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Hyperspectral remote sensing for growth-stage-specific water use in wheat

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ABSTRACT

Precise application of irrigation water to crops requires an accurate calculation of daily crop evapotranspiration (*ET*), which has always remained a challenge to the scientific community. Reflectance-based crop coefficients approach has a strong theoretical base, as both the crop coefficient [ratio of actual crop (ET_c) and reference *ET* (ET_0)] and remote sensing of crop follow a similar response curve mediated by crop growth stages and crop health conditions. This paper investigates the feasibility of linking the evolution of basal crop coefficient (K_{cb}) of wheat to the hyperspectral remote sensing derived vegetation indices, through leaf area index (LAI), the principal plant growth parameter. Two years field experiments were conducted with three cultivars of wheat (*Triticum aestivum* L.) under adequate (6-cm each irrigation) and limited (4-cm each irrigation) water supply. Ground based observations on profile water balance components, hyperspectral remote sensing, fractional ground coverage, LAI, water potential and relative water content in leaves were monitored periodically. Biomass and yields were recorded at harvest. Limited water application forced the crop to attain its peak crop coefficients and LAI values early (at flowering, 80–95 DAS), compared to at milking stage (90–105 DAS) under adequate water supply. Basal crop coefficients (K_{cb}), indicative of transpiration in plants were able to generate a better estimate of the stage-specific crop water use. The prospect of its retrieval through hyperspectral remote sensing was demonstrated. A reduction in K_{cb} could be primarily due to reduction in LAI in wheat, especially when soil moisture was not a limiting factor. Exclusion of residual evaporation and minimizing background effect of soil made the evolution of K_{cb} similar to LAI and LAI similar to Soil Adjusted Vegetation Index (SAVI). These imply that the transpiration and light absorption profile of the crop increase or decrease with nearly the same rate throughout its growth period. The LAI saturated at a value of 3 in limited and 4 in adequate irrigation treatments suggesting that once the canopy coverage is complete, further increase in LAI might not lead to an increase in single crop coefficient values. Interestingly, SAVI showed a linear response to K_{cb}, and also did not saturate before the LAI reached to 4.5 (LAI > 4.0 is reported in full developed canopies of wheat). This makes SAVI superior than NDVI (Normalized Difference Vegetation Index), which saturates at LAI > 3.5, for retrieving crop coefficient; and improving the accuracy in predicting crop water use at specific stages. These relations have high potential at an operational scale for irrigation scheduling over extended wheat growing areas like Indo-Gangetic Plains, through use of high resolution earth observation satellite data.

1. Introduction

Global demand for wheat will reach 840–1000 million tons by 2020 (Rajaram and Braun, 2008). India, the 2nd largest producer of wheat with 80.8 million tons of current production will have a significant role in meeting the demand. However, there are wide gaps between the average national productivity, which has been stagnant at 2.7 t ha^{-1} during last decade, and the yield potentials. Reducing the gaps would be crucial for future global food security. One niche area is irrigation water management, where the misuse of water significantly contributes in increasing the production costs and affecting the environment. To economize the water application to crops, matching the demand and supply is essential. A real-time irrigation scheduling can be critical in water resources management at the farm or regional level, which requires precise estimation of growth stage-specific water requirement by the crop.

The crop coefficient (K_c) based methodology (Doorenbos and Pruitt, 1977) was developed for guiding irrigation scheduling. It is

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further split into evaporation (K_e) and transpiration (K_{cb}) components to predict the effect of specific wetting events (for example, irrigation) on K_c (Allen et al., 1998). This 'dual' crop coefficient method allows better estimates of daily evapotranspiration (ET_c), following irrigation or rain, when soil evaporation can cause significant deviation of actual crop coefficient values. The coefficient is a function of climate, soil and crop types and crop phenology (Allen et al., 1998), and therefore, varies from one region to the other (Ko et al., 2009; Piccinni et al., 2009). Specific adjustment to local climate, soil and environment, thus becomes fairly necessary for better and effective use of the coefficient in precise irrigation scheduling.

The success in obtaining reliable K_c estimates depends on synchronizing the crop coefficient with its definite phenology and health condition (Bausch, 1993; Hunsaker et al., 2005). Remote sensing in combination with conventional method (Allen et al., 1998; Bastiaanssen et al., 1998; Er-Raki et al., 2007) can be a promising approach. While applying remote sensing in estimating ET_c, K_c is related to the vegetation indices derived from remotely sensed crop reflectance values. The relationship has been developed for different crops with moderate to good success (Bausch and Neale, 1987, 1989; Neale et al., 1996; Choudhury et al., 1994; Bausch, 1995). Relations between vegetation indices and K_{cb} appear to be a better approach for predicting the annual ET_c of wheat, and therefore, its water requirements can be made operational at a regional scale under either optimal or sub-optimal conditions (Hunsaker et al., 2007; Er-Raki et al., 2007). Locally calibrated stage-specific values of crop coefficients for winter wheat in the semi-arid region of Delhi are not currently available. In this study, we explored the possibility of utilizing the non-imaging hyperspectral fine resolution data to precisely define the water status of the plant canopy and thereby, to predict the crop coefficient values more accurately. Our specific focus was to evaluate the dual crop coefficient, K_{cb} in its relation to crop growth and spectral indices and to select the most suitable index over the entire range of growth and development in wheat.

