.64	1.57-1.72	1.53	1.46-1.61	1.53	1.47-1.59	1.74	1.71-1.77	1.31	1.24-1.39	1.95	1.91-2.00
Reference: T3 (High Income)												
ICE:Race												
T1: Predom Black	0.99	0.95-1.04	0.99	0.94-1.03	1.15	1.10-1.20	1.2	1.18-1.23	1.24	1.17-1.32	1.06	1.04-1.09
T2: Mixed Race	1.38	1.32-1.44	1.36	1.30-1.42	1.47	1.42-1.53	1.59	1.56-1.61	1.42	1.34-1.51	1.46	1.43-1.50
Reference: T3 (Predom White)												
MHPSA	1.32	1.08-1.63	1.09	0.89-1.35	1.25	1.04-1.53	1.67	1.52-1.84	1.27	0.99-1.66	2.55	2.20-2.97
Observations: 173												

Small Towns

	Anxiety		Depression		Mood		Mental and Behavioral Disorders		suicide-related outcomes		Substance Use Disorder	
	PRR	CI	PRR	CI	PRR	CI	PRR	CI	PRR	CI	PRR	CI
Area/Person												
T1 (0-59.87m2)	0.9	0.82-1.00	0.91	0.81-1.02	0.93	0.85-1.03	0.92	0.88-0.96	1.21	1.05-1.39	0.96	0.91-1.01
T2 (62.11 - 3,120.2m2)	0.72	0.67-0.77	0.78	0.72-0.85	0.75	0.70-0.80	0.84	0.82-0.87	1.05	0.95-1.17	0.87	0.84-0.91
Reference: T3 (4,560.2 - 574,334.7m2)												
Distance												
T2 (2.36 - 6.07km)	0.74	0.69-0.80	0.64	0.59-0.70	0.71	0.66-0.76	0.76	0.73-0.78	0.7	0.63-0.79	0.75	0.72-0.78
T3 (6.16 - 21.03km)	0.54	0.48-0.59	0.48	0.43-0.54	0.47	0.43-0.52	0.48	0.46-0.50	0.6	0.53-0.69	0.44	0.42-0.47
Reference T1 (0-2.34km)												
Perimeter:Area Ratio												
T2 (0.008 - 0.027)	1	0.93-1.07	0.99	0.92-1.08	0.97	0.91-1.04	1	0.97-1.03	1.02	0.92-1.13	1.03	0.99-1.07
T3 (0.027 - 0.23)	1.15	1.04-1.28	1.17	1.05-1.31	1.12	1.02-1.23	1.29	1.24-1.35	0.77	0.66-0.89	1.4	1.33-1.47
Reference: T1 (0-0.007)												
ICE:Income												
T1: Low Income	1.25	1.14-1.37	1.27	1.15-1.42	1.4	1.28-1.53	1.34	1.29-1.39	0.89	0.78-1.01	1.38	1.32-1.45
T2: Mixed Income	1.61	1.49-1.74	1.53	1.40-1.66	1.68	1.56-1.81	1.67	1.62-1.73	1.05	0.94-1.17	1.72	1.65-1.79
Reference: T3 (High Income)												
ICE:Race												
T1: Predom Black	0.97	0.90-1.05	0.85	0.77-0.93	0.85	0.79-0.91	1.13	1.10-1.17	1.03	0.92-1.16	1.2	1.16-1.25
T2: Mixed Race	0.79	0.73-0.86	0.64	0.58-0.70	0.67	0.62-0.72	0.7	0.68-0.73	0.75	0.67-0.84	0.65	0.62-0.67
Reference: T3 (Predom White)												
MHPSA	0.55	0.42-0.73	0.35	0.26-0.46	0.43	0.34-0.56	0.61	0.54-0.70	0.47	0.34-0.65	0.91	0.75-1.12
Observations: 85												

Rural/Isolated

	Anxiety		Depression		Mood		Mental and Behavioral Disorders		suicide-related outcomes		Substance Use Disorder	
	PRR	CI	PRR	CI	PRR	CI	PRR	CI	PRR	CI	PRR	CI
Area/Person												
T1 (0-7,774.03m2)	0.55	0.46-0.64	0.66	0.56-0.79	0.7	0.59-0.81	0.61	0.57-0.64	0.96	0.76-1.20	0.54	0.50-0.58
T2 (8,804.1 - 49,9595.1m2)	1.05	0.93-1.19	1.19	1.03-1.36	1.22	1.08-1.39	1.04	0.99-1.09	1.46	1.21-1.76	0.95	0.89-1.00
Reference: T3 (59,922.6 - 2,249,938m2)												
Distance												
T2 (0.55-3.19km)	1.77	1.56-2.02	1.77	1.53-2.05	1.71	1.51-1.95	1.71	1.63-1.80	1.44	1.19-1.74	1.81	1.70-1.92
T3 (3.41 - 21.56km)	2.09	1.76-2.49	2.09	1.72-2.53	2.16	1.83-2.56	2.28	2.13-2.44	1.95	1.54-2.49	2.38	2.19-2.58
Reference T1 (0-0.45km)												
Perimeter:Area Ratio												
T2 (0.01-0.037)	1.11	0.98-1.27	1.05	0.91-1.21	1.05	0.93-1.20	1.17	1.11-1.23	1	0.84-1.19	1.21	1.14-1.28
T3 (0.041 - 1.1)	1.61	1.43-1.82	1.27	1.11-1.44	1.3	1.16-1.45	1.23	1.18-1.29	0.87	0.74-1.02	1.19	1.12-1.26
Reference: T1 (0-0.01)												
ICE:Income												
T1: Low Income	1.3	1.15-1.48	1.18	1.03-1.35	1.19	1.06-1.34	1.13	1.08-1.18	1.06	0.90-1.26	1.12	1.05-1.18
T2: Mixed Income	1.25	1.10-1.41	1.04	0.91-1.18	1.08	0.97-1.22	1.4	1.34-1.47	0.92	0.78-1.09	1.54	1.46-1.63
Reference: T3 (High Income)												
ICE:Race												
T1: Predom Black	1.10	0.93-1.29	1.14	0.95-1.37	1.25	1.07-1.48	1.23	1.15-1.31	1.1	0.86-1.40	1.22	1.13-1.32
T2: Mixed Race	1.82	1.58-2.10	2.21	1.88-2.6	2.4	2.07-2.78	2.17	2.05-2.30	2.49	2.01-3.10	2.38	2.22-2.55
Reference: T3 (Predom White)												
MHPSA												
Observations: 94												

