Spatial Bootstrapping of High Spatial and Temporal Resolution Thermal Infrared Imagery: A Canopy Wetness Case Study

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Abstract
We measure and compare temperatures of dry and wet plant canopies with a high spatial resolution thermal imaging camera. We then evaluate measurement variability and how this changes during evapotranspiration. Our assessments examine mean temperatures and their variability under constant evapotranspiration conditions. We partition our study by time since wetting (T_n), plant replicate (P_n), moisture condition (M_n), measurement height above target (H_n), and observation day (D_n). Treatments involved wetting half of each plant's canopy, imaging each replicate from two heights (1 and 2 m) nadir to the canopy, and then assessing temperatures within wet and dry zone masks. Images were acquired every 5 minutes for 1 hour and treatments were replicated over two days. Spatial bootstrapping (SBS) was performed independently within each zone for each treatment using 50 random placements of a 3×3 pixel window. Our methods show that natural heterogeneity in dry canopies presents less variable temperatures than wetted canopies, where there was an influence of variable wetting. The allotted treatment duration successfully permits full evaporation of water from the wetted canopy and therefore allowed us to identify the point at which wetted zones returned to a localized equilibrium with the dry zones.

1. Introduction

Moisture interception, absorption, and evapotranspiration combine to form a set of dynamic processes that govern the instantaneous state of plant canopy wetness. This wetness in turn governs latent and sensible heat fluxes, influencing canopy temperatures and thus can be measured indirectly as thermal changes across the canopy and through time. Knowing that evapotranspiration processes (Idso and Baker, 1967 and Oke, 1979) are controlled by water availability, the vapor pressure deficit, air circulation, and temperature, it is possible to control these conditions and to focus on the thermal variability at specific instances, rather than the evapotranspiration processes directly. When the leaves of a plant are wetted as by precipitation, the canopy will appear cooler due to the high specific heat capacity of water. While plant temperature is internally regulated by a process called transpiration, the process of water removal from plant tissues through stoma (Ward and Robinson, 2000), transpiration is considerably reduced under water-limited conditions, leading to corresponding leaf surface temperature increases (Bartholic et al., 1972, Jackson, 1982 and Thompson, et al., 2012). Aerial thermal measurements have been shown to be significantly correlated with leaf stomatal conductance for assessing water status variability (Baluja et al., 2012). Thus an understanding of thermal conditions and their variability across a plant canopy or through time can produce good indicators of vegetation canopy moisture stress (Idso and Baker, 1967, Bartholic et al., 1972, Jackson, 1982, Thompson, et al., 2012, Jones and Leinonen, 2003 and Guiliani and Flore, 2000), particularly when using the mean temperature of a large number of leaves within a canopy (Idso and Baker, 1967, Bartholic et al., 1972, Jackson, 1982, Thompson, et al., 2012, Grant et al., 2007, Jones and Leinonen, 2003, Leinonen and Jones, 2004, Fuchs, 1990, Guiliani and Flore, 2000 and Wiegand and Namken, 1966). There exists strong evidence in support of canopy surface temperature being correlated with its moisture content. A comparison of cotton plants growing on plots with varied soil water conditions were measured using airborne thermal imaging (Bartholic et al., 1972) and it was found that watered crops had lower surface temperature (20-30°C) than drier crops (36-37°C). Several studies have identified similar relationships between temperature and plant moisture content (Idso and Baker, 1967, Bartholic et al., 1972, Grant et al., 2007, Jones and Leinonen, 2003, Leinonen and

