Title: Using Remotely Sensed Thermal and Visual Image Data to Measure Stress and Quality to Assess Plant Water Status and Prescribe Irrigation

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ABSTRACT

Using thermal and visual image data to autonomously and remotely measure a plant's canopy it is possible to enable the plant to signal the stress it is experiencing, gauge its quality and health, and assess its water status and call for irrigation that may be needed. Homogeneity of the plant's canopy is the reference base of remotely sensed imagery. Persistently measuring the canopy temperature and hue, day and night, the biotic signal that indicates the plant's health and water status for prescribing irrigation is signaled. By integrating a low cost radiometric thermal camera, a low cost CMOS visual camera, and a reverse router it is possible to observe and move the image data in real-time to the cloud for processing and dissemination to the internet for subscribers. Near-real-time and archived measurements, indices, and notices are available by browsers, SMS messaging, and e-mail. Formatted messages can also be disseminated to irrigation managers and controllers. Applying persistent thermal and visual image data can be affordably used in most crops. Method and techniques were developed while collecting and analyzing wine grapes, almonds, corn, and turfgrass. The data, indices, and practical application described here-in is from our experience with turfgrass.

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

Introduction

This paper reports recent work addressing mainly cool season (C3) turf grass in the mid latitudes. Turf is an excellent subject because its canopy and plant health can be measured and studied year round and at approximately 40 million acres it is the largest cultivated crop in the United States. In 1993 it was estimated that irrigation must provide 20 to 30 inches of water per year in the South and 40 to 50 inches in the West. These numbers equal 0.5 to 1.5 million gallons of water per acre or 12 to 36 thousand gallons per 1,000 sq. ft. of turf grass[1]. As water availability has become increasingly limited and more costly, water conservation in turfgrass culture has become extremely important.

[1] Water Management on Turfgrasses, Richard L. Duble, Turfgrass Specialist Texas Cooperative Extension, Texas Turfgrass, 45(4):6-14, 1993

When determining the need for irrigation an irrigation manager may be using one of three operationally feasible methods to know when and how much water to apply;

1. An evapotranspiration equation such as Penman–Monteith, from observations from a weather station and applied to the plant by using a coefficient Evapotranspiration c is an estimation of the water used by the turf.
2. a network of soil moisture sensors to measure the water in the soil so one can know, based on the fidelity of the network, where and how much water to replace.
3. Seat-of-the-pants experience that may rely on the irrigation managers knowledge of the stand, the recent weather and irrigation, and the look and feel of the turf.

This paper describes a fourth methodology focused on the plant canopy which is the biotic integrator of evapotranspiration, the water useable by the plant in the root zone, and the plant's health.

In 1981, USDA researcher Dr. Ray D. Jackson, also known as USDA's Father of Remote Sensing because he developed methods used worldwide to evaluate crop health, determined that the difference between a plant's canopy temperature to air temperature ($T_{canopy} – T_{air}$) depends on vapor pressure deficit[2]. Under non-limiting water conditions, healthy plants transpire at the maximum rate. Maximum evapotranspiration increases with increasing vapor pressure deficit. When plant health and water availability is not limiting there is a linear relationship between $T_{canopy} – T_{air}$ and vapor pressure deficit. Figure 1 shows the typical relationship between air temperature, dew point temperature (similar to vapor pressure), solar radiance, and canopy temperature of turf.

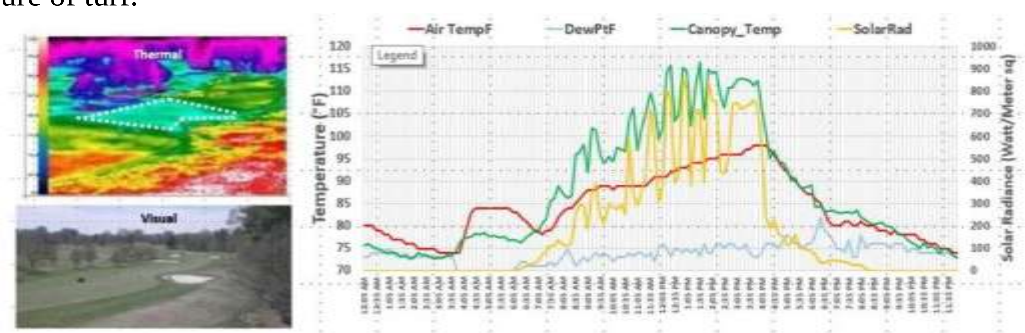

Figure 1. Air and Turf Temperatures in a Section of Fairway

Jackson called this linear relationship the theoretical 'non-water-stressed baseline' and used the idea of upper and lower baselines, to create a crop water stress index (CWSI). This CWSI allows one to relate a crop's temperature to the maximum and minimum values of stress that the plant can experience under similar environmental conditions. The higher the CWSI, the greater the crop stress is assumed to be. It has since been shown that thermal image data make it possible to measure turf canopy temperature, pair it with air temperature measured by a local weather station, and measure daily upper and lower canopy temperature limits to inform a Stress Index. The turf's canopy temperature is the biotic integrator of the air temperature, humidity, pressure, water availability, wind, solar intensity, and sky conditions which contribute to the turf's health and water status. Stress values can be calculated over designated areas from an image frequently. From individual images this is known as the Image Stress Index. The Daily

[2] Jackson, RD, Idso, SB, Reginato, RJ, Pinter, PJJ, Canopy temperature as a crop water stress indicator, Water Resources Research, Volume 17, Issue 4, 1981

Stress Index is the average of the Image Stress Indexes from sunrise to sunset. Figure 2 introduces the Image Stress Index and Daily Stress Index to a typical day.

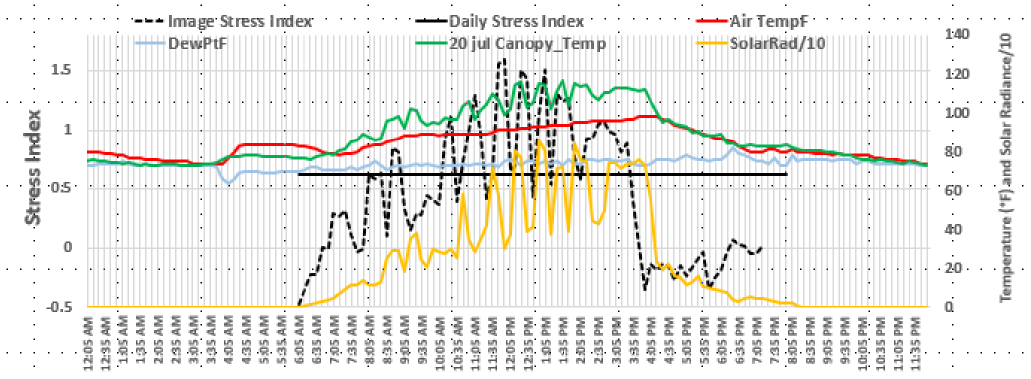

Figure 2. Image Stress and Daily Stress in Section of Fairway

There are two signals that can be obtained from thermal image data of the canopy.
First, an examination of the video stream/time series of images, day and night, will highlight health and stress locations and show (not measure) soil moisture. Secondly, persistent Daily Stress Indexing makes it possible to assess stress and turf water status. If the turf is found to be disease and pests free an elevated Daily Stress Index will signal the turf needs water.

