Natural Environments and Health in Adolescents and Young Adults

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NATURAL ENVIRONMENTS AND HEALTH IN ADOLESCENTS AND YOUNG ADULTS

Carla Philips Bezold

A Dissertation Submitted to the Faculty of

The Harvard T.H. Chan School of Public Health

in Partial Fulfillment of the Requirements

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Natural environments and health in adolescents and young adults

Abstract

There is growing recognition that natural environments, including both vegetation (greenness or green space) and surface water (blue space) can influence health by providing spaces for physical activity and social interactions, reducing stress, maintaining cognitive skills, and mitigating harmful environmental exposures such as pollution, noise, and extreme heat. Studies to date are suggestive but somewhat limited in scope still. Few population-based studies have considered outcomes in adolescence or the impact of cumulative exposure to nature on subsequent health. We investigated the associations between childhood and adolescent exposure to objectively-measured natural environments and mental and physical health in the Growing Up Today Study (GUTS), a prospective cohort of adolescents and young adults living in the United States.

In Chapter 1, we assessed the cross-sectional associations between greenness, blue space, and depressive symptoms during adolescence. Individuals living in areas with greater greenness exposure were less likely to report depressive symptoms, an association that was robust to adjustment to a wide variety of individual, household, and neighborhood social and economic characteristics. There were no associations between any measure of blue space and depressive symptoms. Chapter 2 considered whether surrounding greenness in childhood was associated with the onset of depressive symptoms in adolescence and early adulthood. Growing up in an area of greater greenness was associated with lower onset of depressive symptoms; the association was suggestively stronger in areas of high population density and among younger-onset cases. We observed no associations between surrounding greenness and prevalent or incident overweight and obesity, assessed in Chapter 3. There was suggestive evidence of effect
modification by population density, with inverse associations in areas of high density and positive associations in areas of low density.

Taken together, these papers suggest that greater exposure to greenness may be beneficial for adolescent and young adult mental health. Associations between greenness and both depressive symptoms and overweight and obesity varied across population density, pointing toward the need for further research how the associations between greenness and health may differ across socio-environmental contexts.
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INTRODUCTION
The environments where we live, learn, work, and play have profound influences on our health. Environmental exposure to harmful substances such as air pollution has been consistently shown to adversely affect multiple health outcomes. The built environment, which encompasses the physical aspects of communities such as buildings, streets, open spaces, and infrastructure, has been linked to health outcomes across the life course including diabetes, obesity, cardiovascular disease, and depression. As the proportion of the U.S. population living in urban areas continues to steadily increase, understanding the complex ways the built environment influences health is an important component of public health promotion for people of all ages.

Nature and natural environments have received particular attention in public health research as an aspect of the built environment that can positively influence mental and physical health. References to nature or natural environments can be interpreted to include a wide range of plants, animals, and other nonhuman living things. Epidemiologic research into the relationship between nature and health has predominantly focused on natural environments that are composed of vegetation (operationalized as greenness or green spaces) or water (blue spaces).

Substantial work in environmental psychology suggests that nature can have a direct impact on mental health, emotion, and cognition. The biophilia hypothesis posits that humans have evolved to have an affinity for nature and natural things. Another theory, attention restoration theory, posits that the experience of nature can provide a restorative break for cognition and attention. This process of restoration is particularly relevant for those living in urban environments, which consistently tax attention and cognition.

Experimental and observational studies involving various subject populations have observed reduced stress or improved attention during and after contact with nature. Some of the earliest observations involved surgical patients, where researchers observed those in a room with a view of nature recovered faster. Subsequent experimental studies have shown improvements in self-reported affect, physiological stress response, and autonomic nervous system control. Other studies have observed
improved performance on tests of attention in subjects assigned to view nature compared to subjects who viewed urban scenes.²¹,²²

In addition to the potential direct effects of nature on attention, cognition, and mental health, natural environments can provide compelling spaces for physical activity. Parks and other public open spaces in particular are considered an important resource for physical activity.²³,²⁴ By encouraging physical activity and time outdoors, natural environments may also reduce screen time.²⁵,²⁶

Natural environments can also facilitate social interaction and foster social cohesion,²⁷,²⁸ which can in turn support mental and physical health.²⁹ Particularly in dense urban areas, natural environments represent places where people can come together. For children, natural environments can foster imaginative and creative play and contact with adults.³⁰ A quasi-experimental study in Chicago observed residents assigned to public housing developments with adjacent green spaces had greater social contact with their neighbors, lower aggressive behaviors, and lower community violence compared with those assigned to similar units lacking vegetation.³¹

Finally, natural environments may lessen the impact of other harmful exposures including air pollution, extreme temperatures, and noise. Trees and other vegetation can filter particulate matter.³² The presence of trees in urban environments can provide shade and cooling during times of extreme heat;³³ proximity to bodies of water can similarly temper the sense of extreme temperatures.³⁴ And living closer to a green space is associated with lower levels of noise annoyance.³⁵ The buffering of these harmful exposures represents another mechanism through which natural environments may influence mental and physical health.

Through these pathways – direct impacts on stress and attention, increased physical activity and social interaction, reduced screen time, and buffering of other harmful exposures – natural environments may contribute to immediate and long-term health states. There is growing epidemiologic evidence that natural environments are associated with a range of health outcomes including depression and other mental health conditions,¹⁰,³⁶,³⁷ cardiovascular disease,³⁸ and mortality.³⁹ However, important gaps in the literature remain. This dissertation aims to address some of these limitations by considering the
relationships between natural environments, including both greenness and blue space, and mental and physical health across the life course.

Most of the existing literature on nature and health has focused on children or adults; adolescence remains relatively understudied despite being a critical developmental period. Additionally, most of the epidemiologic evidence for nature’s influence on health has focused on green space or greenness and less attention has been paid to whether exposure to water, or “blue space,” is also relevant for long-term health. Blue space may provide similar benefits as green space for cognitive restoration and stress reduction, and may similarly facilitate social cohesion – suggesting that it too may confer observable mental health benefits. Chapter 1 investigates the association between natural environments, including both greenness and blue space, and mental health in adolescents living in the United States.

The life course model of health demonstrates that children’s health and exposures are connected to their health as adults and that, while health is produced across the lifespan, early years of life may be a critical period. In keeping with this model, a range of environmental and contextual exposures have been shown to influence health outcomes much later in life. The impact of cumulative childhood exposures to nature on later life health has not been explored, although observations of variations in the association between greenness and health across age groups suggest such a life course approach is warranted. Therefore, Chapter 2 considers the association between surrounding greenness in childhood and adolescence and incidence of high depressive symptoms in adolescence and early adulthood.

There is some evidence that green spaces, particularly parks, are associated with greater physical activity and lower screen or sedentary time. Evidence for whether these associations translate into associations between natural environments and overweight or obesity remains limited and mixed. Chapter 3 assesses the cross-sectional and longitudinal associations between greenness and physical activity, screen time, and overweight and obesity. Together these studies contribute to the growing body of evidence characterizing the immediate and long-term associations between natural environments and mental and physical health.
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Chapter 1: The association between natural environments and depressive symptoms in adolescents living in the United States

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Abstract

Purpose: A growing body of evidence suggests that exposure to nature and natural environments may be beneficial for mental health. Most population-based studies have been conducted among adults while few have focused on adolescents. We aimed to investigate the relationship between residential exposure to natural environments, including both greenness and blue space, and depressive symptoms among teenagers living in the United States.

Methods: The study population was 9,386 participants ages 12-18 in the 1999 wave of the Growing Up Today Study (GUTS). We characterized greenness exposure using the Normalized Difference Vegetation Index (NDVI) at 250 and 1250m radii around a subject’s residence. Exposure to blue space was defined as the presence of blue space within 250m and 1250m radii and distance to the nearest blue space. We used logistic regression models to examine associations with high depressive symptoms, measured using self-reported responses to the McKnight Risk Factor Survey.

Results: 1-IQR higher peak greenness in the 1250m buffer was associated with 11% lower odds of high depressive symptoms (95% CI 0.79-0.99), with stronger results observed in middle school compared to high school students. Associations between blue space and high depressive symptoms were consistently null.

Conclusions: Surrounding greenness, but not proximity to blue space, was associated with lower odds of high depressive symptoms in this population of more than 9,000 US adolescents. This association was stronger in middle school students than high school students. Future studies should consider quality and accessibility of natural environments and longitudinal analyses in adolescent samples.
Introduction

A growing body of evidence suggests that short- and long-term exposure to nature and natural environments is beneficial for mental health\textsuperscript{2,3}. Nature may directly influence mental health by improving people’s affective states\textsuperscript{4–8} and activating restorative processes related to cognition and attention\textsuperscript{9}. Natural environments can also provide opportunities to engage in physical activity and social interactions which may in turn benefit mental health\textsuperscript{2,3,10–12}.

Most population-based research on natural environments and mental health has been conducted among adults. Studies across many countries, mostly cross-sectional, have observed associations between surrounding greenness or green space and lower stress, psychological distress, and depressive symptoms. Greenness has also been associated with reduced risk of clinically relevant disorders including anxiety disorders, major depressive disorder, and other forms of psychiatric morbidity\textsuperscript{2}. Evidence for a relationship between greenness and mental health in children is more limited.\textsuperscript{3} Some studies have shown associations between green spaces and behavioral outcomes such as lower odds of behavioral problems\textsuperscript{13} or Attention Deficit and Hyperactivity Disorder symptoms among children and adolescents ages 5-18\textsuperscript{14}. Two population-based studies of emotional well-being found higher greenness was associated with lower emotional distress among children between ages 3 and 10\textsuperscript{15,16}.

Much of the research on effects of natural environments has focused on the implications of exposure to greenness or green spaces, but recent studies have begun to consider whether exposure to blue space (i.e., surface water) may also benefit mental health\textsuperscript{17–19}. Investigators hypothesize blue space may provide similar benefits for cognitive restoration and stress reduction\textsuperscript{12} but population-based evidence is limited and mixed. In a study of middle and high school students, Huynh et al observed an association between blue space near school and better emotional well-being, particularly for those who also lived near their school. Other studies of the relationship between blue space and health, conducted primarily in adults, have observed mixed results\textsuperscript{3,17,19–23}. The mixed findings may be attributed in part to heterogeneous exposure definitions, including distance to coast and presence of any blue space within
various buffers, or to variable outcomes including self-reported general health and various mental health measures.

Depression or depressive symptoms are prevalent mental health outcomes that are frequently studied, particularly in adults. One study in the US observed lower depressive symptom scores in adults living in greener areas\textsuperscript{24}, while a study in Lithuania observed a similar association in women only\textsuperscript{25}. Other studies that considered depression or depressive symptoms have not observed significant associations with greenness or green space\textsuperscript{26,27}. Similar to the studies of blue space, these studies have relied on heterogeneous exposure measures including self-reported access to green space and objective measures such as the Normalized Difference Vegetation Index (NDVI) or distance to a green space. These variable exposure measures may help explain the inconsistent findings.

Adolescence is an important developmental period with mental health an important contributor to adolescent morbidity\textsuperscript{28}. In a given year, depression impacts one in nine adolescents in the US\textsuperscript{29}. However, few studies of the relationship between nature and mental health have examined this age range. One recent study in the Netherlands observed no statistically significant associations between changes in greenery and depressive symptoms in a cohort of adolescents, although it relied on participant-reported green space to characterize exposure rather than an objective measure\textsuperscript{26}. Further population-based studies that look specifically at adolescents, particularly ones relying on objective exposure measures, are needed to more fully understand the relationship between natural environments and mental health in this age range\textsuperscript{3}.

We investigated the relationship between residential exposure to natural environments and depressive symptoms in a large cohort of teenagers living in the United States. We considered both surrounding greenness and various measures of residential exposure to blue space. This study is among the first to consider the relationship between blue space and mental health in a United States cohort and
adds to the literature on natural environments and mental health in adolescents. We consider potential confounding by important neighborhood and environmental attributes that co-vary with greenness, including air pollution and socioeconomic conditions, and possible effect modification by grade level.

**Methods**

Study participants were from the Growing Up Today Study (GUTS). GUTS was founded in 1996 by inviting mothers from the ongoing Nurses’ Health Study II (NHS II) to enroll their children between the ages of 9 and 14 into the study. Once parental consent was obtained, participants who returned completed questionnaires at baseline were considered enrolled (n = 16,875). The study was approved by the Brigham and Women's Hospital Institutional Review Board.

For this study, eligible participants were 12-18 year-old participants in the 1999 wave of GUTS (N=12,413) because that was the first wave at which depressive symptoms were assessed. We excluded participants who did not report on depressive symptoms in 1999 (N=1,598) or who lived outside the contiguous United States (N=27). We further excluded two participants who were younger than 12 when they completed the 1999 questionnaire because our outcome relied on an age-specific z-score. Study participants were assigned addresses based on the addresses of their mothers participating in NHS II. Addresses of all NHS II participants had been previously geocoded and we assigned each eligible GUTS participant the latitude and longitude values corresponding to their mother’s address in 1999. Since address assignment was based on mother’s reported residence we excluded subjects who reported not living with their mothers on the previous questionnaire (N=1,149), attending military or boarding school (N=61), or attending college (N=190), leaving 9,386 participants. Socioeconomic and environmental characteristics of the neighborhoods where the mothers of included subjects lived did not differ substantially from those who were excluded.

