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DETERMINING CROP SOIL WATER DEFICIT WITH AN UAS

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INTRODUCTION

Remote sensing (RS) techniques have been used to identify crops grown during different seasons and to estimate crop bio-physical characteristics and water use. Images from satellites such as Landsat 5, 7, and 8 have been used extensively to map crop evapotranspiration rates (ET) using a suite of algorithms. However, Landsat satellites have a fixed revisit frequency (e.g., 16 days) and pixel spatial resolution of 30 m for the visible (VIS) and mid-infra-red (MIR) bands while the thermal infra-red (TIR) band pixel size is 100-120 m. Furthermore, some RS of ET algorithms require that the TIR band be corrected for atmospheric effects (not trivial). These characteristics limit the application of satellites to generate frequent ET maps (every three or four days) to be used in soil water balance methods to help manage scarce water resources more efficiently. Therefore, there is a need to investigate alternatives to produce higher spatial and temporal resolution maps. With the advent of Unmanned Aerial Systems (UASs) capable of carrying multispectral (i.e., VIS, TIR) cameras it may be possible to monitor ET more effectively. Thus, this study evaluates the use of ET techniques that can be used with an UAS to estimate soil water content.

MATERIALS AND METHODS

Experimental Site

The experiment was conducted on two maize (Zea mays L.) fields. One field deficit irrigated (Treatment 1, TrT 1) and the other fully irrigated (Treatment 2, TrT2) during 2017 at the USDA-ARS Limited Irrigation Research Farm (LIRF), in Greeley, Colorado, USA (40°26'57''N, 104°38'12''W, elevation 1427 m). The alluvial soils of the study field are predominantly sandy and fine sandy loam of Olney and Otero series. The fields were drip irrigated through buried laterals/emitters (sub-surface drip irrigation, SDI). The size of each field is 110 m (width) by 190 m (length). These fields were commonly referred as the “Bowen Ratio” fields because Dr. Walter Bausch (retired) did extensive research on those fields using Bowen Ratio Energy Balance systems. Figure 1 shows the fields.

Figure 1. Research fields at USDA ARS LIRF near Greeley, CO.

Corn variety was Dekalb 51-20. It was planted late on June 2nd of 2017. Emergence occurred around June 8th. Effective full cover was attained around August 9th for TrT2 and August 15th for TrT1.

UAS (Unmanned Aircraft System) Description

The remote sensing system acquired multispectral and thermal data on seven days during the crop cycle. Flights were planned as to coincide as much as possible with the overpass time of Landsat 7 and 8. In this study we present data from July 3rd (MSR), July 19th, July 27th, and August 13th. The nearest Landsat overpass for the August mission was on the 12th. We used an actual crop coefficient (explained later) to convert the August UAS data from the 13th to the 12th.

The airframe used was a DJI Spreading Wings S900 hexacopter (Da-Jiang Innovations Science and Technology Co., LTD, Shenzhen, China). The S900 frame weights 3kg and has a max takeoff weight of 8.2kg. The system is powered by a MaxAmps 13500XL 6S 22.2v 13500mAh LiPo battery (MaxAmps, Spokane, WA, USA). All in all with airframe, battery, land payload the S900 weights 5.8kg and flies safely for about 13 mins.

A 3DR Pixhawk PX4 flight controller (3D Robotics, Berkley, CA, USA) was installed on the UAS. Managing, and coordinating the output of 6 motors manually would be impossible task, as such a flight controller is a necessity. The flight controller translates control inputs from the user and data of current orientation from onboard sensors, and sends the appropriate signal to the motors. The Pixhawk PX4 also acts as an autopilot, allowing for, under supervision, fully autonomous control of the UAS. The PX4 features a 168Mhz Cortex M4f CPU with 256KB of RAM and 2MB of flash memory. The PX4 also features 3d accelerometer, magnetometer, gyroscope, and barometer sensors. The PX4 is also paired with a 3DR/Ublox GPS and compass module, and a LightWare SF11-C 120m laser rangefinder. The accelerometer, magnetometer, compass, and gyroscope make up the inertial measurement unit (IMU) which calculates UAS pitch, yaw, and roll data. The GPS, compass, barometer and laser rangefinder calculates UAS positional data.

