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The Influence of Vegetation and Green Spaces on Air Quality and Outdoor Air Temperature Mitigation on Multiple Scales

Undergraduate Honors Thesis
By McKinley Deery

The University of Vermont 2021
Environmental Studies

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Abstract

City cores and urban areas exhibit warmer temperatures than surrounding areas due to the urban heat island (UHI) phenomenon. UHIs are caused by land-use changes, specifically replacing natural land cover with hard urban surfaces including pavement and built infrastructure, as well as from anthropogenic heat release from fuel combustion within cities. Built materials absorb and retain heat, therefore increasing average outdoor air temperatures, while certain pollutants decrease air quality and contributes to temperature increases. Climate change will most likely cause these conditions to prevail and worsen as heatwaves become more intense and frequent. While heat events persist, the need for cooling systems indoors increases and in turn creates a rise in energy consumption and further anthropogenic heat combustion. An increase in urban vegetation can help to reduce the UHI effect by shading building surfaces, increasing land albedo, and releasing moisture into the atmosphere. While several studies have examined the role of urban greenspaces in offsetting UHIs, there are few data regarding whether UHIs exist at small scales such as in small towns and villages in rural areas. Moreover, there is potential for green spaces within developed rural areas including small towns and villages to improve air quality and decrease outdoor air temperatures at a local scale. In this study, I examine the air filtration and cooling effects of ten small-scale village greens throughout Vermont. These village greens tend to have park-like characteristics including open lawn and tree and shrub vegetation. Many historic Vermont village greens are located adjacent to the areas with the most development within a given town, which includes areas of impervious surfaces such as roads and buildings. In this study, air quality and temperature are measured at two edge locations and one center location within each of ten village greens throughout the Fall of 2020. I hypothesized that the air quality would be higher in the center of greens and generally found this to be true. For temperatures, while I hypothesized the centers of the green spaces to be cooler, a difference of no larger than 0.4°C was observed between the edge and centers of village greens. The ten village greens were also separated into five more urban towns and five more rural towns to compare temperature and air quality among locations to see whether there might be a greater

contrast between edge and center data points in the comparatively urban Vermont towns versus the rural towns. Overall results showed better air quality and wider temperature variation in rural locations compared to urban locations.

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Introduction

An urban heat island (UHI) is an urban or metropolitan area that is significantly warmer than its surroundings due to human industrialization and urbanization (Rizwan, 2008). The main causes of the UHI are the following:

1. absorption and re-radiation of solar radiation due to low albedo materials on urban structures and street surfaces,
2. absorption and re-radiation of solar radiation by air pollution in the urban atmosphere into the atmosphere,
3. release of anthropogenic heat from combustion,
4. increased heat storage by building materials with large thermal admittance (a material's ability to absorb heat and release it into space over time (EPA, 2021)),
5. and decreased water evaporation due to impervious materials and small amounts of vegetation (Kleerekoper, et al., 2012).

Albedo can be defined as the fraction of incoming light or radiation that is reflected by a surface. Materials in the built environment including glass, steel, asphalt, and concrete have fairly low albedos and consequently increase the persistence of the UHI (Ban-Weiss et al., 2015).

The UHI effect is expected to warm urban areas by 3.5–4.5°C and is expected to increase by approximately 1°C per decade (Coburn, 2009). Urban areas occupy only 2% of the Earth's land but account for 60–80% of energy consumption and 75% of global carbon emissions (Akbari, et al., 2016). With the globe's ever-increasing population estimated to be over 7.8 billion by 2021 (Worldometer, 2021), UHIs are expanding and humans are becoming directly exposed to their negative impacts (Rizwan, 2008). The growth of urban areas and the persistence of the UHI effect has increased human vulnerability to heat-related injuries and death (Patz et al., 2005). High temperatures and increased heat events are associated with high levels of heat-related injury and mortality in urban areas (Son et al., 2016) and have shown a significant increase in cardio-respiratory diseases amongst humans (Kleerekoper et al., 2012). Along with extreme heat events, the UHI also contributes to air pollution as anthropogenic sources of heat often contain harmful chemicals, aerosols, and particulates (Rosenweig, 2009).

Vegetation can absorb and metabolize many of these airborne contaminants through the process of phytoremediation. This includes but is not limited to particulate matter, exhaust emissions, volatile organic compounds (VOCs), building materials, textiles, and plastics (Norgate, 2015). Trees are able to absorb pollutant gases including ozone, nitrogen oxides, sulfur dioxide, carbon monoxide, and carbon dioxide which can significantly improve air quality. However, some trees have been shown to produce reactive VOC's which if combined with man-made nitrogen oxides can cause an increase in photochemical smog (Goodwin, 2012).

Vegetation can also reduce outdoor air temperatures through water vapor transport as well as shading (Yu et al., 2019). Through transpiration, vegetation releases water into the atmosphere and the surrounding air is cooled (Yu et al., 2019). Vegetation can shade many areas, reducing some heat gain and regulating temperatures. These factors are dependent on vegetation cover, height, and crown shape and size (Yu et al., 2019).

There are a variety of techniques and strategies used to mitigate UHI including reflective surfaces, bodies of water, and dispersal of vegetation throughout cities (Akbari et al., 2016). Parks reduce impervious surfaces within cities and increase albedo compared to materials like asphalt and concrete, therefore, reducing the UHI (Algretawee et al., 2019). Park size affects UHI, as different magnitudes present different cooling and air filtration effects (Lin et al., 2014). It is important to note however, that while parks do have cooling and air filtration effects, industrial city activity could bring warm, polluted air into the atmosphere, negatively impacting air quality and temperatures within and outside of parks (Kulka et al., 1986). Other forms of urban vegetation include street trees, green roofs, and green walls (Yu, et al., 2019), which may also help offset UHI effects.

Originally, I proposed to conduct research on UHI mitigation potential as measured by temperature and air quality data collected at edge and interior locations of Central Park in New York City. However, the intended data collection in the summer of 2020 was inhibited by *Coronavirus* travel restrictions. As a result, I sought new locations in Vermont to examine the potential of vegetation's role in offsetting UHI through air quality and temperature mitigation. This research tests whether vegetation mitigates UHI in land uses that are not traditionally considered urban but still exhibit localized denser development: village greens and small urban parks within the state of Vermont, USA.

First, I will review background literature on urban heat islands and mitigation strategies. These will include a variety of mitigation tactics that have traditionally applied to more urban settings, but could possibly apply to smaller urban and rural areas. I will also present a summary table of the prominent literature on design strategies for UHI mitigation and their overall effects on temperature, air quality, and human health benefits.

Then I will explore previously unstudied evidence of village greens' and small urban parks' impacts on localized air quality and temperature in the context of Vermont Village Greens. It is unclear whether the phenomenon of the UHI exists in relatively rural areas like Vermont. To contribute to answering this question, my study evaluates air quality and temperature differences between village green edges and centers for ten Vermont towns. The village greens are separated into two categories, urban and rural, in order to compare air quality and temperature in more like settings. Results are shown using scatter plots and histograms, and aerial maps of each green with marked data collection points are presented in the appendices.

I sought to address the following research questions:

1. Do village greens and small urban parks exhibit a mitigating effect on UHI and local air temperatures?
2. Do village greens and small urban parks exhibit a beneficial effect on air quality?
3. Is there a notable difference in air quality and temperature effects between comparatively more rural and urban study areas?

Literature Review

The intensity of the urban heat island (UHI) effect varies from place to place. It is dependent on characteristics of the urban area, population density, microclimate, types of urban materials, and the presence of green areas (Akbari et al., 2016). UHI can be present at any latitude and occur in both day and night hours depending on the local thermal balance (Santamouris, 2015). UHIs are most prevalent in the spring and summer months, as little to no warming effects have been shown during autumn and winter months (Wu et al., 2019). The magnitude of the UHI may increase during clear days, however it is highly impacted by wind and precipitation fluxes (Santamouris, 2015). Predicted climate change heat stressors and global temperature rise are likely to exacerbate UHI (Kleerekoper, et al., 2012). In addition, poor urban design can amplify the effects of climate change and the UHI (Akbari et al., 2016).

Throughout the past several decades, research and development has advanced in understanding the UHI, its environmental and health impacts, and developmental strategies for UHI mitigation (Akbari, et al., 2016). Initial research of the UHI focused on recognition that urban areas have higher temperatures than surrounding rural areas and understanding that these elevated temperatures were due to poor urban design and the built environment (Akbari, 1992). The research concluded that high albedo materials and urban vegetation could reduce buildings’ energy use for cooling and cool outdoor air temperatures by several degrees (Akbari, 1992). These findings have led to further research and implementation measures to cool urban heat islands (Akbari et al., 2016).