Figures

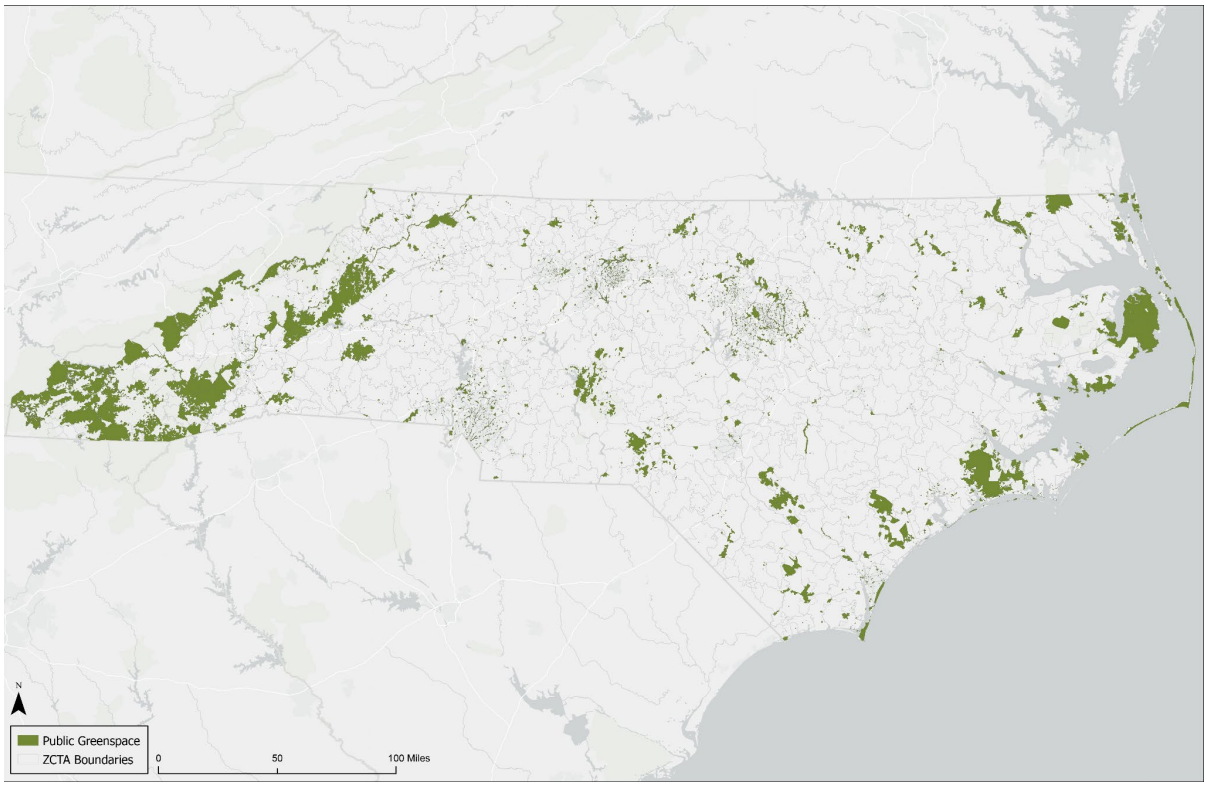


Figure 1 - Map depicting the spatial distribution of public greenspace in North Carolina. Greenspace data is from the Protected Area Database of the United States (PAD_US) and the Trust for Public Land's ParkServe dataset.

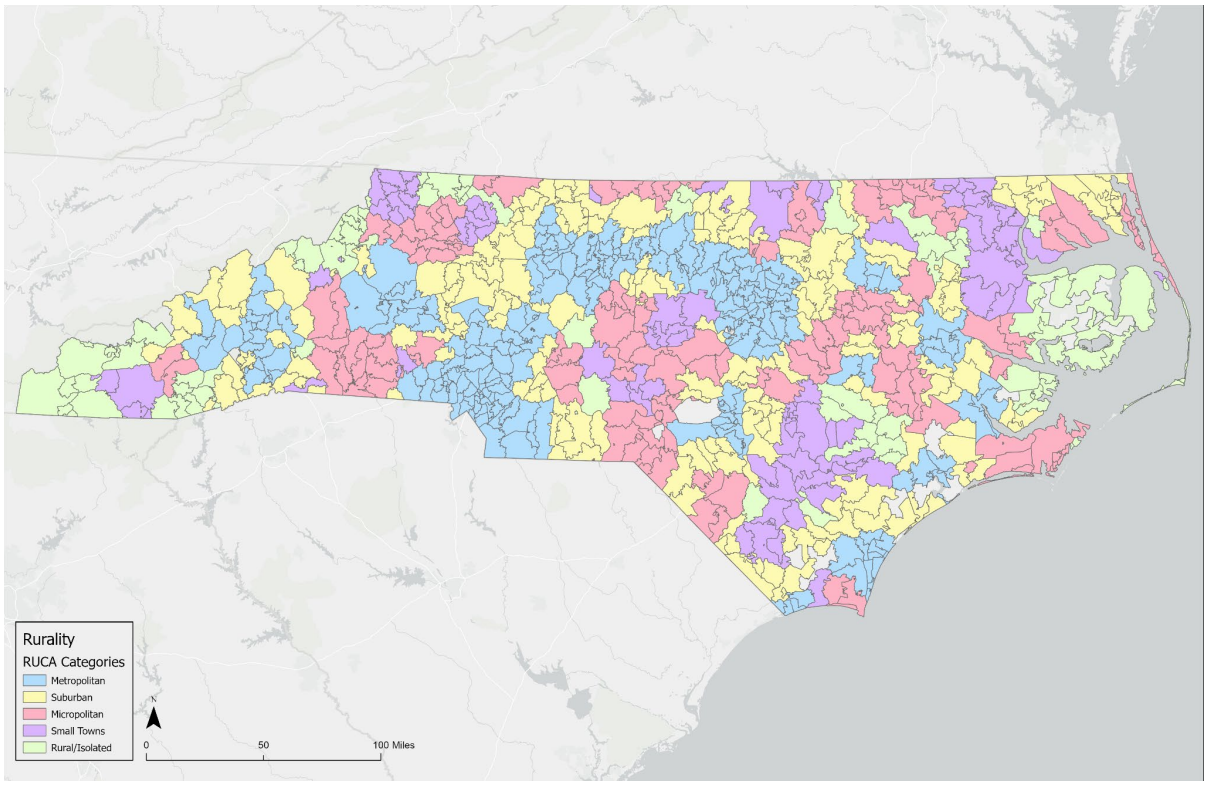


Figure 2 - Map indicating the spatial distribution of urban, suburban, micropolitan, small towns, and rural/isolated ZCTAs. Rurality designations were determined using USDA Rural-Urban Commuting Area (RUCA) codes.