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Jones, 2004, Wiegand and Namken, 1966 and Moran, 2000). Advances in thermal sensor technology and consequently thermal imaging have greatly improved the measurement of vegetation canopy temperatures (Bartholic et al., 1972, Thompson, et al., 2012, Grant et al., 2007, Jones and Leinonen, 2003, Leinonen and Jones, 2004 and Guiliani and Flore, 2000), since imaging allows the distribution and variability of a surface to be recorded, rather than only single spot measurements. Thermal imaging also provides a visual component that can help identify spatial characteristics and changes through time by observing sequences of images that may not change evenly throughout the area measured. The importance of using adequate spectral and spatial resolution is emphasized (Thompson, et al., 2012), to detect canopy variability, noting that with increasing distances between the plant canopy and the sensor results in lower recorded temperatures. This relationship is expected due to the coarser spatial resolution and thus the averaging (and hence dampening) of measured temperatures; however, the importance of averaging temperatures over a canopy to reduce the effects of leaf orientation on temperature measurement has been described (Thompson, et al., 2012), who also stress the benefit of maintaining a consistent viewing angle during image acquisition to reduce extraneous uncertainty. Fuchs (1990) cautions that temperature averaging can limit the ability to measure moisture stress if the measurement framework is viewing only a fraction of the sunlit foliage. Similar studies (Jones and Leinonen, 2003, Leinonen and Jones, 2004, Kimes, 1981 and Nielsen et al., 1984) also recommend that canopy temperature measurements be performed with the infrared thermometer positioned nadir over the canopy, aligned with the sun, as this measurement viewing framework provides the highest infrared temperature readings. Some evidence exists that temperature increases due to moisture stress affects canopies heterogeneously, thus distributed measurements within the canopy are beneficial to capture the variability induced by leaf orientations, IFOV, and shading (Fuchs, 1990, Kimes, 1981 and Nielsen et al., 1984 and Husband and Monteith, 1986), since temperatures for individual leaves may be unduly influenced by local canopy geometry (Grant et al., 2007). The literature identifies sources of introduced error when collecting thermal data over vegetation, namely background effects, diurnal cycles, and illumination effects related to the solar zenith angle. Background constituents in thermal images are noted as potentially problematic throughout the literature (Jones and Leinonen, 2003, Leinonen and Jones, 2004, Guiliani and Flore, 2000 and Siu, 2013). Soil backgrounds have been shown to cause a 10-20°C warming signals compared to the corresponding plant being studied (Jones and Leinonen, 2003). Such influences have been mitigated by higher spatial resolution measurements that are constrained to the foliage or by using an artificial backdrop; (Guiliani and Flore, 2000) used a black polyethylene shield that they placed behind the trees to reduce the influence of other trees or background conditions. Measurements of this backdrop could easily be removed given the contrast with the trees; this however is a laborious task and one that would not work effectively at an operational scale. During periods of maximum moisture stress and evaporative demand, in the mid-afternoon (local time), (Wiegand and Namkenm, 1966) identified the influence of diurnal cycles on measures of plant turgidity, directly related to leaf surface temperature when solar radiation and air temperatures were held constant ($r^2 = 0.864$). Furthermore, as demonstrated for a winter wheat canopy, temperature showed a clear relationship with solar zenith angle, due to its influence on which canopy components are sunlit or shaded at any instance (Husband and Monteith, 1986).

1.2 Goal and Objectives

The goal of this study was to assess the uncertainty in thermal measurements of wet and dry plant canopies and to establish whether changes through time (due to evapotranspiration) could be statistically detected as a result. To achieve this goal, we identified 3 objectives: (1) use a spatial bootstrapping approach to measure both mean temperatures and their uncertainties for wet and dry plant canopies, (2) extend the characterization of plant canopy temperatures and their uncertainties through the time domain, and (3) to compare temperatures among replicates and partitioning variables (measurement height, and date of replicate) within the study.

2. Methods

Thermal imaging was conducted indoors, within a fully controlled experimental setting where air temperature (*AT*), relative humidity (*RH*) and wind speed (*U*) were maintained at constant levels (24.3°C, 64%, and 2.5 $m \cdot s^{-1}$ respectively). Thermal images were acquired using a Process Sensors PTI-180 portable thermal infrared camera (λ = 8-14 μm) with a 0.1°C temperature resolution and 20° field of view, resulting in images with 300 columns and 250 rows. Placing the thermal camera at nadir ensured that each plant was fully within the IFOV, shadows were minimized, and that oblique viewing conditions would not need further corrections (Jackson, 1982, Jones and Leinonen, 2003, Moran, 2000 and Berni et al., 2009). This thermal imaging system permitted downloads of the raw thermal images for further processing and analysis; unfortunately the image acquisition could not be automated and required manual triggering at each interval of the study. The experimental design consisted of five replicate plants (P_n; n = 1, 2, …, 5) of *Impatiens hawkeri* (New Guinea Impatiens) with similar canopies for assessing the uniformity of temperature measurement across variable leaf angles, shading conditions, and canopy architectures. Measurements were acquired every 5 minutes for one hour with each measurement coded by time since treatment start (t_n; n = 0, 5, …, 60). At the start of each treatment, half of the plant canopy was wetted (M_W) with 15 ml of water applied to the plant using a spray bottle in a sweeping motion to simulate a light rain event while the other half remained dry (M_D). The 60-minute experimental duration was needed for the wet surface to return to equilibrium relative to the dry surface (this was determined empirically). Measurements were made at two heights above the canopy (H_1 or H_2), where the subscript indicates the height in meters (corresponding to spatial resolutions of 5.9×7.1 mm and 11.8×14.1 mm at 1 and 2 m heights respectively), and the entire experiment was fully replicated on two days (D_n; n = 1, 2) and emissivity was considered to remain constant at 0.98 as per (Oke, 1979), representative of fresh vegetation. For each treatment, the plant was placed on a large black plastic sheet, ensuring a uniform background in contrast with the plant canopy as inspired by (Guiliani and Flore, 2000). A 25°C threshold was determined to optimally separate the black background from the plant canopy and given the density of the canopy, no soil was ever visible within the IFOV. A fan was used to produce constant air movement at fixed U and all external light sources were eliminated (e.g., windows were covered, doors were shut) to create a completely illumination controlled laboratory space. The moisture class was used to split each image into two subsets (based on masks of fixed size, and constrained to the plant canopy). The final result of (2 days) × (5 plants) × (2 heights) × (2 moisture classes) × (13 periods) = 520 treatments for which temperatures were recorded at the pixel level coded based on combinations of the aforementioned nominal factors (Figure 1). Figure 2 shows a mosaic of thermal images illustrating canopy temperature in 5-minute increments along the time gradient for one treatment (including both the wet and dry halves of the canopy). Using identically sized rectangular masks for each moisture class, M_W and M_D, wet and dry image components were extracted from the original images in each combination of *P, H, T,* and *D* factor.