The UAS has 2 radios installed; a 3DR SiK 915MHz telemetry radio, and a Sanwa (Sanwa Electronic Instrument Co., Ltd., Higashi-osaka, Japan) RX-861, 2.4GHz FHSS-3 8Channel receiver. The telemetry radio communicates with a second 3DR SiK 915MHz radio attached via USB to the ground control station. The ground control station, a Panasonic Toughbook CF-31 with ArduPilot's open source Mission Planner software, handles autonomous/semi-autonomous control of the UAS. The RX-861 receiver pairs to a Sanwa SD10GS 10 channel 2.4GHz FHSS transmitter for manual/semi-autonomous control of the UAS.

The payload for the UAS consists of a FLIR Tau2 LWIR (FLIR Systems, Inc., Wilsonville, OR, USA), and a Tetracam Mini-MCA6 multispectral cameras (Tetracam Inc., Chatsworth, CA, USA). The custom carbon fiber mounting tray for the payload was designed and built by UASUSA (UASUSA, Longmont, CO, USA).

The Tau2 contains a 640 x 480 pixel (0.3 mega pixel) image sensor and has a spectral range from 7.5 to 13.5µm. The Mini-MCA6 features a 6 camera array, with each camera containing 1280 x 1024 pixel (1.3 mega pixel) image sensor. A band-pass filter is fitted to each of the 6 camera with 10nm bandwidth. The center wavelengths of filters used in the study were 860nm, 720nm, 680nm, 570nm, 530nm, and 490nm.

Missions were flown at 95m AGL with a 90% overlap and 70% sidelap, which gives a pixel resolution of 5.2cm and 8.5cm for the Mini-MCA6 and Tau2, respectively. The study site was large to fly on one battery, so the field was split into 2 missions. At the beginning and end of each mission images of a Blackbody and reflectance targets were taken. The blackbody (Omega BB701 Portable blackbody) was set to 100°F. Images of reflectance targets (Labsphere Spectralon targets, 99%, 50% and 10%) were taken at 95m, and ground truth measurements of the targets were taken using a spectroradiometer PSR-1100 (Spectral Evolution Lawrence, MA 01840, USA). Images and mission telemetry logs were downloaded after flights, and a separate GPS file was created from the mission telemetry log. Spectroradiometer data were downloaded and processed using DARWin SP Data Acquisition and Analysis software.

Imagery Pre-Processing

Below is presented a summary of all the steps required to create an ortho-rectified mosaic from the raw images acquired from the UAS.

Steps for preparing multispectral imagery:
Raw imagery from the UAS system is converted to ".tif" (8-bit) format using PixelWrench 2. NIR, Red, and Green bands are stacked together by using a python script, which exploits ArcMap's "CompositeBands_management" function. Where the red band is used as a master band and the NIR and Green bands are aligned to it by using polynomial 2nd order warp. Then, a 3-band false color composite is created.

Steps for preparing FLIR thermal imagery:
Initially, the images are in png (16-bit) format, which is very difficult to visualize and work with, in the software. Therefore, all images are re-scaled to the minimum and maximum digital numbers for the whole flight.

AgiSoft Photoscan project:

- Two different projects are created, one for the Multispectral camera and another one for the Thermal camera. All images are imported in AgiSoft Photoscan (*The mention of trade names or commercial products in this article is solely for the purpose of providing specific information and does not imply a recommendation or endorsement by the U.S. Department of Agriculture*), along with the orientation data.

- All photos are aligned in the software based on the orientation file and the features detected in adjacent images.
- An ortho-rectified mosaic is generated in the software along with the cut-lines polygon showing the overlapping areas for each image.

Geo-referencing Multispectral (MS) and Thermal mosaics:

- The MS mosaic created is aligned to a basemap using ESRI ArcMap GIS software (geo-referencing module).
- Once the MS mosaic is aligned to the basemap, it is used as a basemap for Thermal mosaic alignment using ArcMap.

