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Dynamics of crop coefficients for citrus orchards of central India using water balance and eddy covariance flux partition techniques

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ABSTRACT

Accurate quantification of crop water demand and characterizing its temporal variability is essential in evaluating the role of water saving strategies for sustainable production. Representing evapotranspiration (ET) as a proxy to crop water needs is often misleading, particularly during the periods of high non-stomatal exchanges. This study is aimed at modeling crop water requirements for citrus orchards of central India using single and dual crop coefficient approaches. ET fluxes derived from eddy-covariance (EC) technique were used to develop single crop coefficient (K_c) curves at daily, weekly, and seasonal scales. Site-specific K_c values for initial, mid, and late season were found to be 0.43, 0.78, and 0.80 respectively. ET partitioning was done by estimating soil evaporation coefficient (K_e), and basal crop coefficient in the presence of water stress ($K_s \times K_{cb}$) using soil-water balance (SIMDualKc) and EC flux partitioning (EC FP) methods. SIMDualKc model was calibrated against electrical resistivity tomography (ERT) derived soil water contents ($R^2 = 0.81$, RMSE = 0.021 $cm^3\,cm^{-3}$). Energy based flux partitioning was done by considering the correlation between high-frequency water vapour and carbon fluxes and applying flux variance similarity principles. Direct measurement of evaporation (E) and transpiration (T) at four citrus trees (using micro-lysimeters and sap flow meters) was used to assess the performance of two models. Three-stage basal crop coefficients from SIMDualKc and EC FP methods were found to be 0.18, 0.57, 0.63 and 0.26, 0.51, 0.59 respectively. Both methods were effectively partitioning the ET fluxes at daily scale ($R^2 > 0.5$, RMSE < 0.6 mm, NSE > 0.3), however, variability in estimated fluxes between the two methods is high during the initial stage and gradually diminished with time.

1. Introduction

Sustainable irrigation practices aim at improving crop productivity with manageable resources under changing the hydrologic environment (Saadi et al., 2015). This requires a critical evaluation of water saving strategies (including deficit irrigation, mulching, partial root zone drying, etc.) for improved crop water productivity (CWP), a measure of crop yield per unit of irrigation water. An accurate assessment of crop water requirements during the growth period can help to i) organize irrigation amount and timing, ii) maximize crop yield, and iii) minimize water losses and crop stress (Anderson et al., 2017). In semi-arid developing countries like India, optimal irrigation strategies will also help in the reduction of energy consumption, non-exploitation of groundwater resources, reduced weeding and associated labor costs (Priyan and Panchal, 2017). In eco-hydrology, crop water requirements are interchangeably used with evapotranspiration (ET), a measurable or estimated hydrological parameter. Reference ET (ET_0) is the maximum possible ET that can occur from a well-watered, standard vegetation surface for given meteorological conditions. United Nations Food and Agriculture Organization irrigation and drainage paper guidelines (FAO-56) are widely adopted in estimating the crop water requirements (Allen et al., 1998; Kashyap and Panda, 2001; Liu and Luo, 2010). FAO-56 relates crop evapotranspiration (ET_a) with ET_0 through crop coefficient (K_c), given by (Allen et al., 1998):

$$ET_a = K_c \bullet ET_o \tag{1}$$

Methods for estimating ET_0 can be grouped into: i) mass transfer models such as Dalton, Meyer, Penman (Djaman et al., 2017; Valipour et al., 2017), ii) radiation models such as Priestley Taylor, Ritchie (Tabari et al., 2013), iii) temperature based models such as Hargreaves-Smani, Blaney-Criddle (Bormann, 2011; Muniandy et al., 2016; Valipour et al., 2017), and iv) pan evaporation models (Grismer et al., 2002; Zuo et al., 2016). Nevertheless, each method has advantages and application limitations in terms of data requirement, accuracy, simulation period, and global validity. Numerous studies across the world have concluded that FAO-56 Penman-Monteith method (Allen et al.,

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1998) that combines energy and mass balance approaches is the most accurate, reliable and standard method in estimating ET_0 (Djaman et al., 2015; Pandey et al., 2016; Sentelhas et al., 2010; Tabari et al., 2011). Following Eq. 1, ET_a can be estimated from ET_0 using the scaling factor (i.e., crop coefficient, K_c) that accounts for soil, crop phenological and management conditions. FAO-56 uses two approaches to define this scaling factor, viz. i) single crop coefficient (K_c), that considers the integrated effect of soil evaporation (E) and plant transpiration (T) averaged over each growing season, and ii) dual crop coefficient that is further portioned into soil evaporation coefficient (K_e) and basal crop coefficient in the presence of water stress ($K_{cb} \times K_e$) (Allen et al., 1988). In spite of readily available crop coefficient curves defined for a number of crops considering standard and non-standard conditions, ET_a estimation from FAO-56 guidelines suffers from the following drawbacks: i) season specific ET_a data need to be adjusted and validated considering local agro-climatic conditions, ii) crop coefficients are averaged over each growth stage and hence neglect intra-seasonal variability, iii) influence of water saving strategies on the dynamics of ET_a cannot be readily evaluated, and iv) ignorance of health of the tree can hamper management strategies when applied to diseased trees.