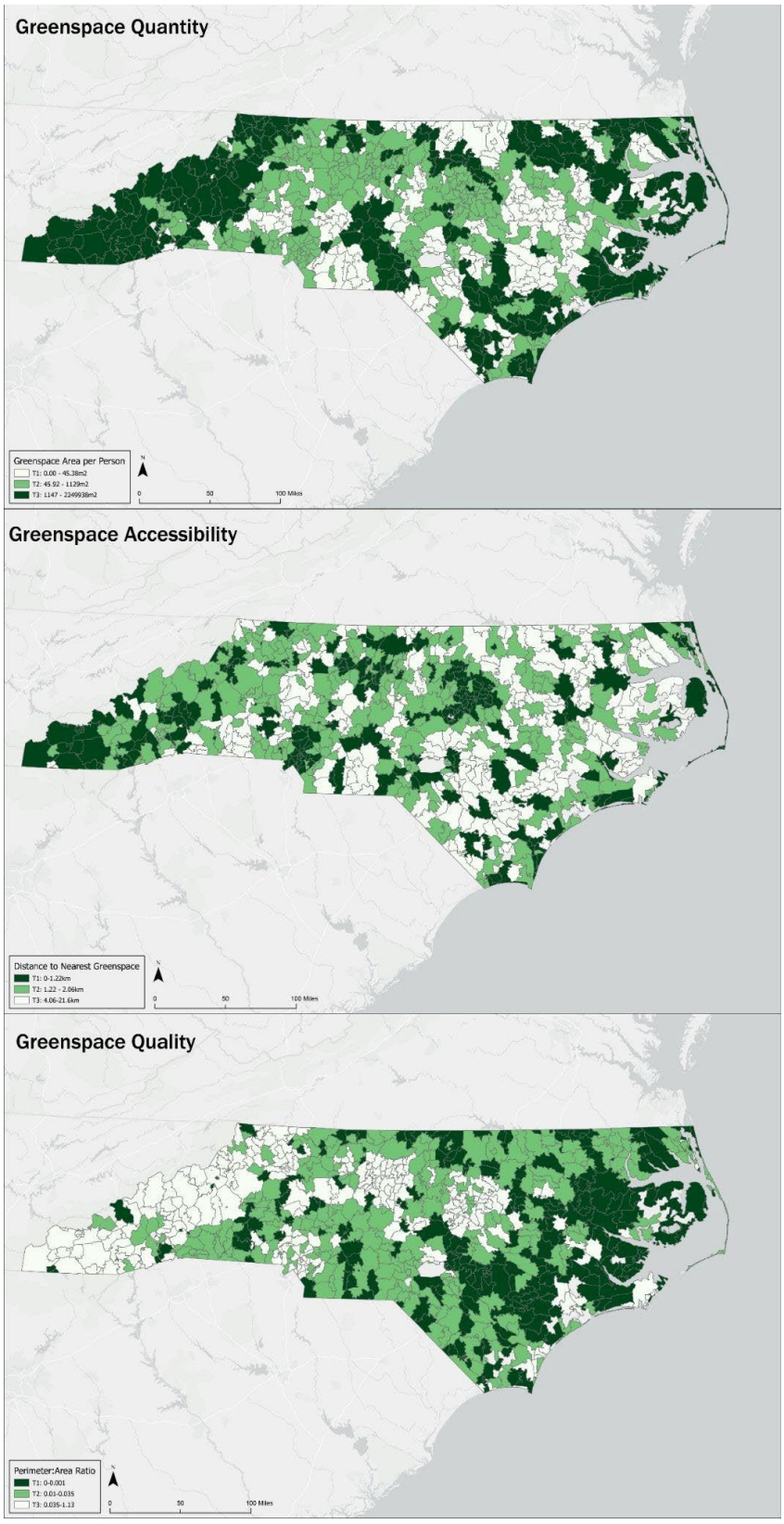


Figure 3 - Distribution of greenspace quantity, quality and accessibility. Greenspace metrics are displayed in tertiles.

Figure 4. Summary of place-based greenspace and mental health findings. Blue boxes indicate a negative association between greenspace and mental health; dark blue boxes indicate the most substantial associations. Red boxes indicate no negative association.

Appendix A. Supplemental Materials

Age and Sex-stratified Results

For children ages 14 and under, this association was most pronounced for anxiety, with a 1.82 (CI:1.72-1.91, p<0.001) higher prevalence of anxiety in ZCTAs with the least amount of greenspace (T1), compared to those with the greatest amount of public greenspace (T3) (Supplemental Table 1). Among 15-17 year olds, ZCTAs with moderate quantities of greenspace (T2) were associated with the highest PRRs; mood disorders saw the greatest increase in prevalence , 1.39 (CI:1.34-1.43, p<0.001) higher PRR compared to ZCTAs with the most amount of greenspace (T3). Among 18-24 year olds, ZCTAs with moderate greenspace quantity (T2) were associated with a higher prevalence of anxiety, depression and mood disorders; mood disorders were associated with the largest PRR (PRR:1.34, CI:1.31-1.36, p<0.001). ZCTAs with the lowest quantities of greenspace (T1) were associated with higher PRRs for mental and behavioral disorders, suicide-related outcomes and substance use disorders; substance use disorders were associated with the highest PRR (PRR :1.29, CI: 1.28-1.30, p<0.001).

Across all three age groups, residence in a ZCTA with moderate greenspace accessibility (T2) was associated with higher PRRs for all mental health outcomes, except for substance use disorders among individuals 14 and younger, and suicide-related outcomes among individuals 18-24. For all three age groups, anxiety was associated with the highest PRRs, 1.12 (CI:1.08-1.16, p<0.001) for children 14 and under, 1.15 (CI:1.11-1.19, p<0.001) for adolescents aged 15-17, and 1.18 (CI:1.16-1.20, p<0.001) among young adults 18-24 years old. Among young adults ages 18-24, residence in a ZCTA with moderate greenspace quality (T2) was associated with higher PRRs for all health outcomes, compared to ZCTAs with the best greenspace quality. This increase in PRR was most substantial for suicide-related outcomes, with a 1.18 (CI:1.15-1.21, p<0.001) higher PRR in ZCTAs with moderate greenspace quality (Supplemental Table 1).

For both males and females, residence in a ZCTA with less greenspace quantity (T1 & T2) was associated with higher PRRs for all mental health outcomes, compared to residence in ZCTAs with the highest greenspace quantity (T3) (Supplemental Table 2). Among males, mood disorders were associated with the most substantial increase in PRR , 1.76 (CI:1.71-1.81, p<0.001), and among females, anxiety was associated with the most substantial increase in PRR , 1.8 (CI:1.76-1.84, p<0.001). Among both males and females, residence in ZCTAs with moderate greenspace accessibility (T2), was significantly associated with higher PRRs compared to ZCTAs with the best greenspace accessibility (T1). The increase in PRRs was highest for anxiety; males were associated with 1.12 (CI:1.09-1.15, p<0.001) higher PRR of anxiety, and females were associated with a 1.18 (CI:1.16-1.20, p<0.001) higher PRR of anxiety, compared to ZCTAs with the best greenspace accessibility.