Absolute Radiometric Calibration:

Finally, the MS mosaic was calibrated using surface reflectance values collected in-situ at at several locations along the field (treatments). These ground-truth RS data were collected with a multispectral scanner MSR5 from CropScan; which also incorporated a thermal infra-red thermometer (IRT) from Exergen. Furthermore, the thermal mosaic was rescaled back to the original 16-bit values and then a linear transformation was performed to obtain surface temperature values in degrees Celsius. The Exergen IRT was used to check and calibrate the thermal image.

ET Algorithms

The FAO Paper-56 (Allen et al., 1998) procedure was followed to calculate "potential" crop ET (ETc) for conditions of now water stress. Weather data needed for the calculation of hourly and daily reference ET (ETref, both alfalfa and grass based) were download from COAGMET station Greeley 04 which is located at the USDA ARS LIRF. Corn crop coefficients were alfalfa based developed in Idaho as published in Hoffman et al. (2007). ETref was calculated using the 2005 ASCE-EWRI standardized Penman-Monteith (PM) equation.

Actual basal crop coefficients were obtained applying the so-called reflectance based coefficients. This is, reflectance data from the RS systems are used to produce vegetation indices that are inserted in linear equations to estimate the actual vegetation coefficient (ratio of actual to potential transpiration). Below the different methods used are listed.

Fractional Cover:

The method proposed by Trout et al. (2008) and Johnson and Trout (2012) was used to calculate actual basal crop coefficient based on surface reflectance (Kcb_ref).

$$Kcb\_ref = 1.13 \times fc + 0.14 \quad (1)$$

Where, fc is fractional vegetation cover; estimated using the Normalized Difference Vegetation Index [NDVI = ((reflectance in the NIR band – reflectance in the Red band)/ ((reflectance in the NIR band + reflectance in the Red band)); as shown in Eq. (2).

$$fc = 1.26 \times NDVI - 0.18 \quad (2)$$

Then, actual corn transpiration (ETa) is calculated as:

ETa = Kcb_ref x ETref (3)
Where, ETref is grass based (ETo) in this case.

Scaled NDVI:
Similar to the method described above only that fractional cover (fc) is estimated using the Brunsell and Gillies (2002) method.

fc = N* = [(NDVI – NDVIo) / (NDVIm – NDVIo)]^2 (4)

where, NDVIo is the minimum value (bare soil) set to 0.15 and NDVIm is the maximum value for fully vegetated pixels, set to 0.92 for our radiometer.

Soil Adjusted Vegetation Index (SAVI) based:
The third RS method adopted was the SAVI based model from Bausch (1993), where:

Kcb_ref = 1.416 x SAVI + 0.017 (5)

SAVI L-factor was set to 0.1.
ETa was calculated as in Eq. (3). However, ETref was that of alfalfa.

NDVI-based:
The fourth method was from Neale et al. (1989), developed for corn near Greeley, CO.

Kcb_ref = 1.181 x NDVI – 0.026 (6)

As in the SAVI method, ETa was calculated as in Eq. (3) using ETref for alfalfa.

Estimating Soil Water Content (SWC)

Chávez (2015) proposed using a relationship between the crop water stress index CWSI (Idso, 1982) and the level of soil water content (depletion) beyond (below) a set threshold (VWC_t) that was called "Soil Water Stress Index" (SWSI). The SWSI (%) was parameterized using a sigmoidal model, for this study, as defined below.

$$SWSI = \frac{a}{1 + \exp\left(-\left(\frac{x - x_o}{b}\right)\right)} \tag{7}$$

Where, x = CWSI (%), x_o= 17.8737, a = 72.6468, and b = 3.7753.