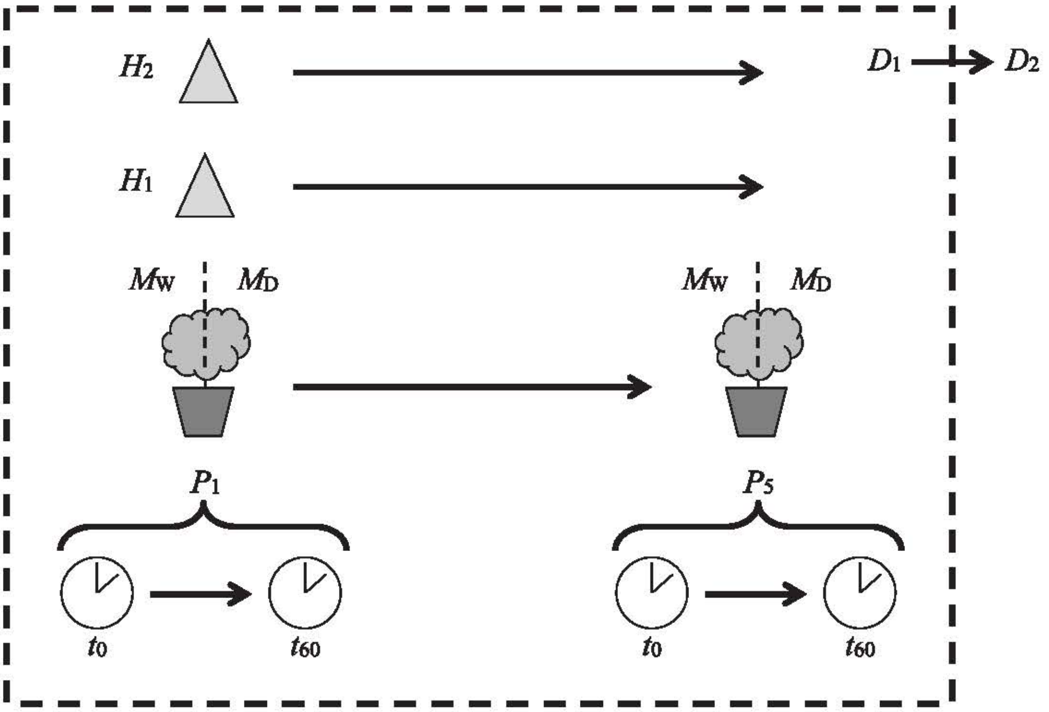

Figure 1: Schematic of the sampling and experimental design. H = 2 measurement heights, D = 2 days of observation, t = 13 temporal periods of measurement, P = 5 plant replicates, and M = 2 moisture classes

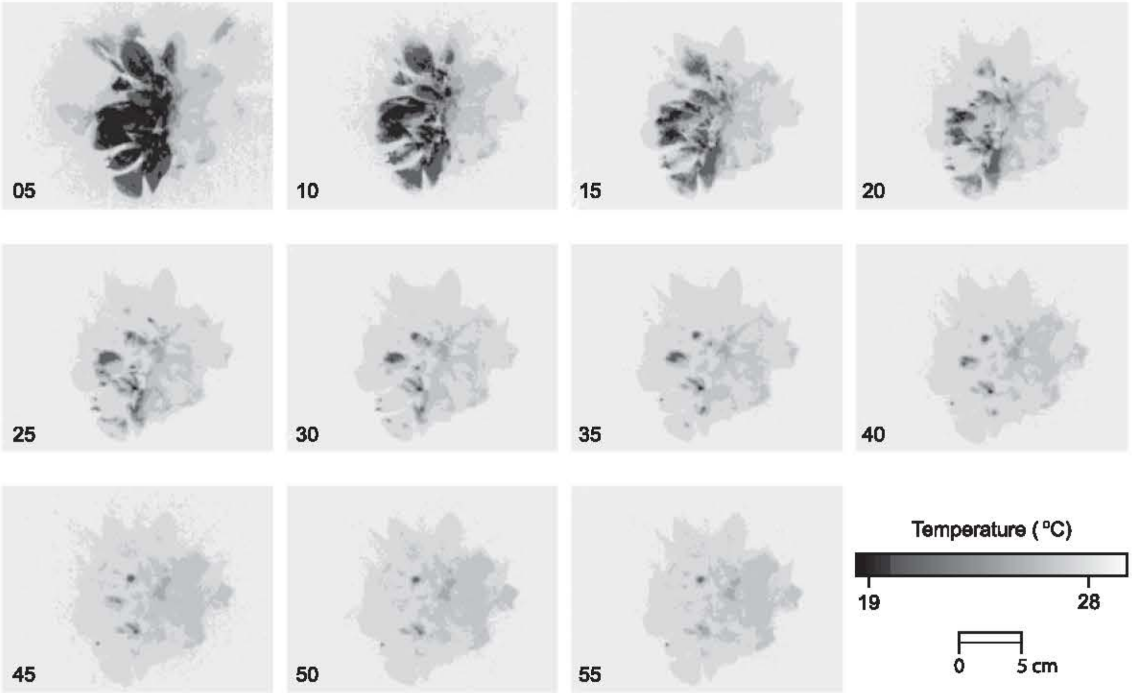

Figure 2: Sample thermal images illustrating the change in canopy temperature, driven by the evaporation process in 5-minute increments (indicated by the number in the lower-left of each sub-image). This example represents treatment H_1, D_2, P_1