Supplemental Table 1 - Age-stratified GLM results investigating the relationship between greenspace quantity, quality and accessibility, and mental health-related ED visits with consideration of three age categories: childhood (ages 0-14), adolescence (ages 15-17), and young adulthood (ages 18-24) in NC (2016-2019).

Childhood: Ages 14 and Under

	Anxiety		Depression		Mood		Mental and Behavioral Disorders		suicide-related outcomes		Substance Use Disorder	
	PRR	CI	PRR	CI	PRR	CI	PRR	CI	PRR	CI	PRR	CI
Area/Person												
T1 (0 - 45.38m2)	1.82	1.72-1.91	1.71	1.63-1.79	1.75	1.67-1.82	1.57	1.55-1.60	1.53	1.46-1.60	1.75	1.60-1.92
T2 (45.92-1,129 m2)	1.54	1.46-1.63	1.46	1.39-1.53	1.54	1.48-1.61	1.35	1.32-1.37	1.30	1.24-1.37	1.62	1.48-1.78
Reference: T3 (1,147 - 2,249,938m2)												
Distance												
T2 (1.23-4.06km)	1.12	1.08-1.16	1.07	1.03-1.11	1.07	1.04-1.11	1.15	1.13-1.16	1.08	1.04-1.12	1.00	0.94-1.08
T3 (4.09-21.6km)	0.91	0.86-0.96	0.88	0.84-0.92	0.88	0.84-0.92	1.01	0.99-1.03	0.84	0.80-0.88	0.79	0.72-0.86
Reference T1 (0-1.22km)												
Perimeter:Area Ratio												
T2 (0.01-0.035)	1.01	0.97-1.05	0.97	0.93-1.00	0.95	0.92-0.98	0.89	0.87-0.90	0.98	0.94-1.01	1.03	0.96-1.10
T3 (0.035-1.13)	0.72	0.69-0.76	0.72	0.69-0.75	0.71	0.68-0.74	0.70	0.69-0.72	0.79	0.76-0.83	0.77	0.70-0.84
Reference: T1 (0-0.01)												
ICE:Income												
T1: Low Income	1.31	1.24-1.38	1.31	1.25-1.38	1.42	1.36-1.48	1.69	1.65-1.73	1.27	1.21-1.34	2.27	2.07-2.49
T2: Mixed Income	1.48	1.42-1.55	1.52	1.46-1.58	1.59	1.54-1.65	1.76	1.73-1.79	1.52	1.46-1.58	2.08	1.93-2.25
Reference: T3 (High Income)												
ICE:Race												
T1: Predominately Black	0.71	0.68-0.75	0.88	0.83-0.92	0.96	0.92-1.00	1.13	1.10-1.15	1.03	0.98-1.08	0.62	0.56-0.67
T2: Mixed Race	1.00	0.95-1.05	1.11	1.06-1.16	1.16	1.12-1.21	1.31	1.28-1.33	1.26	1.20-1.32	0.86	0.79-0.93
Reference: T3 (Predominately White)												

MHPSA	1.49	1.30-1.71	1.50	1.32-1.72	1.56	1.39-1.77	1.49	1.41-1.59	1.21	1.08-1.36	1.29	1.01-1.67
Observations: 808												

Adolescence: Ages 15-17

	Anxiety		Depression		Mood		Mental and Behavioral Disorders		suicide-related outcomes		Substance Use Disorder	
	PRR	**CI**	**PRR**	**CI**	**PRR**	**CI**	**PRR**	**CI**	**PRR**	**CI**	**PRR**	**CI**
Area/Person												
T1 (0 - 45.38m2)	1.15	1.11-1.20	1.18	1.14-1.22	1.16	1.13-1.20	1.11	1.09-1.13	1.16	1.11-1.20	1.15	1.11-1.18
T2 (45.92-1,129 m2)	1.38	1.32-1.43	1.35	1.30-1.40	1.39	1.34-1.43	1.31	1.28-1.33	1.31	1.25-1.36	1.36	1.31-1.41
Reference: T3 (1,147 - 2,249,938m2)												
Distance												
T2 (1.23-4.06km)	1.15	1.11-1.19	1.13	1.09-1.16	1.13	1.10-1.16	1.12	1.10-1.14	1.1	1.06-1.14	1.06	1.03-1.10
T3 (4.09-21.6km)	0.87	0.83-0.91	0.82	0.78-0.85	0.85	0.82-0.88	0.91	0.89-0.93	0.78	0.74-0.82	0.94	0.90-0.97
Reference T1 (0-1.22km)												
Perimeter:Area Ratio												
T2 (0.01-0.035)	1.02	0.98-1.05	0.98	0.95-1.01	0.97	0.94-1.00	0.96	0.94-0.97	1.03	0.99-1.07	0.98	0.96-1.01
T3 (0.035-1.13)	0.79	0.76-0.83	0.77	0.74-0.80	0.75	0.73-0.78	0.77	0.76-0.79	0.87	0.84-0.92	0.72	0.69-0.75
Reference: T1 (0-0.01)												
ICE:Income												
T1: Low Income	1.32	1.26-1.38	1.19	1.14-1.25	1.25	1.20-1.30	1.52	1.49-1.56	1.09	1.03-1.14	1.79	1.71-1.86
T2: Mixed Income	1.6	1.54-1.66	1.52	1.47-1.58	1.55	1.51-1.60	1.75	1.72-1.79	1.46	1.40-1.52	1.97	1.90-2.04
Reference: T3 (High Income)												
ICE:Race												
T1: Predom Black	0.92	0.87-0.96	1.02	0.97-1.06	1.1	1.06-1.14	1.15	1.12-1.18	1.17	1.11-1.23	0.84	0.81-0.87
T2: Mixed Race	1.08	1.03-1.13	1.16	1.12-1.21	1.2	1.16-1.24	1.21	1.18-1.23	1.29	1.23-1.35	0.95	0.92-0.99
Reference: T3 (Predom White)												
MHPSA	1.53	1.34-1.74	1.4	1.25-1.57	1.39	1.26-1.54	1.33	1.25-1.42	1.03	0.93-1.15	1.57	1.39-1.78
Observations: 808												