**Exposures**

Greenness was characterized using the NDVI, an index of vegetative density commonly used in studies of health outcomes. NDVI leverages the fact that chlorophyll in plants absorbs visible light (0.4-0.7 μm), while leaves reflect near-infrared light (0.7-1.1 μm). NDVI is calculated as the ratio of the
difference between the near-infrared and red reflectance to the sum of these two values. It ranges from -1.0 to 1.0, with larger values indicating higher levels of vegetative density. Reflectance data came from the Moderate-resolution Imaging Spectroradiometer on board NASA’s Terra satellite. We used data collected in 2000 to create two measures of greenness exposure at a 250m resolution: mid-July for our primary exposure (“peak” greenness), and an annual average created using one measurement from each season (“average” greenness). In addition to the 250m resolution values we also calculated NDVI in the 1250m surrounding a subject’s residence. The smaller resolution captures an area relatively proximal (and more likely visible) from the home, while the larger spatial area captures a typical walking distance for someone in this age range.

Locations of blue spaces were characterized using the 2014 National Hydrography Dataset (NHD) for interior surface waters and data from the National Oceanic and Atmospheric Administration’s National Centers for Environmental Information for coastlines. The NHD is developed by the U.S. Geological Survey in cooperation with the U.S. Environmental Protection Agency and available for download through the Environmental Systems Research Institute (Esri, Redlands, CA). It identifies all water bodies that comprise the surface water drainage system of the United States including types (river, lake, wetland, etc.), location, and area. Ground-truth confirmation demonstrates that 90% of NHD features fall within 50 ft. of their true position and that less than 1% of the NHD changes over 50 years. Our primary analysis considered all types of perennial (non-intermittent) water together and coasts and inland water bodies (such as lakes and rivers) separately. In all analyses we excluded swamps, ice masses, inundation areas, water treatment facilities, and water bodies characterized as intermittent.

There is no consensus in the literature about the best way to operationalize residential exposure to blue space, and multiple metrics have been implemented previously. We therefore considered several exposure characterizations. Consistent with our neighborhood definitions for greenness, we considered the presence of blue space within 250m and 1250m circular buffers surrounding a subject’s residence as a dichotomous measure. We also considered continuous Euclidian distance to the closest blue space.
Outcome

The primary outcome of interest was high depressive symptoms, assessed using the McKnight Risk Factor Survey (MRFS). The depressive symptom questions on the MRFS consist of six items each scored on a five-point Likert scale. Each item was scored zero (never) to four (always) and the mean of all items was taken. Subjects missing one item were included with their mean score calculated from available responses; subjects missing two or more items were excluded. Of the 12,413 subjects who completed the 1999 questionnaire, 1,592 did not answer any of the depressive symptom questions. There were 136 subjects missing a response to one of the six questions, 3 subjects missing responses to two of the six questions, and 3 with three or more missing responses. Our final sample of 9,386 individuals included 122 subjects who responded to 5 of 6 items and 9,264 subjects who responded to all 6. An age-specific z-score using all available MRFS questionnaires completed by GUTS participants was calculated for each age at the time of questionnaire return. The MRFS does not have an established clinical cut-off for high depressive symptoms. The prevalence of depression in this age range is estimated at 11.5%, so we considered those subjects with the highest 11.5% of scores to be cases of “high depressive symptoms”. In sensitivity analyses we also separately considered the highest 5% and highest 15% of scores as cases.

Covariates

We considered individual, household and neighborhood covariates that may vary with exposure to natural environments and have been identified as potential risk factors for depressive symptoms as potential confounders. Individual covariates were ascertained from GUTS surveys and included participant self-reported race (provided on the baseline questionnaire), grade level, age, and gender. Household covariates included income (reported by mothers in 2001), father’s education (reported by mothers in 1999), and maternal history of depression. Participants were considered to have a maternal history of depression if their mothers reported antidepressant use or depression diagnosis on any previous questionnaire, or if mothers scored above cutoff for probable depression on the Mental Health Inventory administered as part of the NHS II surveys. We considered census tract demographics including
median income, home value, percent white, and percent college educated using data from the 2000 United States Census.\textsuperscript{36} We also considered region of the country and rural/urban classification using the US Census definitions,\textsuperscript{37} and air pollution using household location estimates of concurrent and annual average particulate matter less than 2.5 microns in aerodynamic diameter (PM\textsubscript{2.5}) estimated from GIS-based spatio-temporal models of PM levels\textsuperscript{38}. We included concurrent (July) PM\textsubscript{2.5} in peak greenness models and 1999 average PM\textsubscript{2.5} in all other models. Missing data on covariates was addressed by including a missing indicator.

\textit{Statistical Analysis}

For our primary analysis we constructed logistic regression models for the outcome of high depressive symptoms (present/absent), using generalized estimating equations to account for the fact that some mothers enrolled more than one child so observations are not independent. We considered a continuous measure of depressive symptoms as an alternate outcome. Since the full range of NDVI values is -1 to 1, we scaled NDVI exposures by the interquartile range to increase interpretability of the findings. For blue space, we considered a dichotomous measure of presence of blue space (yes versus no) and a continuous measure of distance to blue space.

For each exposure we constructed crude, fully-adjusted, and parsimonious models. Fully-adjusted models included all covariates considered potential confounders based on published literature. Parsimonious models included only those covariates associated with the exposure and the outcome in this study population. We constructed separate models for blue space and greenness in our primary analysis and also considered both exposures simultaneously.

We examined the possibility of a non-linear relation between each individual exposure and the odds of depressive symptoms non-parametrically with restricted cubic splines\textsuperscript{39}. Tests of deviations from linearity used the likelihood ratio test, comparing the model with only the linear term to the model with the linear and the cubic spline terms. For exposures where linear relationships were not appropriate we used restricted cubic splines. We also assessed possible effect modification by region, gender, and grade.
level (grades 6-8 versus grades 9-12, to compare middle school and high school). We used a Wald test to assess statistically significant interactions and examined stratified models.

**Results**

The study population of 9,386 included more female than male participants and participants were mostly white. Areas with higher greenness had lower population density and slightly lower median home values and household incomes. Individuals in the highest NDVI quintile were more likely to be white, and more likely to come from households making less than $75,000 per year (Table 1.1). Subjects in the lowest quintile of distance to blue space, those living closest to the water, were more likely to come from households making more than $75,000 per year (Table 1.2).
Table 1.1. Distribution of selected covariates by quintiles of peak surrounding greenness (1250m) in 9,386 US adolescents in the Growing Up Today Study, 1999

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<td>Midwest</td>
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<td>6</td>
<td>46</td>
<td>50</td>
<td>40</td>
<td>36</td>
</tr>
<tr>
<td>South</td>
<td>15</td>
<td>24</td>
<td>18</td>
<td>12</td>
<td>11</td>
<td>8</td>
</tr>
<tr>
<td>Northeast</td>
<td>35</td>
<td>7</td>
<td>28</td>
<td>34</td>
<td>48</td>
<td>55</td>
</tr>
<tr>
<td>Urbanicity (%)</td>
<td>Metropolitan</td>
<td>82</td>
<td>92</td>
<td>87</td>
<td>82</td>
<td>79</td>
</tr>
<tr>
<td>Micropolitan</td>
<td>10</td>
<td>4</td>
<td>9</td>
<td>10</td>
<td>13</td>
<td>12</td>
</tr>
<tr>
<td>Rural</td>
<td>8</td>
<td>4</td>
<td>4</td>
<td>8</td>
<td>8</td>
<td>17</td>
</tr>
<tr>
<td>Individual Measures</td>
<td>Female (%)</td>
<td>59</td>
<td>60</td>
<td>57</td>
<td>59</td>
<td>60</td>
</tr>
<tr>
<td>White (%)</td>
<td>93</td>
<td>84</td>
<td>94</td>
<td>95</td>
<td>96</td>
<td>97</td>
</tr>
<tr>
<td>Household Income</td>
<td>≥$75,000 (%)</td>
<td>52</td>
<td>57</td>
<td>51</td>
<td>52</td>
<td>51</td>
</tr>
<tr>
<td>Maternal History of Depression (%)</td>
<td>29</td>
<td>27</td>
<td>30</td>
<td>30</td>
<td>28</td>
<td>29</td>
</tr>
<tr>
<td>Age (years)</td>
<td>14.9 ± 1.6</td>
<td>14.9 ± 1.5</td>
<td>14.9 ± 1.6</td>
<td>14.9 ± 1.5</td>
<td>14.9 ± 1.6</td>
<td>14.9 ± 1.5</td>
</tr>
<tr>
<td>July 1999 PM₂.₅ (µg/m³)</td>
<td>16.2 ± 4.6</td>
<td>12.3 ± 4.8</td>
<td>17.0 ± 4.8</td>
<td>17.8 ± 4.0</td>
<td>17.9 ± 3.4</td>
<td>16.2 ± 3.6</td>
</tr>
</tbody>
</table>
The test for non-linearity suggested a linear relationship was appropriate for the relationship between greenness and odds of high depressive symptoms. Therefore, Table 1.2 shows the results of crude, parsimonious, and fully adjusted logistic models for the association between a continuous measure of NDVI and the odds of high depressive symptoms. In parsimonious models, adjusted for participant race, paternal education, maternal history of depression, census region, census tract percent white, and estimated \( \text{PM}_{2.5} \) exposure, an IQR increase in peak greenness in the 1250m buffer around each participant’s home was associated with 11% lower odds of high depressive symptoms in fully adjusted models (OR 0.89, 95% CI 0.79-0.99). Annual average NDVI in the 1250 meter buffer was also associated with lower odds of depressive symptoms (OR per IQR increase 0.90, 95% CI 0.83, 0.99). Results for both peak and average NDVI at 250m were slightly attenuated compared to the 1250m results, but the direction of association was consistent across resolution levels.

Table 1.2. Odds ratios and 95% confidence intervals for high depressive symptoms associated with a 1-IQR\(^a\) increase in greenness, measured by peak and annual average NDVI at 250 and 1250 meters, in 9,386 adolescents living in the United States in 1999 (N=1,039 cases)

<table>
<thead>
<tr>
<th></th>
<th>Crude</th>
<th>Parsimonious(^b)</th>
<th>Fully Adjusted(^c)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Peak NDVI(^d)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>250m(^e)</td>
<td>0.88 (0.81, 0.96)</td>
<td>0.91 (0.82, 1.02)</td>
<td>0.91 (0.82, 1.02)</td>
</tr>
<tr>
<td>1250m</td>
<td>0.87 (0.81, 0.94)</td>
<td>0.89 (0.79, 0.99)</td>
<td>0.88 (0.79, 0.98)</td>
</tr>
<tr>
<td><strong>Annual Average NDVI(^f)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>250m(^g)</td>
<td>0.92 (0.85, 1.00)</td>
<td>0.93 (0.86, 1.02)</td>
<td>0.93 (0.86, 1.02)</td>
</tr>
<tr>
<td>1250m</td>
<td>0.90 (0.83, 0.98)</td>
<td>0.90 (0.83, 0.99)</td>
<td>0.90 (0.83, 0.99)</td>
</tr>
</tbody>
</table>

\(^a\)1-IQR for Peak 250m: 0.232; Peak 1250m: 0.191; Annual Average 250m: 0.130; Annual Average 1250m: 0.115

\(^b\)Adjusted for census region, census tract percent white, estimated \( \text{PM}_{2.5} \), participant race, paternal education, maternal history of depression

\(^c\)Adjusted for census region, census tract percent white, census tract median income, census tract median home value, census tract percent college degree, census tract urbanicity, estimated \( \text{PM}_{2.5} \), participant race, participant gender, household income, paternal education, maternal history of depression

\(^d\)Peak NDVI is determined from July values

\(^e\)38 subjects not included because of missing NDVI values

\(^f\)Annual Average NDVI is calculated as the average of one measurement from each of the four seasons

\(^g\)61 subjects not included because of missing NDVI values
Estimates from fully adjusted models, where we further adjusted for census tract median income, census tract median home value, census tract percent college degree, census tract urbanicity, participant gender, and household income, were not substantially different from parsimonious models (Table 1.2). In sensitivity analyses we considered alternative cutoffs for “high depressive symptoms” at the top 5% and top 15% of subjects rather than the top 11.5%. The overall trends were similar to those observed with our primary cutoff (Supplementary Table 1.2).