2. Materials and methods

2.1. Study area, climate and soils

The study was carried out at the Experimental Farm, Indian Agricultural Research Institute, New Delhi (28°35′N latitude, 77°12′E longitude and 228.16 m above mean sea level). The climate is subtropical, semi-arid (June being the hottest and January the coldest month) with mean annual rainfall of 652 mm, 84% of which is received through south-west monsoon (July to September). The rainfall was 14.0 mm (between 9th and 23rd February, 2010) and 49.7 mm (between 8th February and 4th March, 2011). Duration of bright sunshine hour was marginally higher in 1st year (5.6 h) than 2nd year (5.0 h).

The soil is a sandy clay loam (typic Haplustept) with medium to weak angular blocky in structure, non-calcareous and slightly alkaline in reaction. The plant available water content is 10–15% (v/v) and the saturated hydraulic conductivity is medium to high.

2.2. Field experiments

Field experiments with three varieties of wheat (*Triticum aestivum* L.) namely, DBW-17, PBW-502 and HD-2987 were conducted during years of 2009–10 and 2010–11 in a strip-plot design. The experimental area was divided into long strips (in north-east direction) of adequate (60 mm depth) and limited (40 mm depth) irrigation treatments with 2 m buffer between the strips. The three varieties were then randomly allocated such that each variety could occupy four plots within a strip. Each plot was 9.5 m × 6 m in dimension.

The field was tilled conventionally before sowing (1 disking + 2 cultivation to 15–20 cm depth). The crop was sown on 24th November (both the years) by seed drill at 4 cm below the surface at spacing of 22 cm row to row and 6 cm plant to plant. Fertilizer doses were 120 kg N (as urea), 80 kg P_2O_5 (as single superphosphate) and 60 kg K_2O (as muriate of potash) ha^{-1}, of which half of N and full dose of P_2O_5 and K_2O was applied in the furrows at the time of sowing, while rest of N was applied as 2 top dressings, 35 and 78 days after sowing (DAS).

Irrigation water was applied through check basin. The depths of water were kept as 60 (adequate) and 40 (limited) mm, each at different growth stages of wheat. A total of 5 and 4 irrigations were applied precisely with the help of Parshall flume to adequate and limited plots, respectively. The irrigation on 113 DAS was skipped in limited irrigation plots to create an additional mild water stress at the dough stage. Two Parshall flumes were installed at the main channel-inlets, secured properly and discharge of water (Q) at head, H_a was measured by the equation:

$$Q = k \times H_a^j \tag{1}$$

where k and j are constants depending on throat width (we had throat width of 15 cm; corresponding k and j values were taken as 0.26 and 1.55, respectively; Sharda et al., 2007). The free flow condition was ensured by observing the ratio of height of water at inlet (converging section) and outlet (diverging section). Before installation, the flumes were calibrated by measuring the time required to irrigate the individual plots. As the field was leveled by laser leveler technology just prior to sowing, uniform distribution of water in the plots was assumed. Recommended agronomic practices were taken to keep the field weed- and pest-free during crop growth.

2.3. Monitoring soil water balance components

Components of soil water balance were measured for the 1 m soil profile, as given by the equation (Hanks and Ashcroft, 1980):

$$ET_c = P + I - D - R - \Delta S \tag{2}$$

where ET_c denotes estimated crop evapotranspiration, P is precipitation, I is irrigation, D is deep percolation below the root zone (or an upward flow i.e. capillary rise, if negative, into the root zone), R is runoff (assumed negligible, as the field was laser-leveled) and ΔS is the change in soil profile water storage between each two consecutive soil water measurement days (all expressed in mm).

Neutron probe access tubes were permanently installed one in each plot. A neutron probe (503 DR Hydroprobe®, CPN International, Inc., CA, USA) was calibrated in the same field and soil water content of 1 m profile was monitored at 0.15 m depth increments. Measurements were taken on each day following irrigation and gradually increasing the intervals (depending on soil water depletion) up to thrice a week when the soil became sufficiently dry. Gravimetric soil water sampling was regularly followed for surface 5 cm layer. Depletion rates (mm d^{-1}) for a particular depth were the changes in soil water content between two subsequent observations, which upon integration over the 1 m profile resulted in total depletion for that period.

Rate of transpiration and root water extraction were computed following the procedure outlined by Stibbe (1975):

$$\overline{E_r} = \left[\frac{1}{t_2 - t_1}\int_{z}^{z_r} \theta_z . d_z\right] \pm \overline{V}_z \pm \overline{V}_r \tag{3}$$

where E_r is the rate of root water extraction in mm d^{-1}; the first term on the right hand side of the equation is the rate of soil water (θ) depletion in the root zone (up to depth z_r) per unit time ($t_1 - t_2$)