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Analyzing Thermal Gradients Using Terrestrial Laser Scanning in
Scrub Oak Habitats

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May 2020

Abstract

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Analyzing Thermal Gradients Using Terrestrial Laser Scanning in Scrub Oak Habitats

ADVISOR: Steven K. Rice

Thermal microclimates are an important component of natural ecosystems because they provide appropriate niche space for many organisms; however, they are not widely studied because of their small scale. Likewise, variation in these microclimates may significantly impact animal thermoregulation and plant physiological processes and be especially important in the face of climate change. The goal of this study is to determine how the size and structure of *Quercus ilicifolia* shrubs influences ground temperature gradients. We hypothesized that differences in leaf cover and leaf area index (LAI) would cause temperature under shrubs to cool relative to the ambient temperature, and that higher LAI shrubs will create steeper temperature gradients. The study was conducted using five *Quercus ilicifolia* (scrub oak) shrubs of varying height and structure in the Albany Pine Bush Preserve. Five temperature logging devices were distributed in a transect from the center of the shrub to twice its radius into the surrounding herbaceous vegetation. Leaf area and leaf area index (LAI) were measured and shrubs were scanned using a terrestrial laser scanner to obtain a 3D point cloud. This was used to calculate shrub canopy volume. The most highly significant thermal gradient present was in the daily maximum temperatures, showing that as one moves closer to the shrub center, the maximum temperature cools continually. However, the remaining temperature data confirmed that differences in shrub structure (leaf area, LAI) do not influence the magnitude of the thermal gradient. While the amount of shade cover did not impact

temperature variation among individual shrubs, we found that there was a consistent temperature gradient from the center to 2x the radius outside the shrub. We concluded that temperature gradients shift independently of shrub structure, but are nonetheless present underneath and directly adjacent to shrubs. Using data obtained from laser scanning, we found a significant association ($p < 0.001$) between shrub leaf area (m^2) and volume (m^3). Overall, we have shown that TLS is a useful way to support field measurements, and scans could be useful in identifying shrubs to scale to a landscape-level microclimate model. This information demonstrates that there are alternative ways to study the impacts of climate change on a small-scale, and may provide the tools necessary to map optimal habitat space for many species.

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Introduction

Thermal microclimates are vital to the well being of many plant and animal species occupying a given niche, and often differ based on vegetative structure and habitat complexity (Milling et al, 2018). Microclimates are also important in our ecosystems because they provide organisms with suitable niche spaces, which in the face of climate change, will likely become increasingly important (Milling et al., 2018). In particular, vegetative structure and density has a noticeable impact on factors that influence microhabitats such as air temperature and light penetration to the ground (Pringle et al, 2003). These components of microhabitats are important to study because they may impact the viability of a given niche space. However, microclimates do not always receive substantial attention by researchers due to the fact that studies focus on larger scale areas. Understanding thermal microclimate is particularly relevant today because with the impending impacts of climate change, it is important to understand how organisms use thermal microhabitats and whether they can help organisms survive regional temperature increases; how do habitats change with differences in vegetation structure, and how does this affect thermal regimes within ecosystems? This study will use terrestrial laser scanning (TLS) and temperature logging data focused mainly on fine-scale sites to obtain information about thermal microclimates and their relationship to shrub structure, and ultimately how these vary across the landscape.

Variation of thermal microclimates within habitats impacts the distribution of both plant and animal species in a landscape, as temperature itself is important for animal thermoregulation (Milling, et al., 2018) and plant physiological processes (Scherrer & Körner, 2011). Scherrer & Körner (2011) demonstrated that both surface and soil

temperatures impact the vegetative structures of a landscape and the construction of that landscape, because many plant species have specific ideal temperature ranges in which seeds germinate and grow. Likewise, the effects of shading based on the structure of vegetation (height, density, etc.) create variation in microclimates, allowing plants to root and grow in specific locations (Milling et al., 2018). Milling et al. (2018) also showed that the distribution of vegetation greatly contributes to areas of refuge for small animals, because many tend to spend the majority of their time in microhabitats that require less energy expenditure on thermoregulation (Milling et al., 2018). Consequently, in the shrublands of the Albany Pine Bush Preserve, vegetation structure should impact the thermal microclimate, and influence the rare and endangered species that inhabit this unique landscape.

The main objective of this project is to determine how the temperature gradient within and around shrubs is affected by variables such as shrub size and leaf density in scrub oak (*Quercus ilicifolia*) individuals. We hypothesize that shrub centers will be the coolest compared to the surrounding herbaceous vegetation, and will present a continuously warmer gradient moving outward toward the shrub edge and will be the warmest outside the shrub canopy. We also predict the shrub center to be warmer during the nighttime, if not the same as the outside temperature due to retention of heat via the shrub canopy cover. Likewise, we hypothesize that temperature gradients surrounding each shrub (from shrub center to 2x the width the shrub) will vary based on the density and leaf area cover of each shrubs, and that more dense shrubs will have a more drastic temperature gradient than those that are less dense. This is because while shrub size is a

factor, shrub density and leaf cover impact the sun's ability to penetrate to the ground, therefore determining a shrub's ability to retain heat.

Literature Review

Thermal microclimates are of crucial importance to the well-being of many animal species and are becoming increasingly important with the continual development of human infrastructure and climate change. Microclimates provided by vegetation cover are particularly important for many species because they both shade out small areas to provide a cool microclimate under the hot sun, and potentially provide insulation by trapping radiation at night (Milling et al., 2017). Likewise, vegetation cover can provide small areas of refuge for prey animals (Milling et al., 2017). Species relying heavily on microhabitats face issues due to climate change, such as the reduction of cool, shady environments, preferential for egg laying in certain species of butterflies (Grundel et al., 1998). It is no secret that rising temperatures can affect the behavior of many animal species, and it is important to identify particular factors that may be impacting organism behavior (Milling et al., 2017).

Numerous studies have shown that perhaps climate change is not having the same raging impact on certain terrestrial species as was initially thought due to the ameliorating effect of time-scale temperature variation (Sears et al., 2011; Milling et al., 2017). Sears et al. (2011) claim that while climate change itself is certainly an issue, it may not be impacting certain species on a local scale quite yet due to the ability of animals to locate suitable microclimates within their existing community. Likewise, many species occupy diverse temperature ranges, and those that thermoregulate may be

able to optimize their body temperature relatively easily under diverse conditions (Sears et al., 2011). Sears et al. (2011) used GIS based simulations of three artificial landscapes of varying topographical and elevational elements to which they applied a model that predicts ideal temperatures for Eastern Fence Lizards, *Sceloporus undulatus* (Sears et al., 2011). Their results show that the more topographically diverse a location, the more it supports a diversity of microclimates (Sears et al., 2011). This diversity increases the time that a thermoregulatory species may remain active, in contrast with a flat landscape that is either suitable or poor, providing increased niche space for such species (Sears et al., 2011). Milling et al. (2017) corroborate these findings by stating that behavioral changes in individuals may act as a “buffer” to the changing temperatures, allowing organisms to maintain their preferred niche for a longer period of time under the warming conditions (Milling et al., 2017). In the present study, this observation is important to note due to the ancient dunes that provide the topographical relief in the Albany Pine Bush Preserve (APBP).