Green Roofs for UHI Mitigation

In urban areas where available ground surface area is limited, green roofs offer a substantial surface for implementation of UHI mitigation techniques (Berardi, 2016). Green roofs increase buildings’ albedos which reduces absorption of solar radiation and therefore lowers surface and air temperatures of the roof area (Yang et al., 2018). Water vapor fluxes that result from green roof vegetation evaporation cycles combined with plant respiration can reduce building energy costs due to increased insulation, lower local air temperatures through evaporation, and decrease stormwater runoff (Marasco et al., 2014). However, several studies about the effects of green roofs on Toronto's urban heat island, reported by Bass et al. (2003) and Kryenhoff et al. (2003), document little to no temperature change (Wang, et al., 2016). Through use of climate and weather simulations, urban surface models, and high resolution land cover data, these studies concluded that a building with 50% green roof coverage would create a less than 0.1°C air temperature difference (Wang, et al., 2016). Another study by Berardi (2016) concluded that an increase in green area on buildings' rooftops in Toronto, Canada could cool urban air temperatures by 0.4°C. On the contrary, a study reported by Rosenweig et al. (2009) showed that a combination of street tree planting and green roof installation simulated an urban air temperature reduction by 0.4–1.1°C in New York City. It is critical to note that gaps in these data can be due to location characteristics, climate, building geometry, and green roof design (Rosenzweig, et al., 2009).

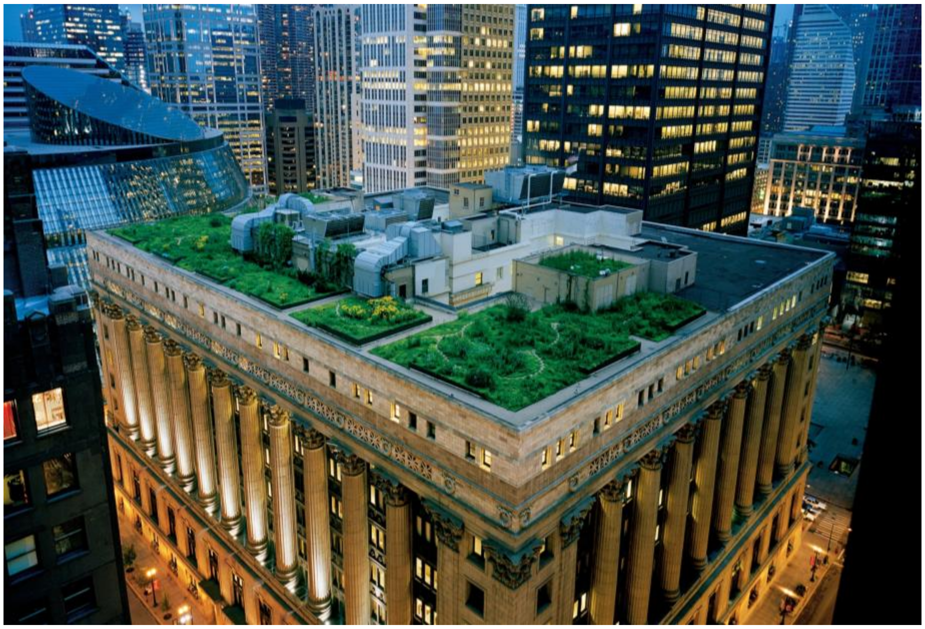


Figure 1. Green Roof.

Green Roof. (2020, January 10). *Green Roofs*. ArchDaily.
https://www.archdaily.com/catalog/us/products/15720/green-roofs-sika

As surface and air temperatures increase due to the UHI effect, storm water that contacts warm pavements and rooftops heats up (James, 2002). One study reported that pavement at 38°C can elevate rainwater temperature from 21°C to over 35°C (James, 2002). This heated storm water eventually becomes runoff and raises water temperatures as it drains into sewers and is released into aquatic ecosystems (James, 2002). Excess storm water runoff can also contribute to pollution and erosion, as well as flooding and sewer damages (Sims et al., 2016). Rooftops make up 40–50% of impervious surface area in the urban environment and therefore provide opportunity for storm water management and UHI mitigation (Sims et al., 2016). A study reported by Ercolani et al. (2018) showed that more than 25% of green roofs had an average retention rate of 80% during intense storms and only 6% experienced overflow. Another study documented by Viola et al. (2017) reported the average storm water retention rate for a green roof with thin soil to be 52.8% and a green roof with deep soil to be 59.6%. The same study reported green roofs to divert storm water to evapotranspiration by 49.9–57.2% (Viola et al., 2017). Transpiration rates of trees planted in green infrastructure have also been shown to promote higher soil moisture conditions and therefore contribute to storm water management (Tirpak, et al., 2019). Gaps in these data are most likely due to climate, green roof design, soil characteristics, and storm intensity and duration (Ercolani et al., 2018).

Currently, green roofs have the ability to create minor energy savings through components like insulation and storm water retention (Talebi, et al., 2019). A study reported by Berardi (2016) showed green roofs on high-rise buildings in Toronto to have savings of 9% for heating, 4% for cooling, and 3% in total energy savings. Another study conducted in Athens, Greece showed green roofs on high-rises to have savings of 13% for heating, 0–4% for cooling, and 3–7% total energy savings (Berardi, 2016). A similar study by Peng et al. (2019) reported green roofs in China to lower building heat gain by 23% in the summer months and consequently lower the need for cooling measures indoors. However, the same study showed green roofs blocked daytime heat gain during the winter months and therefore increased need for heat indoors (Peng et al., 2019). The study ultimately showed that green roofs can reduce summer cooling load by 32.2 kWh and increase winter heating load by 9.5 kWh (Peng, et al., 2019). While green roofs are typically used to enhance energy savings of a building, an increase in thermal capacity can lead to higher cooling and heating consumption if not controlled properly (Berardi, 2016). This generation of benefits is highly dependent on the type of building and ultimately, the size, maintenance, and care for the green roof (Wang et al*.,* 2016).

Figure 2. Green Roof- Ecogarden.

Green Roofs. (2021). Ecogardens. https://ecogardens.com/green-roofs

Reflective Surfaces for UHI Mitigation

Materials used in the built environment of urban areas directly affect the urban thermal balance due to absorption of solar radiation and dissipation of accumulated heat into the atmosphere (Akbari et al., 2016). Due to low albedo building and street fabrics, this radiation is absorbed and positive radiative forcings are induced (incoming energy exceeds outgoing energy) therefore increasing outdoor air temperatures (Kleerekoper et al., 2012). The use of reflective or “cool materials” on the built urban environment that can reflect solar radiation can help to increase cities’ albedos and maintain lower surface and air temperatures, thus mitigating the UHI (Akbari et al., 2016).

Asphalt pavements cover roughly 30 percent of cities’ surface areas (Jacobs, 1995). Road pavement is most typically made out of asphalt; this consists of ⅞ rock aggregate bound by ⅛ dark asphalt, which has a very low albedo (Rosenweig et al., 2009). Asphalt pavement is extremely temperature-sensitive and as high temperatures persist throughout urban areas, pavement can suffer from damages including rutting, cracking, and upheaval (Xie et al., 2019). Reflective or cool pavements reflect solar radiation and induce negative radiative forcings while also having little to no temperature sensitivity and are therefore more durable (Akbari et al., 2016). These pavements are characterized by many types of paving materials and paving surface technologies including chip seals, white toppings, colored concrete, grasscrete, and permeable pavements for water drainage (Akabari et al., 2016). A study reported by Xie et al. (2019) concluded cool pavements can reduce surface temperatures by up to 6°C and reflect over 80% of incoming solar radiation. Another study documented by Wang et al. (2016) showed cool pavement with a surface albedo of 0.2–0.4 to lower ground surface temperature up to 7.9°C at midday in Toronto. However, these temperature reductions and reflectivity are highly dependent on the type of reflective pigments and additives within cool pavements (Xie et al., 2019).

Figure 3. Cool Roof.

