Technical Paper for 2018 Irrigation Show & Education Conference

Title: Using Persistent and Autonomous Thermal and Visual Image Data to Measure Stress and to Know; Where, When & How Much Irrigation Water to Use

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ABSTRACT

Using persistent thermal and visual image data to measure the turf canopy it is possible to enable the turf to tell you about the stress it is experiencing and its water status.

When scouting for stress one is looking for deviations in the canopy where the quality is not up to desired standard. Homogeneity of the turf's canopy is key. When assessing the need for irrigation the turf's irrigator may be using one of three operationally feasible methods of assessing the need for applying water; using an evapotranspiration equation, using a network of soil moisture sensors, or by seat-of-the-pants. Evapotranspiration calculated from observations from a weather station and applied to the turf by a turf coefficient. It is an estimation of the water used by the turf so one can know how much to irrigate. Soil moisture sensors measure the water in the soil so one can know, based on the fidelity of the network, where and how much to irrigate. Seat-of-the-pants is the art of looking at and touching the turf, then applying one's intuition and experience to know when and where to irrigate.

Persistent visual and thermal image data processed to illuminate changes in canopy vigor and canopy temperature is a tool to enhance and extend seat-of-the-pants methodologies.

Key Words: remote sensing, image data, visual, thermal, transpiration, turf quality, turf stress, scouting, irrigation, plant thermography, quality index, stress index, irrigation index,

Note: All Figures are included in Appendix A at full size.

Background

Visual Image Data and its Application for Indexing Turf Stress

Karcher and Richardson (2003) and others, found that an analysis of a digital visual image (400 – 700 nanometers) provides a reliable method to measure the reflectance of color from vegetated surfaces. The digital camera measures the hue degree of the turf (Figure 1). This hue measurement of the turf canopy can represent the homogeneity

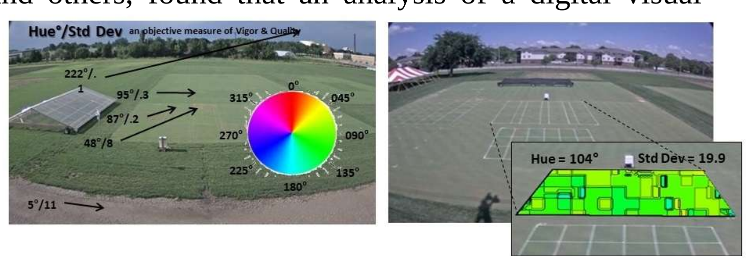

Figure 1. Hue (color) & Standard Deviation of Hue

of the turf color when an area of interest is processed to show the average hue value (the hue degree of each pixel contained in the designated area is measured) and the standard deviation of the average hue value. For that turf surface it is a representation of the turf's vigor and quality. The lower the standard deviation, the better the quality. When a 'typical' value is established a change in the deviation illuminates a change in vigor which is directly related to health. Another indicator of a decline in vigor is a change in the hue degree out of the range of green toward yellow and brown. See the color wheel shown in Figure 1.

This Hue/Std Dev value calculated at every image data collection may also be known as a Quality Index. The Daily Visual or Quality Index (QI) is the average of the standard deviation of the hue, +/- one hour of solar noon; or for 2 hours of no shade during a 'bright' part of the daylight hours.

Thermal Image Data

Using a radiometric thermal image (8,000 – 13,500 nanometers) it is possible to measure the temperature of the turf's canopy. Turf photosynthesizes during daylight hours and respires during nighttime. Both processes release water vapor as a byproduct and the evaporation of that water vapor is a cooling agent (see Figure 2). The observation of the temperature

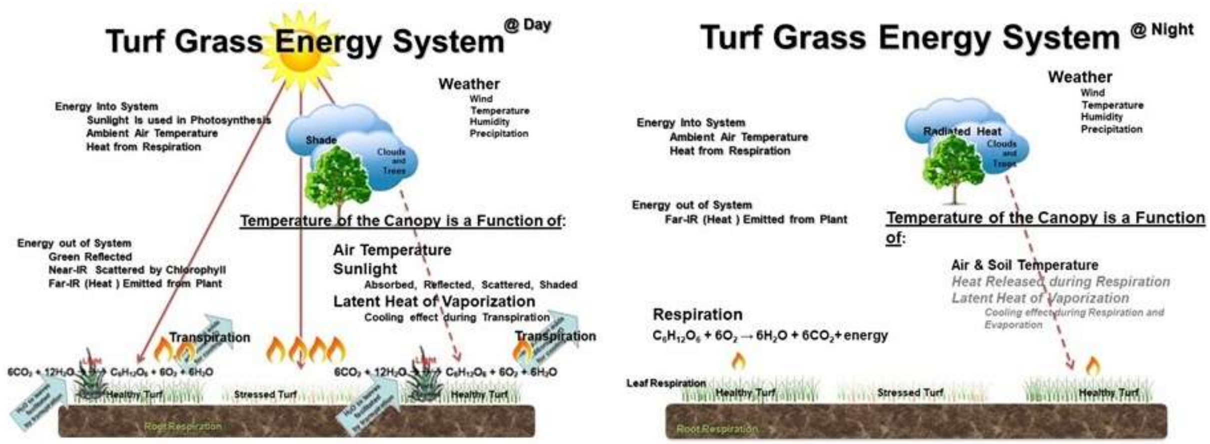

Figure 2 a&b. Turfgrass Energy - Day & Night

across the extant of the turf can indicate locations where stresses may be occurring(Figure 3). Because this cooling process, which is very evident during daylight hours, especially in direct sunlight, can highlight areas of disease, pest, and/or water status stress. This is also valuable tool when evaluated at night because although the variances of the surface temperature are small, radiometric imagers can see and measure those differences so that non-homogenous areas can be evaluated for drainage patterns and/or disease and pest issues.

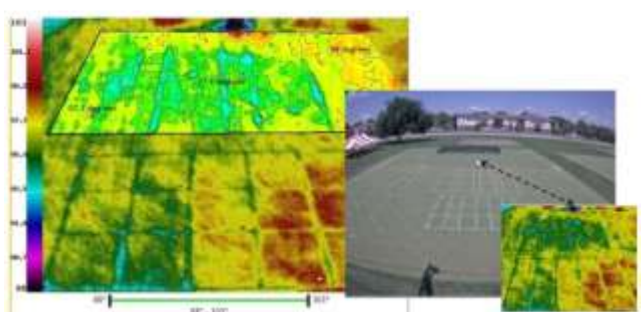

Figure 3. Thermal Image Data

The video record found at https://vimeo.com/269639967 demonstrates this use of nighttime thermal image data to locate the extant of winterkill of a warm season turf two months before green-up of the turf.

Applying Thermal Image Data for Indexing Turf Stress

Jackson *et al*. (1981) appreciated that the canopy to air temperature difference ($T_{canopy} - T_{air}$) depends on vapor pressure deficit (VPD): under non-limiting water conditions, a healthy crop transpires at the potential rate (i.e. evapotranspiration is the maximum it can be, but maximum evapotranspiration increases with increasing VPD). Thus, for several crops, when crop health and water availability is not limiting and when measured under clear sky conditions, there is a linear relationship between $T_{canopy} - T_{air}$ and VPD. Jackson called this linear relationship the theoretical 'nonwater-stressed baseline' (nwsb). For a given crop, at a given VPD, this theoretical baseline provides the minimum possible value of $(T_{canopy} - T_{air})_{nwsb}$. The $T_{canopy} - T_{air}$ for a non-transpiring crop is insensitive to VPD and can be estimated if wind speed and net solar radiation are known. This sets the 'upper limit' (ul) to $(T_{canopy} - T_{air})_{ul}$. Jackson *et al*. used the idea of 'upper and lower' baselines, to create a crop water stress index (CWSI). The CWSI = $(T_{canopy} - T_{air}) - (T_{canopy} - T_{air})_{nwsb} / (T_{canopy} - T_{air})_{ul} - (T_{canopy} - T_{air})_{nwsb}$: where $T_{canopy} - T_{air}$ is the measured difference in temperature, $(T_{canopy} - T_{air})_{nwsb}$ is the estimated difference at the same VPD under non-limiting water conditions (on-waterstressed baseline), and $(T_{canopy} - T_{air})_{ul}$ is the non-transpiring upper limit. This CWSI allows one to relate crop's temperature to the maximum and minimum values possible under similar environmental conditions. The higher the CWSI, the greater the crop stress is assumed to be.

A disadvantage of the above form of CWSI is the need to determine the non-water-stressed baseline by plotting $T_{canopy} - T_{air}$ against VPD. This requires substantial time to be spent determining the baseline for a well-watered crop, and the VPD needs to be known when measuring T_{canopy} of the crop of interest. Also, this index does not account for changes in T_{canopy} due to irradiance and wind speed, and the non-water-stressed baseline is not necessarily the same under different radiation conditions. Finally, the non-transpiring upper limit also varies, with a wide range of values (Ben-Gal *et al*., 2009).

Establishing a Stress Index from empirical observations of the upper and lower limits is possible by understanding that transpiration is a key measurement and applying thermographic techniques to the image data. Experience gained by observing the canopy temperature shows that it is possible to make the canopy temperature an indicator of transpiration and respiration. During the day evaporation of the transpired water vapor cools the leaf/canopy. At night one can see the heat from respiration, transpiration, and evaporation of the near surface moisture. Thus, the turf's canopy temperature is the biotic integrator of the air temperature, humidity, wind, solar radiance, and the turf's health and water status.

More than six years of observation has demonstrated that an equation of the form similar to one outlined by J. Miguel Costa *et al.* (2013), addressing plant–environment interactions is a superb indicator of the stress experienced by turf. By using a thermal imaging data system co-located with a weather station to persistently measure canopy temperature and air temperature it is possible to observe/measure an upper limit and lower limit of water vapor released during transpiration. This Stress Index is used:

$$\mathbf{(SI) = (T_m - T_{LL})/(T_{UL} - T_{LL})}$$

$\mathbf{T_m}$ = canopy temperature minus air temperature measured at image data capture time.