CWSI was estimated as:

CWSI = (1 – ETa/ETc) x 100 (8)

Once the SWSI has been computed, Eq. (9) is inverted to solve it for actual soil volumetric water content (VWC_a). If CWSI is zero then SWSI is zero and the soil VWC is at field capacity or above it (no stress).

$$SWSI = \frac{VWC_t - VWC_a}{VWC_t - VWC_{WP}} \tag{9}$$

Where, VWC_a is the estimated actual soil water level (%). The SWSI scales VWC_a between a volumetric soil water threshold (VWC_t) and the wilting point VWC (VWC_{WP}). Thus, the range is [0, 1]. This is, a SWSI of zero (0) would mean that the soil moisture level was at the threshold level or above and was defined as no soil water stress (in relation to a selected soil management/maximum allowed depletion (MAD). This is, MAD is the fraction that one is allowed to deplete (total) available water (Eq. 11) in the soil before causing water stress in the plant. In this study a MAD of 0.5 (50%) was chosen for corn. On the other hand, a SWSI value of one (1 or 100 %) would mean that all moisture in the soil was used up by the plant and the plant is reaching the wilting point. VWC_t was computed as follows:

$$VWC_t = VWC_{FC} - (MAD \times AV) \tag{10}$$

$$AV = VWC_{FC} - VWC_{WP} \tag{11}$$

where, VWC_{FC} is the VWC at field capacity. AV is available water in the soil, VWC_{WP} is the volumetric water content at wilting point.

Evaluating Estimates of ETa and SWC

Estimates of ETa using Kcb_ref derived from surface reflectance acquired with the UAS and ground based multispectral radiometry were evaluated with ETa values computed using Landsat images and the land surface energy balance known as METRIC (Allen et al., 2007). METRIC uses the TIR band besides VIS and NIR bands and is considered a robust and accurate procedure to compute ETa.

Three sites per treatment were selected to extract pixels for the comparison. These sites were located at 25, 50 and 75% of the length of the field. At these locations and at the center of the plot/treatment (along the width of the field) two neutron probe access tubes (aluminum) were installed (per site).

A neutron probe (NP) was used, on a weekly basis, to measure soil volumetric water content every 30 cm from 0.3 m to a depth of 2.0 m. The NP data were used to evaluate remote sensing estimates of VWCa.

RESULTS AND DISCUSSION

Figure 2 below shows side by side the level of detail obtained for pixels from the UAS image (left) and from the Landsat (right) satellite image. The UAS produce 0.05 m pixels (approximately) while Landsat VIS and NIR pixel size is 30 x 30 m.