In 2003, Drs. Douglas Karcher and Michael Richardson[3] showed that analyses of digital visual images provide a reliable method to measure the reflectance of color from vegetated surfaces and that the color can be measured and expressed as the hue degree. Figure 3 illustrates the hue degree color wheel.

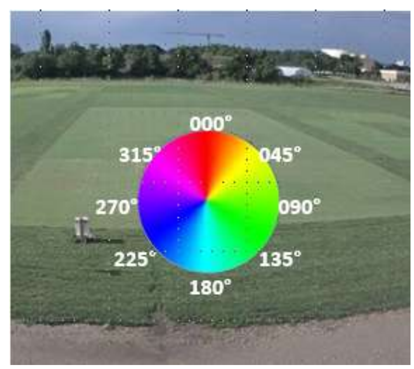

Figure 3. Hue Degree Color Wheel

By establishing an area of interest and then averaging the measured hue values in each of the visual image pixels an average hue (maybe considered like color) and the standard deviation of the hue (may be considered like uniformity, density, or homogeneity) in that area can be determined.

The signals obtained from visual image data of the canopy hue infer chlorophyll content and its standard deviation gives a measure density/homogeneity of the turf. Taken together these values describe quality. They comprise a Quality Index.
The Quality Index.

When paired with the Stress Indices over the period of several days the change of the Quality Index will significantly contribute to the assessment of plant health. A stable hue and a low standard deviation (high degree of uniformity) not only represent high quality but also confirm low thermal stress assessments. Low quality (wandering hue and large standard deviation of the hue) usually follow consecutive days of high stress.

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[3] Karcher, Douglas E. and Richardson, Michael D., Dep. of Horticulture, Univ. of Arkansas, Quantifying Turfgrass Color Using Digital Image Analysis, Crop Science, 43:943–951, 2003

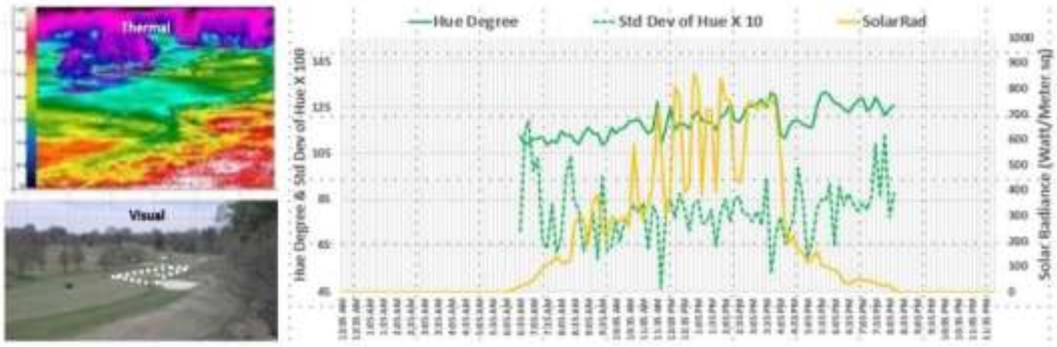

Figure 4. Hue and Std Dev of Hue in a Section of Fairway

When measuring turf for identification of stress, quality, and water status; persistent measurements are essential because the turf is continuously transpiring and respiring in a dynamic environment (see figures 1 & 2). Settling on any one image, or even a few images, for a scouting report or for indexing turf will lead to poor conclusions regarding actions needed. When indexing for irrigation guidance it is recommended that no less than three day running averages of the minimum and maximum canopy temperatures during the daylight hours are used. Detailed discussion of the Stress equation is provided in the background information.

Irrigation Indexing is possible by evaluating and tracking the Daily Stress Index and Quality Index. The daily call for irrigation is signaled when the Daily Stress Index value exceeds a threshold established and indicates it needs water. When the Daily Irrigation Index crosses the turf's threshold that day, irrigation is applied in a predetermined amount. The Index threshold and water amount applied is a constant that is specific to the location and is based on a typical amount of irrigation that might be applied. Daily Irrigation Index measurements continue every day. If the next day the Irrigation Index crosses the threshold, water is applied again. The goal is to put water into the root zone, then irrigate again when called for and not until. There are periods where the Irrigation Index may call for irrigation two or three days in a row or it could go six or more days before water is called for by the turf.

The daily irrigation guidance is checked by evaluating the Quality Index at solar noon. With respect to the signal to irrigate, the greatest weight is given to the Daily Stress Index. But when the quality is seen to wander, i.e. the standard deviation is growing and/or the hue is changing, a close examination of the turf is needed. This check is important because too little irrigation may not be the cause of decreased quality and increased stress. When there have been long periods of rain, cool air temperatures, and frequent cloudy sky conditions, it is important to look closely for disease rather than adding water if the Daily Stress Index measures high.

Using remote sensing for managing turf is complex and requires large amounts of image data measurements and calculations, 24/7/365. Systems that collect, measure, and calculate autonomously, such as a Hawk-Eye™ or an EYAS System used by Turf-Vu can make actionable alerts so that users of the system can go about their business and be alerted when there is something requiring attention.

Background

Visual Image Data and its Application for Indexing Turf Stress

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. Post processing of the visual image data measures the hue and will enhance the near green color and average the hue and the standard deviation of the hue for use.

Figure 5.Original visual image and enhancement of the image to reveal quality, hue and std dev of hue

Illustrated in Figure 5, the hue measurement of the turf canopy can represent the homogeneity 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 homogeneity. 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.

The hue and std dev of the hue values 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. Canopy temperature is very important because turf photosynthesizes during daylight hours and respires during nighttime and both processes release water vapor as a byproduct and the evaporation of that water vapor is a cooling agent. If the turf is being cooled during the day it is very likely photosynthesizing. Nighttime is more complicated because the signal from cooling due to respiration is very small and easily confused, but distinguishable, with evaporation of moisture near the canopy surface. Figure 6 summarizes the process.