$\mathbf{T_{LL}}$ {non-stressed condition} = early daylight canopy temperature minus air temperature

$\mathbf{T_{UL}}$ {stressed condition} = most stressed part of the day canopy temperature minus air temperature

An index value (SI) is calculated over designated areas every image and the Daily Heat Stress Index is the average of the daylight Image Indexes. When normalized by a running average of the T_{LL} and T_{UL}, it can become a reliable, disciplined, and repeatable indicator of turf health and water status; and it informs the accumulated stress of the day.

Figure 4 is a chart depicting the Image Stress recorded approximately every 10 minutes during the day at three different areas on a golf course green.

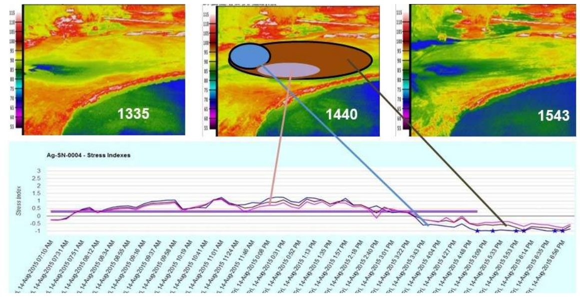

Figure 4. Image Stress at Ten Minute Intervals

Smart Irrigation Month Demonstration

To celebrate Smart Irrigation Month in July 2018, we established a demonstration to look at the application of irrigating simulated reclaimed water versus fresh well water on turf. The reclaimed water vs fresh well water demo was extended into August and an evaluation of the Irrigation Index under long rainy and mostly cloudy conditions was undertaken.

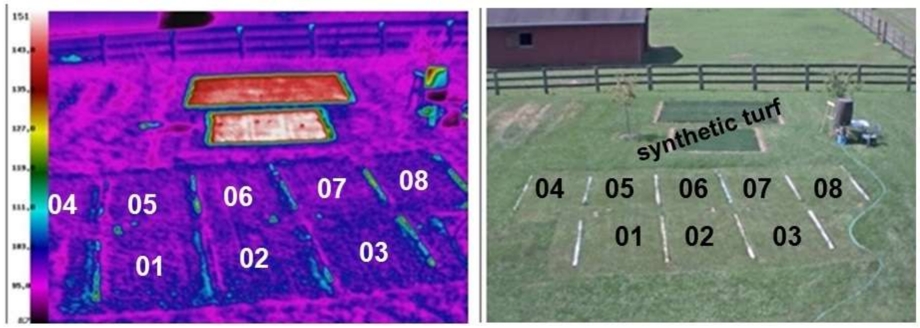

Figure 5. Demonstration Plot Lay-Out

In late June eight plots were established (Figure 5) on a predominately tall fescue area. In June, July, and August, weeds and crabgrass were pulled by hand to keep the plots weed free and ensure a homogenous canopy of turf. As the summer progressed bermudagrass progressively encroached into plots 07 and 08. By late August plot 08 was 50% tall fescue and 50% bermudagrass, plot 07 was 70% tall fescue and 30% bermudagrass[1]. The height of the grass in all the plots was maintained at 0.8" – 1.2", through the demonstration period. The longer cut area around the plots was loosely maintained at 2" – 3".

The summer of 2018 in Northern Virginia, was unusually wet, and the solar radiance due to the cloud cover was less than usual. Typical July-August precipitation would total 8″, and the average solar radiance would be about 240 watts/meter^2/24hrs. During June the plot area received 7" of precipitation. During July rainfall was 13" and the average solar radiance was 209 watts/meter^2/24hrs. August rainfall was 5.8" and the average solar radiance was 180 watts/meter^2/24hrs. Figure 6 plots the July August irrigation and rain events.

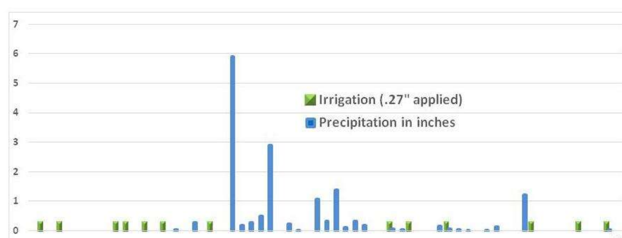

Figure 6. July through August Irrigation and Precipitation

[1] A study of Plot 08 from the August image data will be undertaken at a later date to investigate the difference in hue between the tall fescue and the bermudagrass.

During July, plots 02, 05, and 07 were irrigated with .27 inches of 0.3% brackish water (table salt + well water); plots 01, 03, 04, 05, 07, and 08 were irrigated with .27 inches of untreated well water. Then between July 22 through August 5th, more than 13" of rain fell. During August, plots 02, 05, and 07 were irrigated with .27 inches of 0.6% brackish water (table salt + well water); plots 03, 07, and 08 were irrigated with .27 inches of untreated well water. Irrigation was not applied to plots 01 and 04.

Results of the Visual Image Data Analysis

Results are highlighted by the charting of the data taken from Plot 02 (irrigated with brackish water to simulate reclaimed water) and Plot 06 (irrigated with fresh well water).

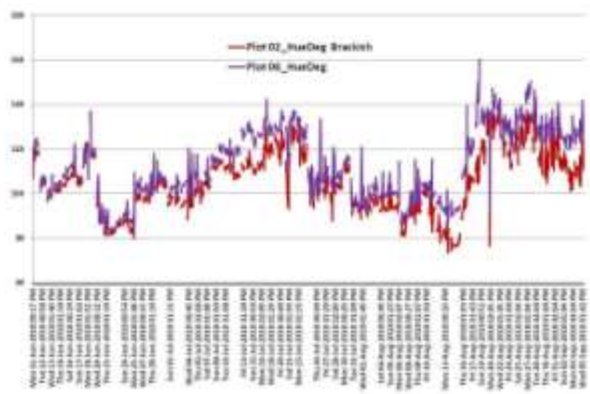

Figure 7. Hue Degree (color); Brackish versus Fresh

"Eye-balling" the plots during July, there was no evidence of declining quality or increased stress in the plots irrigated with brackish water and it was judged that .03% brackish application wasn't enough to get results in a short period of time. It was also assumed that the 22 July - 05 August, rain flushed the brackish remnants out of the root zone. Because there was no detected decline in the turf quality where the brackish water was applied in July, the brackish solution was increased to.06%. Note that during the period leading up to the application of the two different irrigation prescriptions the hue (Figure 8) and deviations of the hue (Figure 8) are very close. Then when the prescriptions, starting 02 July, are applied the data diverges until the rainy period flushes the root zone and the quality and deviation of quality converges again.

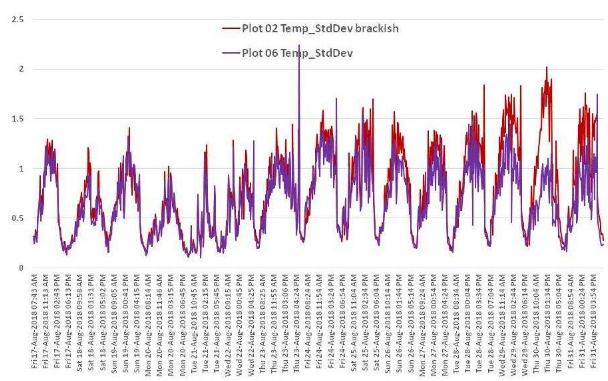

Figure 8. Standard Deviation of Hue; Brackish versus Fresh

In July, had the visual image data been closely examined and an alert for changes in hue deviation been set into the Hawk-Eye™ collection system rather than waiting until September to start organizing the data for this paper, it could have been established that the .03% brackish solution was working. Hawk-Eye™ saw what the eye missed. There was a decrease in quality as evidenced by a slight decline in hue (Figure 7) and an increase in the deviation of the hue (Figure 8).

Then in the August the plots under the .06% prescription a deeper anomaly appears. Starting on 18 August, although the hue (Figure 7) declines in Plot 02 (brackish), the standard deviation of the hue (Figure 8) in plot 06 increases significantly. Brown patch (Figure 9) was the cause of the decline in quality in Plot 06 and it was evident in all the plots irrigated with fresh

Figure 9. Brown Patch in Plot 06

water. In Plot 06 the infection covered approximately 5% of the surface area. Of interest is that the plots irrigated with brackish water and taking the precipitation, showed no signs of brown patch and all the areas near the demo plots (no other locations were irrigated at any time during the summer) showed an indication of disease.

Results of the Thermal Image Data Analysis

Due to a calibration issue and need for a firmware update in the radiometric camera no temperature retrievals where collected and archived until August. Figure 10 is a chart of the average canopy temperature in Plot 02 (brackish) and Plot 06, from 17 through 31 August; And a chart of the standard deviation of the average canopy temperature of the plot. Note that Plot 02 (brackish) is warmer than Plot 06 and it also has a slightly higher standard deviation of its average temperature. This becomes more evident after 22 August when the rain events ended for the month.

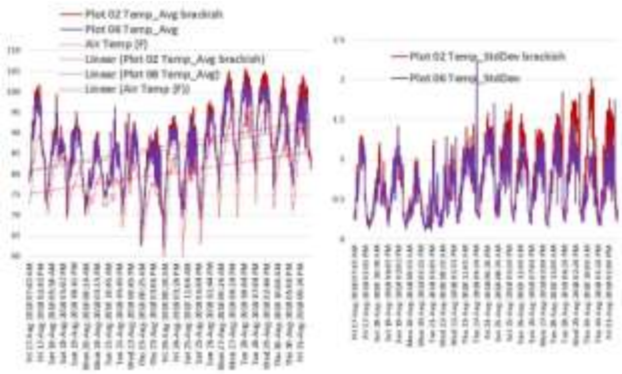

Figure 10. Canopy Temperatures vs Air Temperature; and Standard Deviation of the Canopy Temperatures

Since Plot 06 was infected with brown patch it was assumed that the canopy temperatures would have been higher than Plot 02 (brackish). However, this was not the case. It appears that the .06% saline solution irrigated over the whole Plot 02 was more effective in reducing the hue and interrupting transpiration[2]; thus, causing a loss in evaporative cooling and a relative increase in temperature. As the brown patch grew the temperature difference and the difference in standard deviations grew. But the average heat profile in the infected patch remained cooler and had lower variability from the average than the salt stressed plot.