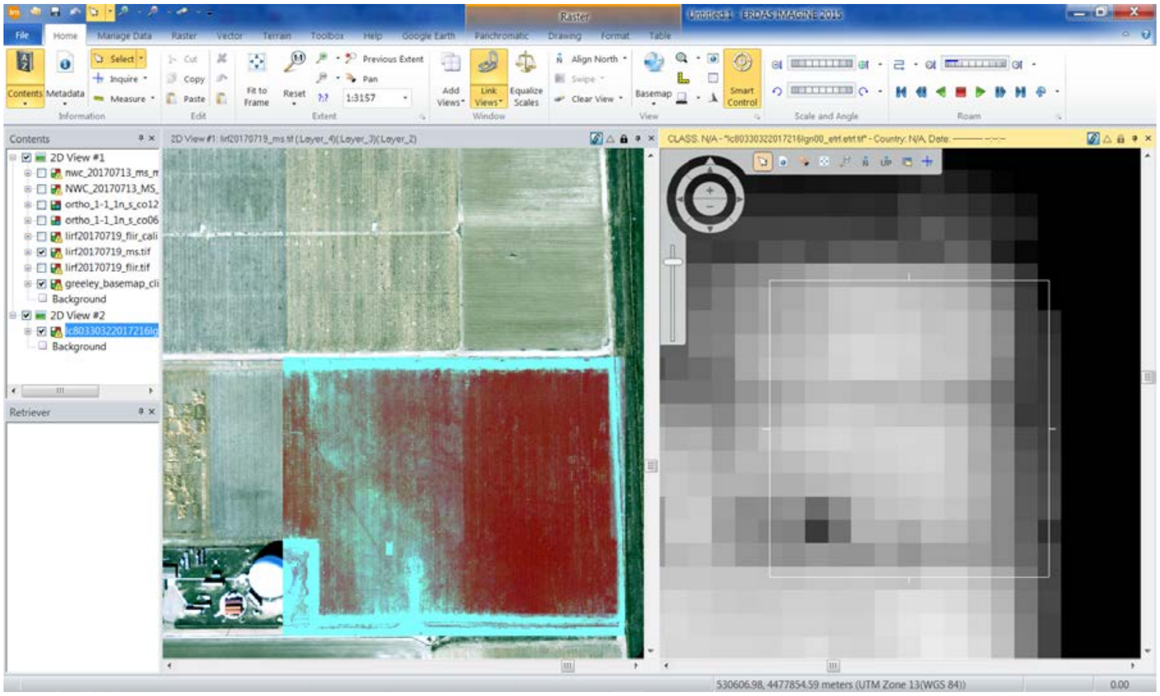

Figure 2. UAS (left red colored image) vs. Landsat satellite (right gray scale image) pixels. Imagery acquired on 19 July 2017 at USDA ARS LIRF near Greeley, CO.

In Fig. (2), the effect of both irrigation treatments is clear. Treatment 1 (west side of the Bowen ratio fields) shows less corn biomass as less red color is seen. In the false color composite (NIR, Red, Green), the brighter (more intense) the red color the larger the vegetation fractional cover (fc) and the leaf area index (LAI). This left field shows much less vegetation than the fully irrigated treatment (east Bowen ratio field). In 19 July 2017, corn had reached V8 at TrT1 and V9 at TrT2. Tables 1 and 2 list the derived ETa values for each method applied for both irrigation treatments, 1 and 2, respectively.

Table 1. Treatment 1 (limited irrigation) actual crop transpiration (mm/d).

Dates	TrT 1 Lim. irrig. Station	ETa mm/d Kcb_ref N*	ETa mm/d Kcb_ref fc	ETa mm/d Kcb_ref SAVI	ETa mm/d Kcb_ref NDVI	ETa mm/d EB METRIC
7/3/2017	1.1	1.07	2.04	2.78	1.86	3.28
	1.2	1.13	2.23	2.99	2.02	2.86
	1.3	1.52	2.81	3.62	2.50	3.57
7/19/2017	1.1	2.03	3.86	5.23	3.67	6.61
	1.2	2.21	4.08	5.48	3.86	6.37
	1.3	1.86	3.69	5.16	3.59	6.37
7/27/2017	1.1	2.13	3.38	4.33	3.10	4.61
	1.2	1.67	2.93	3.81	2.70	4.55
	1.3	2.04	3.30	4.24	3.04	4.37
8/13/2017	1.1	4.32	5.10	6.39	4.67	4.83
	1.2	4.58	5.26	6.57	4.80	4.73
	1.3	4.55	5.24	6.55	4.79	4.53

Table 2. Treatment 2 (fully irrigated) actual crop transpiration (mm/d).

Dates	TrT 2 Full irrig. Station	ETa mm/d Kcb_ref N*	ETa mm/d Kcb_ref fc	ETa mm/d Kcb_ref SAVI	ETa mm/d Kcb_ref NDVI	ETa mm/d EB METRIC
7/3/2017	2.1	1.31	2.63	3.42	2.35	3.29
	2.2	1.30	2.61	3.40	2.34	3.31
	2.3	1.99	3.69	4.58	3.23	3.57
7/19/2017	2.1	1.63	3.26	4.27	2.92	7.00
	2.2	1.67	3.34	4.34	2.98	7.16
	2.3	1.71	3.44	4.46	3.07	7.24
7/27/2017	2.1	5.52	5.57	6.87	5.03	5.74
	2.2	5.41	5.51	6.80	4.98	5.26
	2.3	5.13	5.37	6.64	4.86	4.91
8/13/2017	2.1	4.88	5.33	6.89	5.04	4.63
	2.2	5.03	5.41	6.98	5.12	4.73
	2.3	5.21	5.51	7.10	5.20	4.63

The mean bias error (MBE) and root mean squared error (RMSE) statistical measured were applied to the data reported in tables 1 and 2. Results of the errors in the estimation of ETa (mm/d) are shown below. Statistics align with columns of methods reported above.