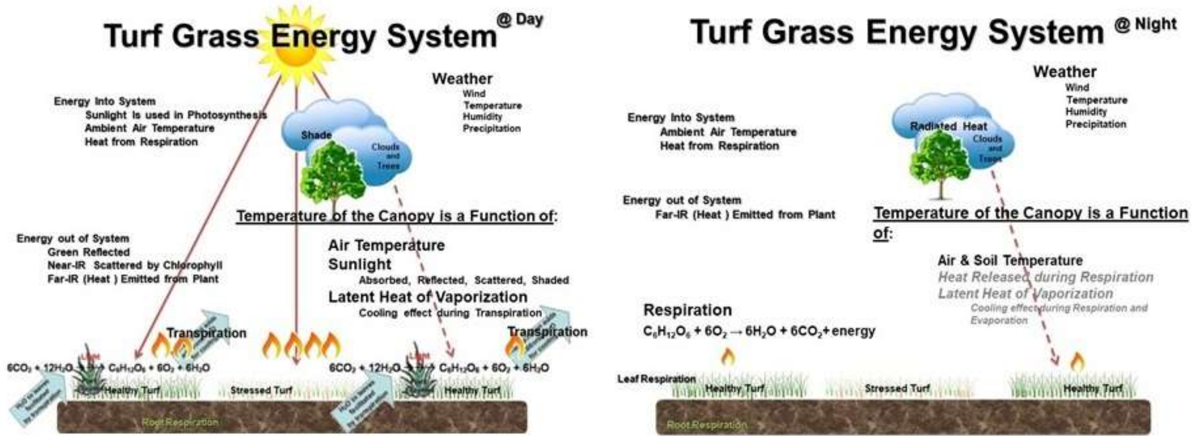

Figure 7. Image Data at 10 minute intervals

The observation of the temperature across the extant of the turf can indicate locations where stresses may be occurring (Figure 7). 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. In analyzing and using thermal image data 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 8 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. Using thermal image data for assessing plant water status and guiding irrigation it is necessary to use frequent image data measurements over the course of the daylight hours, and for several consecutive days, to achieve good results.

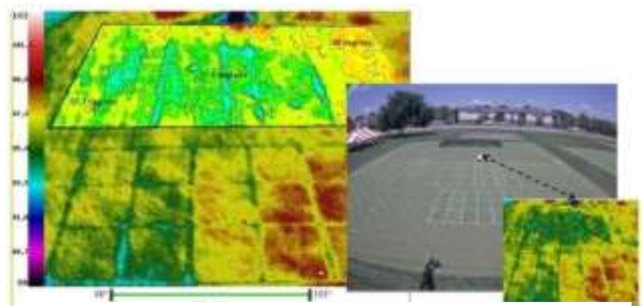

Figure 8. Thermal Image Data

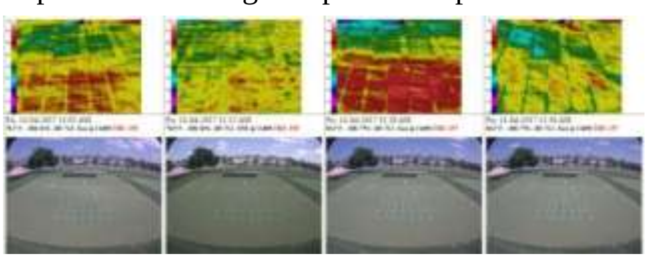

Figure 6. Turf Grass Energy, Day and Night

Applying Thermal Image Data for Indexing Turf Stress

Jackson *et al*. (1981) noted 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)[4].

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)[5], 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:

Equation 1. $$\mathbf{(SI) = (T_m - T_{LL})/(T_{UL} - T_{LL})}$$

$\mathbf{T_m}$ = 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

[4] Ben-Gal, Alon, Agam, Nurit, Alchanatis, Victor, Cohen, Y, Evaluating water stress in irrigated olives: correlation of soil water status, tree water status, and thermal imagery, Irrigation Science 27(5):367-376, April 2009

[5] Costa, J. Miguel, Grant, Olga M., M. Chaves, Manuela, Thermography to explore plant–environment interactions, equation (5), Journal of Experimental Botany, Volume 64, Issue 13, 1 October 2013, Pages 3937–3949

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 6 day 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 9 is a chart depicting the Image Stress recorded approximately every 10 minutes during the day at three different areas on a golf course green.

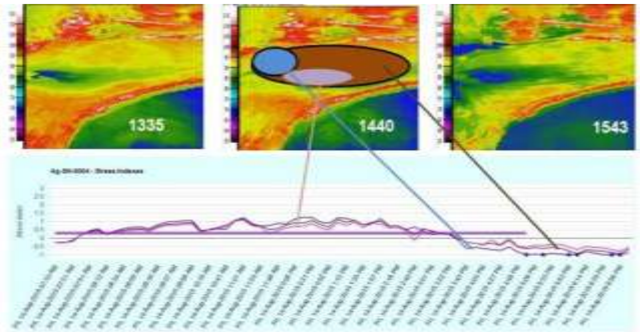

Figure 9. Image Stress at ten minute intervals

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 used is:

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

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. Figure 10 shows the upper level (UL) and lower level (LL) of stress plotted against air temperature, dew point, solar radiation and water (precipitation and irrigation) applied.