While there was no statistically significant interaction (p=0.63) between grade level and greenness, stratified models showed a suggestion of effect modification. The association between greenness and depressive symptoms was stronger in middle school students than it was in high school students (Table 1.3). For students in middle school, an IQR increase in peak greenness in the 1250 meter buffer was associated with 19% reduced odds of depressive symptoms (95% CI 0.68, 0.97) in fully adjusted models, while the association of greenness with depressive symptoms for high school students was substantially weaker. A similar pattern of stronger associations in middle school students was observed across all exposure characterizations.
Table 1.3. Odds ratios and 95% confidence intervals for high depressive symptoms associated with a 1-IQR\textsuperscript{a} increase in greenness stratified by grade level in 9,386 adolescents living in the United States in 1999

Middle School (6-8 grade)
N=3820 (417 cases)

<table>
<thead>
<tr>
<th></th>
<th>Crude</th>
<th>Parsimonious\textsuperscript{b}</th>
<th>Fully Adjusted\textsuperscript{c}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak NDVI\textsuperscript{d}</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>250m\textsuperscript{e}</td>
<td>0.83 (0.73, 0.95)</td>
<td>0.84 (0.70, 1.00)</td>
<td>0.84 (0.70, 1.01)</td>
</tr>
<tr>
<td>1250m</td>
<td>0.83 (0.74, 0.94)</td>
<td>0.82 (0.69, 0.97)</td>
<td>0.81 (0.68, 0.97)</td>
</tr>
</tbody>
</table>

| Annual Average NDVI\textsuperscript{f} |            |                                  |                                   |
| 250m\textsuperscript{g} | 0.84 (0.74, 0.96) | 0.87 (0.76, 1.00) | 0.87 (0.75, 1.00) |
| 1250m          | 0.84 (0.74, 0.95) | 0.87 (0.75, 0.99) | 0.86 (0.75, 0.99) |

High School (9-12 grade)
N=5566 (622 cases)

<table>
<thead>
<tr>
<th></th>
<th>Crude</th>
<th>Parsimonious</th>
<th>Fully Adjusted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak NDVI\textsuperscript{h}</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>250m\textsuperscript{b}</td>
<td>0.92 (0.82, 1.02)</td>
<td>0.97 (0.84, 1.12)</td>
<td>0.96 (0.83, 1.11)</td>
</tr>
<tr>
<td>1250m</td>
<td>0.90 (0.82, 1.00)</td>
<td>0.94 (0.81, 1.08)</td>
<td>0.92 (0.80, 1.06)</td>
</tr>
</tbody>
</table>

| Annual Average NDVI\textsuperscript{i} |            |              |               |
| 250m\textsuperscript{i} | 0.98 (0.88, 1.09) | 0.98 (0.88, 1.09) | 0.98 (0.88, 1.09) |
| 1250m          | 0.95 (0.85, 1.05) | 0.93 (0.84, 1.04) | 0.93 (0.83, 1.04) |

\textsuperscript{a}1-IQR for Peak 250m: 0.232; Peak 1250m: 0.191; Annual Average 250m: 0.130; Annual Average 1250m: 0.115
\textsuperscript{b}Adjusted for census region, census tract percent white, estimated PM\textsubscript{2.5}, participant race, paternal education, maternal history of depression
\textsuperscript{c}Adjusted for census region, census tract percent white, census tract median income, census tract median home value, census tract percent college degree, census tract urbanicity, estimated PM\textsubscript{2.5}, participant race, participant gender, household income, paternal education, maternal history of depression
\textsuperscript{d}Peak NDVI is determined from July values
\textsuperscript{e}17 subjects not included because of missing NDVI values
\textsuperscript{f}Annual Average NDVI is calculated as the average of one measurement from each of the four seasons
\textsuperscript{g}24 subjects not included because of missing NDVI values
\textsuperscript{h}21 subjects not included because of missing NDVI values
\textsuperscript{i}37 subjects not included because of missing NDVI values

Presence of blue space in either 250m or 1250m was not statistically significantly associated with depressive symptoms. This was true when all types of water were considered simultaneously and when interior and coastal water bodies were considered separately (Table 1.4). The results for coastal areas suggested a protective effect of living within 250m of the coast, but the confidence intervals were very wide (OR 0.29, 95% CI 0.04,2.01).
Table 1.4. Odds ratios and 95% confidence intervals for the relationship between high depressive symptoms and presence of water among 9,386 adolescents living in the United States (N = 1,039 cases)

<table>
<thead>
<tr>
<th></th>
<th>Presence of Water in 250m (yes vs. no)</th>
<th>Presence of Water in 1250m (yes vs. no)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Crude</td>
<td>Parsimonious(^a)</td>
</tr>
<tr>
<td>All water types</td>
<td>OR (95% CI)</td>
<td>OR (95% CI)</td>
</tr>
<tr>
<td>Yes</td>
<td>0.89 (0.65 , 1.24)</td>
<td>0.91 (0.66 , 1.27)</td>
</tr>
<tr>
<td>No</td>
<td>Ref</td>
<td>Ref</td>
</tr>
<tr>
<td>Coast Only</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>0.30 (0.04 , 2.05)</td>
<td>0.28 (0.04 , 1.91)</td>
</tr>
<tr>
<td>No</td>
<td>Ref</td>
<td>Ref</td>
</tr>
<tr>
<td>Interior water only</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>0.95 (0.69 , 1.32)</td>
<td>0.98 (0.70 , 1.36)</td>
</tr>
<tr>
<td>No</td>
<td>Ref</td>
<td>Ref</td>
</tr>
</tbody>
</table>

\(^a\)Adjusted for census region, census tract percent white, estimated PM\(_{2.5}\), participant race, paternal education, maternal history of depression

\(^b\)Adjusted for census region, census tract percent white, census tract median income, census tract median home value, census tract percent college degree, census tract urbanicity, estimated PM\(_{2.5}\), participant race, participant gender, household income, paternal education, maternal history of depression
Odds Ratio for High Depressive Symptoms

Distance to Blue Space (m)

Crude

Fully Adjusted

1

Adjusted for census region, census tract percent white, census tract median income, census tract median home value, census tract percent college degree, census tract urbanicity, estimated PM$_{2.5}$, participant race, participant gender, household income, paternal education, maternal history of depression

Figure 1.1. Restricted cubic splines modeling the relationship between distance to blue space and odds of high depressive symptoms in 9,386 adolescents living in the United States in 1999 (N=1,039 cases)

1
We used splines to model the relationship between distance to blue space and depressive symptoms, and observed null associations in crude and adjusted models (Figure 1.1). When considered in models simultaneously, results for blue space and greenness were similar to what we observed in separate models, and the interaction term was not statistically significant (results not shown). Results for the continuous depressive symptoms outcome were consistent in direction with the primary findings, but not statistically significant (adjusted beta coefficient -0.03 (95% CI -0.07 , 0.01) for an interquartile range increase in surrounding greenness in the 1250m buffer).

Discussion

In this population of more than 9,000 US adolescents we observed that surrounding greenness, but not proximity to blue space, was associated with lower odds of high depressive symptoms. In fully adjusted models, we observed 7-12% lower odds of high depressive symptoms associated with an IQR increase in greenness. This relationship was robust to adjustment for socioeconomic and other factors, and consistent across 250m and 1250m neighborhood definitions, although we observed slightly stronger results in the 1250m buffer. Our findings are consistent with previous findings in both adults\textsuperscript{2,20,24,27,40} and children\textsuperscript{23,41}, and add to the growing body of research suggesting a relationship between higher greenness and better mental health across the lifespan.

There was some suggestion of effect modification by grade, although the interaction was not statistically significant. We observed a significant inverse association between greenness and depression in middle school (6th-8th grade) students but not in high school (9th-12th grade) students. This may be due to differences in how middle and high school students interact with their neighborhoods, particularly if high school students are more likely to attend schools further from home or access a broader range of destinations. Unfortunately, we did not have data on the location of school or other important destinations in this study. The results of this stratified analysis suggest that further research in this age range is necessary to understand the diverse ways teenagers are influenced by their environments and how this relationship might vary across this important developmental period.
The relationships between residential proximity to blue space and depressive symptoms in this cohort were consistently null across multiple measures of blue space. Huynh et al observed a weak relationship between blue space near school and emotional well-being in Canadian students of a similar age; the relationship was stronger in those students known to live near school\textsuperscript{21}. A recent study in New Zealand used a view of water, rather than just proximity, to characterize blue space exposure and found water views were associated with lower likelihood of mental health disorders, based on self-reported measures of psychological distress\textsuperscript{17}. The exposure in our study was limited to residential proximity to blue space and did not capture exposures near school or views of water. Moreover, the outcome measure was limited to one type of distress, as characterized by depressive symptoms. Future research should consider alternative characterizations of exposure such as viewshed analysis and exposures beyond the residence.

This study had some important limitations. We were unable to account for the accessibility or quality of natural environments. If nearby green or blue spaces are inaccessible or unpleasant, they may prove insignificant or even detrimental to mental health. We made assumptions about the geographic context most relevant to mental health, defining exposures as those in the areas 250m and 1250m around the home. These definitions are consistent with previous work and studies suggesting 1250m is an average walking distance for someone in this age range\textsuperscript{31} but we may not have fully captured the relevant neighborhood environment. Our exposure definitions were based on study participants’ residential addresses; data were not available on the locations of schools or other places where adolescents may spend a considerable amount of time. Our study was cross-sectional, with depressive symptoms measured at a single point in time and contemporaneously with natural environment exposures. As a consequence, it is possible adolescents’ depressive symptoms were present prior to their exposure to their current natural environment. We used the NHD, released in 2014, to assign exposures in 1999. Since less than 1% of hydrography changes over 50 years, we do not expect substantial misclassification to result.

Despite these limitations, this study of a nationwide sample of teenagers in the United States had several strengths. We were able to consider multiple objective measures of exposure to nature using a
variety of geographic data combined with geocoded individual home addresses. Our study is among the first to consider the relationship between blue space and one measure of mental health in a United States cohort, taking advantage of detailed hydrography data not previously linked to health outcomes. The GUTS cohort includes detailed data on person-specific confounders, and because participants’ mothers are also involved in an ongoing cohort study, detailed data on household characteristics and family history were available. Finally, due to the relatively large sample size and data available across the teenage years were able to observe effect modification by age, with stronger relationships between greenness and depressive symptoms in middle school students compared to high school students.

While there is growing evidence of a relationship between natural environments and mental health, this study is among the first to focus specifically on adolescents. We observed that greenness was consistently associated with lower odds of high depressive symptoms, but we did not observe a similar relationship for proximity to blue spaces. In our study adolescents living in greener areas experienced lower odds of depressive symptoms, with particularly strong associations in middle school students. Future studies should consider longitudinal analyses of this age range or take advantage of natural experiments, for example studies of the impact of improving surrounding greenness of an area, to better understand the relationship between greenness and mental health across the life course.
References


Supplementary Table 1.1. Distribution of selected covariates by quintiles of distance to the nearest blue space in 9,386 adolescents in the Growing Up Today Study living in the United States in 1999

<table>
<thead>
<tr>
<th>Distance to Blue Space</th>
<th>Distance to Blue Space</th>
<th>Distance to Blue Space</th>
<th>Distance to Blue Space</th>
<th>Distance to Blue Space</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Q1 (N=1877)</td>
<td>Q2 (N=1878)</td>
<td>Q3 (N=1877)</td>
<td>Q4 (N=1877)</td>
</tr>
<tr>
<td>Distance to nearest blue space (m)</td>
<td>447 (208)</td>
<td>1115 (194)</td>
<td>1839 (236)</td>
<td>2905 (398)</td>
</tr>
<tr>
<td>Census Tract Measures</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>College educated (%)</td>
<td>34 (17)</td>
<td>34 (18)</td>
<td>33 (17)</td>
<td>32 (17)</td>
</tr>
<tr>
<td>White (%)</td>
<td>91 (11)</td>
<td>91 (11)</td>
<td>90 (12)</td>
<td>90 (12)</td>
</tr>
<tr>
<td>Median Household Income ($)</td>
<td>69K (25K)</td>
<td>67K (24K)</td>
<td>68K (24K)</td>
<td>66K (23K)</td>
</tr>
<tr>
<td>Median Home Value ($)</td>
<td>175K (117K)</td>
<td>170K (111K)</td>
<td>169K (115K)</td>
<td>164K (121K)</td>
</tr>
<tr>
<td>Population Density (people/mi²)</td>
<td>2423 (6353)</td>
<td>2341 (4918)</td>
<td>2543 (4199)</td>
<td>2680 (4798)</td>
</tr>
<tr>
<td>Region (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>West</td>
<td>8</td>
<td>9</td>
<td>14</td>
<td>15</td>
</tr>
<tr>
<td>Midwest</td>
<td>36</td>
<td>38</td>
<td>37</td>
<td>38</td>
</tr>
<tr>
<td>South</td>
<td>14</td>
<td>15</td>
<td>15</td>
<td>13</td>
</tr>
<tr>
<td>Northeast</td>
<td>41</td>
<td>38</td>
<td>33</td>
<td>34</td>
</tr>
<tr>
<td>Urbanicity (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metropolitan</td>
<td>82</td>
<td>82</td>
<td>84</td>
<td>83</td>
</tr>
<tr>
<td>Micropolitan</td>
<td>10</td>
<td>10</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>Rural</td>
<td>8</td>
<td>8</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Individual Measures</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Female (%)</td>
<td>59</td>
<td>59</td>
<td>60</td>
<td>59</td>
</tr>
<tr>
<td>White (%)</td>
<td>94</td>
<td>93</td>
<td>93</td>
<td>92</td>
</tr>
<tr>
<td>Household Income</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>≥$75,000 (%)</td>
<td>55</td>
<td>53</td>
<td>52</td>
<td>53</td>
</tr>
<tr>
<td>&lt;$75,000 (%)</td>
<td>29</td>
<td>28</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>Missing (%)</td>
<td>16</td>
<td>19</td>
<td>19</td>
<td>18</td>
</tr>
<tr>
<td>Maternal History of Depression (%)</td>
<td>31</td>
<td>28</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>Age (years)</td>
<td>14.9 (1.5)</td>
<td>14.9 (1.6)</td>
<td>14.9 (1.6)</td>
<td>14.8 (1.5)</td>
</tr>
<tr>
<td>Annual Average PM2.5 (µg/m2)</td>
<td>12.6 (2.6)</td>
<td>12.9 (2.7)</td>
<td>13.0 (2.8)</td>
<td>13.1 (2.8)</td>
</tr>
</tbody>
</table>
Supplementary Table 1.2. Results of logistic model predicting odds of high depressive symptoms associated with a 1-IQR\(^1\) increase in greenness in 9,386 adolescents living in the United States in 1999 using alternative cutoffs of the top 5% (N=512 cases) and top 15% (N=1,437 cases) for high depressive symptoms