Using Canopy and Air Temperature to Gage Turf Stress (Stress Indexing)

In calculating the stress experienced by the turf we persistently, day and night, measure the turf's canopy temperature and the local air temperature. The Stress Index equation is used:

$$(SI) = (T_m - T_{LL})/(T_{UL} - T_{LL})$$

T_m = canopy temperature minus air temperature measured at image data capture time

T_{LL} {non-stressed condition} = early daylight canopy temperature minus air temperature

T_{UL} {stressed condition} = most stressed part of the day canopy temperature minus air temperature.

From every thermal image data set (typically every 10 minutes) an "Image Index" is calculated. At the end of daylight, the Image Indexes are averaged to establish the "Daily Index". Image Indexes are used to track and report stressing events during the day and the Daily Index relates the turf's experience through the day and provides a measure of day-to-day health. The Daily Index can also inform the need for irrigation. Figure 11 is provided to show the Image Index and Daily Index of Plots 02 and 03 between 20-30 August. Figure 12 shows the upper level (UL) and lower level (LL) of stress plotted against air temperature and the water (precipitation and irrigation) introduced between 17-30 August.

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[2] The relationship of the hue degree to the turf cultivar and the amount of chlorophyll is a question for a more detailed study.

In figure 11, note the response of the canopy temperature to the air temperature and the solar radiance. On several days the canopy temperature declines as the solar radiance and the air temperature increases. This is unusual and may be due to the unusually wet and partly cloudy to mostly cloudy days during the summer. Typical daily profiles in dryer summer conditions look more like 23 August than 24 August. In Figure 12, note the response of the T_{UL} and T_{LL} of the turf to the trend of the temperature and solar radiation and the water introduced. After the very wet summer and then the rain events of 18-22 August, the temperatures and the solar insolation are low. This keeps the daily stress low and because the calculation of the Upper Level of stress is a running average over several days it biases the Stress Indices to lower values than may be expected. Note the high number of Image Indexes below zero and the very low Daily Index of .06 on the 28th of August. On 29 August the Daily SI snaps back to higher values (although not exceeding an irrigation demand threshold after daylight on 28 August.)

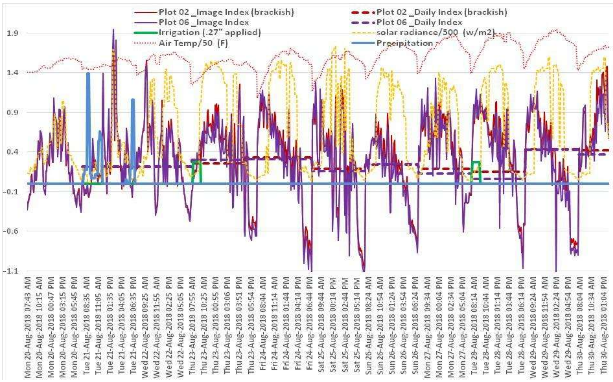

Figure 11. Stress Indexing (Image and Daily) with Air Temperature and Solar Radiance and Irrigation

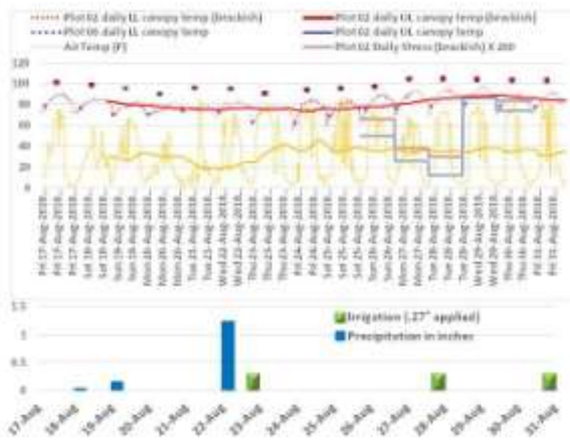

Figure 12. Daily T_{LL} and T_{UL} with Precipitation and Irrigation

Need for Persistence of Image Data

The video record summarized in Figure 13 and detailed at https://vimeo.com/269639967, demonstrating use of nighttime thermal image data to locate the extant of winterkill, also highlights an important consideration when using any types of image data for turf management. That is the need for frequent persistent image data records. It is important to have an understanding of patterns noted in the imagery because occasional (even daily) snapshots of data make it impossible to recognize persistent patterns and may lead to an incomplete understanding of the condition of the turf. Figure 14 illustrates the variability of the thermal character of over a short period (30 minutes) of time. Settling on any one image as a starting point for scouting may lead one to confusion and a poor conclusion regarding actions that may be needed, or not.

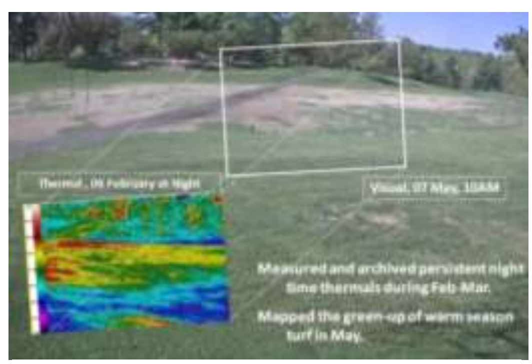

Figure 13. Using Nighttime Thermal to ID Winterkill

When using image data for assessing plant water status and guiding irrigation it is necessary to consider continuous image data measurements over the course of the daylight hours, and for several consecutive days, to achieve good results.

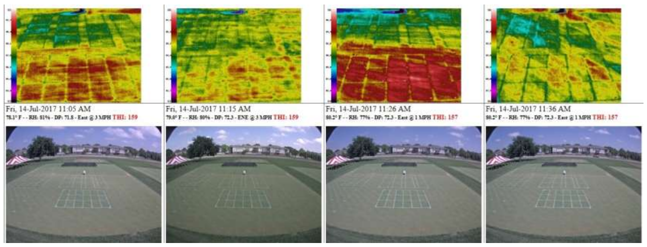

Figure 14. Image Data Time Series

By measuring hue (color) and the temperature of the canopy with a persistent (24/7/365) visual and thermal image data system (a Hawk-Eye™ Remote Sensing System), applying experience and intuition in intelligence algorithms, and by exploiting the Internet-of-Things; the turf can give its voice to when and where it is being stressed, and when and where it wants water.

Irrigation Guidance:

The turf's canopy temperature is the biotic integrator of the air temperature, humidity, wind, solar radiance, and the turf's health and water status. The visual Quality Index and the thermal Stress Index puts a disciplined measurement on the health and water status.

The Daily Irrigation Index threshold is the index value where the plant indicates it needs water. The Prescription is the amount of water the plant is given during the evening after it says it needs it. There are periods where the Irrigation Index may call for the Prescription two or three evenings in a row or it could go six or more days before water is called for by the plant.

The Daily "Irrigation Index" is a function of the Quality Index (QI) and the Daily Stress Index (SI) described in the Visual Image Data and the Applying Thermal Image Data for Identifying Turf Stress sections of this paper. The greatest weight is given to the Daily SI and the QI is used as a cross check when there have been long periods of rain, cool air temperatures, and frequent cloudy sky conditions.

A Hawk-Eye™ System will inform the user when the Indices exceed the threshold set for irrigation guidance. This index result is available 10 minutes after sunset and can be reported via internet in e-mail and to mobile devices by SMS text. Figure

When the Daily Irrigation Index crosses the plant's threshold that day, irrigation is applied in a predetermined amount. The amount is a constant (i.e. the same amount all season) that is specific to the location and it is based on a typical amount of irrigation that might be applied. Daily Irrigation Index measurements continue every day and the next day the Irrigation Index crosses the threshold the water is applied again.

Figure 15 shows the results of an experiment conducted in the mid-west during July 2017. Twelve plots were irrigated with four different prescriptions. Three plots received 100% replacement according to calculated ET. Three plots received 80% replacement according to calculated ET. Three plots received 0% replacement. Three plots received irrigation guidance according to the Hawk-Eye™ prescription.

Plots	17-25 July 2017 Total Inches of Water [illegible]	ET [illegible] recommendation	Turf Quality [illegible]
100% Replacement	4.065"	[illegible]" 51% Reduction over ET Recommendation	7
50% Replacement	2.441"		7
0% Replacement	0.160"		1
Hawk-Eye™ Stress Index	1.585"		7

Figure 15. Variable Irrigation of Plots and Resulting Quality

Summary

Using persistent thermal and visual image data to measure the turf canopy it is possible to enable the turf to tell you about the stress it is experiencing and its water status. This image data, processed to illuminate changes in canopy vigor and canopy temperature, is a tool to enhance and extend a person's senses and their knowledge and experience base.

The Irrigation Month Demonstration to observe and measure the impact of irrigating plots with simulated reclaimed water versus fresh well water on turf went very well despite the wet and could cover. It was shown that one can use a visual image data Quality Index to observe and quantify the impact of using reclaimed water and see when the reclaimed water has been flushed through the root zone. With respect to applying the Stress Index for irrigation guidance we saw that although it is a reliable tool in dry hot climates some work needs to be done to make it work better in more temperate climate where there may be long periods of precipitation and cloud cover.

The original development of the Hawk-Eye™ SI and Irrigation Index discussed here-in was accomplished with image data and meteorology observed and collected from fields, turf plots, and golf courses in California and the mid-west during more than ten summer seasons. That hot dry climate is very different than the mid-Atlantic climate that the demonstration described in this paper was observed in. During the Smart Irrigation Month Demonstration the weather was unusually wet, and the solar radiance due to the cloud cover was less than usual. Because of these factors the turf's demand for water was very small. During August the Hawk-Eye™ System's measure of the turf only called for irrigation (0.27") one day.

As noted in the section "Using Canopy and Air Temperature to Gage Turf Stress (Stress Indexing)" there were some surprising (to me) results and it illuminated the need to factor into the Stress Index to account for long periods of frequent precipitation and mostly cloudy sky conditions.

During this winter season we will evaluate the simple running average calculation that is used to establish the Upper Level of stress with an objective of maturing the algorithm to perform better in wet and cloudy environments.