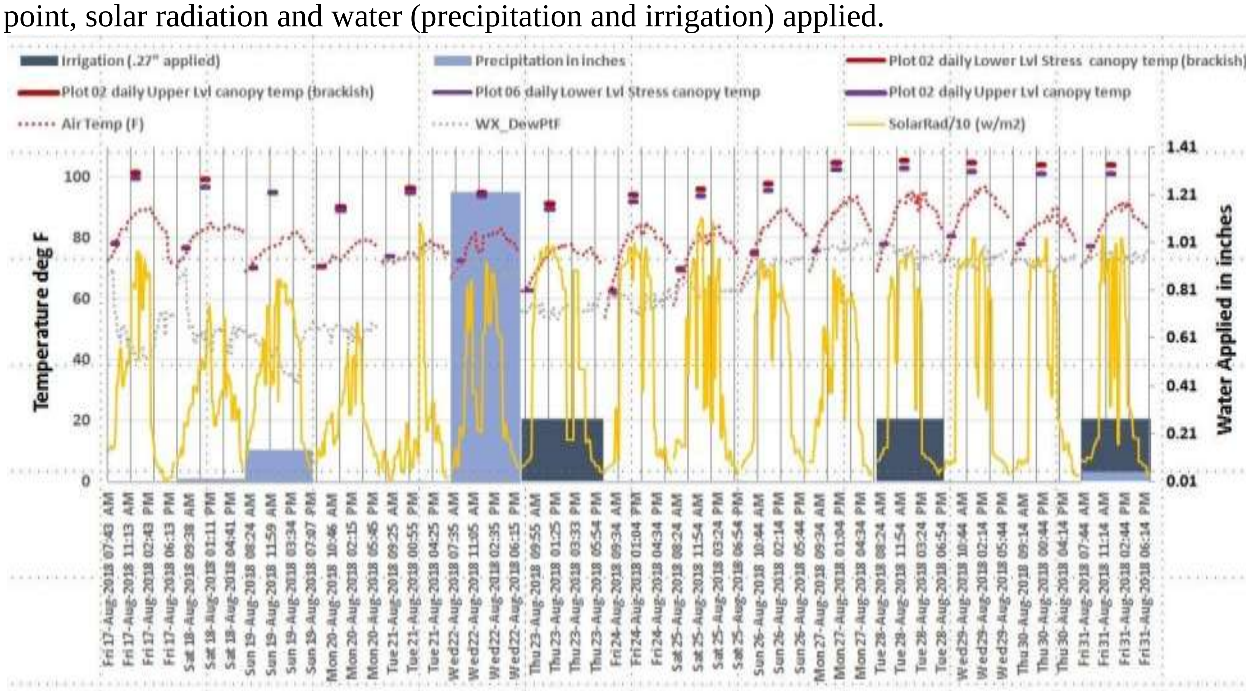

Figure 10. Upper and Lower Stress Temperatures, Canopy Temperature and Water

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. Figure 11 shows the Image Index and Daily Index.

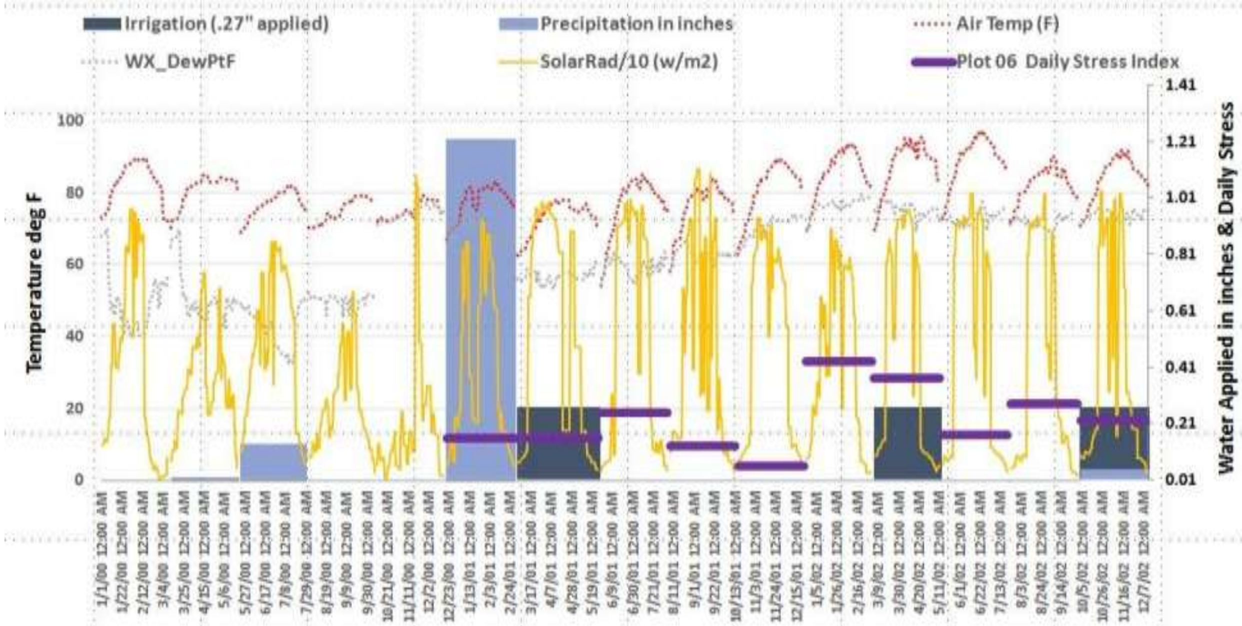

Figure 11. Daily Stress Index

Irrigation Guidance:

The turf's canopy temperature is the biotic integrator of the air temperature, humidity, wind, solar radiance, water availability, and all other factors impacting the turf's health and quality. It can even be considered the integrator of evapotranspiration and useable water in the root zone and the plant's health in real-time. The canopy temperature and air temperatures are used to factor the Stress Index. The hue and standard deviation of the hue from the visual image data is used to factor the Quality Index and it is an important indicator of the turf's health. The canopy temperature, hue, and standard deviation of the hue taken together rather than considered independent signals complement each others' measurement of the turf's health and water status. In a healthy stand of turf the turf's signal that it is dangerously stressed is first observed in the canopy temperature. Usually when water is the issue, large changes in quality that are observed in the visual image data lag the thermal indicator of stress by approximately 1 - 2 days. An interpretation of a rising Daily Stress Index and a stable Quality Index is the signal that the turf is in need of water. But if the plant is stressed it may not be a water issue, there are instances where insufficient water availability is not the issue that needs to be addressed. On site evaluation of the turf is necessary when the Quality Index (no shade) and the Daily Stress Index are out of the standards used at a site. That is when the hue increases or decreases by 10degrees or more and the standard deviation of the hue increases by a factor of 2 or more.

The irrigation prescription that the Daily Stress Index signals for is the amount of water the plant is given during the evening after it says it needs it. The amount applied is a constant unique to the location and the irrigation manager's practices. Some irrigation managers like to irrigate shallow and often, others like to irrigate deep and infrequently. There are periods where the index may call for a prescription two or three evenings in a row or it could go six or more days before water is called for by the plant. When the Daily Stress Index crosses the plant's threshold that day, irrigation is applied in a predetermined amount at night. The Daily Stress Index threshold used at the Hawk-Eye™ lab in northern Virginia is 0.4 and the water applied is .2”. The standard deviation of hue that alerts for an up-close inspection is 8. At the Hawk-Eye™ Lab just enough water to wet the root zone is applied, and then irrigation is applied again when the threshold is crossed again.

Process of using the data for irrigation guidance:
Thermal image data and visual image data is observed autonomously every ten minutes. The systems measure and archive the turf canopy and the site air temperature, humidity, solar radiation, and precipitation every ten minutes all day and night. The process used by Hawk-Eye™ and EYAS Remote Sensing Systems is summarized below.