<table>
<thead>
<tr>
<th></th>
<th>5% Cutoff for High Depressive Symptoms</th>
<th>15% Cutoff for High Depressive Symptoms</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Crude</td>
<td>Parsimonious(^2)</td>
</tr>
<tr>
<td><strong>Peak NDVI(^4)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>250m(^5)</td>
<td>0.88 (0.78, 0.99)</td>
<td>0.92 (0.78, 1.07)</td>
</tr>
<tr>
<td>1250m</td>
<td>0.87 (0.78, 0.97)</td>
<td>0.88 (0.75, 1.02)</td>
</tr>
<tr>
<td><strong>Annual Average NDVI(^6)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>250m(^7)</td>
<td>0.95 (0.84, 1.06)</td>
<td>0.97 (0.85, 1.09)</td>
</tr>
<tr>
<td>1250m</td>
<td>0.89 (0.80, 0.99)</td>
<td>0.89 (0.79, 1.01)</td>
</tr>
</tbody>
</table>

1-IQR for Peak 250m: 0.232; Peak 1250m: 0.191; Annual Average 250m: 0.130; Annual Average 1250m: 0.115

Adjusted for census region, census tract percent white, estimated PM\(_{2.5}\), participant race, paternal education, maternal history of depression

Adjusted for census region, census tract percent white, census tract median income, census tract median home value, census tract percent college degree, census tract urbanicity, estimated PM\(_{2.5}\), participant race, participant gender, household income, paternal education, maternal history of depression

Peak NDVI is determined from July values

38 subjects not included because of missing NDVI values

Annual Average NDVI is calculated as the average of one measurement from each of the four seasons

61 subjects not included because of missing NDVI values
Chapter 2: The relationship between surrounding greenness in childhood and adolescence and depressive symptoms in adolescence and early adulthood

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Abstract

Background: Exposure to nature, particularly vegetation (greenness), may be associated with improved mental health. Childhood exposures can have consequences that persist into adolescence and adulthood; few studies have considered whether this is true for greenness.

Objectives: We tested whether higher surrounding greenness in childhood and adolescence was associated with reduced risk of developing depressive symptoms in adolescence and early adulthood.

Methods: Participants from the Growing Up Today Study (GUTS), initiated in 1996, were included if they provided information on depressive symptoms between 1999 and 2013. Greenness exposure was characterized as the cumulative average value of the normalized difference vegetation index (1000 meter resolution) from 1989 until 2 years before outcome assessment or age 18 based on geocoded addresses. The outcome, high depressive symptoms, was defined as the top 10% of scores on the McKnight Risk Factor Survey or the Center for Epidemiologic Studies of Depression scale, depending on the scale administered on each questionnaire. Data were analyzed using Cox proportional hazards models adjusted for household and neighborhood socioeconomic status and other potential confounders.

Results: We observed a 6% lower incidence of high depressive symptoms associated with an interquartile range increase in greenness (95% Confidence Interval, CI, 11%-0%). This relationship was stronger in areas with higher population density (>1000 people/mi², 8% lower incidence, 95% CI 14%-0%).

Conclusions: Living in an area with greater surrounding greenness during childhood and adolescence may be associated with lower risk of subsequently developing depressive symptoms, particularly for individuals living in areas of greater population density.
Introduction

The relationship between exposure to natural environments and mental health is an emerging area of research. There has been a particular focus on vegetation, with many studies investigating surrounding residential greenness as a marker of exposure to nature. Studies in the United States and around the world have shown that living in an area of higher surrounding greenness or living in closer proximity to a green space is associated with better mental health. Nature can improve physiological and psychological stress responses, revitalize attentional processes, facilitate social interaction, and encourage physical activity, all of which may in turn result in improved mental health outcomes. While this area of research has considered multiple measures of mental health such as emotional resilience, anxiety, and general psychiatric morbidity, the outcome of depression or depressive symptoms has received particular attention. Given that depression is expected to be the leading cause of morbidity in high-income countries by 2030 and represents a substantial and increasing economic burden, identifying modifiable environmental factors that may protect against depression is an important public health priority.

There is also growing recognition of the importance of a life course approach to understanding the determinants of health. Early life and childhood represent critical periods for many exposures, with the effects of many childhood exposures persisting into adulthood. Much of this research has focused on the lasting mental health impacts of potentially harmful psychosocial childhood exposures, such as violence and bullying, but neighborhood and other environmental exposures have also received attention. Higher neighborhood socioeconomic status (SES) during childhood in particular has been linked to improved mental health in adulthood, independent of adult neighborhood exposures, but limited evidence exists for other contextual factors, particularly for those that might confer protective effects.

Few studies have considered whether exposure to nature or natural environments in childhood may have implications for long-term health. There is an increasing body of evidence showing that greater exposure to nature, particularly greenness or green space, is associated with better mental and
behavioral health outcomes in children. Most of this research has been limited to exposures and outcomes characterized over a relatively brief time frame. Some studies have observed an association between childhood exposure to natural environments and adult behaviors including environmental engagement. Only one study of which we are aware has specifically investigated whether childhood exposure to greenness or other forms of nature is associated with reduced risk of poor mental health, specifically depression, in adulthood.

In this study, we consider the prospective relationship between surrounding greenness exposures during childhood and adolescence and depressive symptoms in adolescence and adulthood. We test the hypothesis that greater surrounding greenness during childhood and adolescence is associated with lower onset of high depressive symptoms. We consider as a secondary outcome persistent depressive symptoms, the occurrence of multiple measures of high depressive symptoms over the study period. Since the exposure was greenness in childhood and adolescence we consider whether this relationship is modified by age of first depression onset (before or after age 18). In addition, greenness and other forms of nature may be particularly beneficial for mental health in urban areas, which tax attention and impose social stress more profoundly than areas of lower population density. Therefore we consider whether the association between greenness and mental health differed by population density, which has been shown to be an effect modifier in studies of other health outcomes.

A unique contribution of this study is the availability of data on a variety of potentially important covariates including household and neighborhood attributes such as SES, air pollution, and maternal depression. Various indicators of childhood SES have been shown to be associated with both the occurrence of later-life depressive symptoms and neighborhood characteristics including surrounding greenness. Similarly, there is some evidence that air pollution is associated with depression, and with surrounding greenness but few previous studies have been able to assess whether observed associations between greenness and mental health are independent of air pollution. Parental history of depression is one of the strongest predictors of depression, but few studies have been
able to incorporate data on familial depression into models of contextual characteristics and mental health.

**Methods**

*Study population*

We used data from the Growing Up Today Study (GUTS), a prospective cohort study. GUTS was founded in 1996 by inviting women in the ongoing Nurses’ Health Study II (NHS II) to enroll any of their children who were between the ages of 9-14. Completion and return of the initial questionnaire by the child implied informed consent and questionnaires have been sent directly to participants since 1996. Follow-up questionnaires have been sent annually or biennially. The study was approved by the Brigham and Women's Hospital Institutional Review Board.

A total of 13,754 participants completed one or more questionnaire measures of depressive symptoms any time between 1999 (when this was first asked) and 2013. The exposure, surrounding greenness during childhood, was assigned based on the mother’s home address. We assumed GUTS participants lived with their mothers until age 18 unless they had provided information to suggest otherwise; mother’s addresses were available from the beginning of NHS II in 1989 and updated biennially. We excluded participants who reported living with someone other than their mother (N=2,067) or attending military or boarding school (N=72) prior to the age of 18. We further excluded 269 participants who did not have a valid address or lived outside the contiguous United States for all of childhood. Our final sample size for the primary analysis was 11,346 participants; the mean number of depressive symptom measurements per participant was 3.9 out of a possible six. In secondary analyses of persistent depression, we limited the study population to eligible participants who completed questions on depressive symptoms on at least 3 questionnaires (N=8,375).

*Outcome*
Our main outcome of interest was high depressive symptoms, assessed via self-report using two different symptom scales over the course of the study. In 1999, 2001, and 2003, when most participants were adolescents, depressive symptoms were assessed using the McKnight Risk Factor Survey (MRFS) while in 2007 and 2010, when all participants were adults, depressive symptoms were assessed using the Center for Epidemiologic Studies ten-item depression scale (CES-D 10). The MRFS, validated for adolescents and pre-adolescents, includes six items asking the extent to which individuals experience the following symptoms on a five-point Likert scale ranging from never to always: worthlessness, low energy, depressed, hopeful, trouble concentrating, trouble enjoying usual activities. Other studies have demonstrated modest reliability, as measured by Cronbach’s alpha, and in the current sample, the alpha was 0.77. The CES-D 10, validated for use in adolescents and young adults, includes ten items asking the extent to which individuals experience the following symptoms on a four-item Likert scale ranging from rarely or none of the time to all of the time: bothered, trouble concentrating, depressed, effort, fearful, restless sleep, lonely, trouble getting going, hopeful, happy. Other studies have reported high internal consistency reliability and in the current sample, the Cronbach’s alpha value was 0.77. Scores on the MRFS and the CES-D were highly correlated in a cross-sectional validation study conducted in adolescent and preadolescent girls.

For both the MRFS and the CES-D, a mean score was calculated for each participant at each time point from available responses. Participants who answered all or most of the individual symptom questions were included. Consistent with previous approaches, for the MRFS, which contains six items, individuals missing one of the six items were eligible (N=136 in 1999; N=81 in 2001; N=166 in 2003) while those missing two or more were excluded (N=6 in 1999; N=10 in 2001; N=23 in 2003). For the CES-D, which contains 10 items, individuals missing three or fewer items were eligible (N=318 in 2007; N=163 in 2010; N=107) while those missing four or more were excluded (N=9 in 2007; N=10 in 2010; M=11 in 2013).

Estimates of the 12-month prevalence of depression in adolescents and young adults in the United States range from 8.7% to 11.3%. Since the MRFS does not provide a cutoff to indicate probable
depression, we dichotomized our sample to make the top 10% of the distribution for each questionnaire cycle as cases of high depressive symptoms to facilitate comparisons between the CES-D and MRFS.52 We considered a secondary outcome of “persistent high depressive symptoms,” with individuals defined as cases if they had repeated high depressive symptoms (at least three) during the course of the study, consistent with previous publications from this cohort.52

**Exposure**

Our exposure of interest was surrounding greenness during childhood and adolescence. Greenness was characterized using the Normalized Difference Vegetation Index (NDVI), a measure of vegetative density that is commonly used in studies of health outcomes.1 NDVI leverages the fact that chlorophyll in plants absorbs visible light (0.4-0.7 μm), while reflecting near-infrared light (0.7-1.1 μm), to calculate a continuous measure of vegetation density from the ratio of the difference between the near-infrared and visible reflectance to the sum of these two values.54 NDVI data were downloaded from the Advanced Very High Resolution Radiometer (AVHRR), a remote sensing instrument operated by the National Oceanic and Atmospheric Administration. These data are available at a 1 kilometer resolution and range from 0 to 200. Values less than 100 indicate water and higher values indicate greater density of vegetation. To capture the peak greenness level and maximum variability in greenness, we used mid-July NDVI values to characterize surrounding greenness for each year of the study beginning in 1989.

We assigned individual greenness exposure based on participants’ residential history using ArcGIS (ESRI, Redlands, CA). At each time point, greenness exposure was operationalized as the cumulative average NDVI value from the beginning of the NHS II in 1989 to age 18 (for depression measures in adulthood and persistent depression) or two years before outcome assessment (for depression measures in adolescence). The two year lag was used to ensure exposures were present prior to the occurrence of the outcome. We modelled continuous NDVI scaled by the interquartile range (IQR) to increase interpretability and comparability with previous studies.41,55,56
Covariates

We included covariates measured at the individual, household, and neighborhood levels as potential confounders. We used data reported by mothers in NHS II to characterize household SES according to income (reported in 2001, classified as ≥ versus < $75,000 per year). Participants were asked to report their income in one of nine categories; we dichotomized this variable at the upper bound of the category that included the median. We also used data on paternal education (reported in 1999; classified as college graduate versus not). GUTS participants also reported their race/ethnicity on the baseline questionnaire (classified as white/other race); other individual-level covariates included age and sex. We characterized maternal history of depression as ever/never; participants were considered to have a maternal history of depression if their mothers ever reported antidepressant use or depression diagnosis on any questionnaire between 1993 and 1999, or if they scored below the cutoff (less than 53 on a scale of 0 to 100, with 100 representing the maximum score) for probable depression on the Mental Health Inventory administered as part of the NHS II surveys.\(^{57,58}\) Missing data on household income, parental education, and participant race were characterized with a missing indicator.