Since the IFOV extent becomes larger as the spatial resolution becomes coarser (as camera height increases above the canopy surface), the treatments at H_2 had masks comprising fewer pixels. Mask sizes for H_1 and H_2 are 78×48 and 38×28 pixels respectively. To obtain optimal representations of the moisture classes within the 5 plant canopies, the absolute positions of the masks in the wet and dry zones varied slightly among treatments, due to variability in the orientations of the plants. Spatial bootstrapping (SBS) is a repeated random resampling of an image within a fixed window, within which summary measures (mean, variance, standard deviation, maximum, minimum, first- and third-quartile) can be computed (Remmel and Mitchell, 2013 and Stafford et al., 2013). SBS provides a method for assessing the variability of measurements that are spatially distributed and reduces the influence of extreme values resulting from surface heterogeneities, such that appropriate characterizations of expectation and variability of conditions are achieved. We performed an SBS characterization for each of the 520 treatments to develop confidence limits for wet and dry zones independently. We then tested for significant differences between and among groups of thermal measurements using appropriate *t*-tests and ANOVAs. Spatial bootstrapping (SBS) was implemented to construct expectation ranges about the mean temperatures permitting us to (1) understand the rate and variability of temperature change with time, (2) assess temperature differences between wet and dry canopies, and (3) assess the variability in thermal measurements within images, between measurement heights and dates of image acquisition, and among plant replicates. By using the SBS method, perfect geo-registration among images is not necessary because the change in state at a specific pixel through time is not as important as the trend and related uncertainty. Finally, we performed a diagnostic test, to assess the stability of the SBS methods. This required the incremental increase in the SBS window size; within each 500 random SBS window placements were made on the individual treatments. In these cases, the windows were not constrained to being either within a wet or dry zone to understand the total canopy heterogeneity and hence the variability will be greater than if constrained only to either the wet or dry mask areas.

3. Results

Our study had 5 replicate plants (P_n) to increase the number of measurements entering our statistical tests and to permit better characterization of canopy variability. We tested the null hypothesis that the mean temperatures among the replicate plants were equal. We compare the consistency across the 5 plants in terms of mean temperature (Figure 3) and test for significant differences among the plant canopies by implementing an ANOVA. The ANOVA was significant ($p < 0.05$), indicating that at least one of the plant mean temperatures was statistically different from the others. A subsequent Tukey HSD test showed that mean temperatures between P_1 and P_5 were equal ($p > 0.05$) with slightly higher mean temperatures, but that all other pair-wise comparisons were significantly different ($p < 0.05$). While the distributions appear similar in terms of means and variability, the statistical tests indicate sufficient differences among some plants and therefore an elevated level of canopy heterogeneity exists. Thus, by pooling data from all 5 replicates, we capture the inherent variability of these plants and feel confident that our sampling design captures the variability of these plant canopies. We plot mean temperatures pooled among all grouping factors (P, M, D, and H), where the variability is characterized by the SBS subsampling.

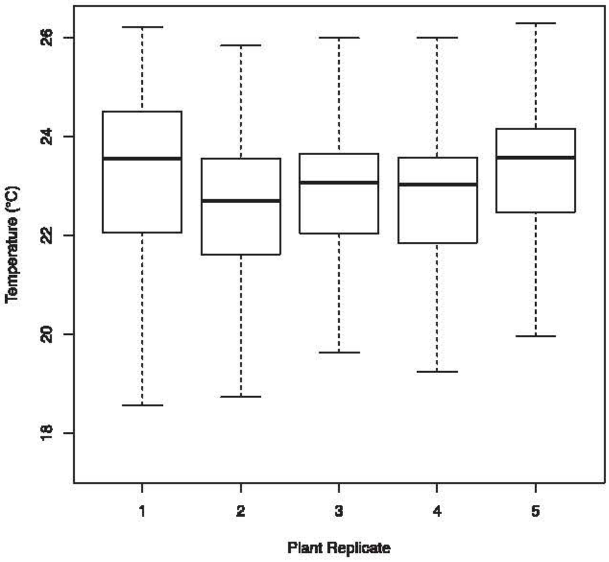

Figure 3: SBS mean temperatures (°C) combining moisture class (M_n), observation day (D_n), measurement height (H_n), and time (t_n), grouped by plant replicate (P_n)

