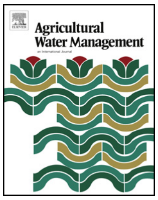
Agricultural Water Management xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat



Evaluation of thermal remote sensing indices to estimate crop evapotranspiration coefficients

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ARTICLE INFO

Article history:
Received 15 February 2016
Received in revised form 30 June 2016
Accepted 4 July 2016
Available online xxx

Keywords:
Canopy temperature
Crop coefficient
Crop water stress index
DANS index
DACT index

ABSTRACT

Remotely sensed data such as spectral reflectance and infrared canopy temperature can be used to quantify crop canopy cover and/or crop water stress, often through the use of vegetation indices calculated from the near-infrared and red bands, and stress indices calculated from the thermal wavelengths. Standardized dual crop coefficient methods calculate both a non-stressed transpiration coefficient (K_{cb}) that is related to canopy cover, and a stress or transpiration reduction coefficient (K_s) that can be related to soil water deficit or other stress factors (e.g. disease). This study compares several remote sensing methods to determine K_{cb} and K_s and resulting evapotranspiration (ET) in a deficit irrigation experiment of corn (*Zea mays* L.) near Greeley, Colorado. Three methods were used to calculate K_{cb} (tabular, normalized difference vegetation index – NDVI, and canopy cover). Four canopy temperature based methods were used to calculate K_s: Crop Water Stress Index – CWSI, Canopy Temperature Ratio – Tcratio, Degrees Above Non-Stressed – DANS, Degrees Above Canopy Threshold – DACT. Crop ET predicted by these methods was compared to observation and water balance based ET measurements. Thermal indices DANS and DACT were calibrated to convert to K_s. Results showed that stress coefficient methods with less data requirements such as DANS and DACT are responsive to crop water stress as demonstrated by low RMSE of ET calculations, comparable to more data intensive methods such as CWSI. Results indicate which remote sensing methods are appropriate to use given certain data availability and irrigation level, in addition to providing an estimation of the associated error in ET.

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1. Introduction

As climate change and population growth both place unprecedented demand on the world's finite fresh water supply, competition among various water users (e.g. irrigation, recreation, industry, and municipal) is likely to increase. As the largest consumptive water user, irrigated agriculture experiences pressure to reduce water use while maintaining high yields (Allen et al., 2007). An additional challenge is presented by climate change which may alter historical precipitation patterns and increase droughts (Walthall et al., 2012). In order to continue to sustain a rapidly growing population with vulnerable and limited water resources, producers must be adequately prepared to adapt irrigated agriculture practices.

One strategy under current research is regulated deficit irrigation where irrigation applications are less than the full crop water requirement. Through regulated deficit irrigation, high water productivity is achieved by careful monitoring of crop water status and timing of irrigation applications. Deficit irrigation ideally results

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Abbreviations: DACT, degrees above canopy threshold (°C); DANS, degrees above non-stressed canopy (°C); D_r, root zone depletion or soil water deficit (mm); *DP*, deep percolation (mm); ET, evapotranspiration (mm/day); ET_c, crop evapotranspiration (mm/day); ET_r, alfalfa-based reference evapotranspiration (mm/day); f_c, fractional vegetation cover; *GW*, ground water input (mm); *I*, total net irrigation amount applied (mm); IRT, infrared thermometer (°C); K_c, crop coefficient; K_{cb}, basal crop coefficient; K_s, stress crop coefficient; LIRF, Limited Irrigation Research Farm; MAD, maximum allowable depletion (mm); NDVI, normalized difference vegetation index; *P*, effective precipitation (mm); RAW, readily available water (mm); RH, relative humidity (%); R_{nir}, reflectance in the near infrared band; R_{red}, reflectance in the red band; SWD, soil water deficit (mm); TAW, total available water (mm); TDR, time domain reflectometer; T_c, crop canopy temperature (°C); T_{cNS}, non-stressed canopy temperature (°C); $T_{critical}$, critical canopy temperature threshold (°C); VI, vegetation index; VWC, volumetric water content (m^3).

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http://dx.doi.org/10.1016/j.agwat.2016.07.007
0378-3774/Published by Elsevier B.V.

Please cite this article in press as: Kullberg, E.G., et al., Evaluation of thermal remote sensing indices to estimate crop evapotranspiration coefficients. Agric. Water Manage. (2016), http://dx.doi.org/10.1016/j.agwat.2016.07.007

in no water losses due to deep percolation because it never fully replenishes the crop root zone. In addition, evaporation losses may be reduced by less frequent irrigation applications. Additionally, crops often have varying water stress sensitivity at different growth stages, which can inform the producer as to when placing more stress on the plant will have a smaller impact on yield (Fereres and Soriano, 2007).

Many farms have been historically over-irrigated, often sacrificing irrigation efficiency for yield stability, although there may still be harmful effects of over-irrigating such as waterlogging and salinity (Montoro et al., 2011). When irrigation water becomes expensive or limited the producers will move from a stress prevention approach to a stress management approach, and deficit irrigation during critical growth periods may be an effective way to maintain production while decreasing water use. A review on deficit irrigation by Fereres and Soriano (2007) affirms the idea that applying less than full irrigation can increase water productivity and even farmers' profits. They noted that successful deficit irrigation strategies are typically found within situations that permit the application of at least 60% of crop water requirement and are designed based on crop drought sensitivity during each development stage. Many other recent studies have explored the outcomes of deficit irrigation with similar results (Conaty, 2010; DeJonge et al., 2011; Fereres and Soriano, 2007; Kang et al., 2000; Taghvaeian et al., 2012).