Young Adulthood: Ages 18-24

	Anxiety		Depression	Mood		Mental and	suicide-	Substance Use

							Behavioral Disorders		related outcomes		Disorder	
	PRR	CI	PRR	CI	PRR	CI	PRR	CI	PRR	CI	PRR	CI
Area/Person												
T1 (0 - 45.38m2)	1.24	1.22-1.26	1.27	1.24-1.29	1.24	1.22-1.27	1.27	1.26-1.28	1.2	1.16-1.23	1.29	1.28-1.30
T2 (45.92-1,129 m2)	1.31	1.28-1.34	1.29	1.26-1.32	1.34	1.31-1.36	1.26	1.25-1.27	1.11	1.08-1.14	1.28	1.27-1.30
Reference: T3 (1,147 - 2,249,938m2)												
Distance												
T2 (1.23-4.06km)	1.18	1.16-1.20	1.09	1.07-1.11	1.08	1.07-1.10	1.09	1.09-1.10	1	0.97-1.02	1.09	1.09-1.10
T3 (4.09-21.6km)	0.69	0.67-0.71	0.61	0.59-0.62	0.63	0.62-0.65	0.7	0.69-0.70	0.54	0.52-0.55	0.72	0.72-0.73
Reference T1 (0-1.22km)												
Perimeter:Area Ratio												
T2 (0.01-0.035)	1.13	1.11-1.15	1.12	1.10-1.14	1.1	1.08-1.11	1.07	1.07-1.08	1.18	1.15-1.21	1.07	1.06-1.08
T3 (0.035-1.13)	0.63	0.62-0.64	0.67	0.66-0.69	0.65	0.63-0.66	0.62	0.62-0.63	0.74	0.71-0.76	0.61	0.61-0.62
Reference: T1 (0-0.01)												
ICE:Income												
T1: Low Income	0.98	0.96-1.00	0.93	0.90-0.95	1	0.98-1.02	1.2	1.18-1.21	0.82	0.79-0.84	1.29	1.28-1.31
T2: Mixed Income	1.3	1.28-1.33	1.27	1.25-1.30	1.33	1.30-1.35	1.55	1.54-1.56	1.17	1.14-1.20	1.67	1.66-1.69
Reference: T3 (High Income)												
ICE:Race												
T1: Predom Black	1.53	1.50-1.56	1.67	1.63-1.71	1.8	1.77-1.84	1.91	1.89-1.92	2.35	2.27-2.43	1.82	1.80-1.83
T2: Mixed Race	1.52	1.49-1.55	1.57	1.53-1.61	1.6	1.57-1.64	1.59	1.58-1.61	1.87	1.81-1.94	1.53	1.51-1.55
Reference: T3 (Predom White)												
MHPSA	1.24	1.17-1.33	1.26	1.18-1.36	1.3	1.22-1.38	1.45	1.41-1.49	1.1	1.01-1.20	1.57	1.52-1.63
Observations: 808												

Supplemental Table 2 -Sex-stratified GLM results investigating the relationship between greenspace quantity, quality and accessibility, and mental health-related ED visits among individuals aged 24 and under for males and females in NC (2016-2019).

Male

	Anxiety		Depression	Mood		Mental and Behavioral	suicide-related	Substance Use

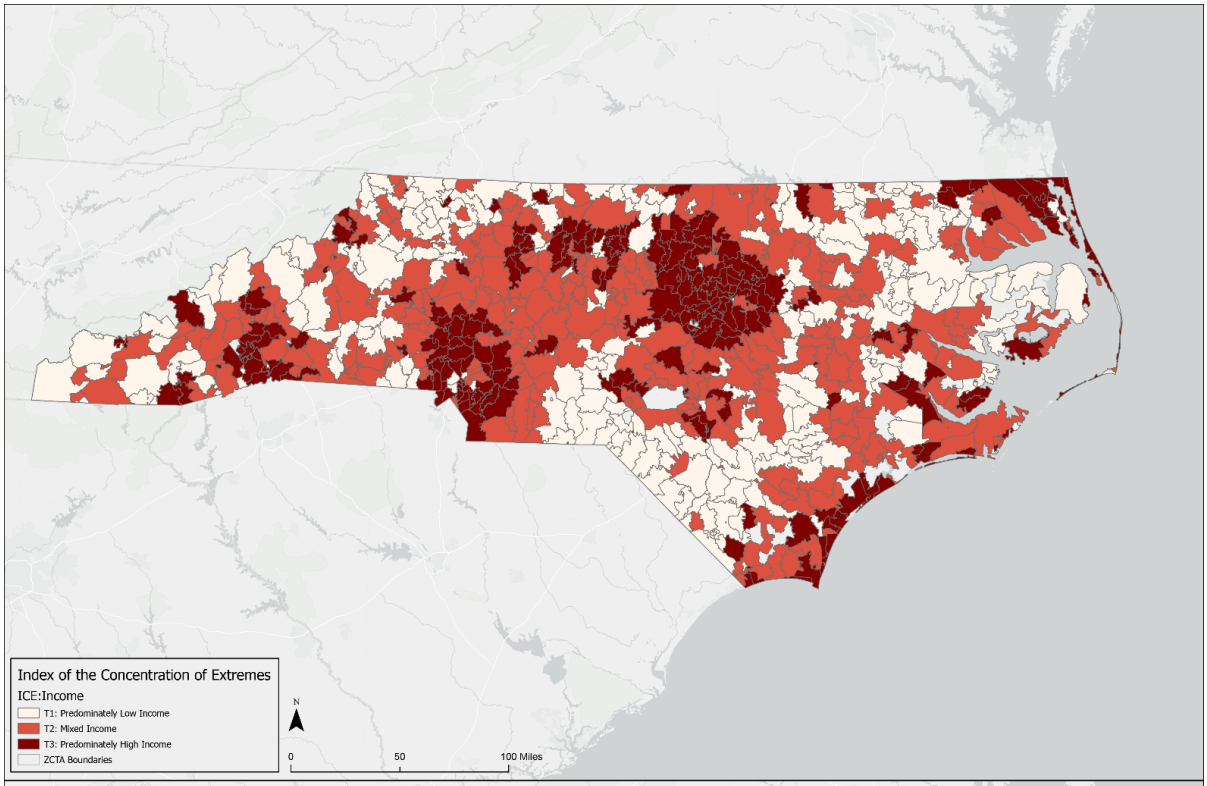
							Disorders		outcomes		Disorder	
	PRR	CI	PRR	CI	PRR	CI	PRR	CI	PRR	CI	PRR	CI
Area/Person												
T1 (0 - 45.38m2)	1.72	1.66-1.78	1.73	1.67-1.79	1.76	1.71-1.81	1.6	1.58-1.62	1.55	1.50-1.61	1.62	1.60-1.64
T2 (45.92-1,129 m2)	1.51	1.45-1.56	1.46	1.41-1.51	1.56	1.51-1.61	1.37	1.36-1.39	1.31	1.26-1.36	1.39	1.37-1.41
Reference: T3 (1,147 - 2,249,938m2)												
Distance												
T2 (1.23-4.06km)	1.12	1.09-1.15	1.08	1.05-1.11	1.07	1.05-1.10	1.1	1.09-1.11	1.09	1.06-1.12	1.07	1.06-1.09
T3 (4.09-21.6km)	0.81	0.78-0.83	0.77	0.74-0.80	0.81	0.79-0.83	0.89	0.88-0.9	0.77	0.74-0.80	0.89	0.88-0.91
Reference T1 (0-1.22km)												
Perimeter:Area Ratio												
T2 (0.01-0.035)	1.03	1.00-1.06	0.98	0.96-1.01	0.96	0.94-0.98	0.95	0.94-0.95	1.01	0.98-1.04	0.95	0.94-0.96
T3 (0.035-1.13)	0.72	0.69-0.74	0.74	0.72-0.77	0.73	0.71-0.75	0.72	0.71-0.72	0.78	0.76-0.81	0.7	0.69-0.71
Reference: T1 (0-0.01)												
ICE:Income												
T1: Low Income	1.37	1.32-1.42	1.23	1.18-1.27	1.34	1.30-1.38	1.66	1.64-1.68	1.2	1.15-1.24	1.8	1.77-1.83
T2: Mixed Income	1.41	1.38-1.45	1.35	1.31-1.39	1.41	1.37-1.44	1.66	1.64-1.68	1.32	1.28-1.36	1.79	1.77-1.81
Reference: T3 (High Income)												
ICE:Race												
T1: Predom Black	0.84	0.81-0.87	0.98	0.94-1.01	1.1	1.07-1.13	1.18	1.17-1.20	1.19	1.15-1.24	1.09	1.08-1.11
T2: Mixed Race	1.12	1.09-1.16	1.17	1.13-1.21	1.22	1.19-1.26	1.23	1.21-1.24	1.31	1.26-1.36	1.15	1.13-1.16
Reference: T3 (Predom White)												
MHPSA	1.47	1.34-1.61	1.48	1.35-1.63	1.52	1.40-1.65	1.51	1.46-1.56	1.21	1.11-1.33	1.58	1.51-1.66
Observations: 808												