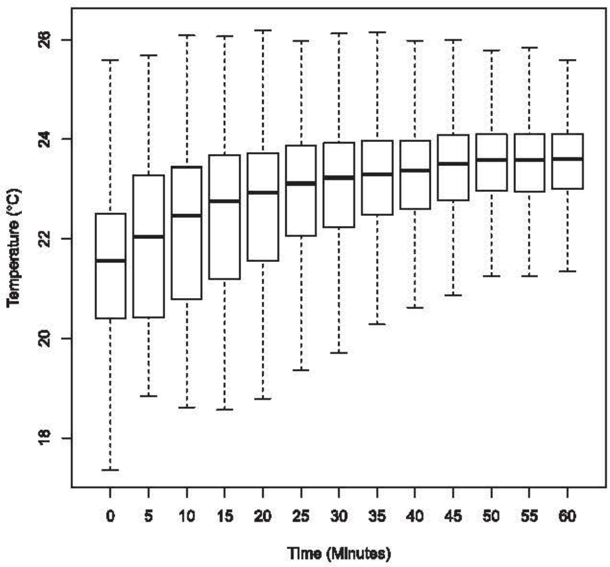

Figure 4: SBS mean temperatures (°C) combining plant replicate (P_n), observation day (D_n), measurement height (H_n) and moisture class (M_n), grouped by time class

Figure 4 shows a gradual increase in mean temperature with time from t_0 to t_{30} after which the temperatures begin to show evidence of stabilization throughout the treatment period end; similarly, the inter-quartile range (IQR) decreases and stabilizes with t. The coupled result of temperature stabilization and lower variability indicate the return to equilibrium conditions after moisture is evaporated from the vegetation surface (i.e., the wet half of the canopy becomes as dry as the dry half of the canopy). The number of outlier temperature values increase toward the latter increments of the treatment period coinciding with the mean temperature increase. These increases result from the size of the SBS window that we used, combined with the greater variability of a dry surface, where shadowing and leaf angle are increasingly pronounced relative to a wetted canopy, and where uneven wetting (and hence evaporation) dominates. The outlier values further display a skewed distribution, with a tail toward cooler temperatures, supporting our hypothesis that uneven moisture on the leaves drives these low outlier values. As a visual inspection would indicate, a null hypothesis that all time periods have equal mean temperatures was rejected by a significant ANOVA test ($p < 0.05$), indicating that at least one SBS mean temperature differed among the time increments. The results were subjected to a Tukey HSD test indicated that from t_{25} to t_{60} the temperatures did not differ significantly, providing evidence to support the stabilizing temperatures in the latter period of the treatment. From t_0 to t_{25}, mean temperatures increase significantly between successive time periods and demonstrate the effect that moisture (and here, evapotranspiration) has on the thermal signatures measured for the plant canopies. The SBS approach permits the construction of expected ranges of variability for the mean temperatures measured, where otherwise a single mean value would be computed for each canopy, with less confidence in the variability or stability of the true measurement value. The comparison of mean temperatures between wet (M_W) and dry (M_D) canopy groupings (Figure 5) indicate, as expected, that wet canopies are generally cooler. Pooling all treatment factors and boosting the number of measurements with the SBS approach characterizes the measurement variability. The variability (represented by the IQR) is greater for wet canopies, but the number of outliers (specifically low temperature outliers) is greater for dry canopies. This again supports our claim that unevenly wet canopies will exhibit greater temperature variability, while the variability of dry canopies is less. Yet, outliers for dry canopies reinforce the reality that small SBS windows and canopy heterogeneity can result in locally unexpected low values. A Student's t-test indicated that mean temperatures between M_W and M_D were statistically different ($p < 0.05$). We acquired thermal measurements from two distances (heights) from the target. We pooled all of our measurements and tested for statistical differences between the two height groups (Figure 6) using a Student's t-test. Statistically the two groups differ ($p < 0.05$), but when outliers are removed, the two groups can be considered equal. This result is supported visually, as the distributions differ primarily in the lower tail (cooler temperatures).

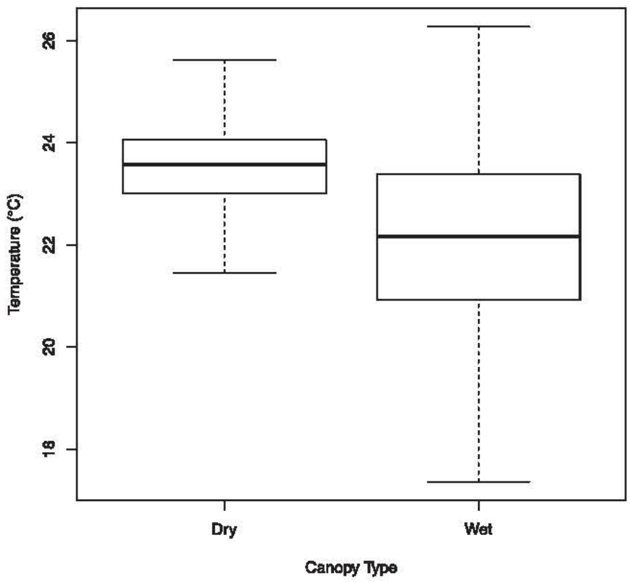

Figure 5: SBS mean temperatures (°C) combining plant replicate (P_n), observation day (D_n), measurement height (H_n) and time (t_n), grouped by M_D and M_W moisture classes