Cool Roofs. (2020, May 11). *Roof Coatings* | *Honolulu, Hawaii* | *Cool Roof Store*. Cool Roof Store Hawaii - Roof Repair + Leak Repair Honolulu. https://www.coolroofstore.net/

Cool roofs are composed of similar surface technologies to cool pavements and reflect solar radiation while inducing negative radiative forcings as well (Akabari et al., 2019). A study reported in Toronto by Wang et al. (2016) documented cool roofs with a surface albedo of 0.3–0.7 to reduce roof surface temperature by up to 11.3°C. A similar study reported from Melbourne, Australia showed cool roofs to reduce air temperatures by 0.3–0.9° C depending on density of cool rooftops in the area (Jacobs et al., 2018). Another study reported by Akabari et al. (2016) documented cool roofs to save areas under the roof 10–50% in cooling energy depending on climate, building type, and operation. The same study reported these cool roofs to offset global carbon dioxide by 78–100 gigatons of carbon dioxide (Akabari et al., 2016). Gaps in these data can be due to latitudinal location, climate, cool roof maintenance, building design, and location characteristics (Xie et al., 2019).

Figure 4. Cool Pavement.

Editors of Curriculum of Hope For a Peaceful World. (2020, May 22). *Cool Pavement Cares For Our Planet*. Spirit of Change Magazine | Holistic New England. https://www.spiritofchange.org/cool-pavement-cares-for-our-planet/

Urban Vegetation for UHI Mitigation

Temperature

Urban greenery, in many forms including green roofs, green walls, green pavements, parks and green spaces, and street tree planting, can significantly mitigate the UHI and decrease urban air and surface temperatures by several degrees (Aflaki et al., 2017). Urban vegetation can reduce the UHI by regulating temperature through water vapor transport, shading, and wind effects (Yu et al., 2019). Horizontal structure of vegetation, including vegetation cover, crown size, and crown shape contributes to evaporation and shading in urban areas (Yu et al., 2019). Vertical structure of vegetation, namely height, influences water vapor transport, wind speeds, and shading in urban environments, as well (Yu et al., 2019). Vegetation coverage has been shown to reduce the UHI effect in spring and summer months and significantly mediate the UHI effect in autumn and winter months if present (Wu et al., 2019). Urban vegetation has consequently become a popular strategy for mitigating the UHI (Pramanik & Punia, 2019). Vegetated areas with high tree cover and height tend to be cooler during night hours due to lower temperatures in the evenings (Chapman et al., 2018). On the other hand, open green spaces and parks tend to be hotter during daylight hours due to lack of shading but cool more rapidly after sunset (Chapman et al., 2018). Therefore, because densely vegetated areas are predicted to be cooler during the day and open, grassy areas are most likely cooler at night, a combination of different types of urban vegetation is most effective in mitigating the UHI (Chapman et al., 2018).

Figure 5. Urban Park- New York, NY.

Stamp, E. (2020, June 4). *Why New York City's Public Spaces Are Under Threat Due to COVID-19*. Architectural Digest. https://www.architecturaldigest.com/story/nyc-public-spaces-covid-19-threat

Monitoring efforts put forth throughout New York City have determined that areas with most vegetation, specifically parks, open green spaces, and neighborhoods with dense street tree planting, are on average 2°C cooler than the least vegetated areas (Susca et al., 2011). Other monitoring efforts in Toronto, Canada have documented temperatures of parks and recreational lands to be 4°C lower than commercial and industrial areas (Rinner & Hussain, 2011). A study reported by Pramanik & Punia (2019) documented that green spaces and areas with dense vegetation in Delhi, India were approximately 3.14°C cooler than densely urbanized, unvegetated areas. Chapman et al. (2018) documented that urban vegetation at a medium density in subtropical city Australian cities could reduce daytime air temperatures by 0.13– 1.38°C. Another study by Cui & Foy (2012) reported that vegetation could reduce Mexico City's UHI by up to 50%. The same study reported vegetation to lower surface temperatures by 2–4°C and air temperatures by 0–3°C during night hours (Cui & Foy, 2012). Aflaki et al. (2017) concluded that the use of urban vegetation in Kuala Lumpur and Hong Kong has the ability to decrease global air temperature and mean radiant temperature by up to 4.5°C. A study reported by Algretawee et al. (2019) showed parks in Melbourne, Australia to cool surrounding city areas by 3– 10°C. The same study showed that parks can have a cooling effect within a 746-meter radius. Gaps in these data are most likely due to landscape metrics, climate, percentage of green space, percentage of water within green space, percentage of built area within green space and degree of greenery (Pramanik & Punia, 2019). There are also gaps in data regarding how vegetation type and horizontal and vertical structure of vegetation can affect the UHI (Yu et al., 2019).

Figure 6. Street Trees- New York, NY.

EMI Landscape Editors. (2021, January 29). *How to select the best trees for City Street plantings?* EMI Landscape. https://www.landscapepros.com/select-best-trees-city-street-plantings/

Figure 7. Urban Park- Boston, MA.

Acitelli, T. (2017, May 15). *Boston's 12 best waterfront parks, mapped*. Curbed Boston. https://boston.curbed.com/maps/boston-best-waterfront-parks

Air Quality

Urban vegetation also has the potential to improve air quality by acting as a barrier to pollutant transport within the urban atmosphere (Khan & Abbasi, 2001). Surface area of leaves and plant buds can slow atmospheric airflow and collect pollutants from the air through deposition (Bealey et al., 2007), while also removing particulate pollution through absorption and adsorption (Salmond et al., 2013). However, vegetation also has the ability to release volatile compounds and pollutants back into the atmosphere which can alter atmospheric chemistry and increase pollutant concentrations (Salmond et al., 2013). A study reported by Santiago et al. (2016) showed that street trees could reduce pollutant concentrations at street level by 20– 60% if the trees' height was lower than the surrounding buildings. However, trees exceeding building height impacted atmospheric air flow and therefore increased pollutant concentrations at street level (Santiago et al., 2016). Another study by Xing & Brimblecombe (2019) showed that pollutant deposition to vegetation in small urban parks (less than 100 meters in length) only improved air quality by 2%. The same study reported that particulate pollutant concentrations were higher on the edges of the park and in close proximity to road boundaries than in the center of the park (Xing & Brimblecombe, 2019).

Figure 8. Street Trees- Savannah, GA.

Mouzon, S. (2020, September 1). *The powerful virtuous cycles of street trees*. CNU. https://www.cnu.org/publicsquare/2020/08/31/powerful-virtuous-cycles-street-trees

Health & Wellbeing

Using urban vegetation to mitigate the UHI is becoming increasingly popular due to both the environmental and health benefits of urban greenery (Willis & Petrokofsky, 2017). Research on the effects of urban vegetation on physical and mental health, has supported parks and open green spaces as health resources for urban populations (Willis & Petrokofsky, 2017). A study reported from Toronto compared neighborhoods with different densities of vegetation and concluded that areas with higher vegetation density were associated with lower incidence of heart and metabolic diseases amongst humans

(Willis & Petrokofsky, 2017). Another study focused on mental health in Wisconsin and found that having more trees in neighborhoods was correlated with more positive mental health amongst residents (Beyer et al., 2017). Urban vegetation therefore has the potential to lower risks of heat-related health problems and mortality due to the persistence of the UHI effect in urban areas as well as lower increased temperatures due to the UHI (Patz et al., 2005).

In Table 1, I summarize the prominent literature on UHI design mitigation strategies and their effects on temperature, air quality, and human health.

Table 1. Summary of UHI design mitigation strategies and effects.

UHI Mitigation Strategy	**Core Components**	**Temperature Benefits**	**Air Quality Benefits**	**Human Health & Well-Being**	**References**
Green Roofs	- Increased albedo - Water vapor fluxes & plant respiration - Storm water retention	MODERATE	HIGH	MODERATE/HIGH	Berardi, 2016; James, 2002; Marasco et al., 2014; Sims et al., 2016; Viola et al., 2017; Yang et al., 2018
Reflective Surfaces	- Increased albedo	HIGH	LOW	MODERATE/LOW	Algretawee et al., 2019; Akbari et al., 2016; Jacobs, 1995; Wang et al., 2016; Xie et al., 2019
Urban Vegetation: Parks	- Increased albedo - Evaporation	MODERATE	HIGH	HIGH	Aflaki et al., 2017 Pramanik & Punia, 2019; Rinner & Hussain, 2011; Susca et al., 2011; Wu et al., 2019
Urban Vegetation: Street Trees	- Shading - Evaporation - Pollutant barrier	MODERATE	HIGH	MODERATE/HIGH	Aflaki et al., 2017; Khan & Abbasi, 2001; Yu et al., 2019

While implementation of these mitigation strategies is important in reducing the UHI, it is also critical to note that individual neighborhoods have their own characteristics that affect the potential for heat island mitigation to reduce temperatures (Xie et al., 2019). These characteristics include available area for implementation measures, the extent to which measures may be able to successfully reduce air temperatures, building geometry and material, and building design and use (Rosenzweig et al., 2009). Ultimately, the development of UHI mitigation strategies specific and appropriate to priorities and conditions of individual neighborhoods will have the most significant effect in reducing heat island induced temperatures (Xie et al., 2019). Using a combination of strategies has also proved to maximize the temperature impact of mitigation measures (Rosenzweig et al., 2009). The addition of urban vegetation and parks, green roof installation, cool pavements, and cool roofs cooperatively will not only reduce the UHI effect but also improve air quality, public health, storm water retention, reduce greenhouse gas emissions, and lower energy demand (Rosenzweig et al., 2009).