However, climate warming is not the only threat to naturally occurring microclimates; human infrastructure and habitat destruction also contribute to the loss of many microhabitats. Habitat destruction can be detrimental to species living in small microhabitats because the loss of their specific niche space may cause significant changes in microclimate, driving these species out of their preferred habitats. Wilcove et al. (1998) examined the impacts of habitat destruction on endangered species, and which anthropogenic factors have the most influence on habitat destruction. The researchers claim that habitat destruction is one of the leading causes of species endangerment (Wilcove et al., 1998), and this is relevant to the study of microclimates because, while

small, microhabitats are immensely important to the various species that occupy them. In the APBP in particular, Karner blue butterflies are a species of conservation concern that rely on microhabitats and, in particular, the blue lupine plant (APBPC, 2017). Between 1980-2000, the population of Karner blue butterflies declined by more than 90% in the APBP, and much of this population decrease was due to habitat destruction and development in the area (APBPC, 2017). Likewise, Davies et al. (2006) articulate the importance of microhabitat in another grassland butterfly species, *Hesperia comma*, stating that climate change has allowed for further range expansion and therefore more thermally appropriate habitat in which individuals may lay their eggs (Davies et al., 2006). This increases the amount of suitable microhabitat with ideal vegetation cover for the butterflies due to warming temperatures (Davies et al., 2006). Interestingly, within the same time frame of the Karner blue butterfly decline (1982-2002), Davies et al. (2006) found that the ideal amount of bare ground in an egg-laying habitat decreased from 41-21%. This would imply that more shade cover was needed to support oviposition due to the warming temperatures. The study used standard transects to identify the presence and abundance of *H. comma* in areas of suitable habitat in Surrey, England, and found that *H. comma* were present in 45 patches in the study area in 1982 (Davies et al, 2006). Over the next 18 years, they found that the species had expanded its range from the initial 45 patches to 74, 29 more patches than were initially occupied (Davies et al, 2006). Overall, Davies et al. (2006) demonstrated that this species of butterfly has an ideal temperature range, particularly in regards to oviposition, and with the warming temperatures *H. comma* individuals have taken advantage of the expanded niche space; and if this is true for one species, it is likely the case for others as well. These studies show that appropriate

microhabitat space can be crucial to organism survival, as species have ideal temperature ranges that they inhabit.

Many organisms have an ideal temperature range within the microhabitats they inhabit, and it is crucial to understand how individuals use vegetative thermal microclimates to their advantage when temperatures are fluctuating. Bakken & Angilleta Jr. (2014) state that organisms, ectotherms in particular, have an “operative temperature” range, and use microclimates as refuge areas to either cool themselves when surface temperatures are warm, or warm themselves when the sun goes down. In that study, they used an operative temperature index to determine how much heat an organism would gain or lose based on the temperature in its current environment (Bakken & Angilleta Jr, 2014). They then calculated the factors that most influence operative temperature for certain organisms, given how various factors (wind speed, air temperature, radiation) affect the individual’s ability to gain or lose heat (Bakken and Angilleta Jr, 2014). They determined that many current models predicting the impacts of climate warming on species’ operative temperatures are not always reliable, but that it is most important to perform these estimates using physical models that take into account organism color, shape, size, and heat storage capacity (Bakken and Angilleta Jr, 2014). Taking these findings into account, other studies have used both thermal imaging and miniature data loggers to measure air and ground temperatures across study sites and mapped the thermal microclimate in those areas (Scherrer & Körner, 2011).

Mapping and analyzing microclimates can be accomplished by various methods, and terrestrial laser scanning (TLS) has been used successfully. TLS functions by emitting frequent laser pulses while scanning the desired area and creating a 3D point

cloud based on the return time of each pulse (Calders et al., 2015). The finer detail provided by ground based scans provides a better opportunity to analyze vertical profiles, as well as the necessary information to calculate plant area index and, under some conditions, measure shrub density (Muir et al., 2018; Calders et al., 2015). Vierling et al. (2008) conducted a review that explored the uses of TLS and attempted to determine whether or not scanning data could suffice as a supplement to/replacement for traditional field measurements (Vierling et al., 2008). They found that the TLS images were particularly useful when studying animal habitat associations (Vierling et al., 2008), and could provide measurements such as canopy height, volume, stand density, number of trees both standing and downed, surface topography, and habitat edge characteristics (Vierling et al, 2008). After a complete review, they determined that there was a significant correspondence between vegetative structure data obtained via TLS and similar measurements taken in the field, demonstrating that TLS may be a sufficient alternative to standard field measurements, particularly when characterizing animal habitats (Vierling et al, 2008). Similarly, Skowronski et al. (2007) conducted a study to monitor wildfire fuel loads and compare LIDAR measurements with those taken in the field (Skowronski et al., 2007). Their findings indicated that the scans were accurate in estimating larger (regional) scale biomass; however, small-scale scans relating height to biomass were less reliable (Skowronski et al., 2007). In this study, we employ TLS to study shrub characteristics as they relate to temperature gradients, and aim to use TLS to eventually model microclimates on a landscape scale.

Materials and Methods

We compared shrub structure and thermal microclimates based on shrubs sampled at three sites in the Albany Pine Bush Preserve. Across the sites, we selected five shrubs with a range of heights and measured shrub structural features, used temperature logging devices to characterize thermal gradients within and surrounding *Q. ilicifolia* shrubs, and performed terrestrial laser scans (TLS) to derive additional structural features of each shrub.

Study Area

The Albany Pine Bush Preserve is located in New York's Capital Region between Schenectady and Albany and is known for being one of the most intact, functional pitch pine–scrub oak barrens in the northeast (APBPC, 2017). This ecosystem, characterized by its shrub-dominated habitat interspersed with trees, is well adapted to dry soils, and sustains relatively frequent fires (APBPC, 2017). During the summer months, temperatures range from 12.8°C – 30.1°C, while it drops to -16.2°C – 4.7°C in the winter (APBPC, 2017). The Pine Bush is home to ~75 species of conservation concern in the New York region, most notably the Karner blue butterfly (*Lycaeides melissa samuelis*; APBPC, 2017), a federally listed endangered species.

Field Methods

We selected five individual scrub oak (*Q. ilicifolia*) shrubs from three management units of the Albany Pine Bush: Karner Barrens East, Karner Barrens West, and Kings Road (Truax) Barrens, all located within 1.1km from each other. Shrubs were deliberately chosen across a range of heights (1.0m – 3.0m). In addition, they were not

within close proximity to other shrubs and were not near roads, trails or other disturbances. Shrub structure and temperature data were obtained for each shrub. Temperature data was collected by placing five data loggers on along a transect from the shrub center to the canopy edge, then an additional radius into the surrounding herbaceous vegetation. The data loggers collected data every 15 minutes during 12 weeks in the middle of the growing season (6/5/19 – 8/29/19).

Shrub Structure and Leaf Area Index: Field measurements of shrub structure consisted of multiple components and included height, diameter, leaf mass (g), leaf area (m^2), leaf area index (LAI; m^2/m^2), and canopy volume (m^3). In the field, we measured the maximum height of each shrub (to the nearest cm), as well the diameter of the crown from two directions, one from North – South, the other East – West. We measured leaf area and leaf area index for all shrubs. To do this, we collected and dried all leaves and calculated total leaf mass, leaf area, and leaf area index (LAI) for each of the five shrubs. To do so, all leaves (including the petioles) were stripped off the shrubs during September 24-27 2019 and oven dried at 60°C for 4 days. We also set aside 10 individual leaves from each shrub to measure specific leaf area (g/m^2) in order to calculate total leaf area of each shrub from leaf mass. We used TLS to estimate ground area covered by the canopy and shrub volume (see below for TLS methods). To calculate LAI (leaf area $\text{m}^2/\text{ground area m}^2$) we divided the total leaf area of the shrub by the ground area value obtained from TLS.