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Figures

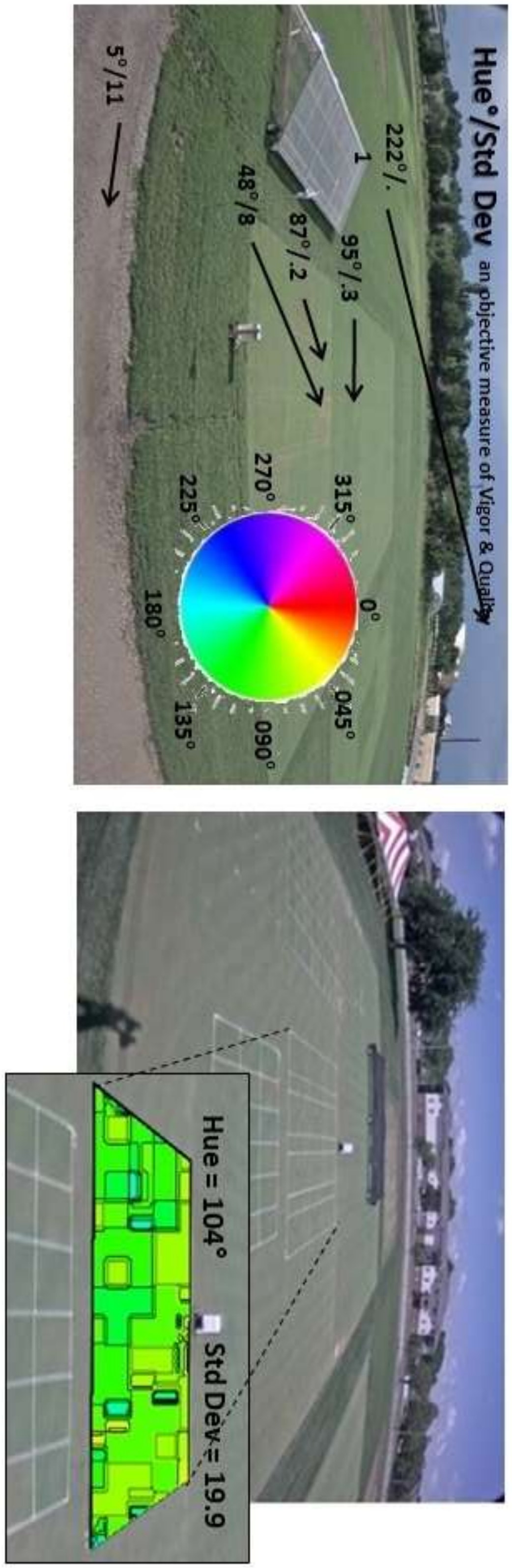

Figure 2. Hue (color) & Standard Deviation of Hue

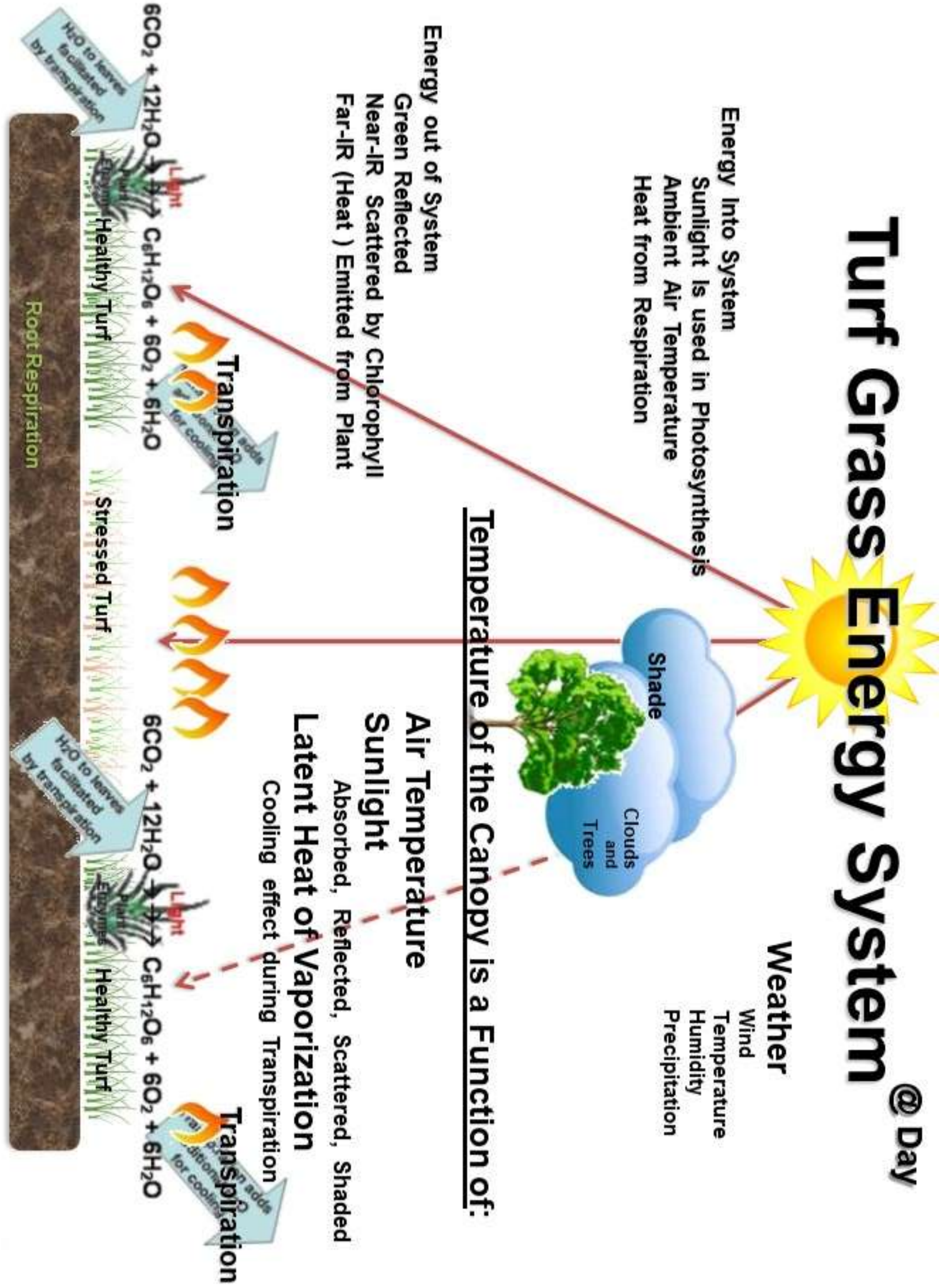

Figure 2a. Turfgrass Energy - Day & Night

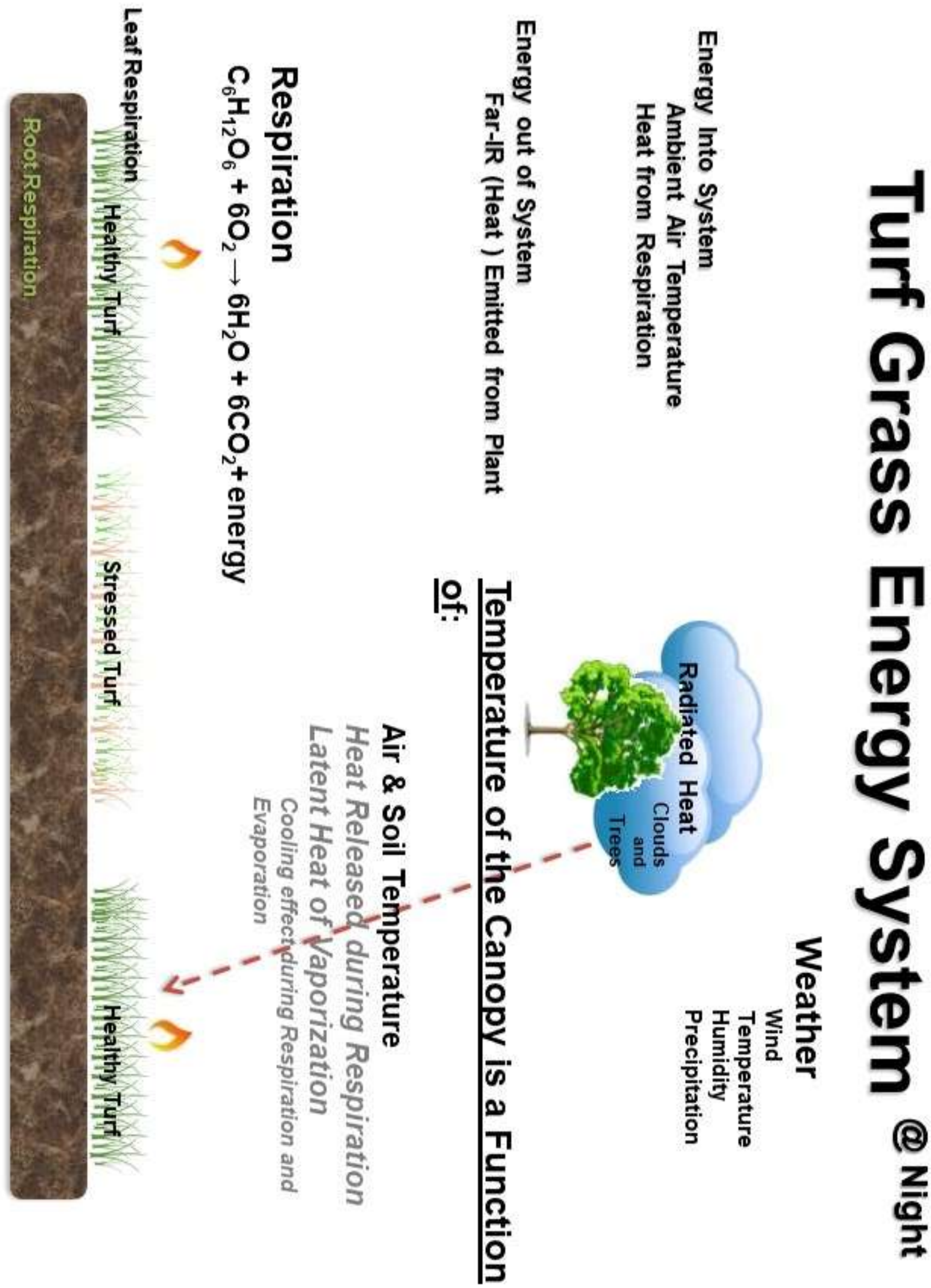