1. An area(s) defined by a polygon defined by the irrigation manager is established in the thermal image and the visual image and set in the system. An area may define an irrigation zone or any other area of interest. Areas can be added or modified anytime as needed.
2. Measurement of the canopy temperature and hue from every image pixel in a designated area is accomplished every 10 minutes, day and night, and paired with the site weather data. All data is saved in the archive.
3. Stress Indexing:
    a. For every thermal measurement from every pixel in the designated area Hawk-Eye™ and EYAS Systems the stress equation to derive the Image Stress Index
    b. At ½ hour before sunset Hawk-Eye™ averages the SI values calculated between ½ after sunrise thru ½ hour before sunset to record the Daily Stress Index.
    c. For alerting purposes a Daily SI threshold for every zone is set in (it can be changed with experience). This alert is in an ASCI form so that it can be provided to an irrigation controller.
4. Quality Indexing:
    a. For every visual measurement from every pixel in the designated area Hawk-Eye™ and EYAS Systems calculates the average hue of an area and the standard deviation of the hue.
    b. At a time interval determined by the system user, usually 2 hours and shade free, the system averages the hue values and the standard deviation values calculated.
    c. For alerting purposes the hue and standard deviation thresholds for every zone is set in (it can be changed with experience).
5. When a Quality alert is computed it is immediately provide to users via SMS message, e-mail, and in browsers that access the site containing their data.
6. When a Daily Stress Index alert is computed ½ hour before sunset it is immediately provide to users via SMS message, e-mail, and in browsers that access the site containing their data.

2018 Irrigation Demonstration

In July 2018, a demonstration was established to evaluate irrigating with brackish (table salt and potable well water) versus fresh/potable well water on turf grass. Late July was very wet so the demo was extended into August in order to evaluate the Irrigation Index under long rainy and mostly cloudy conditions.

In late June eight plots were established (Figure 12) on a mix of tall fescue, bluegrass, and bermuda grasses. In June, July, and August, weeds were pulled by hand to keep the plots weed free and ensure a homogenous canopy of turf. As the summer progressed the bermuda grass progressively encroached into Plots 06, 07, and 08. By late August Plot 08 was 50% bermuda grass, Plots 06 and 07 were 30% bermuda grass. 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 maintained at 2" – 3".

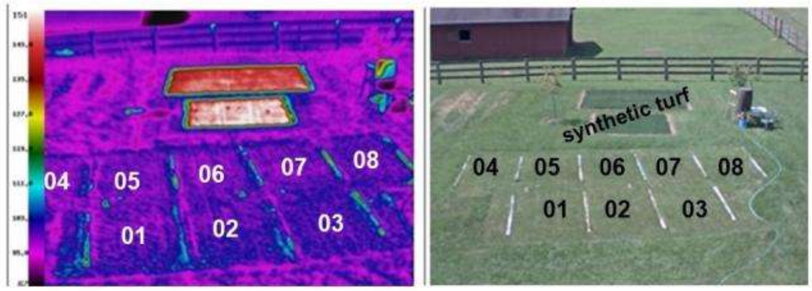

Figure 12. Lay-out of demonstration plots

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 13 plots the July August irrigation and rain events.

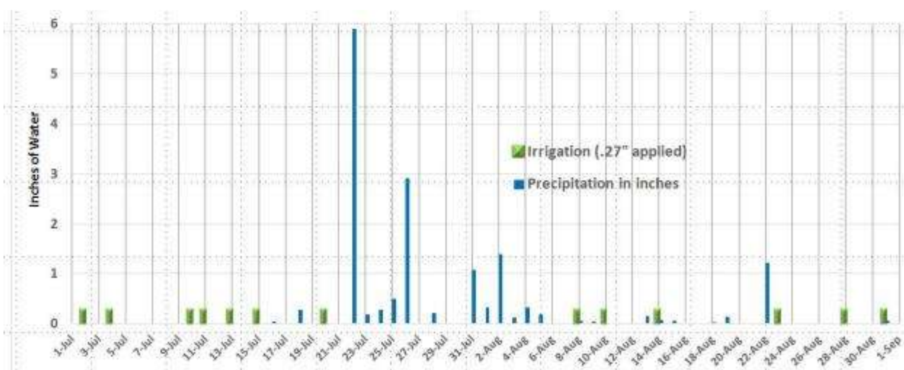

Figure 13. July through August Irrigation and Precipitation

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.

Applying Visual Image Data Analysis

"Eye-balling" the plots during July, there was no evidence of declining quality or increased stress in the plots irrigated with brackish water so 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 by eye-ball and only a very sight measurable decline in the turf quality where the brackish water was applied in July, the brackish solution was increased to.06%.

Results are highlighted by the charting (see Figures 14 & 15) of the data taken from Plot 02 (irrigated with brackish water) and Plot 06 (irrigated with fresh/potable well water). When the .03% prescriptions, starting 02 July, are applied the data diverges vey slightly until the rainy period flushes through the root zone and the quality and deviation of standard deviation of hue converge again. Note that during the period leading up to the application of the different irrigation prescriptions, the hue (Figure 11) and standard deviations of the hue (Figure 12) are very close. To the eye-ball the difference were imperceptible but the data highlights the differences well. Then in August the plots under the increased .06% prescription respond with a deeper anomaly between plots. Starting on 10 August in Plot 02 (brackish) the hue declines more rapidly and by more than 10 hue degrees than in Plot 06 thru 14 August. This may be from a decrease of chlorophyll. The on 18 August the hue degree is relatively steady but the standard deviation of the hue in Plot 06 grows becomes significantly larger than normal.