Leaf Cover: Leaf cover above each of the five data loggers for each shrub was evaluated using hemispherical photography. Photos were taken with a 180° (fisheye) lens to capture the full canopy cover from the locations of each point on the temperature

transects. The photos were then uploaded to ImageJ (ImageJ Version 1.52k, 2019) to calculate the percent leaf cover. In ImageJ, we used the “Oval” tool to create a circle around the photo and clear the remaining, unwanted part of the photo and used the “Threshold” tool to select all the leaf area in the photo; the percentage of leaf cover was estimated from the photo.

Terrestrial Laser Scanning: A terrestrial laser scanner (Faro Focus 3D, Faro Industries, Lake Mary, FL) was used to obtain 3D digital point clouds of the five individual shrubs. To do this, we took three 90° scans from evenly-spaced viewpoints approximately 3m away from each shrub (one from the North, one from the Southeast, and one from the Southwest) using the 20m outdoor instrument setting. The scanner was mounted on a tripod 2m high. Three large Styrofoam balls (30cm in diameter) were mounted 2 m high on poles and positioned to use as landmark points (roughly South, Northeast, and Northwest) to stitch the scans together. Once the scans were completed, they were uploaded to CloudCompare (CloudCompare Version 2.91, 2017).

When stitching the scans together for each shrub, we located each of the three Styrofoam balls in images in CloudCompare. The alignment tool was used to match the landmark points in each image. Once the three scans for each shrub were stitched together, we removed points not associated with the shrub and were left with a 3D point cloud of the shrub. In order to calculate ground area, we measured a distance across the shrub in the scans on CloudCompare and applied them in ImageJ to set the scale of the shrub images, and then traced the shrub edge in ImageJ to estimate the total ground area covered by the shrub. We used this area value to determine the total leaf area and the LAI.

To obtain volume measurements, we used CloudCompare and our completed shrub scans to perform digital measurements. To do so, we used the Compute 2.5D Volume tool, and ensured that Ground/Before to Constant was set at 0.0 (default setting). We then set Ceil/After to have a step of 0.1, projection in the Z direction and cell height to maximum height.

Temperature Data Collection: There have been different methods employed when using small temperature logging devices such as burying them roughly 3 cm below the ground surface to accurately measure temperature ranges in the soil (Scherrer & Körner, 2011) and attaching them to a pole or wooden dowel with pipe supports underneath to keep the device roughly 8 cm above the ground to measure temperature ranges at the ground surface level (Milling et al., 2018). Milling et al. (2018) suggest placing the loggers roughly 8 cm high to keep it from coming into direct contact with the ground (Milling et al., 2018); and this height may be convenient in simulating the approximate height of a wild lupine plant, where Karner blue butterflies tend to lay their eggs (Grundel et al., 1998).

To collect temperature data, we used five small (2.5 cm diameter) temperature data loggers at each shrub (iButtons, model DS 192 1G-F5# Thermochron, 4K, iButtonLink Technology, Whitewater, WI). We employed a similar technique to Milling et al. (2018) by enclosing each iButton at the top of a section of PVC pipe with a washer and cap (with holes to allow for sufficient air flow) 8cm above the ground which was covered by an inverted plastic cup (again with holes for ventilation) that served as a sun screen. Five iButtons were designated for each shrub, extending from the center of the shrub to the North in a line. The first iButton was positioned in the center, the next

halfway between the center and the edge of the shrub, the third at the shrub's edge, the fourth placed outside the shrub at half the radius, and the last outside once the radius from the shrub edge. Distances along each transect were recorded. All iButtons were set to begin collecting temperature measurements (to the nearest tenth (0.1) °C) at 3:00pm on June 5th, 2019, and finished data collection on August 29th, 2019 at 10:45pm, and logged a temperature measurement every 15 minutes. All iButtons functioned throughout the study and each one collected over 8,000 data points. Temperature data was summarized by calculating averages of 24 hour, daily maximum, daily minimum, and daylight hour temperatures (6:00am – 8:00pm).

Data Analysis

With much of our structural data we used regressions to compare leaf mass to values obtained via TLS. Most notably, we used regression to explain the relationship between leaf area and volume, following natural log transformations. Repeated measures ANOVA implemented was used to compare temperature variables at different locations along the transects. If significant overall differences were found, we used the Tukey HSD test to compare means to assess where significant differences were located. Statistical tests were implemented using JMP software (JMP[®] Version 14.0, 2018).

Results

Of the five shrubs sampled throughout this study, we found that shrub size/structure did not influence temperature gradients in the species *Quercus ilicifolia*. Shrubs are numbered based on height from I-V (shortest – tallest). Table 1 depicts the various data collected for each shrub, and shows that total leaf mass (g), total leaf area (m^2), LAI (m^2/m^2), and plant volume (m^3) are not influenced by shrub height. However, we found that leaf area and volume are significantly correlated with each other as shown in Figure 1 ($r^2 = 0.96$). Leaf area measurements were taken using field techniques, while volume was measured using TLS. Table 2 suggests similar results in relation to canopy cover data indicating that shrub size is not correlated with leaf density, because larger shrub size did not indicate increased canopy cover and vice versa. Canopy cover in the smallest shrub ranged from 82-64%, while canopy cover for the largest shrub ranged from 59-33% based on photo locations. Overall canopy cover trends indicate more cover at the shrub center, and increasingly less cover moving outward into the adjacent open space.

Table 1. Shrub structure for five *Q. ilicifolia* shrubs. The table is organized in height order from shortest-tallest (I being the shortest, V being the tallest), and shows the measurements for height, canopy width (in two directions), total leaf mass, total leaf area, leaf area index (LAI), and plant volume.

	I	II	III	IV	V
Height (m)	1.0	1.6	1.6	1.7	2.9
Canopy Width N/S (m)	1.6	3.1	2.0	1.8	4.6
Canopy Width E/W (m)	1.4	1.9	2.1	1.5	3.8
Total Leaf Mass (g)	336	936	690	391	1918
Total Leaf Area (m ²)	2.5	7.8	5.9	2.8	16
LAI (m ² /m ²)	1.0	1.6	1.8	1.9	1.6
Plant Volume (m ³)	2.1	6.8	5.7	2.3	22