Figure 2b. Turfgrass Energy - Night

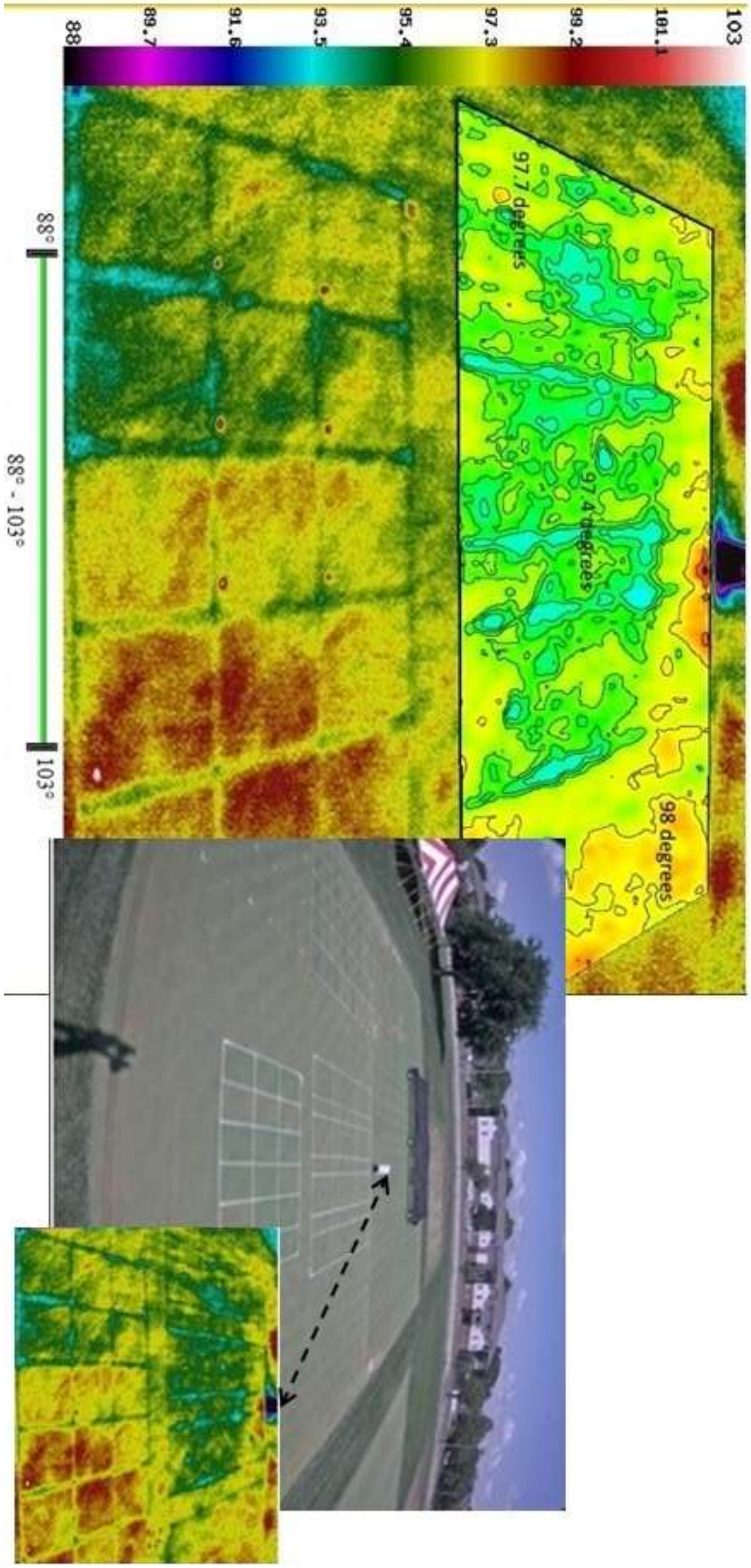

Figure 3. Thermal Image Data

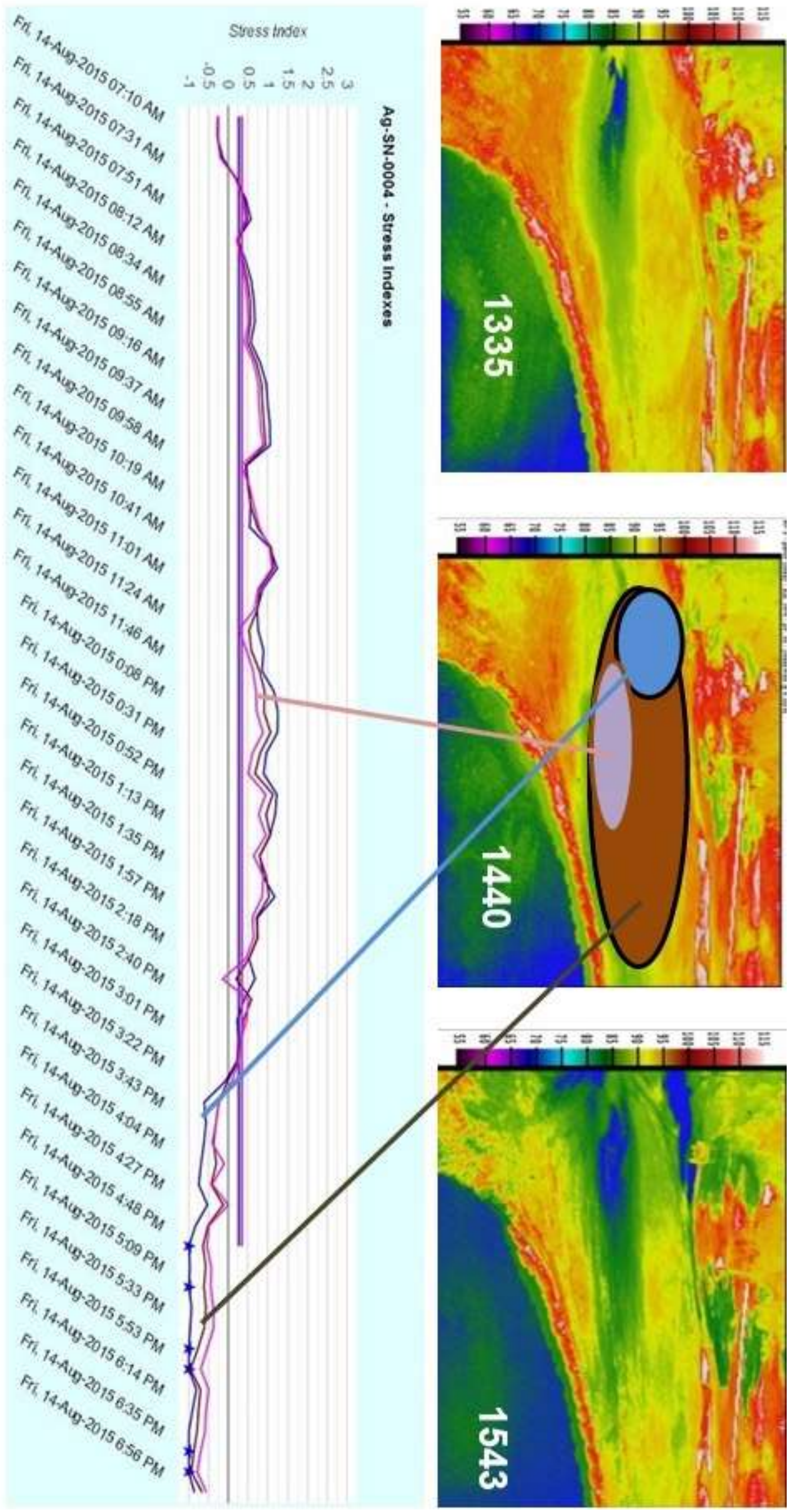

Figure 4. Image Stress at 10 Minute Intervals

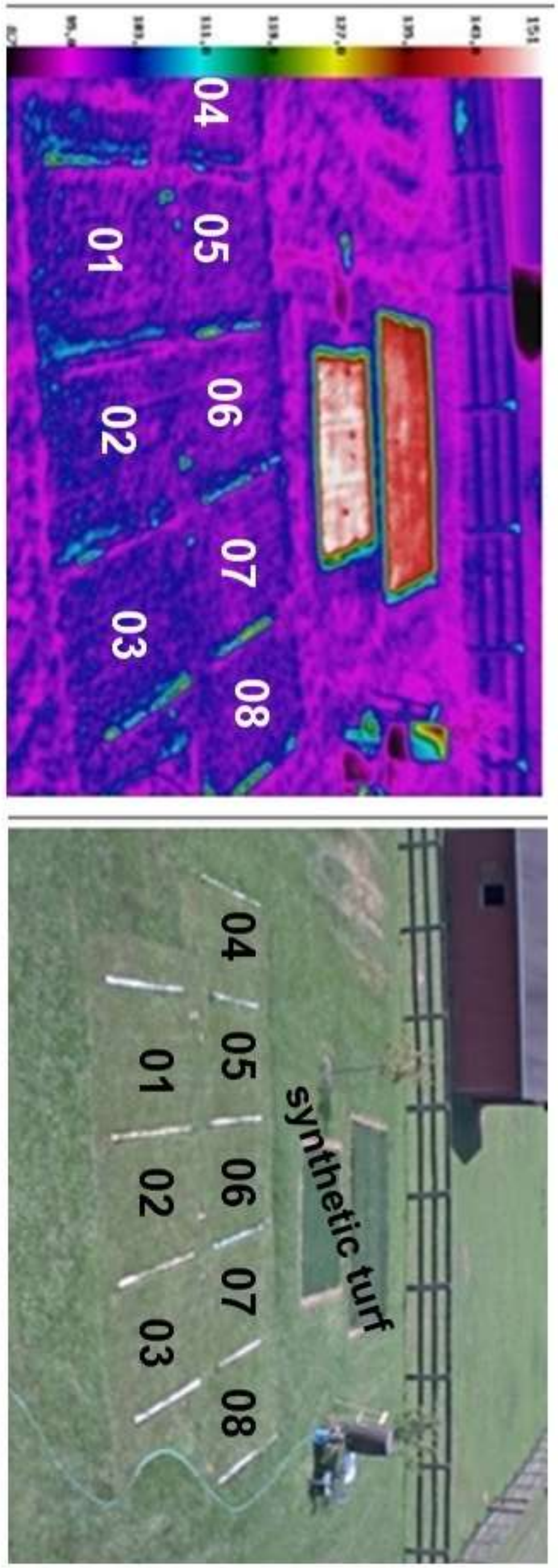

Figure 5. Demonstration Plot Layout

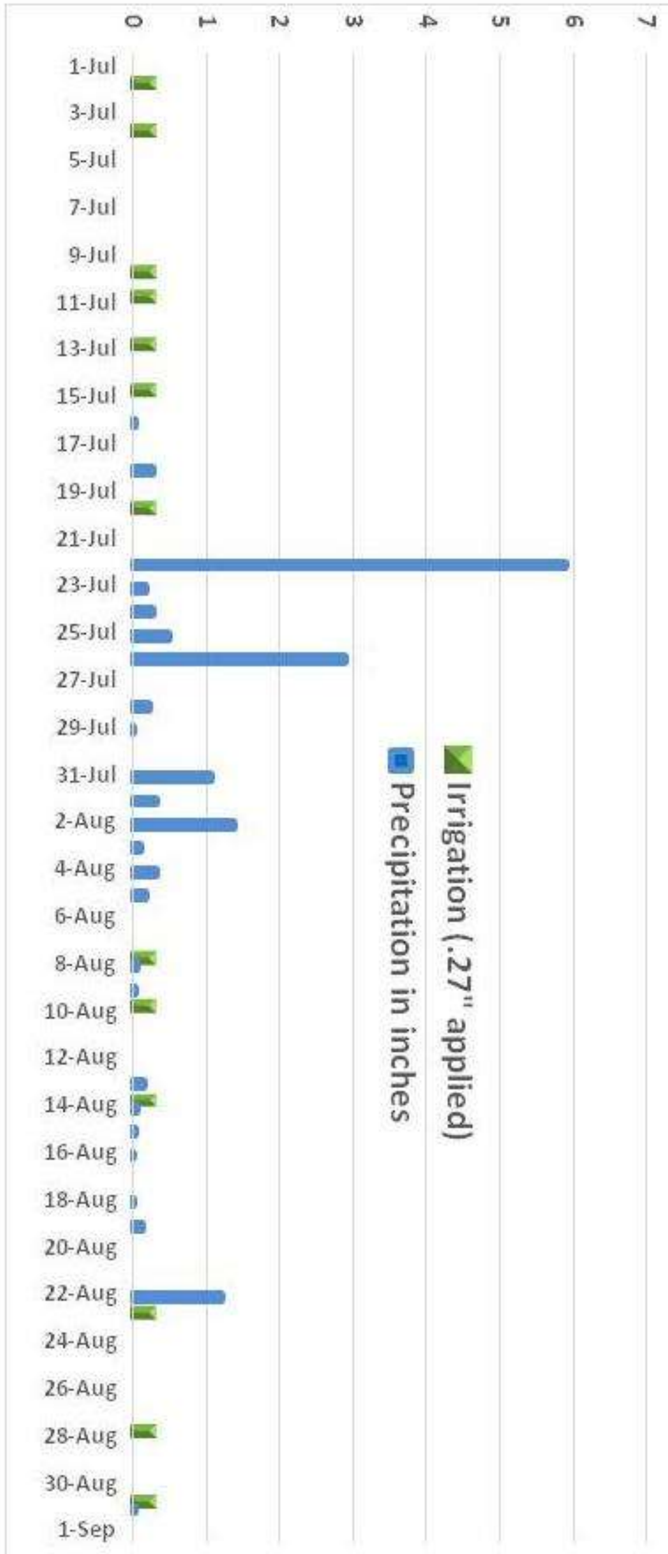

