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A refined method for rapidly determining the relationship between canopy NDVI and the pasture evapotranspiration coefficient

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ABSTRACT

The estimation of actual crop evapotranspiration (ET_c) from any given land cover or crop type is important for irrigation water management and agricultural water consumption analysis. The main parameter used for such estimations is the crop coefficient (K_c). Spectral reflectance indices, such as the normalized difference vegetation index (NDVI) and the crop coefficient of a specific crop or pasture canopy are important indicators of 'vigour', namely the photosynthetic activity and rate of biomass accumulation. Measuring both parameters simultaneously, with a view to understanding how they interact, or for creating optical, surrogate indicators of K_c is very difficult because K_c itself is difficult to measure. In this study a portable enclosed chamber was used to measure ET_c of a pasture and subsequently calculated K_c from reference evapotranspiration (ET_o) data derived from a nearby automatic weather station (AWS). Calibration of the chamber confirms the suitability of the device to measure the amount of water vapour produced by local plant evapotranspiration, producing a calibration factor (C) close to 1 (C = 1.02, R^2 = 0.87). The coincident NDVI values were measured using a portable active optical sensor. In a test involving a pasture (*Festuca arundinacea* var. Dovey) at two different stages of growth in two consecutive growing seasons, the NDVI and crop coefficients were observed to be strongly correlated (R^2 = 0.80 and 0.77, respectively). A polynomial regression (R^2 = 0.84) was found to be the best fit for the combined, multi-temporal K_c-NDVI relationship. The main advantages of this method include the suitability of operating at a smaller scale (< 1 m^2), in real time and repeatability.

1. Introduction

Knowledge of monitoring crop evapotranspiration is important for planning and management of water resources especially where crop water requirements exceeds natural precipitation (Gowda et al., 2008). Current techniques of measuring the actual evapotranspiration of a crop in-situ involve indirect methods such as through energy balance or soil water balance models, or directly using lysimeters, which are often complex and expensive (Allen et al., 1998).

Evapotranspiration can also be measured theoretically from reference crop evapotranspiration. For a given crop, the reference crop evapotranspiration (ET_o) is the maximum rate of evapotranspiration possible for a given environmental condition and is based purely on the environmental evaporative demand and a 'standard' canopy surface. The crop coefficient (K_c), the ratio of actual and reference crop evapotranspiration is unique to a specific canopy (morphology, phenology) and by knowing the crop coefficient for a crop or pasture community, the actual canopy evapotranspiration (ET_c) can be calculated with the help of reference crop evapotranspiration data calculated from the theoretical approach developed by Allen et al. (1998).

Since the actual crop evapotranspiration (ET_c) includes the water transpired by the crops as well as the water evaporated from the soil, the crop coefficient (K_c) can also be alienated into basal crop coefficient (K_{cb}) (transpiration from crop only) and soil evaporation coefficient (K_e). Measuring K_c or the components K_{cb} and K_e ($K_c = K_{cb} + K_e$) is therefore the pathway for estimating actual crop evapotranspiration.

Considerable research has been reported in estimating K_c for irrigation water management at the regional scale using the satellite derived spectral reflectance data, where K_c has been related to the Normalized Difference Vegetation Index (NDVI = (NIR − R)/(NIR + R); where NIR and R are reflectance from near infrared and red bands respectively) (Allen et al., 2010; Bausch and Neale, 1987; Duchemin et al., 2006; El-Shirbeny et al., 2014; Er-Raki et al., 2007; Hunsaker et al., 2005; Johnson and Trout, 2012; Neale et al., 1990; Neale et al., 2003; Nouri et al., 2014). Johnson and Trout (2012) developed Landsat-5 satellite-based time-series of K_{cb} for four different crops using mean NDVI from several experimental plots on each clear-sky satellite overpass date. The NDVI was subsequently converted to

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green fractional cover (f_c) using a predefined formula, and finally to K_{cb} based on lysimeter experiments conducted by Bryla et al. (2010). Allen et al. (2010) explored the linear relationships between ET_rF (synonymous with the crop coefficient K_c) and top of atmosphere NDVI from two years of data for Southern Idaho using Mapping Evapotranspiration at high Resolution with Internalized Calibration (METRIC) energy balance process to near-real time estimates of ET_rF from Landsat or other satellite imagery. In both cases the concurrent measurement of related parameters could not be attained, and reliance has been placed on secondary data or pre-defined formula. Bausch and Neale (1987) used a hand-held radiometer and electronic module to measure the radiance and found that the seasonal NDVI curve was curvilinear and resembled the basal crop coefficient (K_b) curve for corn. Duchemin et al. (2006) found linear relationships between NDVI and K_{cb} with a good accuracy (± 15%) using high spatial resolution Quickbird satellite imagery to measure top-of-atmosphere NDVI and in-situ eddy covariance instrumentation to calculate the actual evapotranspiration. An ET-NDVI relationship for urban vegetation was explored by Nouri et al. (2014) from high spatial resolution WorldView-2 imagery and systematic evaluation of evapotranspiration through observational-based approaches. The experimental site of Nouri et al. (2014) includes cover grass that is similar to pasture, however, because of the presence of trees, shrubs and water bodies in the experimental area the relationship derived cannot be exactly the same as pasture. All of these existing methods of linking NDVI to K_c are based on predominantly satellite based measurement of NDVI and evapotranspiration or K_c measured or collected from secondary sources.