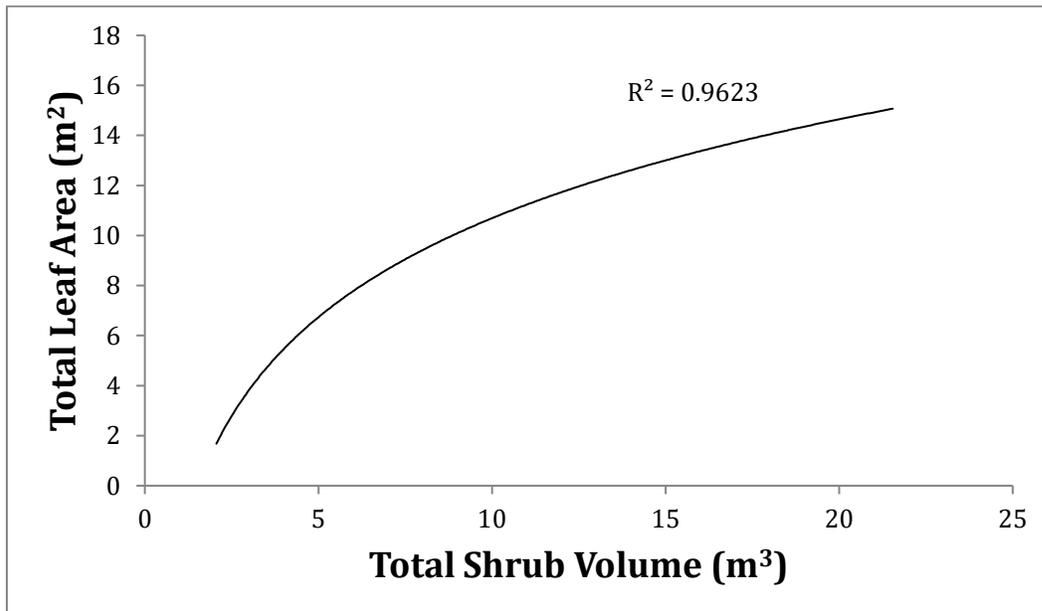


Figure 1. Positive correlation between volume (m³) and leaf area (m²) indicates significant relationship between variables. Leaf area was measured by leaf harvest and volume was estimated using TLS.

Table 2. Percent canopy cover at each iButton location. Table is organized by smallest to largest shrub volume (rows) and position under shrub (column). Shrubs are arranged from shortest (I) to tallest (V; see Table 1).

	Center (%)	Center/Edge (%)	Edge (%)	Edge/Outer (%)	Outer (%)
I	82	75	70	51	59
II	81	71	62	44	37
III	77	75	58	25	13
IV	77	73	39	18	7
V	64	66	62	45	33

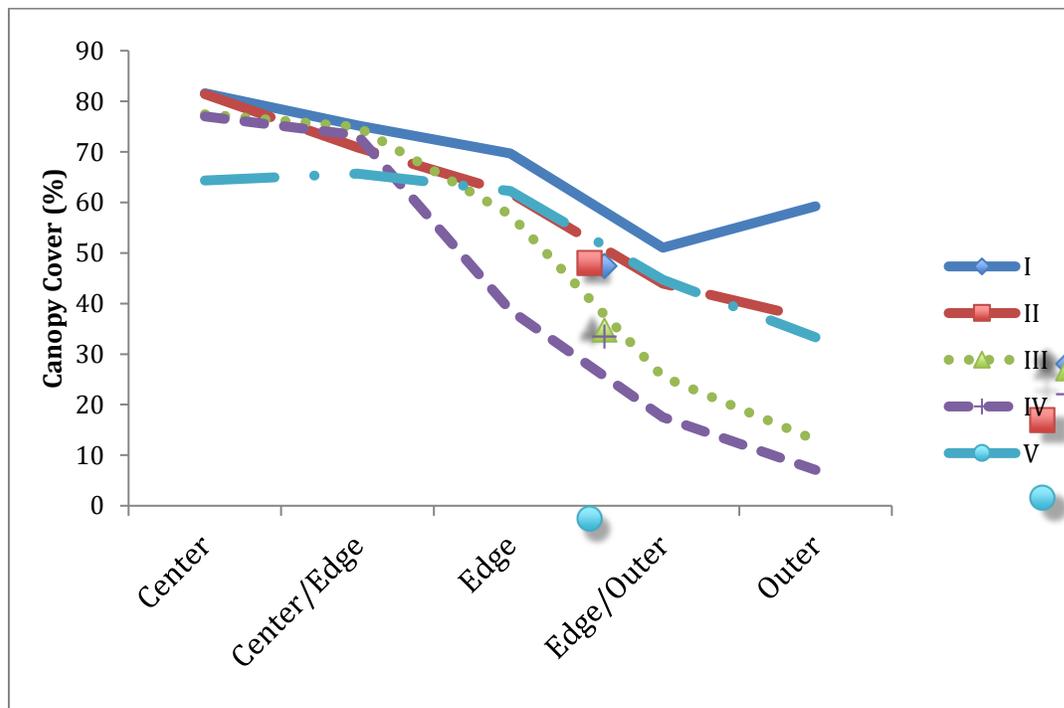
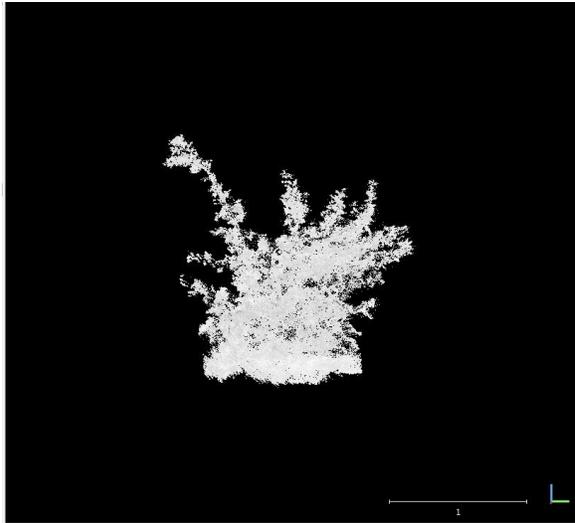
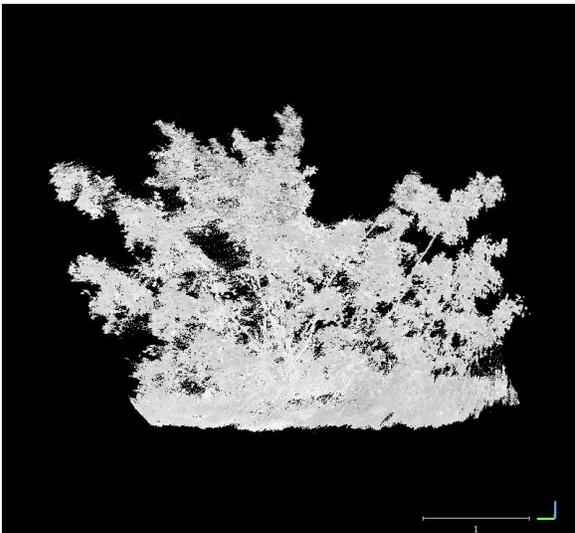


Figure 2. Canopy cover values at each location indicate varying shrub densities. Canopy cover was based on hemispherical photography. Labels I-V indicate shrubs that differ in height, I being the shortest, V being the tallest (see Table 1).

When analyzing fully stitched together TLS images from three scans of individual shrubs, point returns ranged from 301,000 – 2,000,000+; larger shrubs produced a greater number of point returns than smaller shrubs. Images depict a notable level of detail, showing evident branches and individual leaves.



Shrub IV



Shrub V

Figure 3. Depictions of fully stitched together shrub scans in CloudCompare. The upper image illustrates Shrub IV, while the lower illustrates Shrub V (in reference to Table 1). The volumes (m^2) for these shrubs were $2.3m^2$ and $22m^2$ respectively. Likewise, the leaf area was $2.8m^2$ and $16m^2$ respectively.