We used data from the U.S. Census to characterize participant neighborhood SES and demographics. Census tract SES variables included median income, home value, percent white, and percent college educated; values for all years were based on the 2000 Census.\(^{59}\) We also considered Census tract population density. As with our assessment of greenness exposure, we used average Census tract values from 1989 to age 18 or two years before the time of assessment. This allowed us to capture changes in neighborhood characteristics that could occur as a result of moving during childhood. Since air pollution may be a confounder or an intermediate in the association between greenness and depression, we additionally considered models adjusted for residential address-level estimates of annual average particulate matter less than 2.5 microns in aerodynamic diameter (PM\(_{2.5}\)). Values of PM\(_{2.5}\) were estimated from validated GIS-based spatio-temporal models of PM levels\(^{60}\) and coded as the cumulative average value from 1989 to age 18 or two years before outcome assessment.
For our primary analysis we used Cox proportional hazards models using calendar time in months as the time scale. Participants were followed from the time of the return of the 1996 questionnaire to first report of high depressive symptoms, return of the 2013 questionnaire, or the date of the last returned questionnaire if participants were lost to follow-up. All models were stratified by age (in months) and questionnaire cycle. In fully-adjusted models we further adjusted for participant race and sex, household income, paternal education, maternal history of depression, and census tract population density, median household income, median home value, percent white, and percent college educated. In a third set of models we further adjusted for estimated PM$_{2.5}$. We used a robust sandwich covariance matrix to account for non-independence of sibling clusters since some mothers enrolled more than one child. Since the exposure was cumulative average greenness throughout childhood, we considered high depressive symptoms reported at the first outcome assessment in 1999 to be incident cases on the assumption that average greenness across childhood is relatively stable.

We also considered whether childhood greenness was associated with persistent high depressive symptoms using a logistic generalized estimating equations (GEE) to account for sibling clusters. We regressed the binary outcome of persistent depressive symptoms across adolescence and adulthood on the cumulative average greenness exposure from 1989 to age 18. In adjusted models we included covariates for participant race, household income, paternal education, maternal history of depression, and cumulative average measures (also calculated from 1989 to age 18) for census tract population density, median household income, median home value, percent white, and percent college educated. To assess whether observed associations were independent of air pollution we further adjusted for estimated PM$_{2.5}$.

We examined the possibility of a non-linear relation between each individual’s greenness exposure and the odds of depressive symptoms non-parametrically with restricted cubic splines. Tests of deviations from linearity compared the model with only the linear term to the model with the linear and the cubic spline terms. Some previous studies have observed the relationship between greenness and
health to vary by population density or urbanicity.\textsuperscript{36,37} We therefore considered whether the results of our Cox proportional hazards model or logistic regression model for persistent depression were modified by Census tract population density, dichotomized as low (\(\leq 1000\ \text{people/mi}^2\)) or high (>1000 people/mi\(^2\)).\textsuperscript{63} Since our exposure was only updated through age 18, we evaluated whether the relationship between surrounding greenness and depression differed between cases that occurred up to age 18 and those that occurred after. We also assessed potential effect modification by sex, since patterns of depressive symptoms differ between males and females.\textsuperscript{64} We tested interaction terms for statistical significance using a Likelihood Ratio Test for Cox proportional hazards models and a generalized score test for logistic regression models; we also evaluated stratified models.

**Results**

The 11,346 participants included in this study were predominantly white (93%) and more participants were female (58%) (Table 2.1). Study participants who grew up in areas with greater density of vegetation were more likely to come from households making less than $75,000 per year and more likely to be white. They were also more likely to live in Census tracts with lower levels of college education and greater proportions of white participants.
<table>
<thead>
<tr>
<th></th>
<th>NDVI Tertile 1 (least green)</th>
<th>NDVI Tertile 2</th>
<th>NDVI Tertile 3 (most green)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>All participants</td>
<td>N=3,782</td>
<td>N=3,780</td>
</tr>
<tr>
<td><strong>Individual Measures</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Female (%)</td>
<td>58</td>
<td>58</td>
<td>59</td>
</tr>
<tr>
<td>White (%)</td>
<td>93</td>
<td>87</td>
<td>95</td>
</tr>
<tr>
<td>Household Income Reported in 2001 ≥$75,000 (%)</td>
<td>52</td>
<td>55</td>
<td>52</td>
</tr>
<tr>
<td>Father's Education</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>College or Greater (%)</td>
<td>60</td>
<td>64</td>
<td>62</td>
</tr>
<tr>
<td>Maternal History of Depression (%)</td>
<td>29</td>
<td>29</td>
<td>30</td>
</tr>
<tr>
<td><strong>Normalized Difference Vegetation Index (NDVI)</strong></td>
<td>156.32 (11.07)</td>
<td>143.51 (8.46)</td>
<td>158.53 (2.45)</td>
</tr>
<tr>
<td>Average PM$_{2.5}$ (µg/m$^3$)</td>
<td>13.77 (2.70)</td>
<td>13.88 (3.35)</td>
<td>14.45 (2.16)</td>
</tr>
<tr>
<td>Baseline Age (1996)</td>
<td>11.38 (1.56)</td>
<td>11.44 (1.55)</td>
<td>11.42 (1.57)</td>
</tr>
<tr>
<td><strong>Census Tract Measures</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>College Educated (%)</td>
<td>32 (16)</td>
<td>34 (16)</td>
<td>33 (16)</td>
</tr>
<tr>
<td>White (%)</td>
<td>89 (12)</td>
<td>81 (16)</td>
<td>91 (10)</td>
</tr>
<tr>
<td>Median Home Value ($)</td>
<td>163K (109K)</td>
<td>203K (136K)</td>
<td>149K (86K)</td>
</tr>
<tr>
<td>Median Household Income ($)</td>
<td>65K (22K)</td>
<td>68K (22K)</td>
<td>66K (21K)</td>
</tr>
<tr>
<td>Population Density (people/mi$^2$)</td>
<td>2867 (5345)</td>
<td>5513 (8310)</td>
<td>2258 (2033)</td>
</tr>
<tr>
<td>Low Density (≤1000 people/mi$^2$)</td>
<td>35</td>
<td>10</td>
<td>27</td>
</tr>
<tr>
<td>High Density (&gt;1000 people/mi$^2$)</td>
<td>65</td>
<td>90</td>
<td>73</td>
</tr>
</tbody>
</table>

1NDVI tertiles based on cumulative average greenness from 1989 to age 18
235 participants missing data
32,103 participants missing data
4848 participants missing data
5Reported values are cumulative averages from 1989 to age 18
Table 2.2 shows the results for Cox proportional hazards models for the association between surrounding greenness and high depressive symptoms. Results are presented for linear exposure-response relationships since there was no evidence of deviations from linearity. In the full population, in age-adjusted models higher greenness was significantly associated with 7% reduced hazard of developing depressive symptoms for 1-IQR (14.78) higher greenness. The size of the IQR in this study is similar to that observed in previous studies of NDVI and health.\textsuperscript{42,56} HRs were slightly attenuated after adjusting for all covariates, with a 5% lower incidence of high depressive symptoms per IQR increase in greenness (95% CI 11% lower to 1% higher). Further adjustment for PM\textsubscript{2.5} did not substantially alter any of the observed associations.

Considering if effects might vary depending on population density, while the p-value for the interaction did not reach statistical significance (p=0.17), stratified models suggested a potentially stronger association among individuals who lived in a higher population density census tract. In high density areas, an IQR increase in greenness was associated with 8% lower incidence of high depressive symptoms (95% CI 15% to 1% lower) while the association in low density areas did not reach statistical significance (Table 2.2). Although interaction between greenness and age above or below 18 was not statistically significant (p=0.42), stratified models suggested a slightly stronger association in participants with younger-onset depression. Among those under 18, an interquartile range increase in greenness was associated with 11% lower incidence of high depressive symptoms (95% CI 19% to 3% lower).
Table 2.2. The relationship between surrounding greenness and high depressive symptoms in 11,346 participants in the Growing Up Today Study, 1996-2013.

<table>
<thead>
<tr>
<th></th>
<th>Person-Months</th>
<th>Cases</th>
<th>Age-Adjusted HR (95% CI) (^1)</th>
<th>Fully-Adjusted(^2) HR (95% CI)</th>
<th>Fully-Adjusted + PM(_{2.5})(^3) HR (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall</td>
<td>1,296,341</td>
<td>2,546</td>
<td>0.93 (0.88, 0.97)</td>
<td>0.95 (0.89, 1.01)</td>
<td>0.94 (0.89, 1.00)</td>
</tr>
<tr>
<td>Population Density</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High (&gt;1000 people/mi(^2))</td>
<td>839,437</td>
<td>1,695</td>
<td>0.91 (0.86, 0.97)</td>
<td>0.92 (0.85, 0.99)</td>
<td>0.92 (0.85, 0.99)</td>
</tr>
<tr>
<td>Low (≤1000 people/mi(^2))</td>
<td>456,904</td>
<td>851</td>
<td>1.00 (0.89, 1.12)</td>
<td>1.05 (0.91, 1.22)</td>
<td>1.05 (0.91, 1.22)</td>
</tr>
<tr>
<td>Age</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cases before age 18</td>
<td>573,956</td>
<td>1,260</td>
<td>0.91 (0.85, 0.97)</td>
<td>0.89 (0.82, 0.97)</td>
<td>0.89 (0.81, 0.97)</td>
</tr>
<tr>
<td>Cases after age 18</td>
<td>722,385</td>
<td>1,286</td>
<td>0.94 (0.88, 1.01)</td>
<td>1.00 (0.91, 1.09)</td>
<td>0.99 (0.91, 1.08)</td>
</tr>
</tbody>
</table>

\(^1\)Results quantified from Cox Proportional Hazards models are expressed as hazard ratio for high depressive symptoms associated with an interquartile range (IQR) change in greenness, where 1 IQR = 14.78

\(^2\)Adjusted for participant race and sex, household income, maternal history of depression, paternal education, and census tract population density, median household income, median home value, percent white, and percent college educated

\(^3\)Adjusted for participant race and sex, household income, maternal history of depression, paternal education, census tract population density, median household income, median home value, percent white, and percent college educated, and estimated PM\(_{2.5}\)
For the outcome of persistent depression, there was evidence for a possibly non-linear exposure-response relationship in adjusted models so results of a restricted cubic spline are presented in Figure 2.1 while linear models are presented in Table 2.3. There was moderate evidence that growing up in an area with greater surrounding greenness was associated with lower odds of persistent depression in the population overall, but this association was attenuated at the highest levels of greenness (Figure 2.1). There was statistically significant evidence (p=0.02) for an interaction between greenness and high versus low population density. Results of stratified models are presented in Figure 2.2 and Table 2.3. Growing up in a high density area was associated with 23% lower odds of persistent depressive symptoms (95% CI 38% to 3%) per interquartile range higher greenness (Table 2.3). There was no evidence of effect modification by sex for either outcome.
Results quantified from logistic regression models with a generalized estimating equation are expressed as odds ratio for high depressive symptoms. Adjusted for participant race and sex, household income, maternal history of depression, paternal education, and census tract median household income, median home value, percent white, and percent college educated.

Defined as high depressive symptoms on three or more questionnaires over the study period (1999-2013)

Figure 2.1. Restricted cubic spline for the adjusted association\(^1\) between surrounding greenness in childhood and persistent depression\(^2\) in 8,375 adolescents and young adults (N=295 cases)

\(^1\)Results quantified from logistic regression models with a generalized estimating equation are expressed as odds ratio for high depressive symptoms. Adjusted for participant race and sex, household income, maternal history of depression, paternal education, and census tract median household income, median home value, percent white, and percent college educated.

\(^2\)Defined as high depressive symptoms on three or more questionnaires over the study period (1999-2013)
Figure 2.2. Restricted cubic splines for the adjusted association\(^2\) between surrounding greenness in childhood and persistent depression\(^3\) in 8,375 adolescents and young adults (N=295 cases) living in the United States, stratified by population density

\(^1\)Low population density: \(\leq\)1000 people/mi\(^2\); High population density >1000 people/mi\(^2\)

\(^2\)Results quantified from logistic regression models with a generalized estimating equation are expressed as odds ratio for high depressive symptoms. Adjusted for participant race and sex, household income, maternal history of depression, paternal education, and census tract median household income, median home value, percent white, and percent college educated

\(^3\)Defined as high depressive symptoms on three or more questionnaires over the study period (1999-2013)
Table 2.3. Odds ratios and 95% confidence intervals for the relationship between surrounding greenness in childhood and persistent depression\(^1\) in 8,375 adolescents and young adults (N=295 cases) living in the United States.