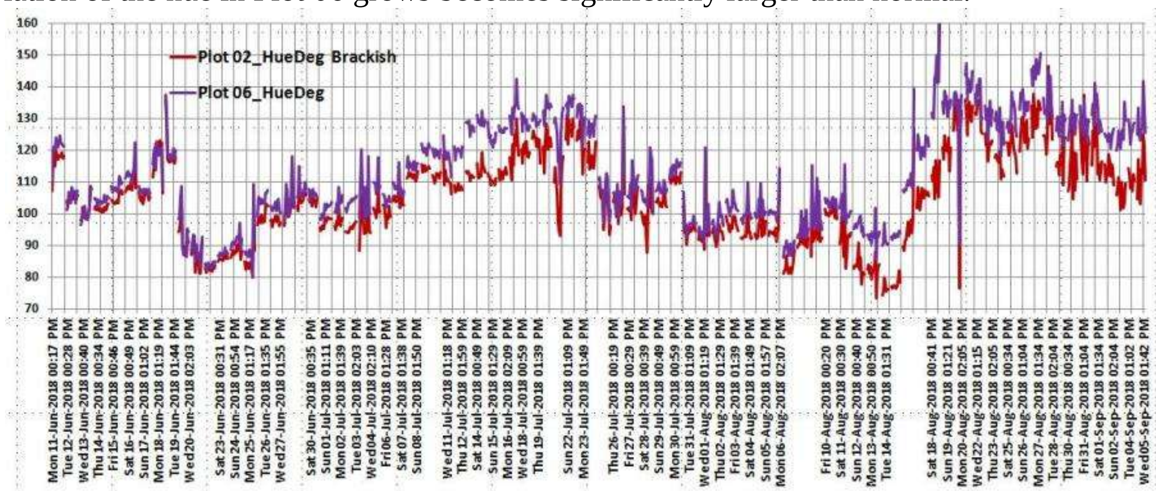

Figure 14. Plot 02 and Plot 06 hue degree

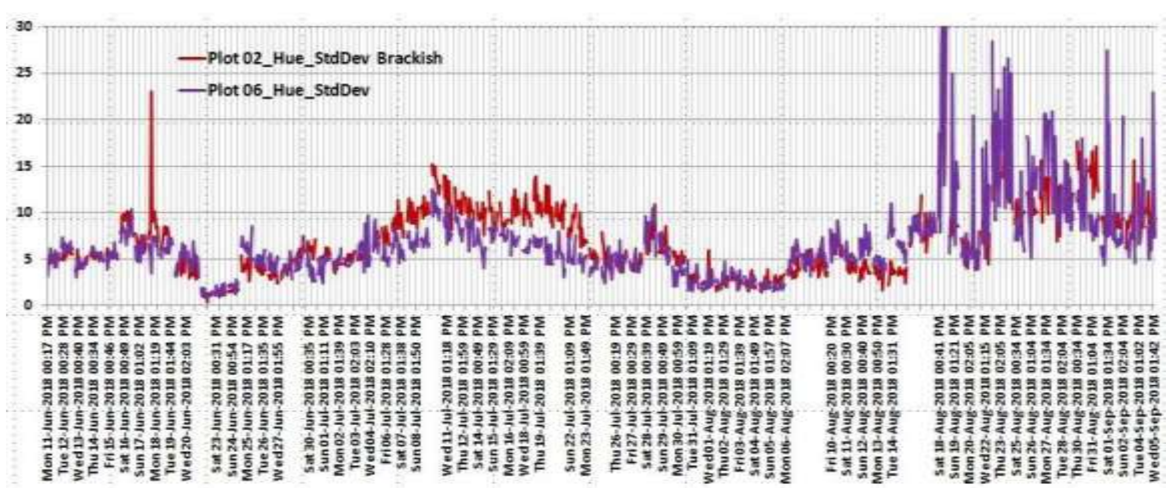

Figure 15. Plot 02 and Plot 06 Standard Deviation of Hue

The increase in standard deviation of the hue in Plot 06 was unexpected because plot 06 was not irrigated with the brackish solution. The expectation was that the turf grass hue and standard deviation of the hue would remain lower than the brackish water stressed plot 02. However when Plot 06 was examined in late August it was seen that the increase in the deviation of the hue that becomes very pronounced by 17 August was due to the increase of the bermuda grass growing in Plot 06. In Plot 02 there was also an outbreak of brown patch that caused an increase in the standard deviation of the hue. The infection covered approximately 10% of the surface area. It is interesting that all the areas near the demo plots where not irrigated during the summer and did not show any indication of disease.

Figure 16. Plot 02 and Plot 06 in September

Applying Canopy and Air Temperature to Gage Turf Stress

For Stress and Irrigation Indexing

Using the equation (SI) = $(T_m - T_{LL})/(T_{UL} - T_{LL})$, described above, Daily Stress Indices were calculated 13 July through 05 September. Figure 14 charts the Daily Stress Index and the water applied from precipitation and irrigation. Plot 02 was irrigated with brackish water and Plot 06 was irrigated with fresh/potable well water.

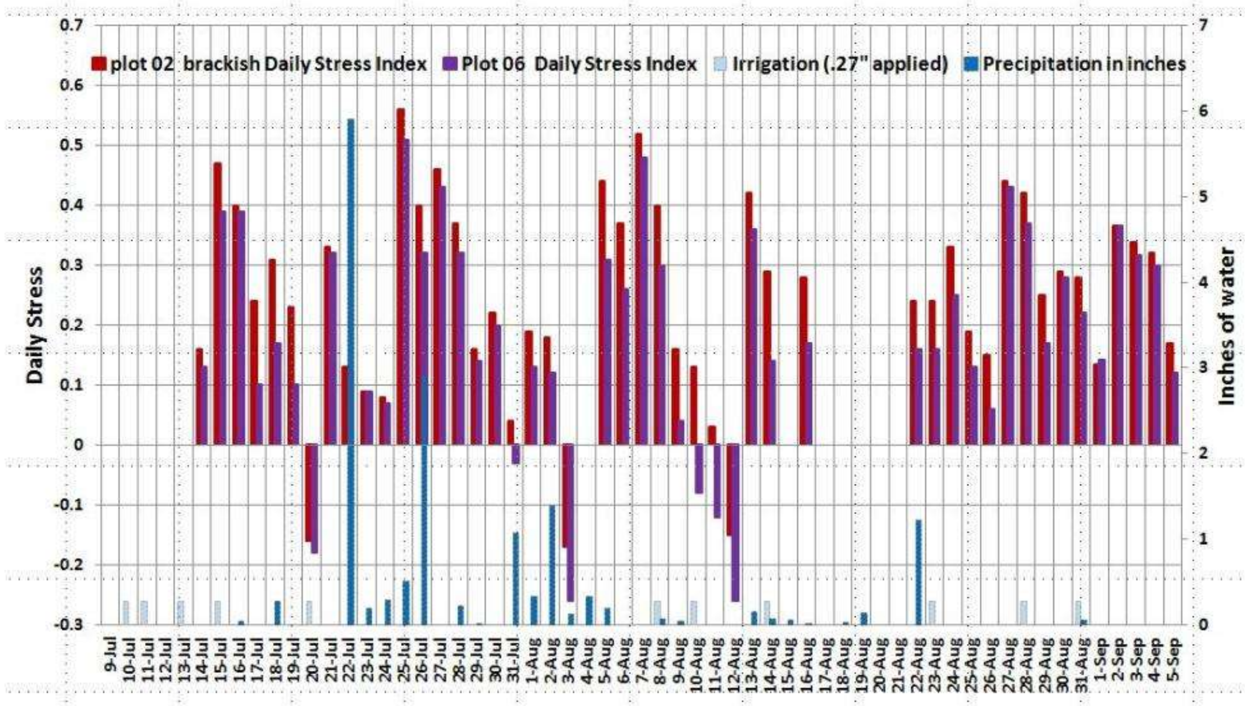

Figure 17. Daily Stress and Water Applied by Precip and Irrigation, 09Jul-05Sep

The convention used to determine if irrigation was required was to evaluate the daily Stress Index and apply irrigation the morning after the Index exceeded .4. This technique worked well in terms of letting the Daily Stress Index signal when irrigation would be required, except on two occasions; 25 - 28 July, which was wet and frequently overcast, and 22 August through early September where brown patch was evident in Plot 02.