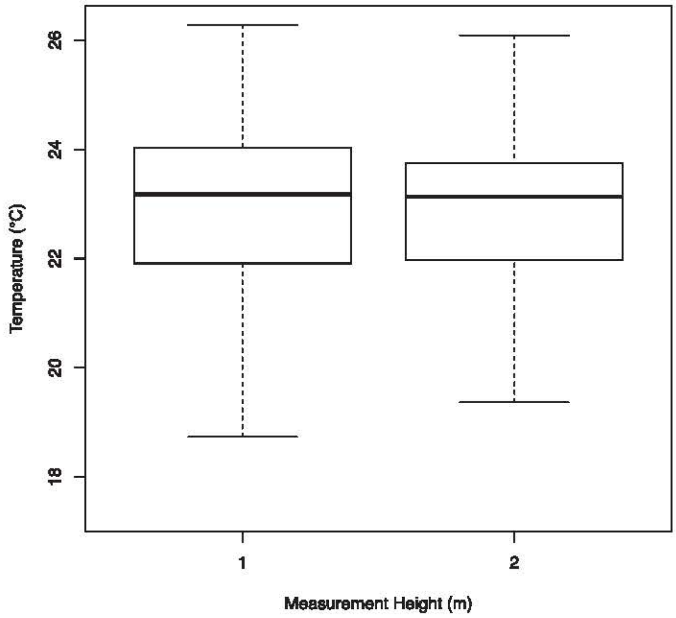

Figure 6: SBS mean temperatures (°C) combining plant replicate (P_n), observation day (D_n), moisture class (M_n) and time (t_n), grouped by H_1 and H_2 measurement heights (m)

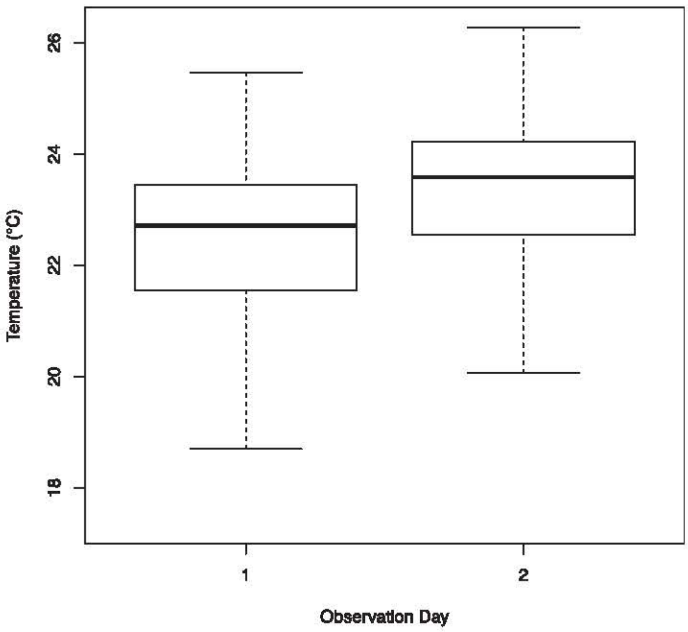

Figure 7: SBS mean temperatures (°C) combining time (t_n) plant replicate (P_n), measurement height (H_n) and moisture class (M_n), grouped by D_1 and D_2 observation days

However, when we pool the two groups, the slight differences between groups pool to characterize the overall canopy heterogeneity and is not a concern related to influencing specific measurements. Our introduction of this parameter was to incorporate the likelihood that measurements will not always be taken from identical distances, thus our pooled sample is more representative of true measurement frameworks where spatial resolutions may differ somewhat. The large number of outliers for H_2 indicates that the data is skewed toward cooler mean temperatures, since larger pixels average temperatures over greater distances and thus dampen the effect of temperature extremes. Mean temperatures were compared between observation days D_1 and D_2 (Figure 7).