Research Objectives

This study sought to understand whether Vermont Village Greens play a role in mitigating urban heat islands (UHIs). In carrying out this study and analyzing the collected data, I evaluated whether there are:

1. air filtration effects of village greens,
2. outdoor air-cooling effects of village greens,
3. observable differences in air filtration or cooling effects between rural and urban areas, and
4. small-scale UHI reductions associated with village greens.

In addition, I offer suggestions for the ways in which design of village greens can help improve their potential for UHI mitigation.

Materials & Methods

Study Area

Village greens in the following ten Vermont towns and cities served as the locations for this study: Burlington, Cambridge, Huntington, Jericho, Middlebury, St. Albans, Orwell, Vergennes, Waterbury, and Westford. Each village green has specific and unique land characteristics that could affect UHI mitigation potential and air quality data. Burlington, Middlebury, St. Albans, Vergennes, and Waterbury are urban municipalities, while Cambridge, Huntington, Jericho, Orwell, and Westford are more rural. Appendix A shows aerial maps of each village green with marked measurement points. They were created using the Vermont Interactive Map Viewer at https://vcgi.vermont.gov/. Aerial maps were generated with satellite imagery produced in 2016. When creating each map, a base map and operational layer was used.

Data were systematically monitored in three locations for each village green: in the center of each green and at greens' east and west edges. These sampling locations were chosen in order to observe differences in points with the most surrounding vegetation (center) and comparatively less surrounding vegetation (east and west edges). Throughout October and November 2020 each location was visited on two different days. In order to maximize consistency of weather patterns, air temperatures on sampling dates were between 10°C and 25°C, winds were minimal, and cloud cover was between 25-50%. In order to ensure the credibility of data calculated from the experiment, it is important to establish quality assurance and control measures for the study. Therefore, the air quality instrument was calibrated before and after each monitoring period.

Data Collection: Temperature and Air Quality

This study measured both air quality and outdoor air temperature within the various village greens with an Atmotube Pro portable outdoor air monitoring tool. Outdoor air temperature was recorded in degrees Celsius. Air quality was measured at a particulate pollutant scale of PM2.5 (particles with a diameter less than 2.5 $\mu g/m^3$). Particles of this size have the potential to penetrate into lungs, irritate the respiratory system, and impair lung function (Xing et. al., 2016). Common harmful PM2.5 particles can be found in emissions from fuel combustion, most significantly from vehicle emissions, as well as in off gases from textiles and plastics. PM2.5 particles also form in the atmosphere during chemical reactions, often triggered by anthropogenic pollutant emissions (EPA, 2020). The EPA defines the national 24-hour standard of PM2.5 as 35 µg/m³. In order to meet the 24-hour standard, an area's average annual PM2.5 concentrations must be less than or equal to 35 µg/m³ (EPA, 2020).

All air quality and temperature measurements were taken at face-value and results are reported as such. However, the Atmotube Pro monitor has a typical accuracy of ±10 µg/m³ for PM measurements and a typical accuracy of ±0.5°C (Table 2), creating a limitation in the results.

Table 2. Atmotube Pro measurement range and accuracy (https://help.atmotube.com/technical/1-atmotube-specs/).

Atmotube	PRO
TVOC output range	0 - 60 ppm
TVOC typical accuracy	15% of measured value
PM output range	0 - 1000 µg/m³
PM typical accuracy	0 to 100 µg/m³ ±10 µg/m³ 100 to 1000 µg/m³ ±10%
Temperature	±0.5°C (±0.9°F)
Humidity	±3%RH
Pressure	±1 hPa

To measure air quality and outdoor air temperature throughout each green, sampling points were selected based on the following criteria:

1. the number of sampling points were equal at each location,
2. each sampling point was selected in regard to the east edge, west edge, and center of each location, and
3. each sampling point was unshaded at the time of data collection.

The average outdoor concentration of pollutants is used to calculate the air quality index (AQI). AQI focuses on human health impacts due to inhalation of polluted air. Air quality index is calculated with the following formula:

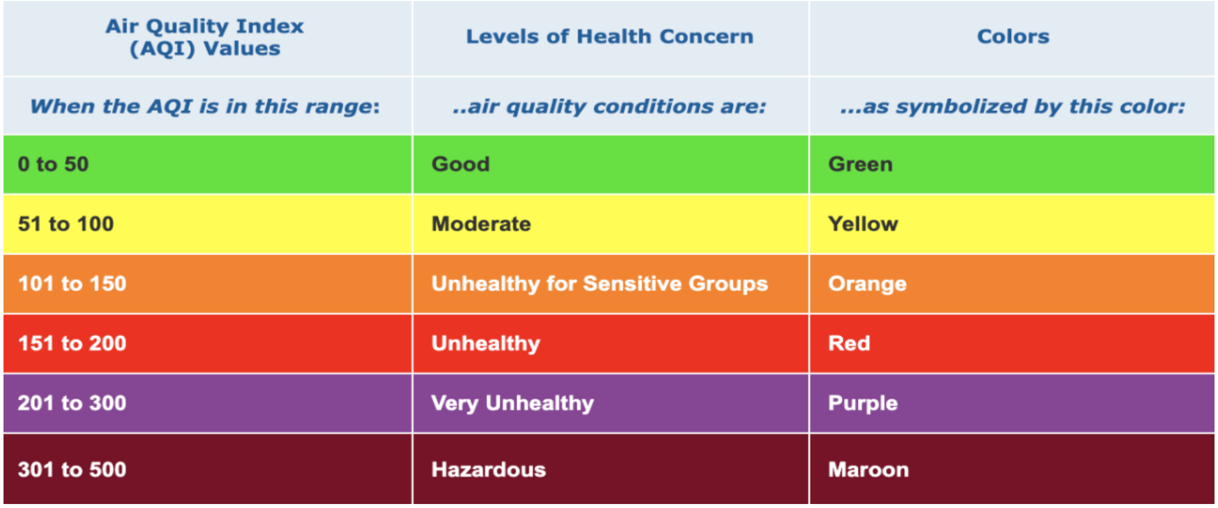
$$\text{AQI} = \frac{AQI_{high} - AQI_{low}}{C_{high} - C_{low}}(C - C_{high}) + AQI_{low}$$

AQI = air quality index

C = pollutant concentration (EPA, 2020)

This formula is presented for reference only as AQI was not directly calculated in this study. For determining AQI, the interpretations in Table 3 are used.

Table 3. AQI Values (Air Quality Index Basics, n.d.).



Air Quality Index (AQI) Values	Levels of Health Concern	Colors
When the AQI is in this range:	*..air quality conditions are:*	*...as symbolized by this color:*
0 to 50	Good	Green
51 to 100	Moderate	Yellow
101 to 150	Unhealthy for Sensitive Groups	Orange
151 to 200	Unhealthy	Red
201 to 300	Very Unhealthy	Purple
301 to 500	Hazardous	Maroon

Results

Data were collected in October (sampling 1) and November 2020 (sampling 2), with two visits to each Vermont Village Green. Appendix A shows the map of each green and Appendix B is a table of the raw data for air quality and temperature, which are presented herein.

PM2.5 Concentrations

PM2.5 concentrations in each village green location are plotted in scatterplots from both sampling dates in Figure 10 for rural towns and Figure 11 for urban towns . They have been divided into 2 groups: rural and urban. For the majority of sampling dates and locations, the center sampling points had lower PM2.5 concentrations than the edge sampling points in both urban and rural study areas (Figures 10 & 11). Lower overall PM2.5 concentrations were observed in village greens that are more densely vegetated with trees and shrubs, while less dense, more open village greens presented slightly higher PM2.5 concentrations (Figures 10 & 11 & Appendix 11). Urban study areas had higher PM2.5 concentrations than rural overall (Figure 10 &11).