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Cases</th>
<th>Age-Adjusted OR (95% CI) (^2)</th>
<th>Fully-Adjusted(^3) OR (95% CI)</th>
<th>Fully-Adjusted + PM(_{2.5})(^4) OR (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall</td>
<td>8,375</td>
<td>295</td>
<td>0.86 (0.74, 1.00)</td>
<td>0.87 (0.72, 1.06)</td>
<td>0.86 (0.72, 1.05)</td>
</tr>
<tr>
<td>Population Density</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High (&gt;1000 people/mi(^2))</td>
<td>5,441</td>
<td>198</td>
<td>0.77 (0.64, 0.91)</td>
<td>0.77 (0.61, 0.97)</td>
<td>0.77 (0.62, 0.97)</td>
</tr>
<tr>
<td>Low (≤1000 people/mi(^2))</td>
<td>2,934</td>
<td>97</td>
<td>1.32 (0.88, 1.98)</td>
<td>1.32 (0.83, 2.11)</td>
<td>1.30 (0.83, 2.04)</td>
</tr>
</tbody>
</table>

\(^1\)Defined as high depressive symptoms on three or more questionnaires over the study period (1999-2013)

\(^2\)Results quantified from logistic regression models with a generalized estimating equation are expressed as odds ratio for high depressive symptoms associated with an interquartile range (IQR) change in greenness, where 1 IQR = 15.10

\(^3\)Adjusted for participant race and sex, household income, maternal history of depression, paternal education, and census tract median household income, median home value, percent white, and percent college educated

\(^4\)Adjusted for participant race and sex, household income, maternal history of depression, paternal education, census tract population density, median household income, median home value, percent white, and percent college educated, and estimated PM\(_{2.5}\).
Discussion

In this study of adolescents and young adults followed for up to 17 years, we observed an association between higher surrounding greenness during childhood and adolescence and lower risk of subsequently developing depressive symptoms. These associations appeared stronger in adolescence than early adulthood, and in areas of high versus low population density. We observed a similar pattern when considering persistent depressive symptoms that were evident across several questionnaire cycles.

Our findings are similar to those of a retrospective study of Australian adults which observed that greater contact with nature in childhood was moderately correlated with lower depressive symptoms in adulthood. This association was primarily mediated through adult contact with nature. This study was able to characterize contact with nature rather than simply presence of nature, but relied on self-reported exposure and was unable to control for household or neighborhood socioeconomic status in childhood. We know of no other studies that have characterized the association between exposure to greenness measured by NDVI in childhood and risk of depression in adulthood.

This study complements a small but growing number of prospective studies evaluating a potentially protective association between greenness or green space and risk of depression conducted in various age groups. Gubbels et al. measured depressive symptoms at two time points 1-2 years apart and observed changes in depressive symptoms associated with an increase in perceived greenery among adults but not adolescents. Other prospective studies in the United Kindgom and Canada have observed similar beneficial relationships between greater greenness and improved depressive symptoms or lower risk of depression in adults.

We observed a suggestion of a stronger association between greenness and depressive symptoms in areas of high population density. Many previous studies of greenness and mental health, particularly those with repeated follow-up measures, focus on a single metropolitan area or other relatively homogenous region. Indeed much of the literature on greenness or green space and mental health has focused specifically on urban areas. Few population-based studies have considered how the relationship between greenness and mental health varies across population density, but studies of other
health outcomes have observed similarly stronger associations in denser or more urban areas.\textsuperscript{36,37} Our results suggest that the relationship between greenness and mental health may be most salient for people living in areas of higher density. This finding is consistent with mechanisms posited to underlie the association between greenness and mental health. Urban areas can consistently tax attention and cognition\textsuperscript{35} and impose greater stress and social demands on residents than areas of lower population density.\textsuperscript{70} Greenness and other forms of nature can act as an antidote to these influences by providing a restorative break for cognition and attention\textsuperscript{13,35} and reducing stress.\textsuperscript{6}

We observed a suggestion of stronger associations between surrounding greenness and high depressive symptoms when we limited our analysis to observations prior to age 18; after adjustment for neighborhood and household socioeconomic variables, there was no association between childhood and adolescent greenness and incident young adult depression (N=1,158 cases). Since exposure was only characterized through age 18, it is possible that associations of greenness with incident depression are limited to more proximal exposures. The analysis of depressive symptom onset after age 18 was also limited to individuals who were free of depression up to that point and excluded the 1,260 individuals who were characterized as having high depressive symptoms as teenagers. Since depression in adolescence is a strong predictor of depression in adulthood\textsuperscript{71,72} it is also possible a sample limited to newly onset depression in adulthood represents a distinct subset for whom childhood exposures are less relevant.

Some important limitations must be noted. We relied on NDVI data measured at a 1,000 meter resolution. There is no consensus in the literature about the most relevant spatial area for characterizing greenness in relation to mental health, and it is possible the use of this relatively large area fails to capture the relevant geographic context. Other studies of adolescent health have considered multiple spatial resolutions and observed the strongest associations at 1,000 meters.\textsuperscript{73} However, the use of this relatively low-resolution NDVI measure may result in exposure measurement error. Measurement error in our exposure may also result from using only residential address, and not locations of schools or other places where children may spend time, to characterize exposure. NDVI also does not provide information on
how participants interact with greenness or the type or quality of greenness. There may also be some
misclassification of depression status since depressive symptoms were measured rather than clinical
diagnosis. Additionally, since depression was not assessed on the first GUTS questionnaire we assumed
all participants were free of depression at baseline. While this likely resulted in some misclassification of
new cases of high depressive symptoms, because our exposure was a cumulative average measure across
childhood and therefore highly correlated from one observation to the next, we do not expect this
assumption to substantially bias our estimates. When we excluded participants who had high depressive
symptoms in 1999 our results were similar in direction but attenuated in magnitude. This is consistent
with our finding of stronger associations between greenness and depressive symptoms for younger-onset
depression.

Our study participants were predominantly white and resided in census tracts that were, on
average, more affluent than a typical U.S. neighborhood with respect to income and home value. All
participants had mothers who were nurses, suggesting some level of economic and social stability in their
lives. As a result, caution should be exercised in generalizing the findings. However, some previous
studies have shown stronger associations between greenness and mental health in less advantaged
individuals and communities so it is possible our observed associations represent an underestimate of the
association we would see in a more representative population.\textsuperscript{14,74}

This study also had some unique strengths, including detailed prospectively assessed residential
history available for nearly all of childhood for a sample of participants growing up across the United
States. We were able to characterize cumulative childhood greenness exposure, an improvement over
studies that relied on exposure characterized at a single point in time. We also had repeated measures of
depressive symptoms throughout adolescence and adulthood, which enabled us to characterize the
association between greenness and depressive symptoms across the transition from adolescence to
adulthood.

In this analysis of more than 11,000 young adolescents followed into early adulthood living in the
United States, we observed higher surrounding greenness in childhood and adolescence was associated
with lower incidence of high depressive symptoms. This association was limited to areas of higher population density and suggestively stronger in adolescent-onset than in adult-onset depressive symptoms. We observed a suggestive but not significant association between surrounding greenness in childhood and adolescence and persistent depression in the population overall, but we did observe an association among individuals who grew up in higher density areas. Overall, our findings suggest that greater surrounding greenness during childhood and adolescence may be beneficial for mental health, particularly for individuals living in areas of higher population density. These findings are consistent with a growing body of literature on the benefits of green areas across the life course and provide support for policies that improve the greenness of urban built environments. Future research should explore the potentially differential associations of greenness and health across urbanicity in greater detail and work to elucidate the mechanisms that may make greenness particularly relevant for the mental health of urban residents.
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Chapter 3: Surrounding greenness and overweight and obesity in the Growing Up Today Study

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Acknowledgements

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Abstract

**Background and Objectives:** Living in an area with greater surrounding greenness or more green space has been associated with greater physical activity in adolescents, but evidence for an association with weight is inconclusive. We hypothesized that greater surrounding greenness would be associated with lower incidence of overweight and obesity.

**Methods:** 10,255 participants in the Growing Up Today Study II, ages 9-17 at enrollment in 2004, were followed through 2011. We used the Normalized Difference Vegetation Index (NDVI) to characterize exposure to greenness; the primary outcome was overweight or obesity calculated from self-reported height and weight every 2-3 years. We used logistic regression and Cox proportional hazards models to characterize baseline and prospective associations, respectively, between surrounding greenness and overweight/obesity and assessed whether these associations were modified by sex or population density.

**Results:** There was no association between surrounding greenness and overweight/obesity. There was suggestive evidence of variation in the baseline relationship between greenness and overweight/obesity by population density; in the least dense areas higher greenness was associated with greater prevalence of overweight and obesity while in the densest areas the greenness was associated with lower prevalence of overweight and obesity.

**Conclusions:** Surrounding greenness was not associated with incident overweight and obesity overall in this cohort of adolescents and young adults in the United States, but we observed suggestive evidence that there may be variations in the association by population density.
Introduction

Globally, nearly a quarter of children and adolescents in developed countries are overweight or obese, and the prevalence of obesity has been increasing in recent years among both adults and children. Obesity and overweight in childhood are risk factors for health problems later in life including cardiovascular disease and mortality and pose a substantial economic burden to individuals and the health system. While childhood overweight and obesity are the consequences of a complex interaction of factors, characteristics of the built environment have received attention as one potentially important modifiable risk factor. The availability of parks and other green spaces or the overall greenness of an area is a specific characteristic of the built environment that has received increasing attention.

Availability of green spaces can encourage routine and recreational physical activity and discourage sedentary time, both of which can in turn affect body weight. Early studies of physical activity focused specifically on the presence of parks and were generally suggestive of positive associations between parks and physical activity for children and adolescents. Since parks are only one contributor to available green space, more recent studies have used satellite measures of vegetation that capture overall greenness such as the Normalized Difference Vegetation Index (NDVI) or land use data on availability of green space and have found inconsistent but mostly positive associations with physical activity. A smaller number of cross-sectional studies have investigated associations between green space or greenness and screen time and suggest that greater green space is associated with lower amounts of screen time, particularly among younger children.

Evidence for whether associations between greenness and physical activity and screen time translate into improved body mass index (BMI) remains limited and inconsistent. Most studies to date have been cross-sectional, but a few longitudinal studies have observed greater greenness or access to green space was associated with a healthier BMI over time. However, these studies are frequently limited by characterizations of green space at a single time point and/or a focus on a single geographic area.
The current study uses prospective data from an ongoing cohort of children and adolescents living across the United States to characterize the cross-sectional and prospective associations between surrounding greenness and overweight and obesity. We further consider whether this association is mediated by physical activity or screen time. We hypothesize that living in an area with higher surrounding greenness is associated with lower incidence of overweight and obesity, and that this association is partly explained by levels of physical activity and screen time. We consider potential effect modification of this association by population density, motivated by previous studies of greenness or green space and BMI\textsuperscript{21} and physical activity\textsuperscript{13} that have observed an association only in areas of higher density. We also consider potential effect modification by sex and age (18 and under versus older than 18) since previous studies have shown both of these characteristics may modify the association between greenness and BMI.\textsuperscript{25} Importantly, we are able to adjust our analyses for a variety of important potential confounders including household and neighborhood socioeconomic status (SES) and familial characteristics such as maternal BMI.

**Patients and Methods**

*Study Population*

The study population included participants in the ongoing Growing Up Today Study II (GUTS II), which began in 2004. Mothers participating in the prospective Nurses’ Health Study II were invited to enroll their children ages 9-17. A total of 10,919 children assented to participate by returning completed questionnaires. We excluded participants who did not have a valid baseline address available (N=6), who lived outside the contiguous United States at baseline (N= 33), who were less than 9 years old at baseline (N=1), or who were missing data on body mass index (N=623) leaving 10,255 children eligible for analysis. In adjusted models we further excluded 82 participants who were missing data on maternal BMI, an important predictor of a child’s BMI. The analysis of incident overweight and obesity was limited to those participants known to be free of overweight and obesity at baseline in 2004 (N=8,032). Return of
questionnaires implied informed consent and the study protocol was approved by the Institutional Review Board at Brigham and Women's Hospital.

Exposure

We characterized exposure at each time point using the Normalized Difference Vegetation Index (NDVI), a measure of vegetative density. NDVI is derived from remote sensing data and takes advantage of the fact that vegetation, due to chlorophyll in plants, reflects more near-infrared light (0.7 to 1.1 µm) and absorbs more visible light (0.4 to 0.7 µm) compared to areas without vegetation. NDVI is calculated as the difference in near-infrared and visible light reflectance divided by their sum, resulting in a ratio with values ranging from -1.0 to 1.0. Larger values indicate higher levels of vegetative density while negative values indicate water and a value of zero indicates barren ground or impervious surface.26 Because it is derived from satellite data, NDVI captures both publicly accessible green spaces such as parks and school-yards and private spaces such as household lawns and gardens. This measure is recognized in the literature as an appropriate characterization of greenness exposure for studies of health.27,28 For this analysis we downloaded NDVI at a 250 meter resolution from the Moderate-resolution Imaging Spectroradiometer (MODIS) on board NASA’s Terra satellite. We characterized exposure to greenness using the NDVI in two spatial areas: the 250m parcel containing each participant’s address, and the average NDVI in a 1,250 meter radius surrounding a participants home. The 250m resolution (the smallest available from our NDVI data) captures the greenness of the immediate home environment, and the 1,250m distance captures a reasonable walking distance for an adolescent.29 We used mid-July NDVI values to capture peak greenness levels and the maximum variability in exposure. Participant exposures were assigned based on geocoded locations of their mother’s address, reported every two years beginning in 1989 as part of the Nurses’ Health Study II.