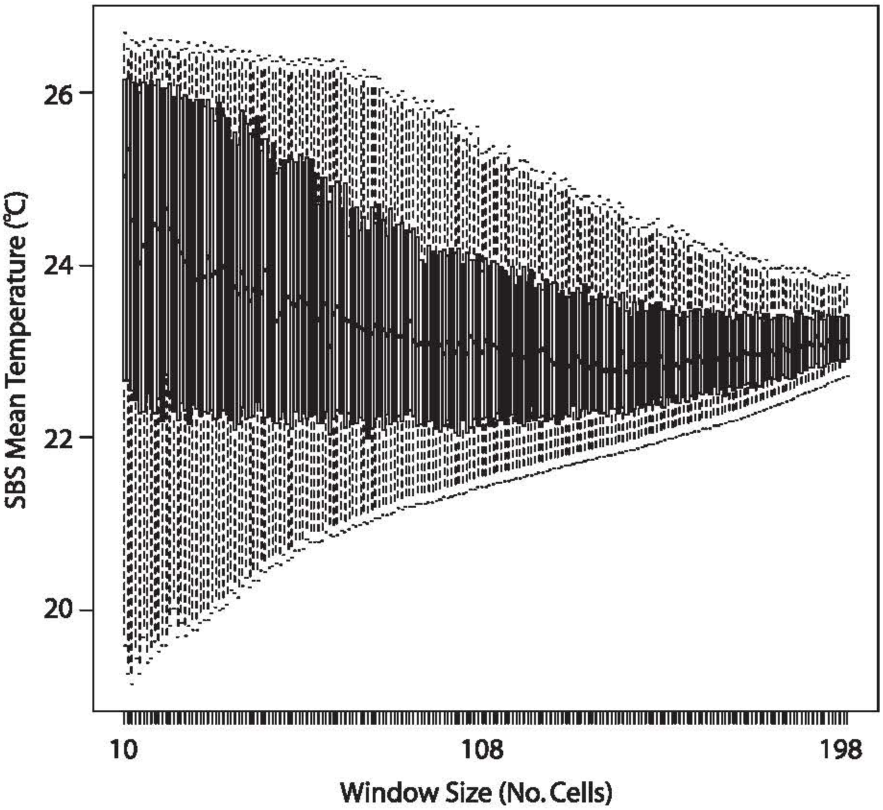

Figure 8: SBS stability with increasing sampling window size (in total number of pixels)

The box plots show cool-skewed distributions. A Student's *t*-test was significant ($p < 0.05$), indicating that mean temperatures on D_2 are warmer than on D_1. Given the number of observations made, sampling had to be conducted across two days. Since the values are significantly different, we keep them pooled for the remainder of our analysis. The additional variability again reflects the reality of data collection under slightly differing conditions. The difference is attributed to a slight difference in the ambient room temperature between the two dates of image acquisition. Since the distributions are nearly identical, a bias shift could be applied to all measurements on one day to align the two dates of measurement if this were deemed necessary in an operational sense; however, this is beyond the need of this study. As for our diagnostic test of SBS window sizes, as expected, larger windows express lower overall variability due to the averaging effect of multiple measurements, and smaller windows display greater variability (Figure 8 illustrates one example of these results). Note that the window size on the x-axis represents a total number of pixels within a SBS window (e.g., 3×3 = 9 pixel window), and since the windows in this diagnostic are not constrained to a specific wet or dry zone, they can become much larger than they could in our study. Our results indicate that a stable and optimal SBS window size, if considering the whole image collectively, would be about 100 pixels, or having a dimension of nearly half the dataset. While this acts to minimize the variability, our goal was to emphasize the heterogeneity while performing repeated sampling of subset areas for conducting statistical comparisons.