Figure 6. July through August Irrigation and Precipitation

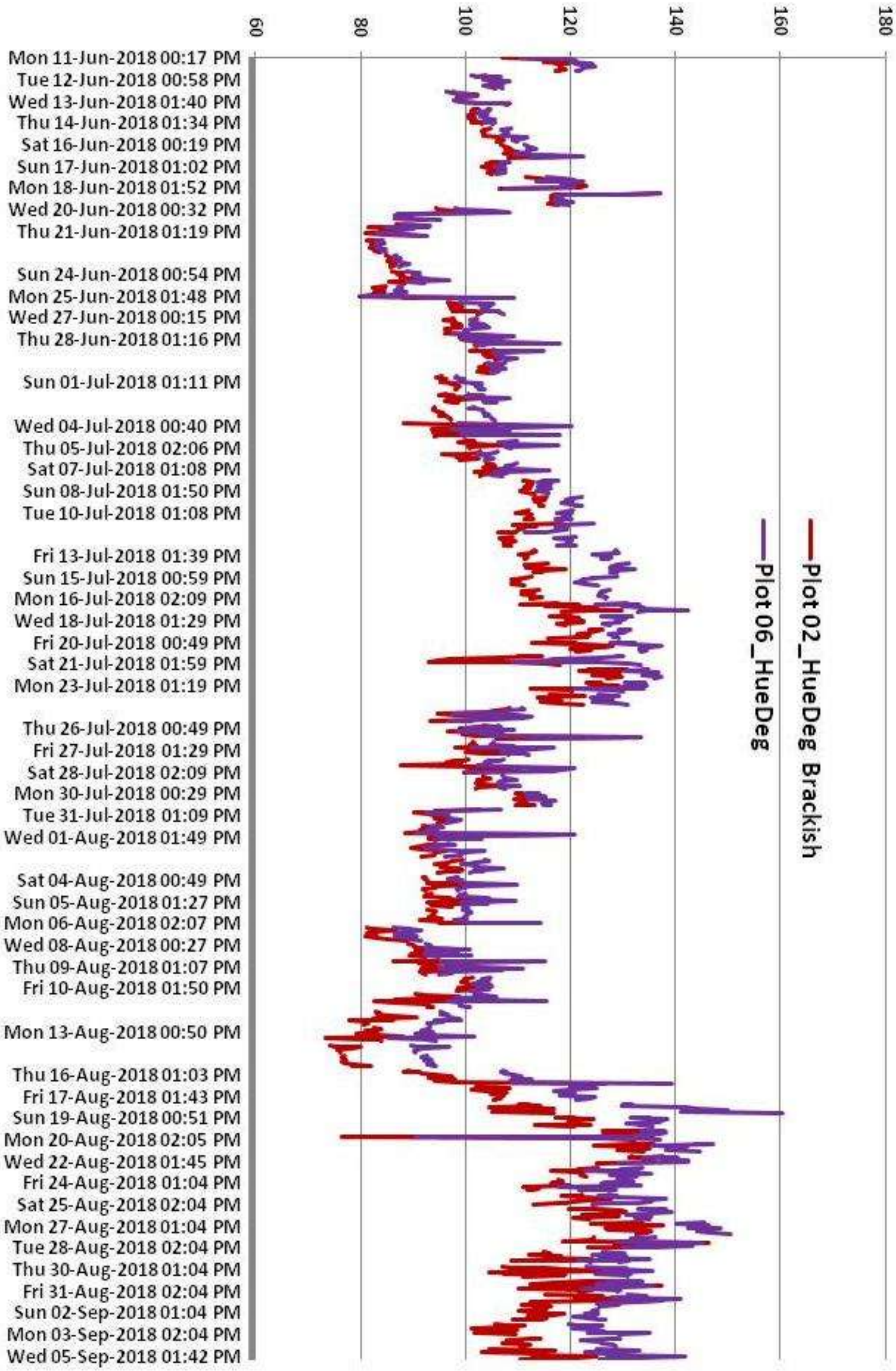

Figure 7. Hue Degree (color); Brackish versus Fresh

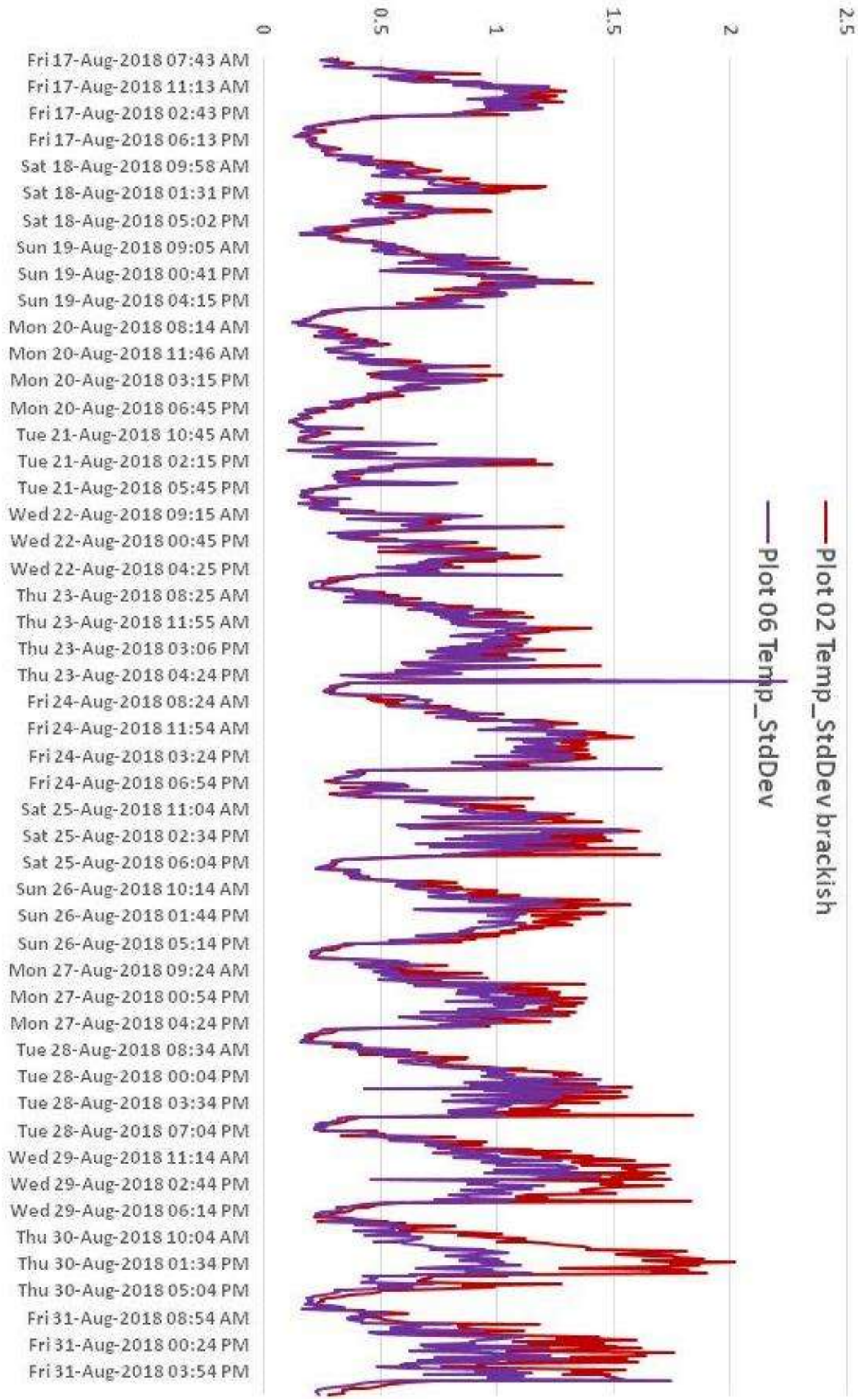

Figure 8. Standard Deviation of Hue; Brackish versus Fresh

Figure 9. Brown Patch in Plot 06