Time varying exposure at each questionnaire cycle was defined as the greenness value at the NHS II address immediately prior (for example, the exposure matched with the 2006 outcomes measures was
surrounding greenness in 2005). Exposure was updated every two years until participants turned 18; for measurements taken after age 18 we carried forward the last exposure measure from the address where participants were 18 or younger. To improve interpretability and comparability with existing literature, we scaled NDVI values by the interquartile range.\textsuperscript{17,30}

**Outcome**

The outcome, overweight or obesity, was calculated from self-reported height and weight collected on each GUTS questionnaire. BMI was computed at each time point as kilograms per meter squared (kg/m\(^2\)); this method of BMI calculated based on self-reported height and weight has been shown to be valid among preadolescents and adolescents.\textsuperscript{31,32} We classified the participants as underweight, healthy weight, overweight, or obese using the international obesity task force (IOTF) standards developed by Cole and colleagues.\textsuperscript{33,34} Due to small numbers, participants classified as underweight were included in the reference (healthy weight) category.

**Covariates**

Covariates measured at the individual, household, and neighborhood levels were considered as potential confounders. Indicators of SES at both the household and neighborhood levels are important confounders to consider in studies of greenness and health since they are recognized predictors of overweight and obesity\textsuperscript{35} and also associated with greenness.\textsuperscript{30,36} We characterized household SES using income (reported by mothers in 2001 and classified as \(\geq\) versus < $75,000 per year) and paternal education (reported in 1999 and classified as college graduate or not). GUTS participants also reported their race/ethnicity on the baseline questionnaire (classified as white/other race); other individual level covariates were age and sex. We used a missing indicator for missing values of household income, paternal education, and participant race. To characterize neighborhood SES for each address we used census tract median home value, median household income, percent white, and percent college educated
(based on 2000 US Census data). We also considered census tract population density and US Census region as covariates. Census tracts were updated each NHS II questionnaire cycle (every 2 years) through age 18, allowing us to capture changes in neighborhood conditions that resulted from moving.

Maternal BMI is one of the strongest predictors of a child’s weight status.\textsuperscript{37} Since the neighborhood environment is shared by mothers and children, it is possible maternal weight at baseline of this study is also influenced by surrounding greenness. To account for the strong association between maternal BMI and child BMI without adjusting for a potential downstream consequence of exposure, we adjusted for maternal BMI at age eighteen. All participants in NHS II reported their height and weight at age eighteen on the baseline questionnaire in 1989; in a validation study the correlation between BMI calculated from these data and BMI determined from medical records was 0.84.\textsuperscript{38} In a sensitivity analysis we adjusted for maternal BMI in 2003, the year prior to the baseline GUTS questionnaire.

We considered whether physical activity or screen time, reported by participants on all questionnaires, mediated the association between surrounding greenness and overweight/obesity. For physical activity, participants reported their activities by season over the last twelve months in hours per week (never, <0.5, 0.5 to 3, 4–6, 7–9, and 10+ hrs/wk) for a total of 19 activities for boys and 18 for girls (football was not included on the girls questionnaire). We calculated an annual average value of total moderate and vigorous physical activity (MVPA) by summing the total physical activity time reported in each season and then averaging across all four seasons. Screen time was assessed based on responses to questions about time spent engaging with television, electronic (video and computer) games, and DVDs/videos in hours per week separately for weekdays and weekends (<0.5, 1.0-5.5, 6-10, 11-15, 16-20, 21-30, and 31+). A total screen time value was calculated as the sum of the midpoints of each response (using 31 hours for the highest option). A similar instrument that assessed inactivity was reasonably correlated with 24-h recall ($r = 0.54$).\textsuperscript{39}

Studies of greenness and health often consider air pollution as a potential confounder, since air pollution is associated with greenness\textsuperscript{40} and an important predictor of many health outcomes including childhood obesity.\textsuperscript{41} However, air pollution may also be affected by greenness, making it an intermediate
rather than a confounder of the association between greenness and health. To assess the role of air pollution in observed associations we considered particulate matter 2.5 microns or less in diameter (PM$_{2.5}$) as a covariate. PM$_{2.5}$ was estimated at the household address and included as a time-varying annual average calculated from a spatiotemporal national model.$^{42}$

**Statistical Analysis**

To assess the association between surrounding greenness and baseline overweight and obesity we used logistic generalized estimating equations (GEE) to estimate odds ratios and 95% confidence intervals. This allowed us to account for the fact that some mothers enrolled more than one child and our data contained sibling clusters.$^{43}$ For the analysis of greenness and incident overweight and obesity we used Cox proportional hazards models to estimate hazard ratios and 95% confidence intervals, using calendar time as the metameter and the robust sandwich covariance matrix to adjust standard errors to account for non-independent sibling clusters. All Cox proportional hazards models were stratified by age and questionnaire cycle. We considered a tiered approach to assess confounding include: a basic model adjusted only for age and sex; a model adjusted for maternal BMI at age 18; and a model further adjusted for all relevant demographic and socioeconomic characteristics. We further adjusted for PM$_{2.5}$ in a sensitivity analysis.

We assessed effect measure modification by sex, age (18 and under versus over 18), and population density (in tertiles), motivated by evidence from previous studies of greenness and body weight or weight-related outcomes.$^{25,44}$ We tested for statistically significant interactions between each of these characteristics and the exposure using a generalized score test for baseline logistic models and a likelihood ratio test comparing a model with the interaction to one without for incident Cox proportional hazards models. We investigated whether the association between surrounding greenness and weight status was mediated by physical activity or screen time using the publicly available Mediate macro to calculate mediation proportions for these variables, comparing a model with these variables to one
without.\textsuperscript{45} We tested for deviations from linearity in all exposure-response relationships non-parametrically with restricted cubic splines.\textsuperscript{46}

**Results**

Descriptive statistics for the 10,255 study participants eligible at baseline are presented in Table 1. Study participants were mostly white (91\%) and there were slightly more female participants (55\%) than males. Participants who were overweight or obese had slightly lower household and neighborhood socioeconomic status. For example, 58\% of overweight/obese participants had a father with a college degree compared to 67\% of normal weight participants.
Table 3.1. Baseline characteristics of 10,255 participants ages 9-17 in the Growing Up Today Study II, 2004.

<table>
<thead>
<tr>
<th>Overall (N=10,255)</th>
<th>Normal Weight at baseline (N=8,032)</th>
<th>Overweight/Obese at baseline (N=2,223)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Individual Measures</strong></td>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td>Female</td>
<td>55</td>
<td>57</td>
</tr>
<tr>
<td>White Race</td>
<td>91</td>
<td>92</td>
</tr>
<tr>
<td>Annual household income &gt; $75K</td>
<td>52</td>
<td>53</td>
</tr>
<tr>
<td>Father college educated</td>
<td>65</td>
<td>67</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mean (SD)</th>
<th>Mean (SD)</th>
<th>Mean (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Screen time (hours/week)</td>
<td>21.88 (15.06)</td>
<td>20.80 (14.26)</td>
</tr>
<tr>
<td>Physical Activity (hours/week)</td>
<td>14.01 (9.27)</td>
<td>14.19 (9.21)</td>
</tr>
<tr>
<td>Normalized Difference Vegetation Index (NDVI)</td>
<td>0.68 (0.15)</td>
<td>0.67 (0.15)</td>
</tr>
<tr>
<td>Age (years)</td>
<td>13.50 (1.83)</td>
<td>13.55 (1.83)</td>
</tr>
<tr>
<td>Maternal BMI at age 18</td>
<td>20.92 (9.27)</td>
<td>20.58 (2.52)</td>
</tr>
<tr>
<td>Maternal BMI at baseline</td>
<td>25.63 (5.48)</td>
<td>24.89 (4.93)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mean (SD)</th>
<th>Mean (SD)</th>
<th>Mean (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent College Educated</td>
<td>35 (18)</td>
<td>36 (18)</td>
</tr>
<tr>
<td>Percent White</td>
<td>90 (12)</td>
<td>90 (12)</td>
</tr>
<tr>
<td>Median Home Value ($)</td>
<td>183K (130K)</td>
<td>188K (134K)</td>
</tr>
<tr>
<td>Median Household Income ($)</td>
<td>70K (26K)</td>
<td>71K (26K)</td>
</tr>
<tr>
<td>Population Density (people/mi²)</td>
<td>2535 (6075)</td>
<td>2522 (5762)</td>
</tr>
<tr>
<td>Region</td>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td>West</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Midwest</td>
<td>37</td>
<td>36</td>
</tr>
<tr>
<td>South</td>
<td>15</td>
<td>14</td>
</tr>
<tr>
<td>Northeast</td>
<td>33</td>
<td>33</td>
</tr>
</tbody>
</table>

1. P-values calculated using chi-squared tests for categorical variables and t-tests for continuous variables comparing normal weight and overweight/obese groups
2. 113 participants were missing screen time data
3. 23 participants missing physical activity data
4. 82 participants missing maternal BMI at age 18
5. 374 participants missing maternal BMI at GUTS II baseline, measured in 2003
Linear models are presented for all exposure-response relationships since there was no evidence of significant deviations from linearity. After adjustment for confounders neither measure of surrounding greenness was associated with overweight and obesity (Table 2). We observed similarly null results for the relationships surrounding greenness at both 250m and 1,250m and incident overweight and obesity (Table 3). For example, the hazard ratio for an IQR increase in greenness at 1,250m was 0.97 (95% CI 0.86, 1.09). The IQRs in our study were similar to those observed in other studies. Adjustment for concurrent maternal BMI as opposed to maternal BMI at age 18 did not alter any of the observed associations; further adjustment for estimated PM$_{2.5}$ also did not impact any of our estimates (data not shown).
Table 2. Odds ratios and 95% confidence intervals\(^1\) for the association between an interquartile range increase in Normalized Difference Vegetation Index (NDVI) and prevalent overweight/obesity in 10,255 participants (N=2,223 cases) in the Growing Up Today Study II, 2004.

<table>
<thead>
<tr>
<th></th>
<th>Basic Model(^2) OR (95% CI)</th>
<th>Basic Model+ Maternal BMI(^3,4) OR (95% CI)(^5)</th>
<th>Fully adjusted(^4,5) OR (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>250m NDVI</td>
<td>1.07 (1.00 , 1.14)</td>
<td>1.06 (0.99 , 1.14)</td>
<td>0.99 (0.90 , 1.09)</td>
</tr>
<tr>
<td>1250m NDVI</td>
<td>1.10 (1.04 , 1.17)</td>
<td>1.09 (1.03, 1.16)</td>
<td>1.04 (0.95, 1.14)</td>
</tr>
</tbody>
</table>

\(^1\)Results quantified from logistic regression models are expressed as odds ratio for overweight/obesity associated with an interquartile range (IQR) change in greenness, where 1 IQR =0.233 for 250m NDVI and 0.175 for 1250m NDVI

\(^2\)Adjusted for age (in months) and sex

\(^3\)Adjusted for age (in months), sex, and maternal BMI at age 18

\(^4\) Restricted to participants with data on maternal BMI at age 18 (N=10,173 participants, 2,209 cases)

\(^5\) Adjusted for age (in months), sex, maternal BMI at age 18, participant race, household income, father’s education, census tract median home value, census tract median income, census tract percent white, census tract percent college educated, census tract population density, and region

Table 3. Hazard ratios and 95% confidence intervals\(^1\) for the association between an interquartile range increase in Normalized Difference Vegetation Index (NDVI) and incident overweight/obesity in the Growing Up Today Study II, 2004-2011 (N=1,179 cases, 430,470 person-months)

<table>
<thead>
<tr>
<th></th>
<th>Basic Model(^2) HR (95% CI)</th>
<th>Basic Model+ Maternal BMI(^3,4) HR (95% CI)(^5)</th>
<th>Fully adjusted(^4,5) HR (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>250m NDVI</td>
<td>1.04 (0.96 , 1.13)</td>
<td>1.06 (0.98 , 1.14)</td>
<td>0.99 (0.89 , 1.10)</td>
</tr>
<tr>
<td>1250m NDVI</td>
<td>1.05 (0.98 , 1.13)</td>
<td>1.06 (0.99 , 1.15)</td>
<td>0.97 (0.86 , 1.09)</td>
</tr>
</tbody>
</table>

\(^1\)Results quantified from Cox proportional hazards models are expressed as odds ratio for overweight/obesity associated with an interquartile range (IQR) change in greenness, where 1 IQR =0.231 for 250m NDVI and 0.196 for 1250m NDVI

\(^2\)Adjusted for age (in months) and sex

\(^3\)Adjusted for age (in months), sex, maternal BMI at age 18

\(^4\) Restricted to participants with data on maternal BMI at age 18 (1,166 cases, 427,514 person-months)

\(^5\) Adjusted for age (in months), sex, maternal BMI at age 18, participant race, household income, father’s education, census tract median home value, census tract median income, census tract percent white, census tract percent college educated, census tract population density, and region
There was no evidence of effect modification by sex in either baseline or incident models (p=0.48 and 0.21, respectively, for the 1,250m NDVI). All participants were under 18 in the baseline analysis, but there was no evidence of effect measure modification by age (18 and under versus over 18) in the incident analysis (p=0.36 for the 1,250m NDVI). While there was no statistically significant interaction between greenness and tertiles of population density (p=0.12 for 1,250m NDVI), when we constructed stratified models we observed suggestive evidence that population density may be an effect modifier of the baseline association between greenness and overweight and obesity (Table 4). In the lowest tertile of population density (corresponding to less than 509 people/mi²), a 1-IQR increase in greenness was associated with higher odds of overweight and obesity (OR = 1.24, 95% CI 1.04 - 1.49 for the 250m NDVI). In the highest tertile of population density (more than 2,426 people/mi²), the association was inverse (OR = 0.87, 95% CI 0.74 - 1.03 for the 250m NDVI). We did not observe a similar pattern in models of incident overweight and obesity stratified by population density (Table 4). Since the associations between surrounding greenness and overweight and obesity were null, we were unable to assess mediation by physical activity or screen time. Supplementary Table 1 presents the baseline associations between surrounding greenness and physical activity and screen time.
Table 3.4. Associations between an interquartile range increase in Normalized Difference Vegetation Index (NDVI)\(^1\) and prevalent and incident overweight/obesity in the Growing Up Today Study II, stratified by population density.