4. Discussions

Our study measured temperature differences between wet and dry plant canopies and their respective change with time using a high spatial resolution thermal camera. The goal was to capture the uncertainty of these plant canopies, guided by 3 objectives. We were able to implement a spatial repeated sampling procedure (SBS) that permitted the computation of stable mean (expectation) and variance estimates for individual and pooled treatments that could be further used for hypothesis testing between or among groups of pooled treatments or replicates. We were also able to group measurements within temporal bins and assess whether temperatures changed statistically through time, relative to the estimated uncertainty surrounding the measurements based on SBS estimates. Finally, we used this framework to conduct hypothesis tests between and among grouping variables. The SBS method develops stable estimates of temperature and the associated variability that is otherwise based on limited observations using traditional methods. The SBS method also ensures that repeated samples consider a neighbourhood of values, rather than a simple bootstrapping where random often isolated values are selected. Within the context of measuring temperature across heterogeneous plant canopies, we are able to explain the relationship between temperature, canopy wetting, and time (our surrogate for evaporation) due to our implementation of SBS. Having 5 plant replicates increased our sample size for statistical analyses and broadened the domain of canopy variability for our single species study. Statistically, results differed among some of the plant replicates; thus, grouping them provided a more robust comparison between wet and dry canopies distributed across this underlying variability. Although the plants appeared similar, their slight temperature differences reveal the inherent natural variability imposed by canopy structure (i.e., leaf angle, shading). As per our methods, using mean canopy temperatures instead of individual leaf temperatures is recommended (Fuchs, 1990 and Husband and Monteith, 1986) to mitigate the micro-architecture effects of these canopies when measured at high spatial resolution. The SBS technique is dependent on the size of the window used for the analysis, we opted to use a 3×3 pixel window because it was small enough to capture both the local heterogeneity and consistency of the canopy (e.g., random placements could be either fully within a single leaf or cross their boundaries). Furthermore, our diagnostic tests indicated that this relative window-size was suitable for making measurements to adequately capture the natural variability in plant canopy structure. The mean temperature between the smallest SBS window and the optimal is less than 1°C and the characterization of variability differs only by a fraction of a degree; thus our implementation of a 3×3 SBS window does not bias results substantially, but does capture the inherent variability within the canopy. This natural variability is reinforced by the differences among the replicate plants and ensures broad control of this aspect, permitting statistical differences in temperature to accurately reflect the influence of moisture rather than canopy architecture. The wet and dry surface temperatures differed as expected; however, the mechanisms controlling the difference varied. The large temperature variability for the wet surface is primarily a result of the uneven distribution of water to the surface (e.g., like a rain event) leaving areas of the plant having more water than others and thus evaporating at different rates (Siu, 2013). Recall that when a plant is wet and is exposed to a source of heat, evaporation will occur; the process by which energy is supplied to a surface in the form of latent heat to vaporize the water into a gas allowing it to escape to the air layer above the surface. Greater volumes of water on a surface take longer to evaporate; therefore, if the distribution of water is uneven on the surface of the plant, then the distribution of latent heat will also vary, increasing the spatial variability of sensible heat. Our use of a small SBS window allowed us to capture the local heterogeneity due to the variability in canopy water content; dry surface temperatures are less variable than those to which we added water. We discovered that the natural heterogeneity of a dry canopy presents less temperature variability than a wetted canopy. Changing the height of the camera to the target was intended to show that as the camera got further away the plant temperature and variability would decrease due to a coarsening of the spatial resolution and a relative dampening (averaging) of temperatures over a wider area. Basically, raising the camera increases the distance between the camera and the target, but the fixed IFOV angle and numbers of image rows and columns, will create a coarser recording of surface temperatures (larger target areas will be integrated to form the recorded thermal measurement recorded at each pixel). At coarser spatial resolution, the surface characteristics become increasingly homogenous as local detail becomes reduced. This relationship was in fact observed as a statistically significant result, driven primarily by low temperature outliers in H_2, indicating that the SBS method sometimes captured anomalously low temperature pixels within windows containing primarily higher temperatures (an effect of the variable wetting). The change in detail will alter the observed (or measured) temperatures, and the construction of variability ranges with SBS; it is therefore important to be aware of the spatial resolution of observation when interpreting measured temperatures. The rate of temperature change of our wetted canopy is controlled primarily by the rate of evaporation. Under sunny cloudless conditions, evaporation is optimized and thus other factors such as wind and stomata conductance will impact the evaporation rate; however, in our study the evaporation process was controlled, where wind speed and room temperature was held constant and light levels were not altered. Having constant illumination ensured that plant stomates remained open allowing water to be transpired and evaporated and hence would only close if water stressed. The first half of our experimental period shows larger temperature variability due to the dominant presence of water on the plants, while during the latter part of the experimental period, the variability is reduced during drier conditions. The overall warming trend over the treatment period indicates that the intercepted water was evaporating. Conversely, the stabilizing temperatures towards the end of the treatment period imply that evaporation diminished and the vapor pressure deficit reduced, reaching a localized equilibrium. The scale of measurement and analysis in this study is quite fine, encompassing spatial resolutions on the order of millimeters to less than 2 cm. While the mean temperatures and uncertainties obtained in this study cannot be appropriately extrapolated to the scale of airborne or space-based platforms (primarily given the scale of the targets observed), the methods could easily be implemented on data from such sources to assess the spatial uncertainty of such measurements. The notion that measurements vary across a heterogeneous surface leads to a measure of variability that can be assessed using SBS to explore the underlying processes that govern the patterns observed; we make no claims that the measurements made at one scale can be easily scaled to those made at another spatial resolution. Our controlled experimental design permitted the analysis of specific elements of thermal measurement and assessment without dealing with atmospheric effects or the reality of mixed pixels, primarily to illustrate the potential of the method. Our diagnostic test further indicates that large numbers of pixels comprising SBS windows lead to more stable estimates. Thus, to scale our method to airborne or space-based platforms we suggest that the number of pixels representing the observed plant (e.g., tree) canopy be comparable to those used in our study to ensure that representative and stable measurements of temperature and its variability are obtained.

5. Conclusions

The relationship between temperature and plant-water status was explored in this study, specifically from the perspective of canopy heterogeneity and its role in temperature distribution and measurement. Our study measured the surface temperatures of plants under wet and dry conditions in order to explore the absolute differences in canopy temperature due to the addition of water and to understand the variability in these measurements. We were able to track the change in temperature through time and to recognize the lag until canopy temperatures return to dry equilibrium. We determined that the allotted time for each treatment successfully captured the evaporation of water from the wetted canopy and revealed that by about the 25 minute mark, evaporation had diminished, allowing temperatures to reach a localized equilibrium. Our goal of assessing of the differences in mean temperatures between wet and dry canopies indicated that wetted plant surfaces have greater temperature variability than the natural heterogeneity revealed when the same surface is dry. The SBS method was able to characterize the local heterogeneity due to the variability in canopy water content as a result of the uneven distribution of water on the surface. Our study was successful in exposing the slight inter-plant variability in canopy architecture among our plant replicates under wet and dry conditions. The difference in surface temperatures among the plant replicates inferred that the observation of temperatures is influenced by the inherent variability imposed by plant surface structures. Our results indicate that there is a small influence on temperature measurement due to a change in spatial resolution. Our expectation was confirmed; a coarser spatial resolution will yield a greater local homogeneity and thus the increased smoothing will provide lower temperatures. Mean temperatures between the two measurement heights (different spatial resolutions) were statistically different, though the mean values were very close; the variability in the distributions was greater with higher spatial resolution. The increased homogeneity of the coarser spatial resolution yielded a tighter range of temperature variability because there were more low-temperature outliers where individual cooler pixels were encountered by the random window placement by the SBS method. Finally we constructed expectation ranges for canopy temperature using the spatial bootstrapping methodology (depicted by boxplots) for data partitioned by time (t_n), plant replicate (P_n), measurement height (H_n), moisture class (M_n), and observation day (D_n).

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