Daily mean temperature data was calculated in four ways (average daily maximum, average daily minimum, average 24 hour temperatures, and average daylight hour temperatures). Average daily maximum temperatures ranged from 30.4-39.1°C; average daily minimum temperatures ranged from 10.3-13.1°C; average 24 hour temperatures ranged from 20.5-22.6°C; and average daylight hour temperatures ranged from 24.1-28.1°C (Figures 4-7).

The only category in which we found a reliable gradient was in the average daily maximum temperatures, showing that as one moves inward toward the center of the shrub, the maximum temperatures continue to cool (Figure 8). However, we also found a significant difference in average 24-hour temperatures between the center-edge and outer iButton locations (Figure 10). Daily minimum and average daylight hour temperatures presented little to no gradient based on location (Figures 5,7,9). Analysis of temperature data revealed that the thermal gradient around a shrub was not influenced by size and structure of individual shrubs, but daily maximum temperatures did indicate the presence of a significant thermal gradient.

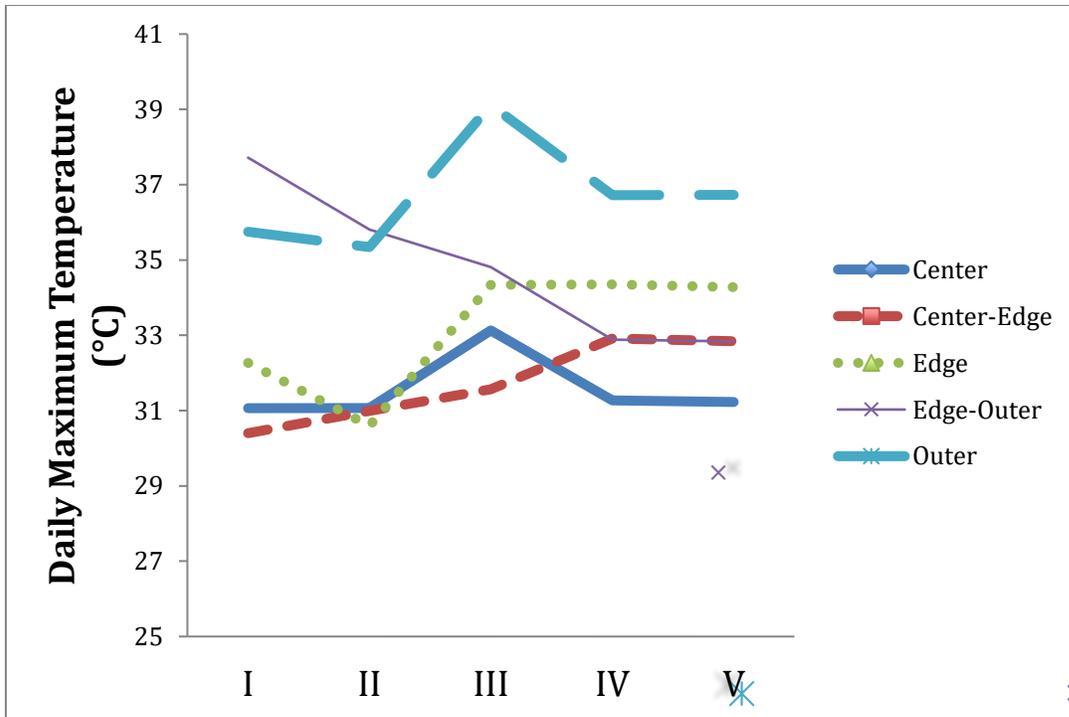


Figure 4. Average daily maximum temperatures logged by iButtons indicate differences in temperature based on iButton location and individual shrub. Maximum daily temperature values were averaged and plotted for each position at each shrub. Outermost iButtons recorded the warmest temperatures overall, while iButtons closer to the shrub center recorded cooler maximum temperatures. Each line depicts the position of each iButton from center-outer.

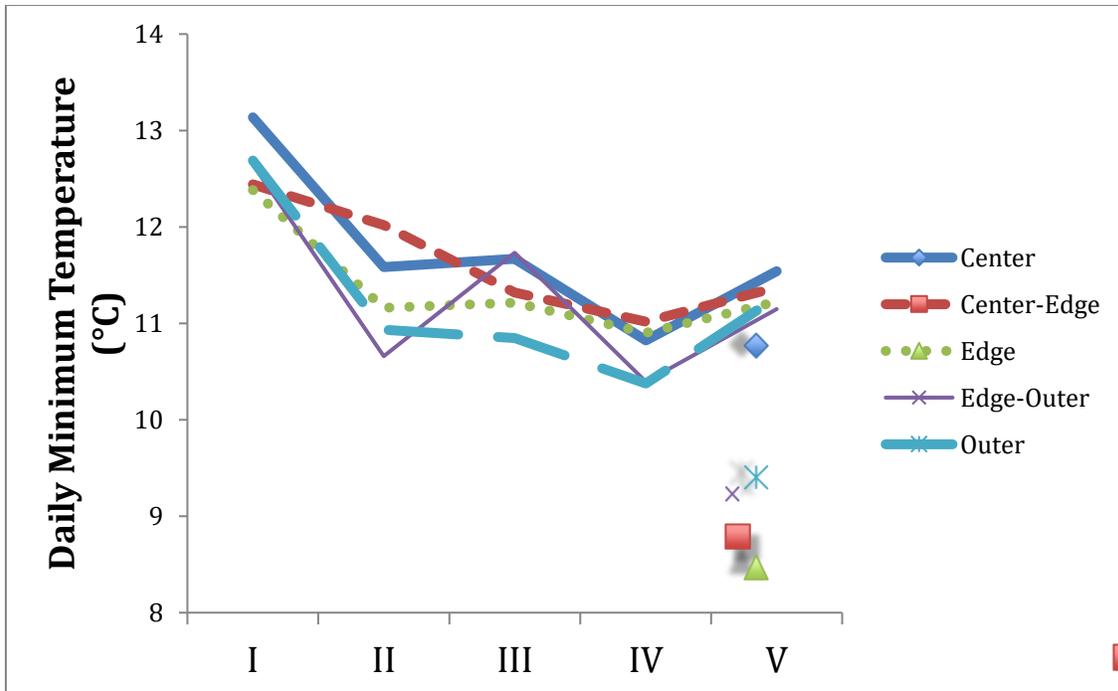


Figure 5. Average daily minimum temperatures logged by iButtons demonstrate little temperature difference based on individual shrubs. Minimum daily temperature values were averaged and plotted for each position at each shrub. The graph shows no significant variation in daily minimum temperatures based on iButton location. Each line depicts the position of each iButton from center-outer.