Advances in satellite imaging systems, and data and information delivery systems is seeing a growth in interest of irrigation scheduling in a more reliable way. However, many of the existing, spectral reflectance index-K_c (or $-K_{cb}$) relationships have been derived where spatial scale and sensor resolution are not matched, and they are only known for a limited number of agricultural-relevant plant canopies.

There is currently no 'simple' method of directly relating the spectral reflectance index of choice with K_c. All previous research points to a statistically robust relationship between the parameters but the calibration methods are optimal for a gross measurement of regional scale evapotranspiration. Moreover, accessing satellite based NDVI data for any calibration is constrained to the revisit time of the satellite and this can be from few days to weeks (e.g. 16 days for Landsat), further exacerbated by weather. While depending on satellite data for a decision making such as irrigation scheduling is problematic in its own right, in the case of crop or pasture management, any relationship between a VI and ET may also vary with often rapidly-evolving plant growth. Irrespective of the delivery of any decision support tools for, say, irrigation management, there is a need for a consistent and time-efficient means of creating relationships between spectral VIs and ET, which is convenient, portable and suitable for varying skill levels of the user.

Handheld, active, optical reflectance sensors like GreenSeeker® (Trimble, Sunnyvale, California, USA) or the CropCircle® (Holland Scientific Inc., Lincoln, NE, USA) can read the NDVI of the target plant canopy instantly regardless of the environmental conditions (Rahman et al., 2014). It is desirable to be able to measure the crop evapotranspiration coincident with such measurements; in situ, at the same spatial scale and at very near, if not at the same time. One solution is the use of a portable hemispherical evaporation chamber for directly recording evapotranspiration in situ (Stannard, 1988). This is a convenient method requiring only a few minutes onsite to set up and less than a minute of measurement time (McLeod et al., 2004). Responsive sensors are mounted inside the chamber to record temperature and humidity so that the vapour generated from the target area can be accurately measured from the change in vapour concentration inside the chamber when the area covered by the chamber and the air inside mixed uniformly with the help of a fan. A number of studies have used devices to contain the atmosphere over plant targets to quantify evapotranspiration in conditions ranging from forest to desert (Garcia et al., 2008; Macfarlane and Ogden, 2012; McJannet et al., 1996), vegetated rangeland (Stannard and Weltz, 2006), as well as in some pastures and emerging crops (McLeod et al., 2004; Stannard, 1988). The dimension of the containment chamber, instrumentation and procedures vary depending on the purpose and circumstances but the principle of instantaneous ET measurement is similar in each study. Careful calibration and device operation is important for successful use of this technique. When operated correctly, the performance of this chamber compared with other theoretical approaches of measuring ET has demonstrated the potential value of using such methods for completing evapotranspiration measurements (McLeod et al., 2004). To date these devices have only been used to understand the water demand and evapo-transpiration dynamics of the species in question.

With the availability of high spatial and temporal resolution multispectral satellite systems, and the emergence of ultra-high spatial resolution aerial platforms such as drones and miniature multispectral imaging devices as their payloads, there is considerable interest in being able to conveniently derive VI-K_c relationships so that these systems can be used for irrigation scheduling. The specific objective of this study is to bring together the two sets of measurements; namely spectral reflectance index measurements and K_c measurements into a single field measurement process for determining VI- K_c relationship. In this case we demonstrated the technique for a pasture species of importance to grazing industries worldwide (Rahman et al., 2014).

2. Materials and methods

2.1. Instrumentation and calibration

A schematic diagram of the ET dome and instrumentation is shown in Fig. 1 and is based upon the designs of (McLeod et al., 2004; Stannard, 1988). The diameter of the clear perspex dome is 0.68 m and the height is 0.36 m including a 2 cm thick foam-rubber ring on its base to ensure a good seal with the canopy/ground surface. A humidity sensor (Vaisala Oy, HMP 35A, Helsinki) and a thermocouple (ICT International, Australia) were mounted inside the dome to monitor the change in the air humidity and temperature, respectively and both sensors were connected to a data logger (SM1E904, ICT International, Australia) which was able to record the data at one second interval. The humidity sensor was specifically chosen for its fast response time. Two fans of 80 mm diameter were used to mix the air and accumulating water vapour uniformly inside the dome. Whenever the dome was positioned over a 'target' surface, the fans were running continuously while the dome was positioned to ensure rapid mixing of the vapour and presentation of that mixed vapour to the overhead environmental sensors.

A crucial first step in dome deployment is calibrating the dome to ensure that water vapour accumulation, as measured by the environmental sensors, is the same as water lost to the atmosphere contained in

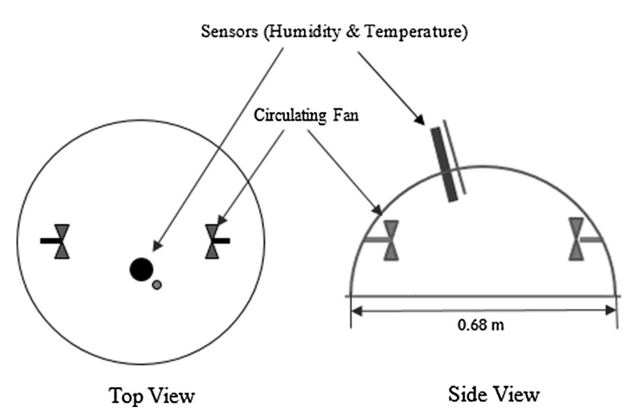

Fig. 1. Schematic representation of the ET dome fitted with necessary accessories.