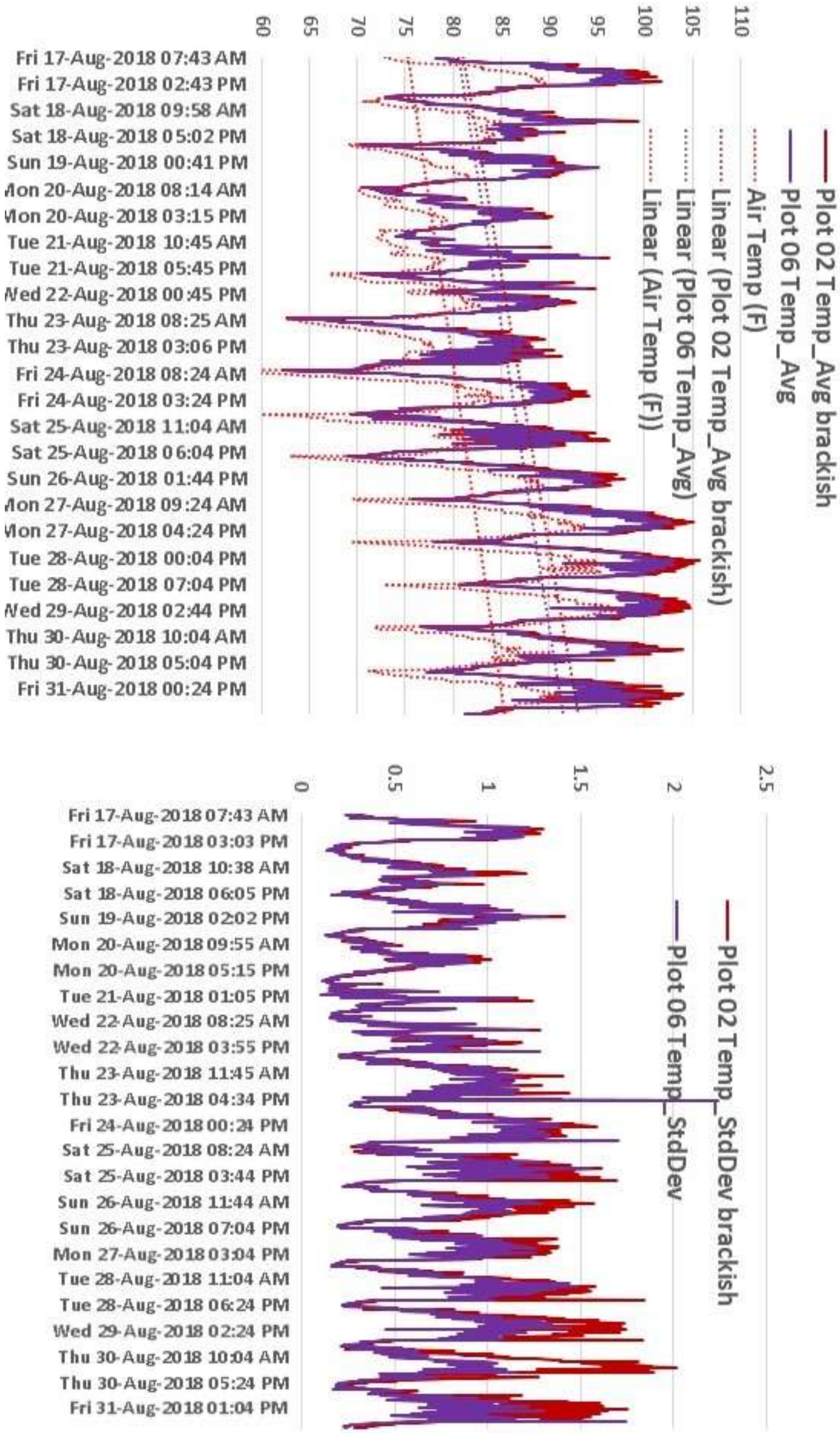

Figure 10. Canopy Temperature versus Air Temperature; and Standard Deviation of the Canopy Temperature

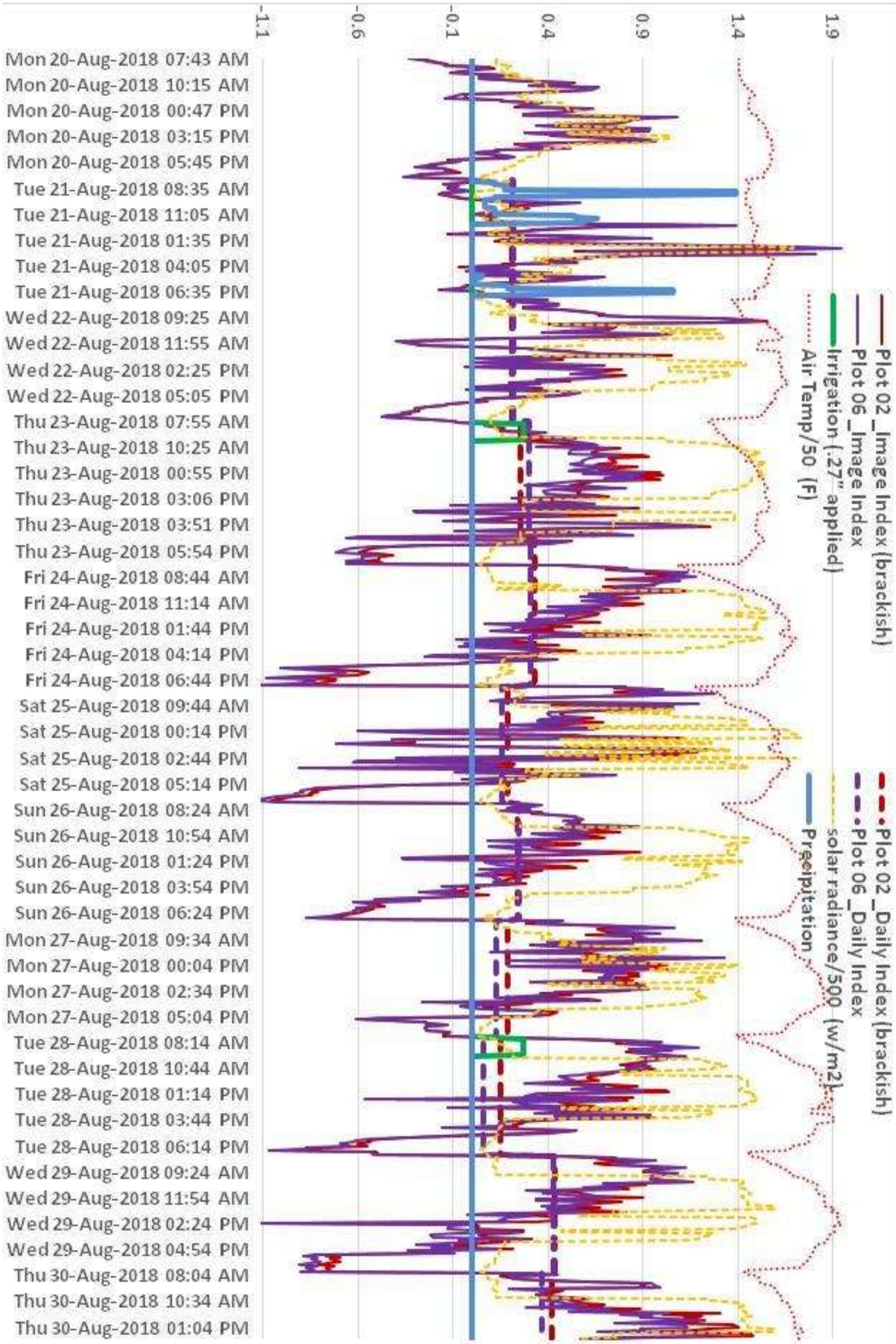

Figure 11. Stress Indexing (Image and Daily) with Air Temperature and Solar Radiance and Irrigation