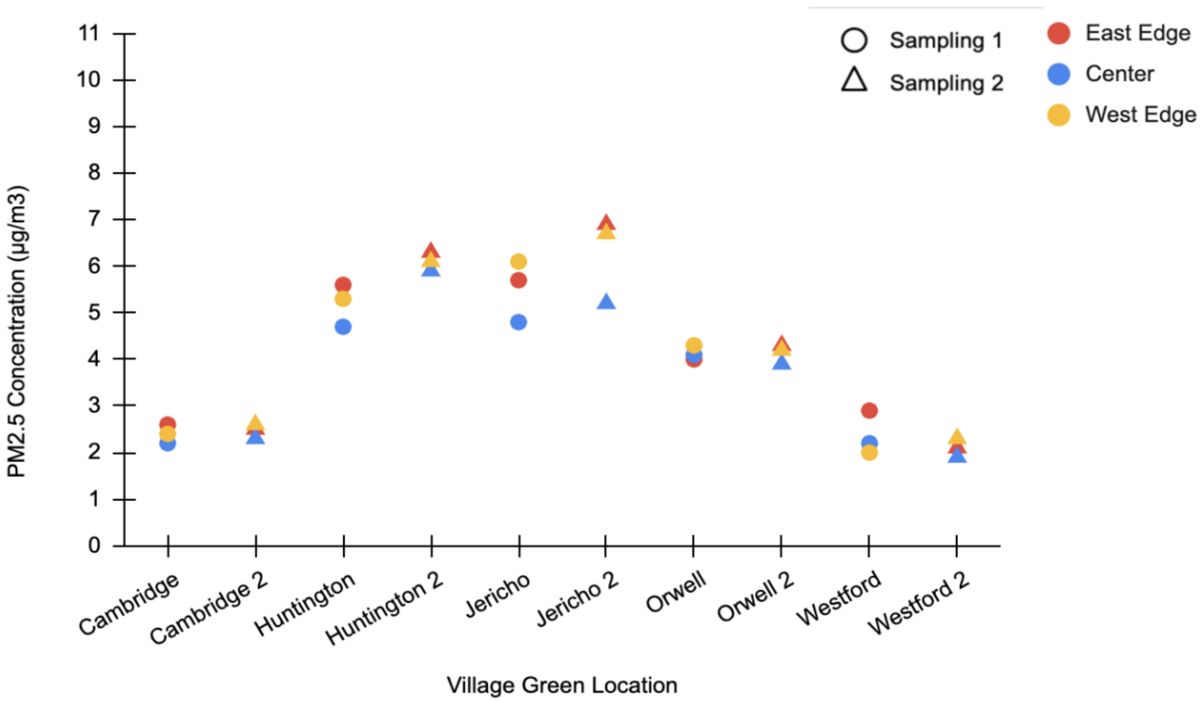


Figure 10. Rural Towns Air Quality: Scatterplot of PM2.5 concentrations in each rural study area at 2 sampling dates in October and November 2020.

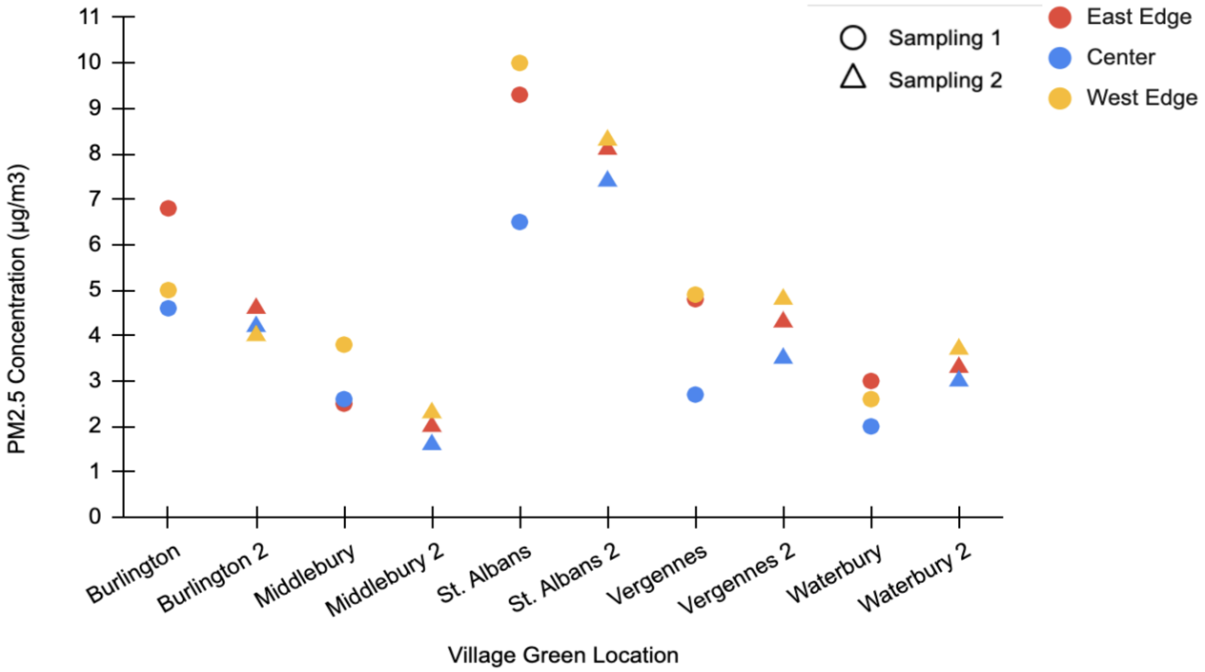


Figure 11. Urban Towns Air Quality: Scatterplot of PM2.5 concentrations in each urban study area at 2 sampling dates in October and November 2020.

Temperatures

Average temperatures in rural and urban study areas at both sampling dates are shown in Figure 12. Table 4 presents average documented temperatures from both sampling dates at all village green locations.

Rural study areas had slightly wider temperature variation among all towns and dates sampled compared to urban study areas. However, average temperatures in both urban and rural study areas across both dates were not statistically different among the days sampled (Figure 12). There was also minimal temperature variation between center points and edge points, however edge points did present slightly lower temperatures. As shown in Table 4, the highest documented temperature was 23.8°C in Burlington. The widest temperature variation also occurred in Burlington with a difference of 0.4°C between center and edge points (Table 4). However, it is important to note the air quality sensor used has a temperature accuracy range of ± 0.5°C.

Minimal variation in these data could be attributed to time of sampling, overall weather patterns, and sun exposure amongst other factors. The relatively small size of the study areas may also have contributed to minimal temperature differences between center and edge points; UHIs may not form smaller patches of green space.