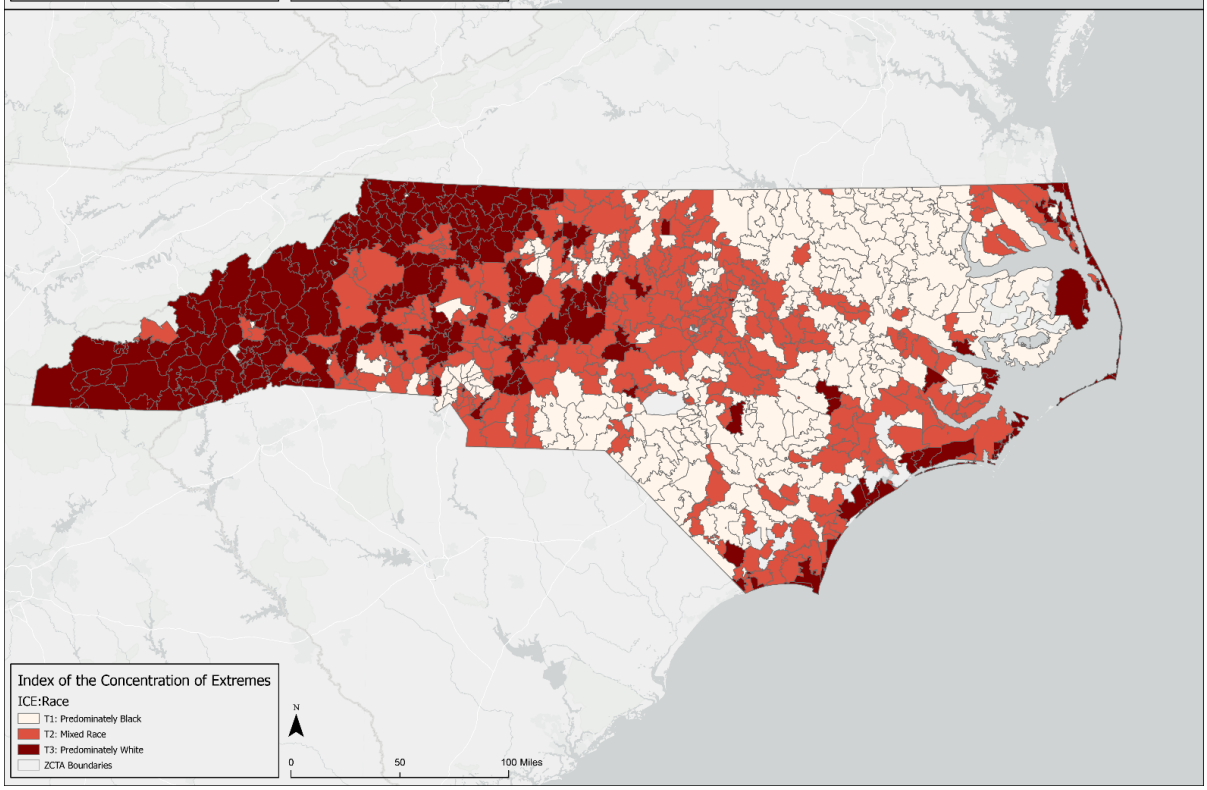
Female

	Anxiety		Depression		Mood		Mental and Behavioral Disorders		suicide-related outcomes		Substance Use Disorder	
	PRR	CI	PRR	CI	PRR	CI	PRR	CI	PRR	CI	PRR	CI
Area/Person												
T1 (0 - 45.38m2)	1.8	1.76-1.84	1.78	1.74-1.82	1.79	1.76-1.83	1.69	1.67-1.71	1.56	1.51-1.61	1.73	1.71-1.76
T2 (45.92-1,129 m2)	1.53	1.50-1.57	1.48	1.44-1.52	1.53	1.50-1.57	1.44	1.42-1.46	1.35	1.31-1.40	1.47	1.45-1.49
Reference: T3 (1,147 - 2,249,938m2)												
Distance												