MBE =	-2.0	-0.9	0.2	-1.3
RMSE =	2.1	1.6	1.7	1.5

Initially, the method by Neale et al. (1989) shown above as Kcb_ref NDVI resulted with the lowest error (i.e., -1.3±1.5 mm/d or -23±23%) which is considered a large error. However, by looking at the ETa values of the table it can be seen that some methods perform better at certain level of crop fractional cover. Furthermore, it was found that Landsat TIR image for the west side of the Bowen ratio field (TrT2) was contaminated with radiation from the adjacent airport runway (see Fig. (2) black pixels) because the TIR pixel size is 100-120 m and therefore some thermal pixels covered part of the experiment field and some of the runway. The pixel size of the thermal image provided had been re-sampled to the size of the VIS – NIR bands, which is 30 m. Thus, a new analysis was performed including only treatment 2 (west field) and separating the data in two groups (i.e., acquired at effective full cover and before reaching full cover). Results for this new analysis are presented in Tables 3 and 4, for fractional cover between 15 and 60% and for fc ranging from 70-92%, respectively.

For the corn vegetative growth period (water stressed) showing low biomass percent cover (Table 3), the lowest error was for the SAVI based Kcb_ref method. This method's error was -9.8±9.3%; which is more acceptable. This result is not surprising since SAVI was developed to improve NDVI for conditions of soil background effects as in the case of low biomass percent cover.

In the case of the analysis for the full cover condition (Table 4), the NDVI based Kcb_ref method developed by Neale et al. was superior with the lowest error of 1.2±4.5%.

Table 3. ETa errors for treatment 1 for fractional cover between 15 and 60%.

	Lim irrg	15<fc<60%		%Error
	N*	fc	SAVI	NDVI
MBE =	-62.4	-31.9	-9.8	-37.1
RMSE =	6.5	8.4	9.3	6.4
range from:	-68.8	-40.3	-19.1	-43.5
range to:	-55.9	-23.6	-0.5	-30.7
amplitude	13.0	16.7	18.6	12.8

Table 4. ETa errors for treatment 1 for fractional cover at 70-92%.

	Lim irrg	fc ~ 92%		%Error
	N*	fc	SAVI	NDVI
MBE =	-4.5	10.7	38.6	1.2
RMSE =	5.5	4.9	6.1	4.5
range from:	-10.0	5.8	32.5	-3.2
range to:	1.0	15.7	44.6	5.7
amplitude	11.0	21.5	77.2	8.9

In the case of the evaluation of estimated VWC with NP data, the first analysis presented below is for fc less than or equal to 60. All data from all stations were used in the analysis. The lowest error was for the SAVI based Kcb_ref method with an error of 6.6±15.7% (absolute error and not volumetric).

MBE =	-18.2	-9.7	6.6	-13.0
RMSE =	16.0	19.7	15.7	18.6

Now, considering estimated VWC for fractional cover between 70 and 92%, the lowest error was that of the NDVI based Kcb_ref method developed by Neale et al. with an error of 13.5±11.7% (show below).

MBE =	4.5	21.5	21.5	13.5
RMSE =	15.3	14.4	14.4	11.7

It is expected to have a somewhat larger error in the volumetric water content estimation since it is difficult to accurately represent field capacity and wilting point (and MAD) for all six stations considered. We used different field capacity (FC) and wilting point (WP) values for each station based on observing NP VWC data. However, some stations presented a larger VWC at the 30 or 60 cm depth; indicating a change in soil texture. Rigorously, one should determine the soil FC and WP for each textural class presented in the field and for all layers through the crop root zone. Nevertheless, results encountered during this study are encouraging.

CONCLUSIONS

In this study, it was shown that using high resolution remote sensing imagery, paired with a reflectance based crop coefficient, it is possible to estimate actual crop transpiration for corn with good accuracy. Furthermore, there is evidence that using the estimated ETa and a proposed soil water stress index, it is possible to estimate actual soil volumetric water content through the crop root zone. The methodology presented could be used to improve irrigation water management as in the case of center pivot variable rate irrigation for instance and when deficit irrigation is practiced since actual crop coefficients are needed instead of tabulated coefficients for full irrigation.

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