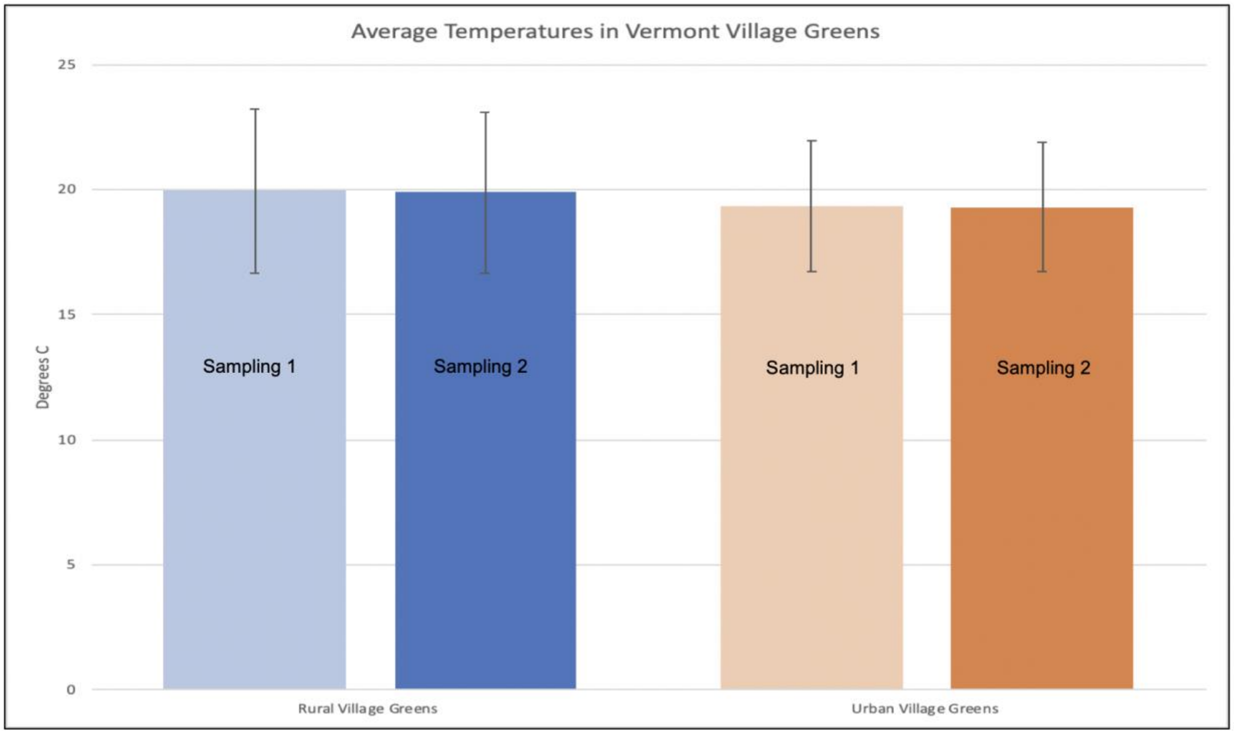


Figure 12. Mean air temperatures including center points and edge points for all sampling days in rural and urban study areas. Whiskers represent highest and lowest documented temperatures.

Table 4. Measured air temperatures in each village green on both sampling dates.

	Village Green Location	Sampling Date 1			Sampling Date 2		
		East Edge	Center	West Edge	East Edge	Center	West Edge
rural	Cambridge	22.5°C	22.4°C	22.4°C	22.3°C	22.1°C	22.4°C
	Huntington	20.5°C	20.5°C	20.5°C	17.8°C	17.8°C	17.7°C
	Jericho	20.1°C	19.8°C	20.1°C	20.6°C	20.6°C	20.4°C
	Orwell	20.3°C	20°C	20°C	11.1°C	11.1°C	11.1°C
	Westford	22°C	22.1°C	22.2°C	22.4°C	22.3°C	22.3°C
urban	Burlington	15.6°C	15.6°C	15.8°C	23.8°C	23.4°C	23.4°C
	Middlebury	17.7°C	17.7°C	17.8°C	21.3°C	21.3°C	21.3°C
	St. Albans	21.6°C	21.5°C	21.2°C	20.3°C	20.1°C	20.3°C
	Vergennes	17.4°C	17.3°C	17.3°C	21.6°C	21.4°C	21.3°C
	Waterbury	19.4°C	19.4°C	19.5°C	15.3°C	15.3°C	14.9°C

Discussion & Study Limitations

We expected to see lower PM2.5 concentrations and lower air temperatures at center sampling points than edge points based on prior reports documenting the beneficial role of vegetation in mitigating UHI effects, even in relatively small built areas such as Village Greens. Generally speaking, the air quality data showed more evidence of this mitigating effect than the temperature data. Below is a discussion of how these results compare to prior research, as well as study limitations and lessons learned.

Results showed sampling points in the center of village greens to have the lowest PM2.5 concentrations. Temperatures appeared to be lowest in village greens with most visible vegetation. Therefore, this study shows that village greens do have positive benefits on air quality and temperature and have the potential to mitigate small scale UHIs.

Overall, all village greens presented very low PM2.5 concentrations. The EPA considers PM2.5 concentrations of 0-12 μg/m³ to be 'good.' All monitoring collected during this study period showed PM2.5 results below 10 μg/m³ (Figures 10 & 11). The center sampling points had predominantly lower PM2.5 concentrations than the edge sampling points, suggesting that vegetation helped mitigate air quality increasingly toward the interior of each green.

Temperature results, by contrast, showed little variation among edge and center, among sampling days at each site (in October and November) and among the ten towns, regardless of being comparatively more urban or rural. To see an effect on temperature, the vegetation mass may need to be larger than the sizes of these ten village greens. Park sizes and shapes have been shown to have effects on UHI (Lin et al., 2014). Therefore, the magnitude of each village green could have played a role in air quality and temperature measurements. Minimal variation in these data could also be attributed to time of year when sampling occurred, overall weather patterns, sun exposure, and cloud cover. Having completed this research in the autumn months may have limited efficacy of temperature results. Wu et al. (2019), noted the UHI effect to be stronger in spring and summer months, so those months would have been preferable for sampling. In the future, it would be more ideal to conduct measurements during summer months when cooler temperatures are more desirable for human populations, and baseline temperatures are warmer, increasing effects of evapotranspiration (Peng et. al., 2019), and the edge versus center temperature readings may diverge more.

This research aimed to control for windy days, but wind direction can also influence both temperature and air quality in urban green spaces (Santamouris, 2015). While the air quality and temperature monitor was reset and recalibrated after each sampling, there was no validation of the data. Measurement accuracy of the monitor itself also provides a degree of uncertainty and is a limiting factor in this study. Therefore, air quality and temperature measurements were taken at face value and do provide a limitation in this research. Outdoor air temperatures, cloud coverage, and shading were regulated as best as possible, but were not entirely consistent and therefore provide another limitation in this study.

In order to maximize UHI mitigation in village greens, a variety of vegetation sizes and types should be used (Rosenzweig et al., 2009). Planners should consider how and where to add vegetation in regard to UHI mitigation, park aesthetics, and safety. Vegetation orientation should be considered in regard to wind and sun patterns, as well as in park use. Mixed canopy heights may benefit UHI mitigation by providing variation in shading. A variety of vegetation density should also be considered, however without compromising safety. Planners should also consider addition of water features within parks as surface waters can increase land albedo and reflect incoming solar radiation (Song & Park, 2015).

Further research could benefit from looking at the presence of coniferous vs. deciduous plants as well as leaf mass per area on adjacent plant biomass. Size and shape of plant biomass can impact evaporation levels, wind patterns, and shading (Yu et al., 2019) providing other possible discrepancies in air quality and temperature measurements.

Traffic patterns on roadways surrounding parks as well as density of adjacent buildings could provide opportunity for further research (Baldauf, 2017). Proximity to surface waters may also effect vegetations' air filtration and outdoor-air cooling effects and may be significant to address in further studies (Dai et al., 2018).

Design recommendations for village greens to improve their UHI mitigation potential could include the following:

- Addition of water features in village greens (Song & Park, 2015)
- Variety of native vegetation types and sizes throughout village greens
- Mixture of canopy heights throughout village greens (low, moderate, and high)
- Incorporation of street trees on all roadways and sidewalks surrounding village greens
- Addition of green roofs around all buildings surrounding village greens
- Addition of reflective or light paved surfaces on all roadways, sidewalks, and other asphalt surfaces surrounding village greens
- Addition of permeable pavement surfaces on sidewalks, pathways, etc.

Conclusions

The influence of even small village greens in small (rural) and medium sized (urban) towns may have an effect on local air quality and temperature that is worth consideration in town planning and park design. While originally this research was planned for Central Park in New York City, the adaptation to smaller scale green spaces in comparatively very rural Vermont has allowed me to develop methods that could be applied in future research.

I was able to reach conclusions on all objectives listed for this study. Air filtration, air cooling, and small scale UHI reduction associated with village greens was observed in air quality results. Minimal variation in temperature data was observed and therefore does not suggest village greens to have an effect on outdoor air temperature. However, prominent literature has suggested that plant biomass in urban settings can have cooling effects on outdoor air temperatures. Study area size and magnitude therefore may have to be larger in order to see significant results in temperature variation.

This data not only provides information for rural park design and planning, but also suggests opportunities for further research. Exploring how size and magnitude of village greens and small urban parks comparatively effect air quality and temperature, as well as how type of vegetation in these greens comparatively effect air quality and temperature could provide important data for further studies. Analysis of different study areas in other states and/or countries with small urban parks and/or village greens could provide comparable data in further research. Further studies could also benefit from more precise air quality and temperature monitoring devices and longer-term sampling periods at edge and center points. To compare the greens more with their context and identify UHIs more clearly, the air quality and temperature data could also be collected at incremental distances from green spaces into their surroundings.

Even in rural towns, planning and design of green spaces can offer UHI mitigation benefits related to the ways vegetation is arranged in space, use of water features, diversity of plant biomass, and variety of canopy heights. The addition of green roofs and reflective surfaces in the built environment surrounding village greens also has the potential to improve UHI mitigation benefits.