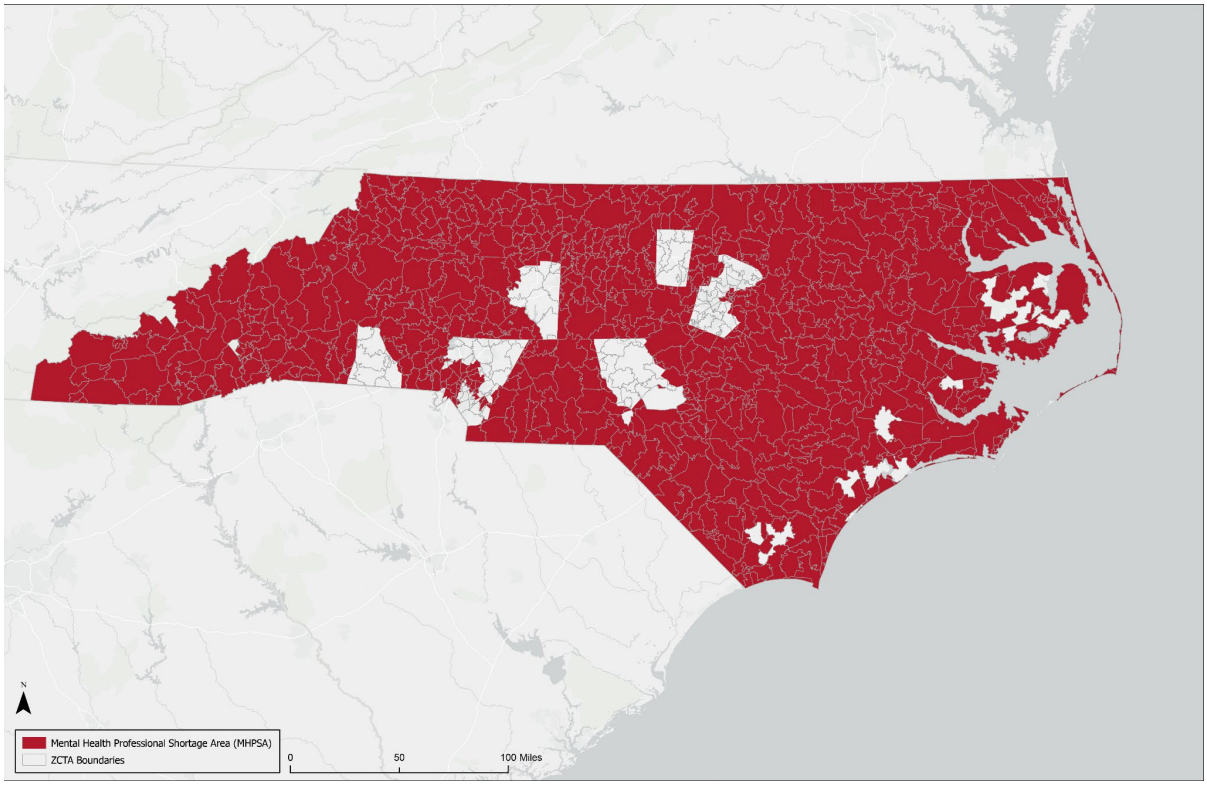
T2 (1.23-4.06km)	1.18	1.16-1.20	1.1	1.08-1.13	1.1	1.08-1.12	1.13	1.12-1.14	1.03	1.01-1.06	1.12	1.11-1.14
T3 (4.09-21.6km)	0.88	0.86-0.90	0.79	0.77-0.81	0.81	0.79-0.82	0.9	0.89-0.91	0.73	0.70-0.75	0.92	0.91-0.94
Reference T1 (0-1.22km)												
Perimeter:Area Ratio												
T2 (0.01-0.035)	1.01	0.99-1.03	1	0.98-1.02	0.98	0.97-1.00	0.96	0.95-0.96	1.04	1.01-1.06	0.96	0.95-0.97
T3 (0.035-1.13)	0.72	0.70-0.73	0.74	0.72-0.76	0.71	0.70-0.73	0.7	0.69-0.71	0.84	0.82-0.87	0.68	0.67-0.69
Reference: T1 (0-0.01)												
ICE:Income												
T1: Low Income	1.42	1.39-1.45	1.32	1.28-1.35	1.43	1.40-1.46	1.76	1.75-1.78	1.11	1.07-1.15	2.11	2.08-2.14
T2: Mixed Income	1.46	1.43-1.49	1.4	1.38-1.43	1.47	1.45-1.50	1.72	1.70-1.73	1.28	1.25-1.31	2	1.98-2.03
Reference: T3 (High Income)												
ICE:Race												
T1: Predom Black	0.85	0.83-0.87	0.92	0.89-0.94	0.97	0.95-0.99	1.05	1.04-1.07	1.2	1.16-1.24	0.96	0.95-0.97
T2: Mixed Race	1.06	1.03-1.08	1.11	1.09-1.14	1.13	1.11-1.15	1.16	1.15-1.18	1.31	1.27-1.35	1.09	1.07-1.10
Reference: T3 (Predom White)												
MHPSA	1.4	1.32-1.50	1.39	1.31-1.49	1.42	1.34-1.51	1.49	1.45-1.55	1.09	1.02-1.18	1.72	1.64-1.80
Observations: 808												

Supplemental Figure 1 - Distribution of ICE Metrics, computed as tertiles. Map (A) corresponds to the ICE:Income metric and map (B) corresponds to the ICE:Race metric. Tertile 1 corresponds to predominately low income (ICE: Income) and predominately Black (ICE: Race); Tertile 2 corresponds to mixed income (ICE: Income) and mixed race (ICE: Race), and Tertile 3 corresponds to predominantly high income (ICE: Income) and predominantly White (ICE: Race)