Prior to analyzing this summer 2018 data set it was assumed that the water available to the turf would be directly reflected in the Daily Stress Index if all other stressors such as disease, traffic, amendments and water, and environmental parameters were the same on the same turf varieties and cut heights. The only variation in stressors that was applied differently to the plots during this demonstration was the brackish water verses the fresh/potable water irrigation.

Between 22 though 26 July more than 9 inches of precipitation fell on the plots. Anticipating that there would be sufficient water available to the turf and that stress from direct sunlight due to cloudy sky conditions would be lower, no irrigation was applied. Although it was considered that the decision was validated because the uniformity of the turf in Plot 02 brackish improved due to flushing the brackish water out of the root zone, it did not explain the high stress values in Plots 02 and 06 (see Figure 17). The stress values did not decrease when water should have been available to the turf grass leaves to be used in photosynthesis and expelled as waste by transpiration to cool the canopy. It is hypothesized that the stress equation did not take into account a stressor other than air temperature. Experience shows that the canopy temperature is a true measure of the stress as is the standard deviation of the hue when the stress is severe but there are many other factors impacting the water status of the grass and stresses that the turf experiences. For the late July period it is theorized that the Daily Stress values did not follow an expected decrease due to an abundance of water because of a significant decrease in solar radiation and vapor pressure deficit (Most weather stations measure dew point and calculate relative humidity. Both behave as vapor pressure does.) which are not part of the on-scene measurements used in the stress equation. The stress is a function of the environmental parameters air temperature, solar radiation, and dew point depression. The later terms are not factored into the stress equation's environmental factor. Only air temperature is considered. During the July 22 through 05 August period the weather was persistently wet and often overcast. This is reflected in the low solar radiances on 22-26 July and the very low dew point depressions 21 -25 July.

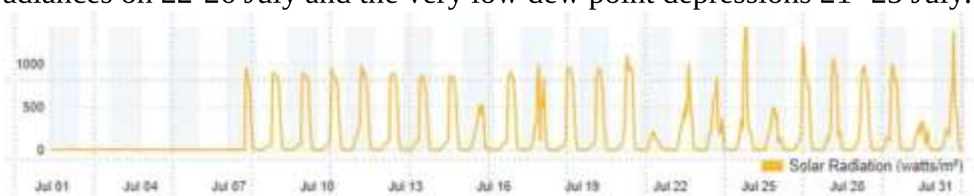

Figure 18. Solar Radiance, July 2018

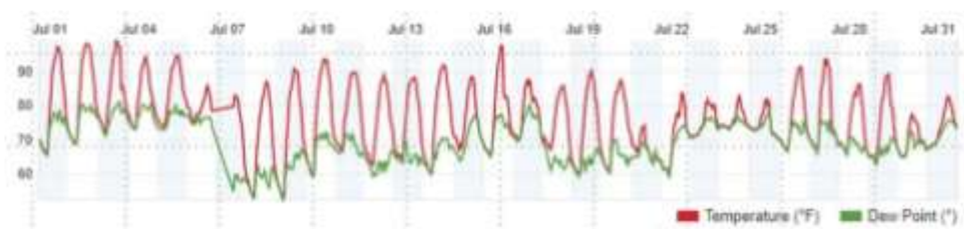

Figure 19. Temperature and Dew Point in degF

The canopy temperature is the biotic integrator of all the stresses and is the true stress indicator. But since only air temperature is factored in the equation (SI) = $(T_m - T_{LL})/(T_{UL} - T_{LL})$, the solar radiation and dew point depression are not considered in the Stress equation. This is a consideration for improvement of the stress equation in the future.

Also needed was closer examination of the main stressors of canopy temperature, air temperature, and solar radiation impacting Plots 02 and 06 during the 17 August - 05 September. As seen in Figure 20, the turf was irrigated when the Daily Stress exceeded 0.4, and the stress decreased as expected.

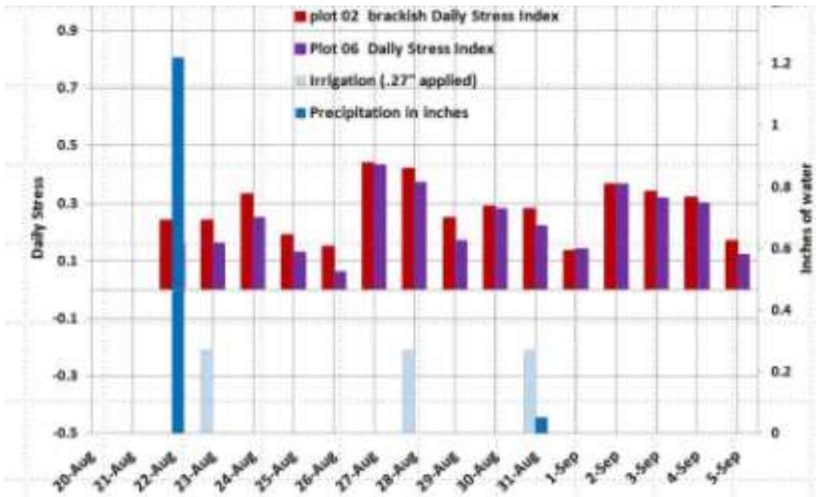

Figure 20. Daily Stress and Irrigation, 20 Aug - 05 Sep

However when the plots were assessed for quality (see Figures 14 and 15), the hue in both plots had increased substantially and the standard deviation of the hue in plot 02 was very high. Of note was that for the first time all summer, Plot 02's standard deviation of the hue that was not only very big but it was very erratic. An "eye-ball" inspection found that the quality in Plot 02 was impacted by brown patch and the quality in Plot 06 was probably reflected in the increased amount of bermuda grass in the plot. It also appears that the .06% saline solution irrigated over the whole Plot 02 was effective in interrupting transpiration; 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.

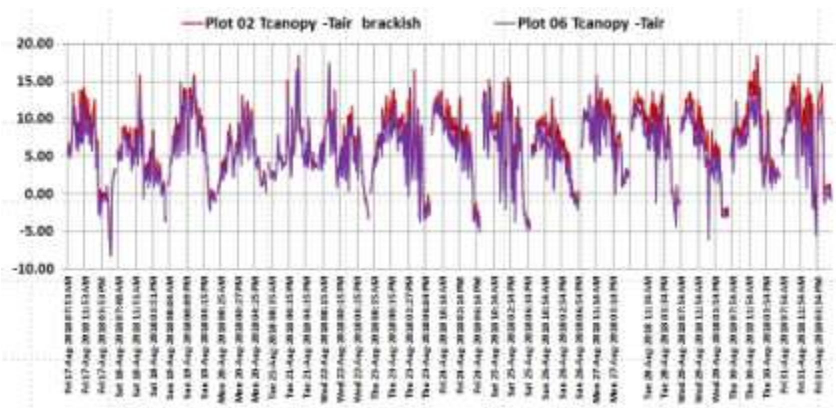

Figure 21. Canopy Temperature - Air Temperature, mid-Day 17 - 31 Aug 2018

Summary

Using persistent thermal and visual image data to measure a plant's canopy it is possible to enable the plant to report its health and water status. Thermal and visual image data, processed to illuminate changes in canopy temperature and vigor, is a tool to autonomously and remotely enhance and extend a person's senses and knowledge of a plant stress, quality, and water status.