Managed deficit irrigation relies on quantification of crop water use, or evapotranspiration (ET). Standardized methods of measuring and estimating ET assume fully irrigated conditions and therefore do not accurately estimate water use if soil water deficit conditions limit ET. Thus, methods that are sensitive to crop development and stress are necessary during droughts or under deficit irrigation. Reference evapotranspiration is the ET from a reference crop (12 cm high clipped grass or 50 cm tall full-cover alfalfa) and therefore incorporates the effects of weather into the ET estimate (ASCE, 2005). To use the reference ET calculation method to estimate crop ET, the ratio of a cropped and reference surface is combined into a crop coefficient according to ASCE (2005) as:

$$ET_c = ET_r \cdot K_c \tag{1}$$

where K_c is the crop coefficient, ET_c is crop ET (mm), ET_r is alfalfa or tall reference surface ET (mm). The effect of microclimate on ET is described by ET_r and the properties of the crop which affect ET are quantified by K_c (Allen et al., 1998). This method can be used to calculate the ET of a crop under "standard" (i.e. non-stressed) conditions, but cannot directly estimate the ET of a water stressed crop. Allen et al. (1998) separated the crop coefficient into evaporation and plant transpiration components, the latter which included a stress coefficient for soil water limiting conditions (K_s) shown as:

$$ET_c = (K_{cb}K_s + K_e)ET_r \tag{2}$$

where K_{cb} is the basal crop coefficient representing transpiration when the plant is under no stress, and K_e is the evaporation coefficient.

The basal crop coefficient K_{cb} can be obtained from published tabular values such as those listed for a short crop reference in Allen et al. (1998) and typically has a trapezoidal shape that has a strong relationship with canopy cover. A source of error with tabulated values is that corn under different environmental and management conditions does not grow at the same rates. Basing the crop coefficient on growing degree days may be more accurate, but even this method can vary from with regional, management, and climatic variability. Water stress may further alter growth rates based on timing of water deficit or water application, and Mahan et al. (2014) suggest canopy temperature should be considered along with growing degree days to improve the utility of heat units. Alternately, canopy cover or reflectance data can be used to estimate K_{cb} throughout the season.

Reflectance-based basal crop coefficient (K_{cb}) methods developed by Neale et al. (1989) and Bausch (1993) have been used to improve irrigation scheduling of corn. Reflectance-based basal crop coefficient methods rely on remote sensing data to calculate a vegetation index and a linear relationship between the vegetation index and the reflectance-based crop coefficient. One of the most commonly used vegetation indices is the normalized difference vegetation index (NDVI):

$$\mathrm{NDVI} = \frac{R_{nir} - R_{red}}{R_{nir} + R_{red}} \tag{3}$$

where R_{nir} is reflectance in the near infrared band and R_{red} is reflectance in the red band. Using NDVI, Neale et al. (1989) developed a relationship for corn in Greeley, Colorado, to determine the basal crop coefficient K_{cb} from remotely sensed data (NDVI). A more recent development in the estimation of actual crop coefficients was the work of Trout et al. (2008) and Johnson and Trout (2012) which showed that K_{cb} can be estimated from fractional vegetation cover (f_c). Johnson and Trout (2012) also demonstrated that if f_c measurements are not available, NDVI can be used to estimate f_c by

$$f_c = 1.26(\mathrm{NDVI}) - 0.18 \tag{4}$$

Once f_c has been obtained either through Eq. (4) or more directly by image processing, the basal crop coefficient can be estimated as

$$K_{cb} = 1.13 f_c + 0.14 \tag{5}$$

Reflectance-based crop coefficients assess current crop conditions instead of assuming the crop is under "standard" conditions, an advantage over tabular values. Whether measured vegetation indices or fractional vegetation cover is used to calculate K_{cb}, it will determine ET_c better than a tabulated crop coefficient because it reflects not only the actual growth stage of the crop but also reductions in canopy cover due to previous stresses.

The dual crop coefficient approach reduces the stress coefficient K_s when the soil water content is less than the level of maximum allowable depletion (MAD) (Allen et al., 1998). K_s represents the fraction of potential transpiration rate that a crop is experiencing reduced from 1.0 according to the level of water stress. Thus, under soil water limiting conditions, K_s will be less than 1. K_s can be as low as 0 in the case that the plant can no longer extract water from extremely dry soil. K_s, according to the Allen et al. (1998) FAO-56 soil water depletion method, is calculated by:

$$K_s = \frac{TAW - D_r}{TAW - RAW} \tag{6}$$

where TAW is the total available soil water in the root zone (mm), D_r is the root zone depletion (mm), and RAW is readily available water (mm). RAW is the portion of TAW which a crop can extract from the root zone without water stress impacts on ET, growth, and yield.

Daily ET_c must be calculated in order to determine the soil water deficit through the water balance method. The water balance method uses inputs of ET_c (mm), deficit for the day of interest ($D_{r,i}$, mm), effective precipitation (P, mm), net irrigation (I, mm), deep percolation (DP, mm), and ground water flux (GW, mm) to calculate daily soil water deficits (Allen et al., 2007):

$$D_{r,i} = D_{r,i-1} + ET_c - P - I + DP - GW \tag{7}$$

In the absence of a high water table, GW inputs are assumed negligible. $D_{r,i}$ is calculated by taking into account the cumulative effect of the daily inputs and outputs on the previous day's deficit ($D_{r,i-1}$).

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