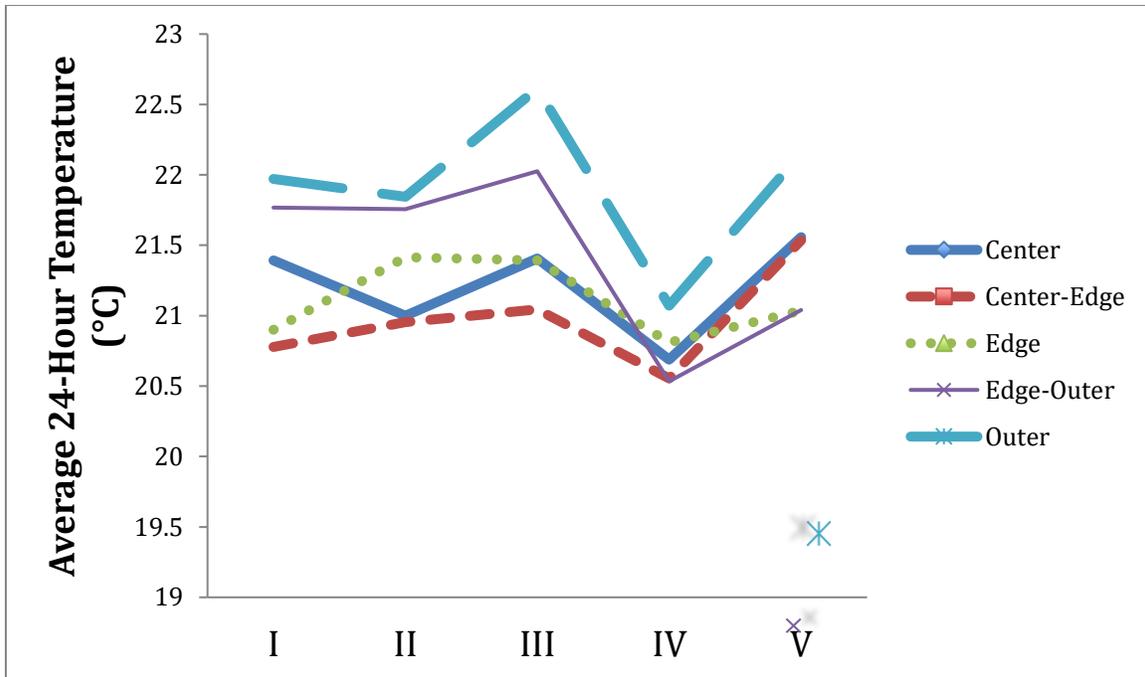


Figure 6. Average 24-hour temperatures indicate temperature variation based on iButton location and individual shrub. Daily temperature values were averaged and plotted for each position at each shrub. Overall, the outermost iButtons recorded the warmest temperatures, while all other iButton positions produced no notable trends. Each line depicts the position of each iButton from center-outer.

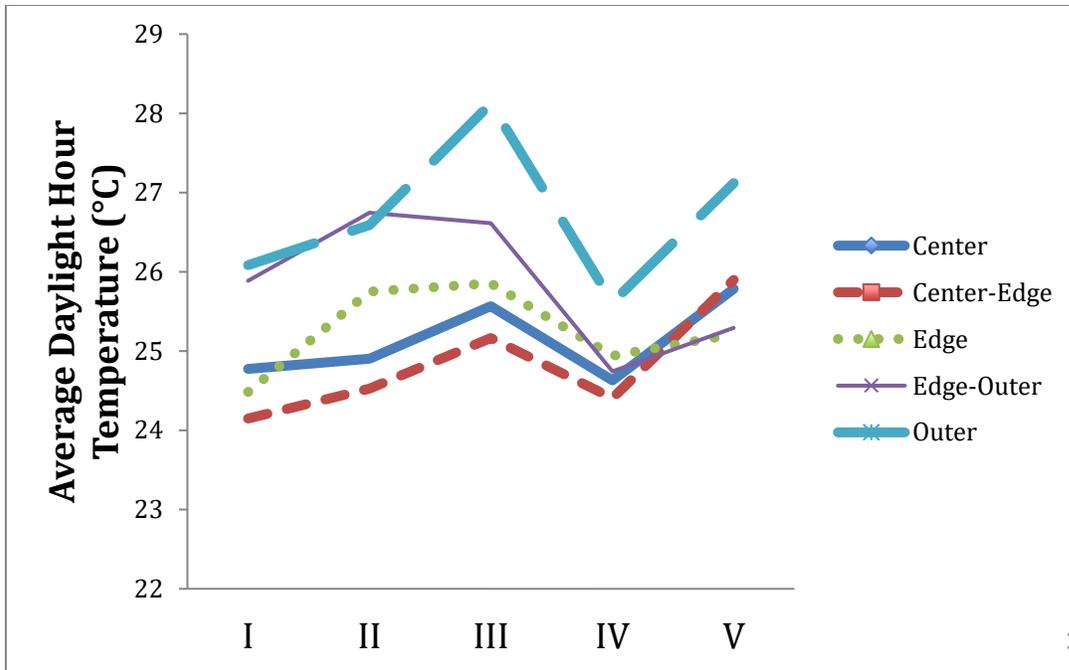


Figure 7. Average daylight hour temperatures (6:00am – 8:00pm) logged by iButtons show some temperature variation based on iButton location and individual shrub. Temperature values logged between 6:00am and 8:00pm were averaged and plotted for each position at each shrub. Outermost iButtons recorded the warmest temperatures, while the center-edge position was warmer for some shrubs (though not all), and other locations showed little variation. Each line depicts the position of each iButton from center-outer.