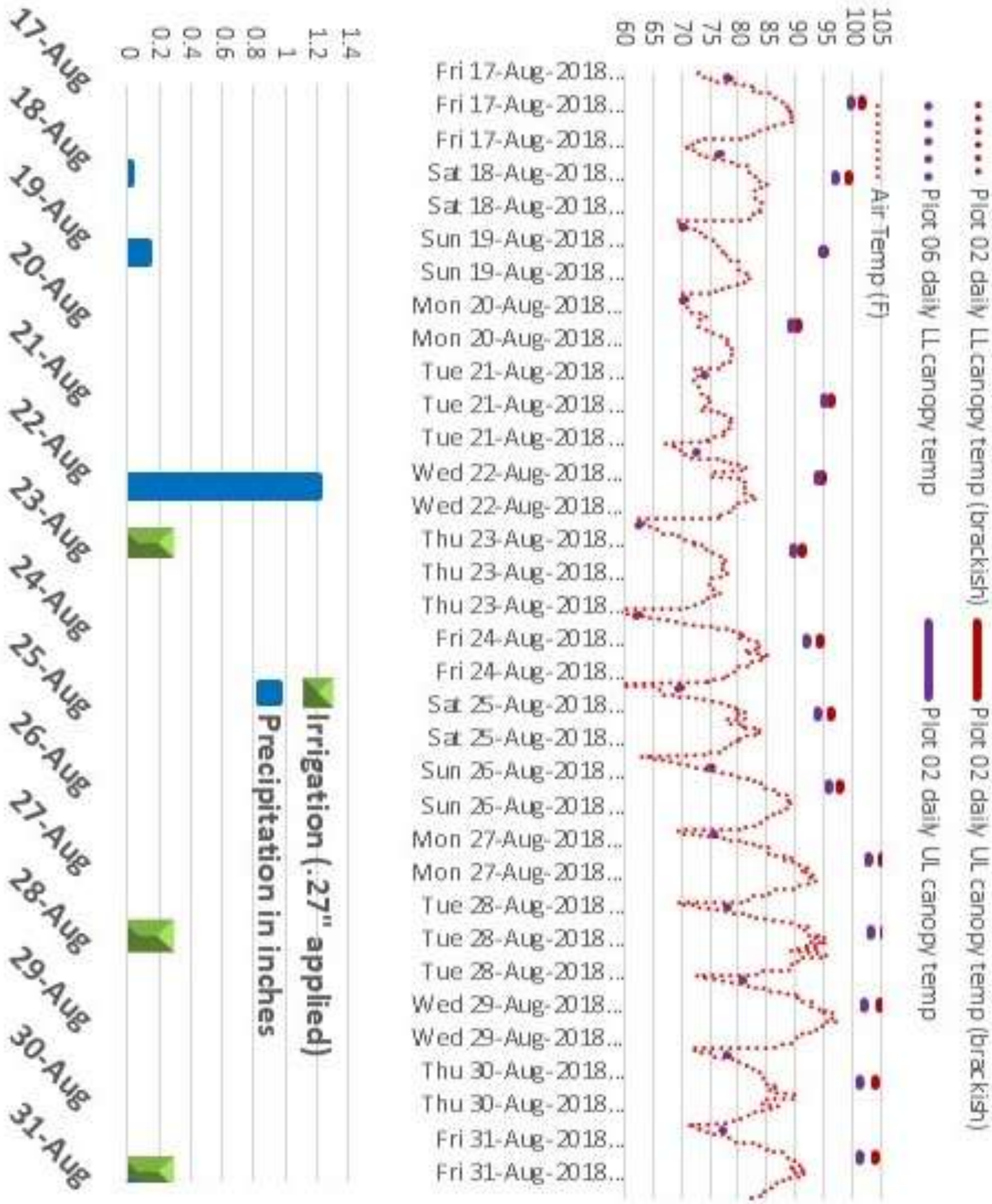

Figure 12. Daily LL and UL with Precipitation and Irrigation

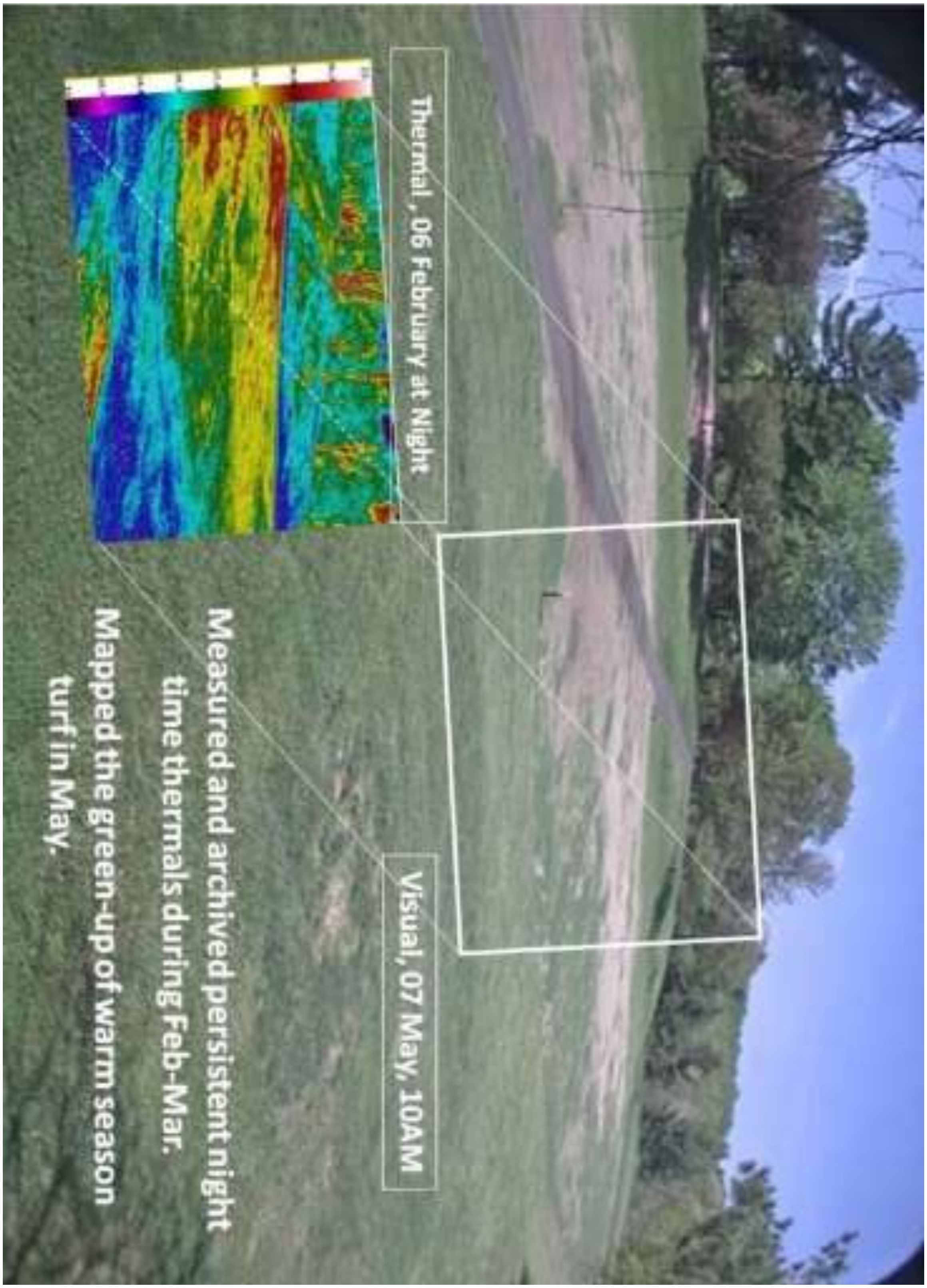

Figure 13. Using Nighttime Thermal to ID Winterkill

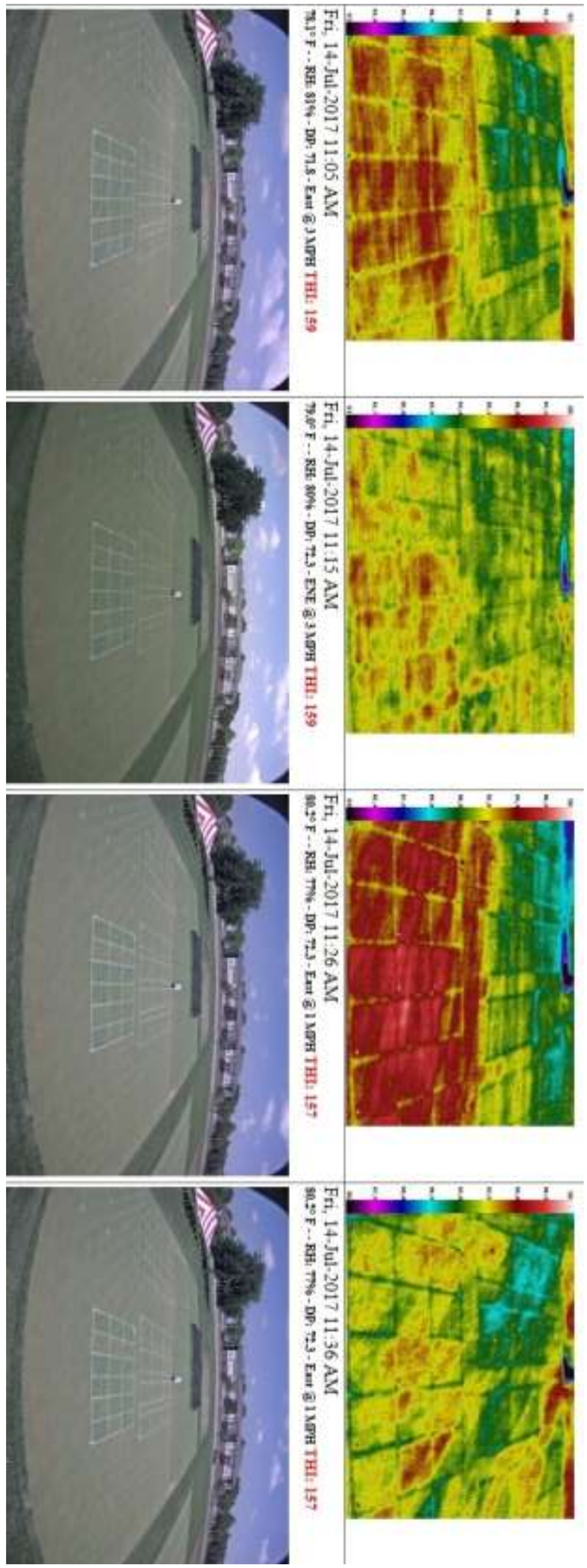

Figure 14. Image Data Time Series

Plots	17-25 July 2017 Total Inches of Water (irrigation + 0.18" precipitation)	ET K_c=.8 recommendation	Turf Quality (from std dev Hue)
100% Replacement	4.065"	3.063" 51% Reduction over ET Recommendation	7
50% Replacement	2.641"		7
0% Replacement	0.160"		1
Hawk-Eye™ Stress Index	1.585"		7

Figure 15. Variable Irrigation of Plots and Resulting Quality