<table>
<thead>
<tr>
<th></th>
<th>Subjects</th>
<th>Cases</th>
<th>Basic Model(^1)</th>
<th>Maternal BMI(^2,3)</th>
<th>Fully adjusted(^3,4)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>OR (95% CI)</td>
<td>OR (95% CI)</td>
<td>OR (95% CI)</td>
<td>OR (95% CI)</td>
<td>OR (95% CI)</td>
</tr>
<tr>
<td><strong>Prevalent Overweight and Obesity(^5)</strong></td>
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<tr>
<td><strong>250m buffer</strong></td>
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<td>3,419</td>
<td>763</td>
<td>1.24 (1.08, 1.43)</td>
<td>1.25 (1.08,1.46)</td>
<td>1.24 (1.04,1.49)</td>
</tr>
<tr>
<td>Medium Density(^7)</td>
<td>3,418</td>
<td>736</td>
<td>1.03 (0.90, 1.17)</td>
<td>1.00 (0.87,1.13)</td>
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<td>0.96 (0.85,1.08)</td>
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<td>763</td>
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<td>Low Population Density(^6)</td>
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<td>1.13 (0.98,1.31)</td>
<td>1.09 (0.90,1.32)</td>
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<td>(P) for interaction = 0.95</td>
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<tr>
<td>Low Population Density(^6)</td>
<td>140,896</td>
<td>418</td>
<td>0.98 (0.84,1.14)</td>
<td>0.99 (0.85,1.16)</td>
<td>0.91 (0.72,1.15)</td>
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<td>Medium Density(^7)</td>
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<td>0.95 (0.82,1.09)</td>
<td>0.87 (0.70,1.09)</td>
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<tr>
<td>High Density(^8)</td>
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<td>1.14 (0.99,1.31)</td>
<td>1.16 (1.01,1.33)</td>
<td>1.11 (0.91,1.36)</td>
</tr>
</tbody>
</table>

\(^1\)Adjusted for age (in months) and sex
\(^2\)Adjusted for age (in months), sex, and maternal BMI at age 18
\(^3\)Restricted to participants with data on maternal BMI at age 18 (N=10,173 participants, 2,209 cases)
\(^4\)Adjusted for age (in months), sex, maternal BMI at age 18, participant race, household income, father’s education, census tract median home value, census tract median income, census tract percent white, census tract percent college educated, census tract population density, and region
\(^5\)Results quantified from logistic regression models with a generalized estimating equation are expressed as odds ratio for overweight/obesity associated with an interquartile range (IQR) change in greenness, where 1 IQR = 0.233 for 250m buffer and 0.175 for 1250m buffer
\(^6\)0-509 ppl/mi\(^2\)
\(^7\)509-2,426 ppl/mi\(^2\)
\(^8\)>2,426 ppl/mi\(^2\)
\(^9\)Results quantified from Cox proportional hazards model are expressed as hazard ratio for incident overweight/obesity associated with an interquartile range (IQR) change in greenness, where 1 IQR = 0.231 for 250m buffer and 0.196 for 1250m buffer
Discussion

In this cohort of adolescents and young adults in the United States, we observed overall null associations between surrounding greenness and both prevalent and incident obesity and overweight. While the statistical tests for interaction between measures of greenness and tertiles of population density did not reach significance, stratified models suggested effect measure modification by population density, particularly at baseline. In the least dense areas higher levels of greenness were associated with higher odds of overweight and obesity. Other studies of weight and related outcomes have produced similar evidence of a stronger association between greenness or green space in areas of higher population density.\textsuperscript{44,47} In our study, this pattern of an inverse association between greenness and overweight and obesity in high population density areas did not hold in the analysis of incident overweight and obesity; associations were null across all population densities.

The literature about greenness or green space and weight in children and adolescents is mixed and relies on variable characterizations of exposure including NDVI, land use or land cover data, and measures of distance to parks and public open spaces.\textsuperscript{17,21–25,48–50} The studies that use NDVI as an exposure have generally observed inverse associations between NDVI and BMI.\textsuperscript{17,21,48} but differences between their findings and ours may be attributable to study design or population differences. These studies have been cross-sectional or relied on exposure characterized at a single time point within a single geographic area. While these studies do not report average population density for their populations, they are likely similar to the highest density tertile in our study where we observed a suggestive inverse association in the cross-sectional analysis. Findings from prospective studies using green space or parks as the exposure have found conflicting results. A prospective study in Australia found greenness was associated with lower BMI in adolescent boys, but not younger boys or girls.\textsuperscript{25} This study was limited to a single characterization of greenness exposure and did not adjust for area-level SES or population density, which may partially explain differences in our findings. Prospective studies using only parks as the exposure have been split, with one finding no association\textsuperscript{49} and another observing higher BMI at age 18 in those that grew up further from a park.\textsuperscript{24}
Some limitations of this study should be noted. NDVI does not provide information on quality, type, or accessibility of surrounding greenness. We assigned exposure based on maternal residential addresses only and did not have data on surrounding greenness at other locations such as school. This may result in measurement error in our exposure, but we do not expect this error to be differential with respect to weight status and would likely bias our estimates toward the null. Our reliance on self-reported body mass index may result in misclassification of the outcome, but we expect this to be minimal since self-reported BMI in adolescents is a validated measure. Any misclassification of overweight and obesity is likely non-differential with respect to greenness, also biasing our estimates toward the null. There was dropout among GUTS participants over the course of the study, which could result in selection bias if those who chose to leave differed with respect to exposure and outcome. While we weren’t able to assess outcomes for those who left the study, we were able to assess exposures and covariates since follow-up in NHS II is relatively complete. At each time point, those who remained in the study did not differ substantially from those who dropped out with respect to greenness exposure or census tract SES. Finally, our study population was predominantly white and lived in census tracts that were, on average, more affluent than a typical US neighborhood. Therefore, our findings may not be generalizable to a more diverse or less advantaged population. However, previous studies of other metabolic outcomes have observed stronger associations among less advantaged populations, suggesting that our findings may be an underestimate of what we would observe in a more diverse cohort.

There were also some unique strengths to this study, including repeated measures of body mass index through adolescence and into adulthood. We used repeated measures of surrounding greenness to characterize exposure and were able to assign objective exposures by combining participants’ geocoded home addresses with satellite data on density of vegetation. We were able to control for a range of socioeconomic confounders at the household and neighborhood level and for maternal BMI at age 18, to account for the important shared familial component of BMI. In contrast to many studies that focus on a single geographic area, our study included participants that lived across the United States. This allowed us
to characterize the association of greenness and overweight/obesity across a wide range of population densities.

In this prospective study of adolescents living in the United States, we did not observe an association between surrounding greenness and the incidence of overweight and obesity or prevalence of overweight and obesity at baseline. We observed a suggestion that this association may vary across categories of population density. Further research is needed to better characterize the associations between greenness and BMI across areas of varying density. Future studies should focus on the mechanisms that may link greenness and BMI in urban areas and the specific types of urban greenness that may be most relevant for adolescent weight.
References


APPENDIX
<table>
<thead>
<tr>
<th></th>
<th>Excessive Screen time²</th>
<th>Insufficient Physical Activity³</th>
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<tbody>
<tr>
<td></td>
<td>6,574 cases</td>
<td>2,704 cases</td>
</tr>
<tr>
<td></td>
<td><strong>OR (95% CI)</strong></td>
<td><strong>OR (95% CI)</strong></td>
</tr>
<tr>
<td></td>
<td>Basic model⁴</td>
<td>Maternal BMI⁵,⁶</td>
</tr>
<tr>
<td>250m NDVI</td>
<td>0.94 (0.89 , 1.00)</td>
<td>0.93 (0.88 , 0.99)</td>
</tr>
<tr>
<td>1250m NDVI</td>
<td>0.96 (0.92 , 1.01)</td>
<td>0.96 (0.91 , 1.01)</td>
</tr>
</tbody>
</table>

¹One Interquartile range =0.233 for 250m NDVI and 0.175 for 1250m NDVI
²Defined as more than 2 hours per day of television, DVDs, and video/computer games, 113 participants were missing screen time data
³Defined as less than 1 hour per day of moderate-vigorous physical activity, 3 participants missing physical activity data
⁴Adjusted for age (in months) and sex
⁵Adjusted for age (in months), sex, and maternal BMI at age 18
⁶Restricted to participants with data on maternal BMI at age 18 (N=10,173 participants, 2,209 cases)
⁷Adjusted for age (in months), sex, maternal BMI at age 18, participant race, household income, father’s education, census tract median home value, census tract median income, census tract percent white, census tract percent college educated, census tract population density, and region
CONCLUSION
This dissertation considered the cross-sectional and longitudinal relationships between natural environments and health in a cohort of preadolescents and adolescents in the United States followed through early adulthood. These papers are among the first to focus specifically on adolescence, which is a critical developmental period but has received less attention than other stages of life in research on the built environment and health.\textsuperscript{1,2} We considered mental health, operationalized as high depressive symptoms, and high body mass index during adolescence and adulthood as outcomes. Throughout all three papers we used objective measures of exposure to natural environments, created by combining geocoded residential addresses with satellite data on surrounding and proximal natural environments. Our study participants were children of women previously enrolled in an ongoing cohort study who provided detailed data on household SES, family history, and maternal characteristics that allowed us to account for important confounders throughout our analyses. The availability of residential addresses going back to nearly the time of birth for most participants allowed us to characterize cumulative exposure to nature during childhood and assess its association with subsequent health. Taken together, the three chapters provide support for a role of nature in promoting health across the life course and suggest some future research directions.

The first paper assessed the cross-sectional associations between surrounding greenness, blue space, and depressive symptoms in teenagers. Participants living in areas of higher greenness were less likely to report high depressive symptoms, an association that was robust to adjustment for socioeconomic status at the household and neighborhood level. There was suggestive evidence for a stronger association between greenness and depressive symptoms in middle school students compared to high school students, reinforcing the need for more studies in adolescents to further elucidate how associations between nature and health may vary by age and stage of life. Depressive symptoms were not associated with any measure of proximity to blue space.

The second paper extended on the findings of the first by considering the prospective association between surrounding greenness and depressive symptoms. For this paper we considered cumulative
average greenness exposure through childhood and its association with the onset of depressive symptoms. We found participants growing up in a greener area were less likely to experience high depressive symptoms; this association was stronger in areas of high population density. When we considered the association between surrounding greenness and persistent depressive symptoms, the occurrence of repeated reports of high depressive symptoms, we observed a similar pattern. The suggestive variation in associations by population density is consistent with the mechanisms underlying the hypothesized association between greenness and mental health. In particular, denser and more urban environments can tax cognition and impose greater social stress on residents than areas of lower density, greenness and other forms of nature can provide an antidote to these stressors.

In the third paper, we assessed the cross-sectional and longitudinal associations between surrounding greenness and body mass index (BMI). There were no associations between greenness and either prevalent or incident overweight and obesity in the population overall. There was suggestive evidence that the association between greenness and overweight and obesity varied across population density in a pattern consistent with what we observed in the second paper—greenness was associated with less overweight and obesity in higher-density areas, and more overweight and obesity in lower-density areas. This variation was limited to the analysis of prevalent overweight and obesity, stratification by population density did not alter our conclusions for the incidence analysis.

The findings in these three chapters add to a growing body of evidence characterizing the relationships between natural environments and population health. We observed associations between greenness and mental health during adolescence and suggestive evidence that even within adolescence associations may vary. Further research into the ways in which contextual factors influence health in this critical period is important for understanding how nature can influence health across the life course. Reinforcing the importance of a life course approach to understanding how nature can affect health, we observed associations between greenness in childhood and subsequent high depressive symptoms. This association was strongest in areas of high population density, where nature can provide an important
antidote to the stressors of urban life. Our results for the analysis of greenness and BMI, while generally null, do provide support for the importance of population density as an effect modifier in the relationship between nature and health.
References