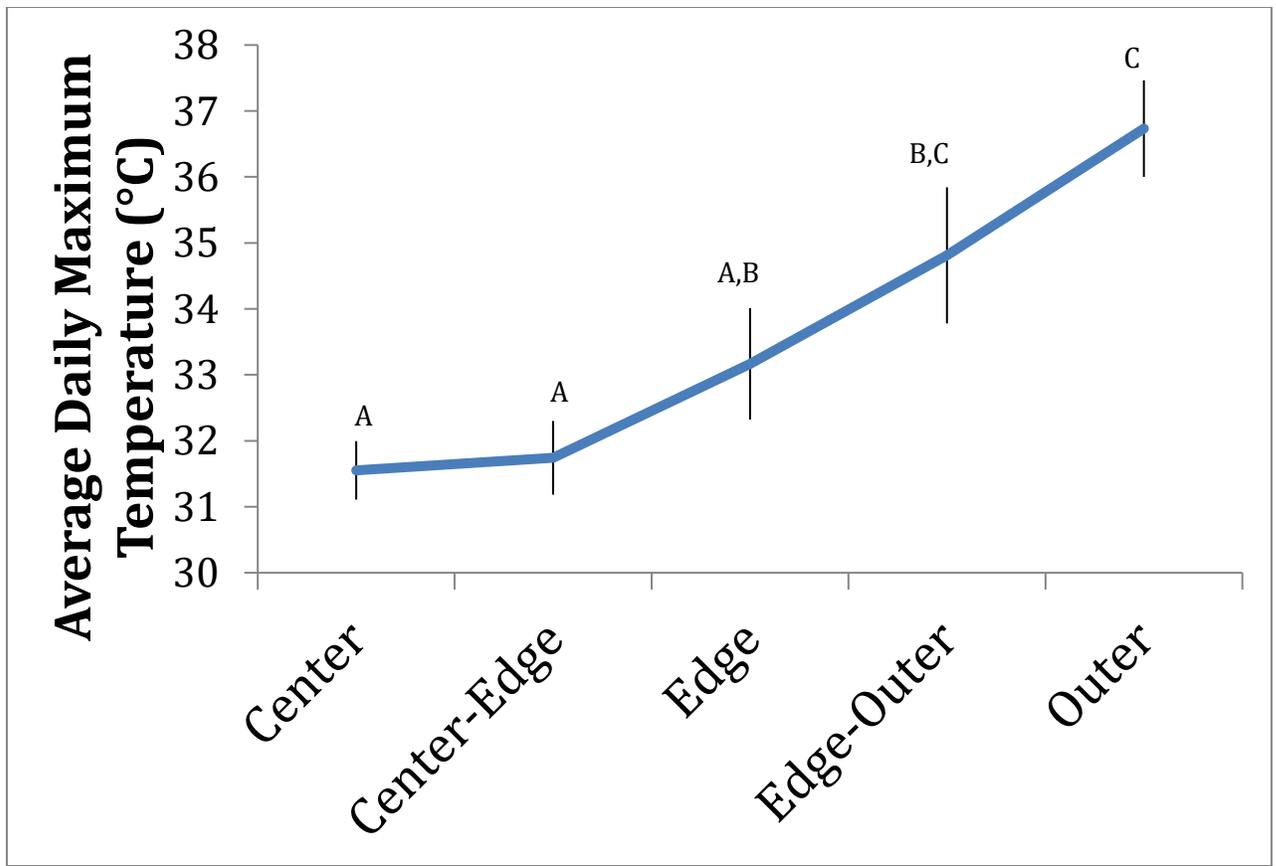


Figure 8. Gradient of average daily maximum temperatures suggest significant differences among iButton locations. Results show that maximum temperatures continue to warm moving outward from the center of a shrub, and indicates high significance ($p=0.0001$) A, B, and C on the graph indicate locations that are significantly different from one another and were determined using JMP (ex: all A's are not significantly different from each other, but A is significantly different from B and C). Error bars represent standard error at each location.

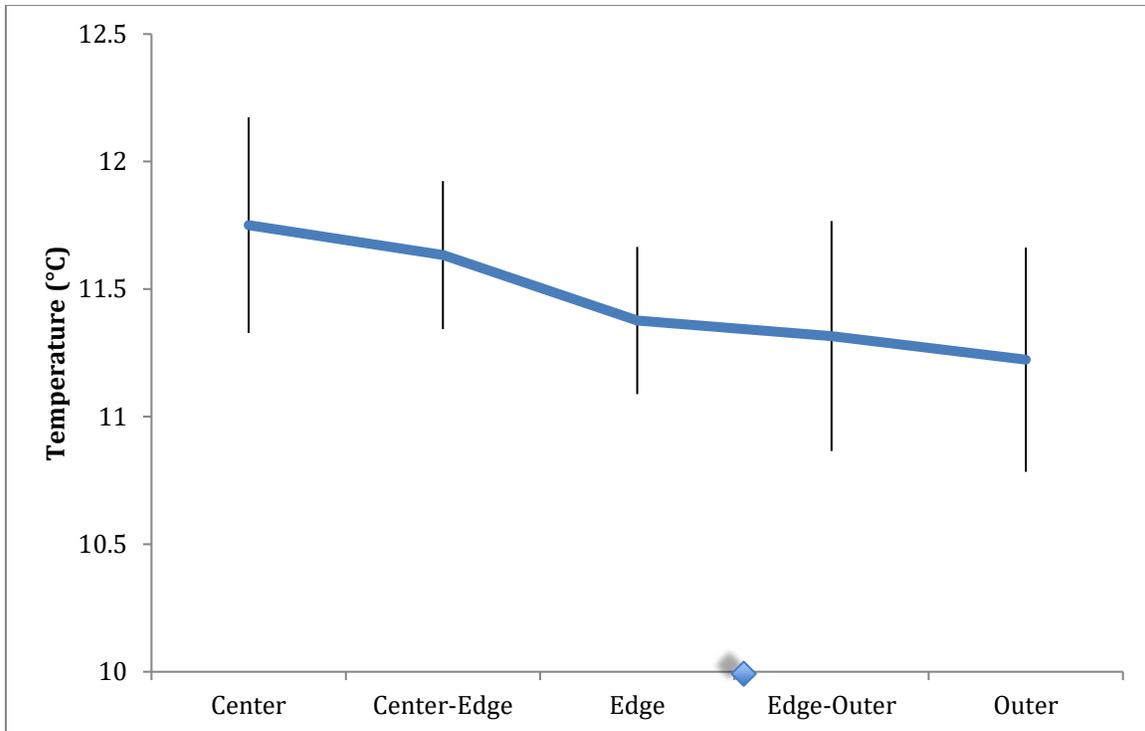


Figure 9. Average daily minimum temperatures indicate no significant differences based on iButton locations. Results show no significant differences in minimum temperatures based on location ($p=0.79$). This result also suggests that shrub centers are not significantly warmer during the nighttime. Error bars represent standard error at each location.

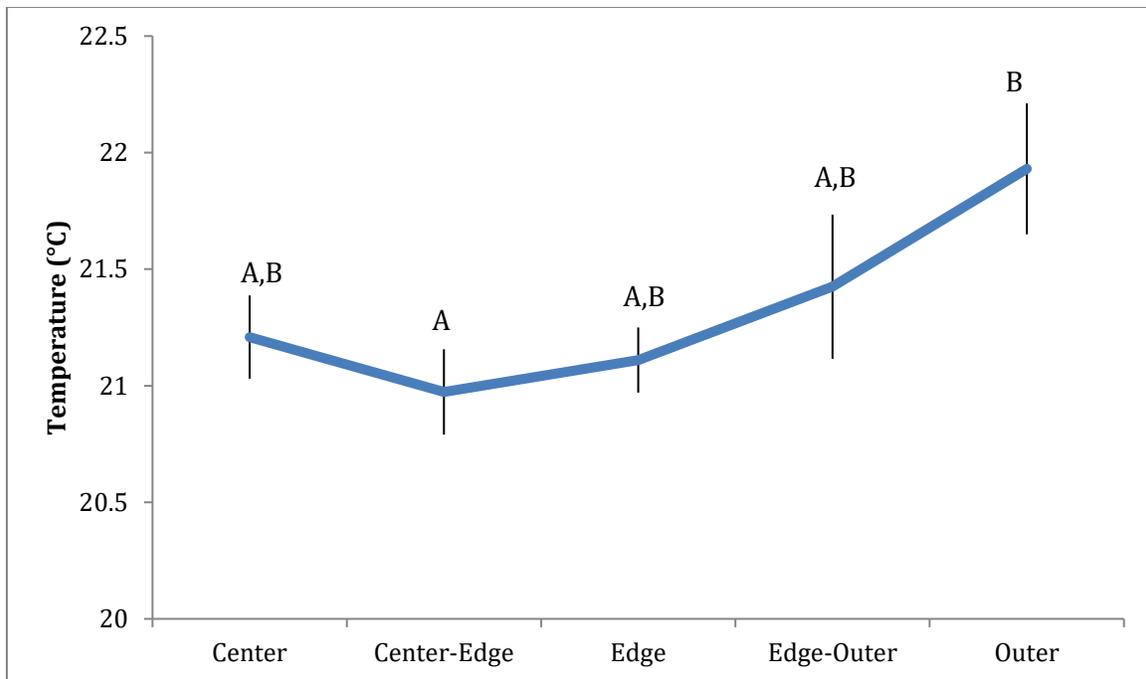


Figure 10. Average 24-hour temperatures are significantly different at center-edge and outer locations. Center-edge and outer locations were determined to be significantly different from each other ($p=0.029$), while all other iButton locations demonstrated no significance. A and B indicate locations that are significantly different from each other (see Figure 9). Error bars represent standard error at each iButton location.