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Appendices

Appendix A: Village Greens and Data Collection Points

Maps. Aerial views of each village green site with labelled data collection points.

This map was created with the VT Interactive Map Viewer.

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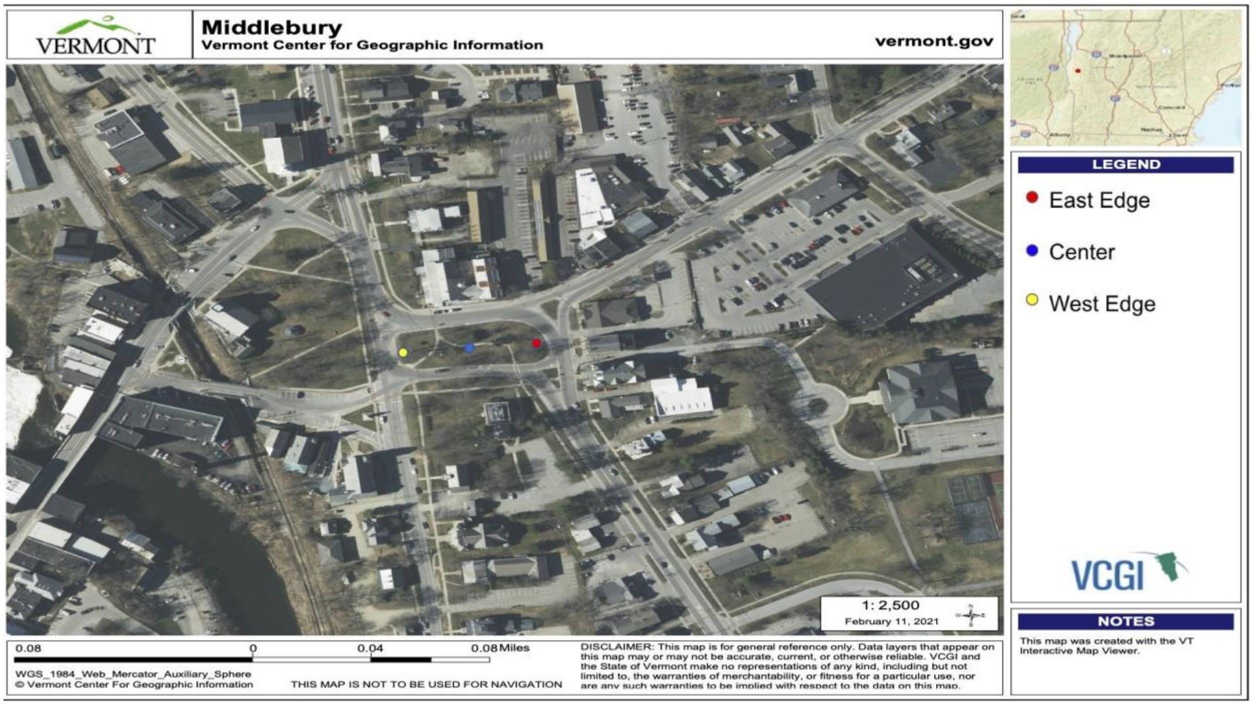

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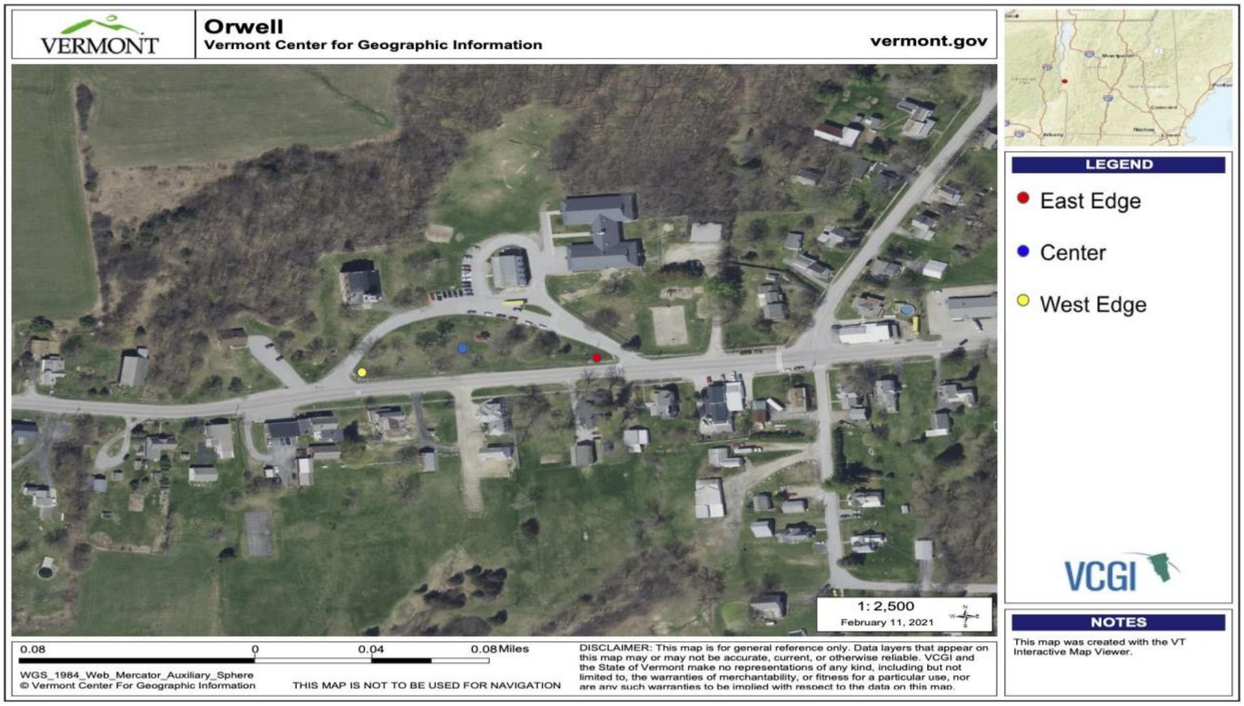

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Appendix B: Raw Data Tables

Table 5. Raw AQI and temperature data from each village green location. AQI was measured at 4 levels: PM1, PM2.5, PM10, and VOCs- however only PM2.5 was evaluated in this study. PM1 is defined by ultrafine particles with a diameter of less than 1µm; PM2.5 is defined by particles with a diameter of less than 2.5µm; and PM10 is defined by particles with a diameter of less than 10µm. VOCs are volatile organic compounds that are emitted as gases from certain solids and liquids and include a variety of human-made chemicals. VOCs can cause damage to the human respiratory and central nervous systems and have proven to be carcinogenic (EPA, 2021).

BURLINGTON	Date	Time	Weather Conditions	AQI	Temperature
Sampling 1	10/11	11:39 AM	15.3 C, sunny		
East Edge				PM1: 5.0 PM2.5: 6.8 PM10: 7.7 VOCs: 0	15.6 C
Center				PM1: 3.1 PM2.5: 4.6 PM10: 5.8 VOCs: 0	15.6 C
West Edge				PM1: 3.5 PM2.5: 5.0 PM10: 6.1 VOCs: 0	15.8 C
Sampling 2	11/6	12:02 PM	23.8 C, partly sunny		
East Edge				PM1: 3.1 PM2.5: 4.6 PM10: 5.8 VOCs: 0	23.8 C
Center				PM1: 2.6 PM2.5: 4.2 PM10: 5.0 VOCs: 0	23.4 C
West Edge				PM1: 2.7	23.4 C

				PM2.5: 4.0 PM10: 5.2 VOCs: 0	

CAMBRIDGE	**Date**	**Time**	**Weather Conditions**	**AQI**	**Temperature**
Sampling 1	10/15	1:12 PM	22.4 C, partly cloudy, windy		
East Edge				PM1: 1.2 PM2.5: 2.6 PM10: 4.2 VOCs: 0	22.5 C
Center				PM1: 1.0 PM2.5: 2.2 PM10: 3.6 VOCs: 0	22.4 C
West Edge				PM1: 1.1 PM2.5: 2.4 PM10: 3.7 VOCs: 0	22.4 C
Sampling 2	11/8	11:18 AM	22.2 C, sunny		
East Edge				PM1: 1.8 PM2.5: 2.5 PM10: 3.9 VOCs: 0	22.3 C
Center				PM1: 1.4 PM2.5: 2.3 PM10: 3.6 VOCs: 0	22.1 C
West Edge				PM1: 1.7 PM2.5: 2.5 PM10: 4.0	22.4 C