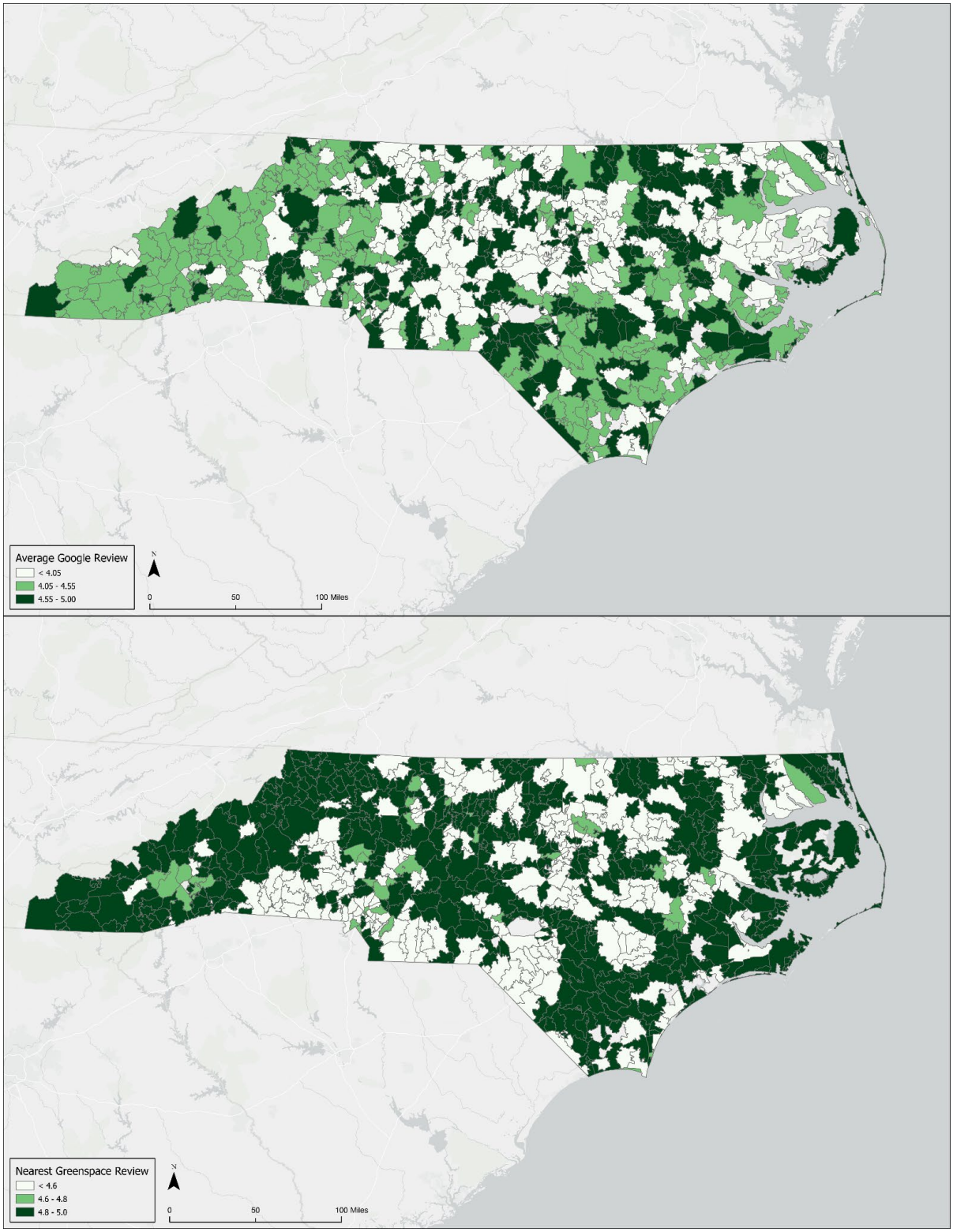




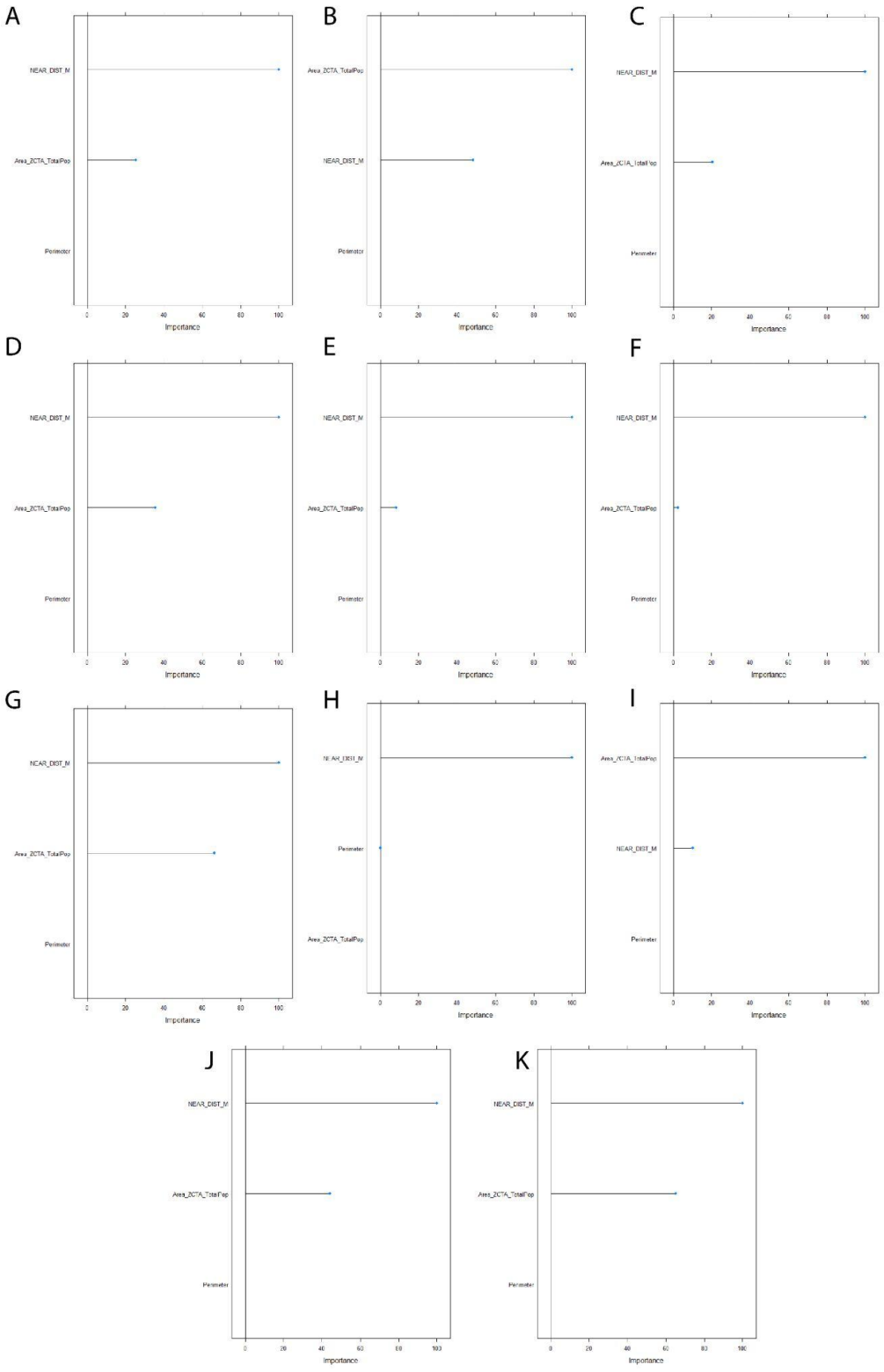
Supplemental Figure 2 - Distribution of Mental Health Professional Shortage Area (MHPSA) designations.



Supplemental Figure 3 - Distribution of greenspace google review data; computed as tertiles.



Supplemental Figure 4 - Elastic net regression results indicating greenspace metric importance for (A) the state-wide GLM, (B) the urban-stratified GLM, (C) the suburban-stratified GLM, (D) the small town-stratified GLM, (E) the rural/isolated-stratified GLM, (F)the 14 and under-stratified GLM, (G)the 15-17 year old-stratified GLM, (H) the 18-24 year old-stratified GLM, (I) the male-stratified GLM, and (J)the female-stratified GLM.



Vita

Sophia Ryan grew up in Weybridge, Vermont. She studied physical geography at the University of Vermont, where she conducted stream water chemistry research. As a master's student, Sophia has focused on studying the geography of mental health. Sophia's work investigates spatiotemporal mental health clusters, the association between greenspace and mental health outcomes among adolescents, and the mental health response following exposure to extreme social (e.g., COVID-19 pandemic) and natural (e.g., hurricane) stressors. She is also interested in understanding how socio-demographic and environmental variables interact to increase the odds of an individual, or a community, experiencing heightened poor mental health outcome burdens. Sophia won an NSF-REG award to support her greenspace and mental health research, and her work has been published in the *Journal of Adolescent Health*, *Social Science and Medicine – Mental Health*, and *Public Health Reports*.