The two cases, 25 - 28 July, and 22 August through early September, where the Daily Stress Index and the quality of the turf did not track the water available, highlighted the need to improve the analysis and reporting of the irrigation guidance provided from thermal and visual image data. The 25 – 28 July instance demonstrated the need to make the environmental terms of the stress index better reflect the natural environment beyond only considering air temperature. Recently the Stress Index was modified to decrease the T_{LL} and T_{UL} running averages from 6 days to 3 days to account for shorter term variations of the weather impacting the turf. From the late August experience a protocol for setting "Alerts" in the Hawk-Eye™ application was established to better alert to the relationship between the Daily Stress and the standard deviation of the hue.

Both cases highlight the large amount and complexity of the data and information embedded in the thermal and visual data. A few images or the resultant data checked occasionally do not lend to any deep and meaningful analysis to provide to irrigation guidance. More importantly it is unreasonable to expect irrigation managers balancing multiple tasks to follow the image data closely enough to exploit its full value. More than one irrigation zone and especially in a large enterprise with many irrigation zones and large acreage can become so labor intensive that even analysis support from consultants can become expensive. Figure 23 illustrates the organization of some of the data. It's a lot, if one uses it all.

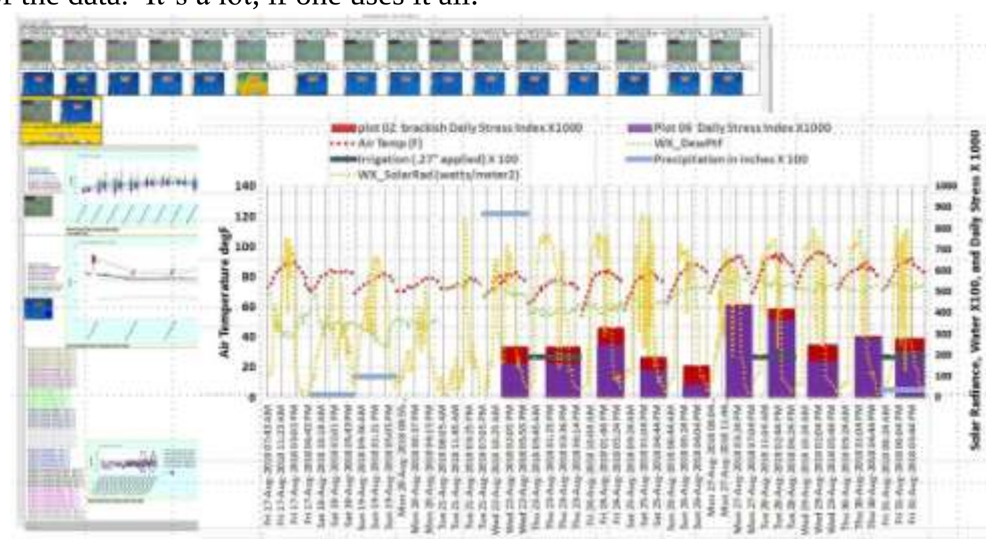

Figure 22. Air Temperature, Water, Solar Radiance, and Daily Stress

An analysis of the relationships between each of the parameters that lead to irrigation guidance can help focus an analysis and it will support an improvement to the stress index equation.

correlation of	2018 Value 17 - 31 August	2018 Demo Plots	2018 Value on 25 August	2020 Value on 27 Oct
Image Stress to canopy temperature - air temperature	0.9756	brackish	0.9758	0.4659
Image Stress to canopy temperature - air temperature	0.9731	Plot 06	0.9731	
Image Stress to solar radiation	0.3966	brackish	0.1834	0.4620
Image Stress to solar radiation	0.3189	Plot 06	0.1396	
Image Stress to Air Temperature	-0.1005	brackish	-0.3045	-0.3939
Image Stress to Air Temperature	-0.1510	Plot 06	-0.1510	
Image Stress to Dew Pt Temperature	-0.0293	brackish	-0.3045	-0.1247
Image Stress to Dew Pt Temperature	-0.0031	Plot 06	-0.1510	
Image Stress to canopy temperature	0.4347	brackish	0.5133	0.4659
Image Stress to canopy temperature	0.3809	Plot 06	0.3809	

correlation of	2018 Value 17 - 31 August	2018 Demo Plots	2018 Value on 25 August	2020 Value on 27 Oct
Daily Stress to solar radiation	-0.0259	brackish	0.0968	0
Daily Stress to solar radiation	-0.0395	Plot 06	-0.0395	
solar radiation to air temperature	0.4150		0.4356	0.8889
canopy temperature to air temperature	0.8475	brackish	0.6445	0.8925
canopy temperature to air temperature	0.8536	Plot 06	0.6444	
canopy Temperature to Solar Radiation	0.5957	brackish	0.5226	0.8925
canopy Temperature to Solar Radiation	0.5725	Plot 06	0.5158	
canopy temperature to dew pt	0.2503	brackish	-0.5934	0.5823
canopy temperature to dew pt	0.2572	Plot 06	-0.5944	

Table 1. Correlation of Parameters Pertinent to Irrigation Guidance

Table 1 is a correlation of the parameters that are pertinent to irrigation guidance. Future work aimed at an Artificial Intelligence approach to the data analysis and reporting may find these relationships important.

Conclusion

Applying remote sensing to provide irrigation guidance requires frequent and persistent thermal and visual image data measurements of a plant canopy and the local/on-scene meteorological parameters

Extremely large data sets, “big data”, are generated. To affordably use the data and information in operational time frames actionable indices and alerts are needed to exploit the image data.

Current Stress Indexing and Alerts available in the commercially available Hawk-Eye™ and EYAS Systems provide good irrigation guidance, but, improvements can be made by incorporating solar radiance and dew point depression to an equation of the form in equation 1 discussed here-in. There is opportunity to bring Artificial Intelligence to this point.

With respect to the standard deviation of the hue, using the kurtosis and skewness of the deviation may allow a deeper understanding of the uniformity of a turf canopy.

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