				VOCs: 0	

HUNTINGTON	Date	Time	Weather Conditions	AQI	Temperature
Sampling 1	10/10	1:02 PM	20.5 C, partly cloudy		
East Edge				PM1: 4.3 PM2.5: 5.6 PM10: 6.5 VOCs: 0	20.5 C
Center				PM1: 4.1 PM2.5: 4.7 PM10: 6.5 VOCs: 0	20.5 C
West Edge				PM 1: 4.6 PM2.5: 5.3 PM10: 6.8 VOCs: 0	20.5 C
Sampling 2	11/5	1:15 PM	17.7 C, sunny		
East Edge				PM1: 5.1 PM2.5: 6.3 PM10: 8.1 VOCs: 0	17.8 C
Center				PM1: 4.8 PM2.5: 6.1 PM10: 7.9 VOCs: 0	17.8 C
West Edge				PM1: 4.9 PM2.5: 5.9 PM1: 8.0 VOCs: 0	17.7 C

JERICHO	**Date**	**Time**	**Weather Conditions**	**AQI**	**Temperature**
Sampling 1	10/10	2:33 PM	20 C, partly cloudy		
East Edge				PM1: 5.5 PM2.5: 5.7 PM10: 8.0 VOCs: 0.22	20.1 C
Center				PM1: 2.0 PM2.5: 4.8 PM10: 7.8 VOCs: 0.16	19.8 C
West Edge				PM1: 4.5 PM2.5: 6.1 PM10: 6.8 VOCs: 0.18	20.1 C
Sampling 2	11/5	2:20 PM	20.5 C, sunny		
East Edge				PM1: 4.6 PM2.5: 6.9 PM10: 6.8 VOCs: 0.12	20.6 C
Center				PM1: 3.6 PM2.5: 5.2 PM10: 5.7 VOCs: 0.09	20.6 C
West Edge				PM1: 4.2 PM2.5: 6.7 PM10: 6.6 VOCs: 0.16	20.4 C

MIDDLEBURY	**Date**	**Time**	**Weather Conditions**	**AQI**	**Temperature**

Sampling 1	10/21	12:48 PM	17.3 C, sunny		
East Edge				PM1: 1.1 PM2.5: 2.5 PM10: 3.3 VOCs: 0	17.7 C
Center				PM1: 1.0 PM2.5: 2.6 PM10: 3.3 VOCs: 0	17.7 C
West Edge				PM1: 1.0 PM2.5: 3.8 PM10: 5.5 VOCs: 0	17.8 C
Sampling 2	11/7	11:49	21.6 C, sunny		
East Edge				PM1: 1.3 PM2.5: 2.0 PM10: 4.3 VOCs: 0	21.3 C
Center				PM1: 1.2 PM2.5: 1.6 PM10: 4.0 VOCs: 0	21.3 C
West Edge				PM1: 1.2 PM2.5: 2.3 PM10: 4.2 VOCs: 0	21.3 C

ORWELL	**Date**	**Time**	**Weather Conditions**	**AQI**	**Temperature**
Sampling 1	10/14	11:58 AM	20.2 C, sunny		
East Edge				PM1: 4.2 PM2.5: 4.0	20.3 C

				PM10: 3.8 VOCs: 0	
Center				PM1: 3.7 PM2.5: 4.1 PM10: 3.2 VOCs: 0	20.0 C
West Edge				PM1: 3.9 PM2.5: 4.3 PM10: 3.5 VOCs: 0	20.0 C
Sampling 2	11/1	12:39 PM	11.1 C, sunny		
East Edge				PM1: 3.9 PM2.5: 4.3 PM10: 4.1 VOCs: 0	11.1 C
Center				PM1: 3.4 PM2.5: 3.9 PM10: 3.7 VOCs: 0	11.1 C
West Edge				PM1: 4.2 PM2.5: 4.2 PM10: 3.5 VOCs: 0	11.1 C

ST. ALBANS	**Date**	**Time**	**Weather Conditions**	**AQI**	**Temperature**
Sampling 1	10/23	12:38 PM	21 C, partly cloudy		
East Edge				PM1: 7.6 PM2.5: 9.3 PM10: 10 VOCs: 0	21.6 C

Center				PM1: 4.8 PM2.5: 6.5 PM10: 7.1 VOCs: 0	21.5 C
West Edge				PM1: 8.2 PM2.5: 10.0 PM10: 11.0 VOCs: 0	21.2 C
Sampling 2	11/10	12:04 PM	20.5, partly cloudy		
East Edge				PM1: 6.5 PM2.5: 8.1 PM10: 10.1 VOCs: 0	20.3 C
Center				PM1: 5.2 PM2.5: 7.4 PM10: 8.5 VOCs: 0	20.1 C
West Edge				PM1: 7.0 PM2.5: 8.3 PM10: 9.1 VOCs: 0	20.3 C

VERGENNES	**Date**	**Time**	**Weather Conditions**	**AQI**	**Temperature**
Sampling 1	10/21	1:30 PM	17 C, sunny		
East Edge				PM1: 1.5 PM2.5: 4.8 PM10: 8.6 VOCs: 0	17.4 C
Center				PM1: 1.0 PM2.5: 2.7	17.3 C

				PM10: 4.8 VOCs: 0	
West Edge				PM1: 1.7 PM2.5: 4.9 PM10: 8.1 VOCs: 0	17.3 C
Sampling 2	11/7	12:50	21.6 C, sunny		
East Edge				PM1: 2.0 PM2.5: 4.3 PM10: 7.3 VOCs: 0	21.6 C
Center				PM1: 1.3 PM2.5: 3.5 PM10: 5.9 VOCs: 0	21.4 C
West Edge				PM1: 1.6 PM2.5: 4.8 PM10: 6.5 VOCs: 0	21.3 C

WATERBURY	**Date**	**Time**	**Weather Conditions**	**AQI**	**Temperature**
Sampling 1	10/23	11:46 AM	19.4 C, partly cloudy		
East Edge				PM1: 1.0 PM2.5: 3.0 PM10: 4.0 VOCs: 0.24	19.4 C
Center				PM1: 1.0 PM2.5: 2.0 PM10: 3.1 VOCs: 0.21	19.4 C

West Edge				PM1: 1.0 PM2.5: 2.6 PM10: 4.0 VOCs: 0.23	19.5 C
Sampling 2	11/15	12:48 PM	15 C, partly cloudy		
East Edge				PM1: 1.8 PM2.5: 3.3 PM10: 4.4 VOCs: 0	15.3 C
Center				PM1: 1.8 PM2.5: 3.0 PM10: 4.0 VOCs: 0	15.3 C
West Edge				PM1: 2.1 PM2.5: 3.7 PM10: 4.7 VOCs: 0	14.9 C

WESTFORD	**Date**	**Time**	**Weather Conditions**	**AQI**	**Temperature**
Sampling 1	10/15	12:28 PM	22.2 C, partly cloudy, windy		
East Edge				PM1: 1.4 PM2.5: 2.9 PM10: 4.2 VOCs: 0	22.0 C
Center				PM1: 1.0 PM2.5: 2.2 PM10: 3.7 VOCs: 0	22.1 C
West Edge				PM1: 1.0 PM2.5: 2.0	22.2 C

				PM10: 3.2 VOCs: 0	
Sampling 2	11/8	12:45 PM	22 C, sunny		
East Edge				PM1: 1.3 PM2.5: 2.1 PM10: 4.6 VOCs: 0	22.4 C
Center				PM1: 1.2 PM2.5: 1.9 PM10: 4.2 VOCs: 0	22.3 C
West Edge				PM1: 1.5 PM2.5: 2.3 PM10: 4.4 VOCs: 0	22.3 C

Appendix C: Atmotube Pro Specifications.

Table 6. Atmotube Pro technical specifications (https://help.atmotube.com/technical/1-atmotube-specs/).

Atmotube	**PRO**
TVOC sensor	Sensiron SGPC3 Digital, auto calibration 2s interval
PM sensor	Sensirion SPS30 PM_1, $PM_{2.5}$, PM_{10}
Temperature/Humidity/Pressure sensor	Bosch BME280
Pressure sensor	Yes
Memory size	256 kB
History size	10 days
Bluetooth	Bluetooth 5.0 Improved antenna performance
Battery capacity	2000 mAh
Battery life	Up to 10 days
Weight	3.7 oz (104 g)
Size	Height x width x depth 3.4 x 2 x 0.9 in 86 x 50 x 22 mm