Discussion

In conducting this study we had two main goals, 1) to assess the temperature gradients present around *Q. ilicifolia* shrubs and determine whether shrub size/structure impacts these gradients, and 2) to determine the viability of TLS scans for substituting field measurements for use in thermal modeling. With regard to our first goal, we predicted that larger shrubs would have a greater impact on thermal regime, and found that shrubs did impact environmental temperatures, particularly the daily maximum temperatures. However, our results indicated that shrub size and structure did not have any significant impact on the microclimates we assessed. Therefore, our hypothesis was not supported. Based on the lack of correlation between shrub structure and temperature, it appears that while variable shade cover may have an impact on temperature in a certain habitat, the small scale of microhabitats may not produce the same effect (Grundel et al., 1998). With our *Q. ilicifolia* individuals we found that the shrubs themselves produce a recognizable gradient from the center to twice the radius of the shrub, but that size and structure did not impact the temperature gradient. Milling et al. (2018) found similar results in arid shrubland habitats where the operative temperature of *Artemisia tridentata wyomingensis* was not impacted by shrub structure in habitats of differing structure and complexity. Interestingly, they found at one study site that the impacts of habitat structure and shrub volume did not change the temperature measurements seasonally, while at the other site shrub volume had a notable impact on thermal microclimates in the summer (Milling et al, 2018). Milling et al. (2018) also claim that the diurnal temperature range did in fact differ between study sites, while in the present study we found no notable differences in temperature ranges during the daylight hours based on shrub location.

Overall, both the results of the present study and those of Milling et al. (2018) show a lack of correlation between habitat structure and temperature gradients.

The temperature category in which we found the most notable gradient was in the daily maximum temperatures, and this may have been a result of the study site distribution (Figures 4-7). While the daily maximum temperatures expressed the most highly significant differences in iButton location (Figure 8), the average 24-hour temperatures also showed differences, but only between the center-edge and outer iButton locations (Figure 10). Because neither of the other temperature categories (average daily minimum or average daylight hour) showed any significant differences, and the average 24-hour data was only significant among two locations, we postulated that perhaps the data was skewed by other herbaceous vegetation growing throughout the summer as was visualized when analyzing the canopy cover photos. We therefore performed the same analysis on the temperature data by splitting it into the first and second parts of the summer (6/05/19 - 7/16/19 and 7/17/19 - 8/29/19). This analysis was important to conduct because if other non-*Q. ilicifolia* vegetation was growing, it may indicate an inaccurate temperature gradient if such vegetation was more heavily present during certain parts of the summer. In this analysis we found no significant differences in the temperature gradients between the first and second halves of the summer, indicating that the presence of other herbaceous vegetation did not skew our data.

One potential explanation for the lack of significant shrub structure effect may have to do with the consistency of the dry, sandy soils among our sites. Radiation from the sun is absorbed in different ways depending on the substrate present, which impacts the surface temperature maintained at the ground level (Buxton, 1924; Milling et al.,

2018). Pringle et al. (2003) also found that the intensity of incident radiation was a key factor in determining areas of thermal refuge, particularly for ectothermic species, overall having a recognizable impact on microhabitats (Pringle et al., 2003). Because our study sites were relatively similar in terms of substrate, it is possible that radiation from the sun was absorbed similarly across all sites, rather than differentiating between grassy sites, sandy sites or rocky sites.

These observations may be additionally useful in understanding the use of microclimates by various species. As it has been discussed, it appears that on the scale of microclimates, climate warming has not had a drastic impact on many species as would be expected (Sears et al., 2011), but warming may still have varying effects. For example, Karner blue butterflies, a native species to the APBP, rely on blue lupine plants to feed their larvae, and studies have shown that larvae develop faster when feeding on shade-grown lupine rather than the same lupine grown in sunnier environments (Grundel et al., 1998). However, Stamp & Bowers (1990) showed that buck moth (*Hemileuca lucina*) caterpillars demonstrate an increased growth rate in relation to warmer temperatures when able to bask and feed on young leaves (Stamp & Bowers, 1990). With a modeled 10°C increase in average springtime temperatures, it was observed that caterpillar growth rate nearly doubled, demonstrating how thermal environments may influence caterpillar feeding and development (Stamp & Bowers, 1990). Though these findings are different, they both imply that maintaining appropriate thermal microclimates may be critical to the developmental necessities of certain species. In our study we observed that while the thermal gradient was not affected by vegetation structure, there is still a valuable gradient

present that evidently houses various microclimates, and we predict that these microclimates have numerous means of impacting the species in their refuge.

In accomplishing our second overall goal, we were able to successfully draw connections between TLS scanning data and field measurements. Most notably, we concluded that the relationship between leaf area and volume demonstrates a predictable positive correlation (Figure 2). This result is important because leaf area measurements were taken tediously in the field, while volume was measured using TLS, demonstrating that TLS scanning may be an effective tool to corroborate or even replace field measurements. Olsoy et al. (2015) demonstrated similar effectiveness of TLS when modeling areas of refuge for prey animals by comparing canopy cover photos with TLS scans to analyze how vegetation cover would conceal prey animals. They found that both methods of analysis were strongly correlated ($r^2 = 0.85$) illustrating how TLS can be an effective tool to estimate concealment based on vegetation (Olsoy et al, 2015). Olsoy et al. (2015) also state that TLS can be useful for estimating canopy cover, characterizing alterations in vegetation structure, and modeling leaf densities and their seasonal changes. Overall, our study corroborates the findings of others, claiming that TLS can be a useful tool for analyzing vegetation and habitat structures.

If we were to conduct this study again, conducting TLS scans in color would be helpful not only in stitching together the scans, but also in helping to better visualize the landscape. Likewise, it would be beneficial to take canopy cover photos both when placing the iButtons initially, and when removing them (as we did in this study), to help determine if other herbaceous vegetation was growing and impeding our results.

From this study we were able to conclude that observing the presence of a thermal gradient is possible when examining daily maximum temperatures, and that shrub size and structure do not change the consistency of temperature gradients in *Q. ilicifolia* shrubs. These conclusions are valuable in furthering this work as we hope to use our daily maximum temperature data and apply the knowledge that shrub size and structure do not influence temperature gradients to predict temperature depressions on a larger scale. The conclusions drawn from this study may be useful to future studies that aim to observe microclimates, for example, in attempting to map optimal microhabitats or areas of refuge for certain species (Hertz et al., 1994; Pringle et al., 2003; Grundel et al., 1998). Likewise, these thermal maps may aid researchers in identifying areas of sunlight exposure (or lack thereof) for ectothermic species that rely on both basking and thermal refuge (Hertz et al., 1994). Overall, terrestrial laser scanning has proven to be a useful tool in assessing thermal microclimates, and such microclimates should continue to be explored because it is evident that they are a haven to many animal species.

Acknowledgements

I would like to thank the Union College Student Research Grant for providing the funding necessary for this project and to Cole Belmont and the Union Makerspace for the use of the laser scanner and help with 3D analysis. Special thanks to Neil Gifford and Steve Campbell at the Albany Pine Bush Preserve for granting access to our study sites and providing knowledge on the habitats and communities. Thanks to Sean Rigney for his help collecting field data and TLS scans. Finally, I thank Professor Steven Rice for his guidance and direction throughout the entirety of this process.

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