Commonly used methods for quantification of ET_a include: soil water balance (Bodner et al., 2007; Senay et al., 2011), bowen ratio energy balance (Inman-Bamber and McGlinchey, 2003; Malek, 1993), lysimeters (Liu and Luo, 2010; Miranda et al., 2006), and micro-meteorological techniques including EC (Er-Raki et al., 2009; Peddinti et al., 2018). Even though diurnal ET_a variations are obtained, these methods can not partition ET_a and hence limit their applications mostly to single crop coefficient analysis (Gowda et al., 2008). A number of studies have concluded that, dual crop coefficient technique outperforms its counterpart in estimating ET_a for a wide range of cropping systems like maize, wheat, citrus, pecans (Er-Raki et al., 2009; Zhao et al., 2013; Ibraimo et al., 2016) under different water conservating strategies including drip irrigation, plastic or organic mulching, partial root zone drying, and deficit irrigation (Anderson et al., 2017). Direct measurement of E and T fluxes using micro-lysimetry (Liu et al., 2002) and sap flow techniques (Rana et al., 2005) are expensive and time-consuming, hence limit their role to performance evaluation and validation of estimation methods. Of the available indirect methods for partitioning ET fluxes, methods based on micro-meteorological measurements and hydrological balance are more common (Zhao et al., 2015).

Globally, India ranks fourth in orange production, accounting for about 11% of worlds' tonnage. However, India ranks 64th in orange crop productivity (yield per unit area), accounting for 9.23 tons/ha. Vidarbha region in Maharashtra, central India is the leading producer of mandarin oranges (*Citrus reticulata*) accounting for 40% of country's production with a yield of 6 tons/ha, far below the nation's average (Peddinti et al., 2018). Low crop yield in Vidarbha region is chiefly attributed to: i) improper management activities assisted with erratic rainfall patterns, and ii) propagation of a water mold disease 'root rot gummosis' (*Phytophthora* Spp.). The disease propagation has a strong correlation with soil moisture and temperature (Choudhari et al., 2018; Savita and Avinash, 2012). Irrigation in excess of crop water demand increases soil moisture within the rhizosphere, a condition favorable for further growth of disease-causing bacteria. Sub-optimal irrigation strategies result in increased water stress, thereby reducing root water uptake and crop yield. Hence, an accurate assessment of citrus crop water requirements is not only important from irrigation scheduling viewpoint, but also in managing and controlling the disease (Choudhari et al., 2018; Peddinti et al., 2018).

This research is aimed at understanding the dynamics of crop water requirements in citrus orchards of central India. Tower based EC flux measurements were collected at high frequency for one crop cycle to develop diurnal and seasonal K_c curves, and adjust the FAO-56 specified crop coefficients applicable to the region. Dual crop coefficients (K_e and $K_{cb} \times K_s$) were analyzed using water balance and flux partitioning techniques. The water balance was performed separately for soil evaporation and root zone layers using SIMDualKc model. EC flux partitioning was done by cross-correlating stomatal (photosynthesis and transpiration) and non-stomatal (respiration and evaporation) exchanges of high-frequency CO_2 and H_2O concentrations using flux-variance similarity theory. Intermodel comparison for dual crop coefficients was performed using residual statistical indicators. Applicability of the two models to partition ET_a is further validated using the measured evaporation and transpiration data sets.

2. Materials and methods

2.1. Study area

This study was conducted in the citrus orchards of Goregone village (latitudes: 21° 25′ 30.7″ to 21° 26′ 2.4″ E, longitudes: 78° 9′ 30.2″ to 78° 10′ 5.6″ N, elevation: 392 m asl) in the Vidarbha region of central India. As per Köppen-Geiger classification, the area falls under tropical savanna climate zone (Aw) characterized by lengthy dry months followed by short but extremely rainy wet months (Kottek et al., 2006). Mean annual precipitation in the region is about 900 mm with more than 70% occurring during monsoon (Jul-Sep). Mean annual ET_0 is estimated to be 1500 mm. Average daily maximum temperatures (32 to 45 °C) occur during summer months (Mar-Jun), while average daily minimum temperatures (15 to 24 °C) occur during winter months (Dec-Feb). The humidity of the region varies from 35% in summer to 73% in monsoon (CGWB, 2013). Mean seasonal wind speed over the region is in the range of 1.5 to 2.7 m/s. Citrus crops in India are generally grown in three cycles: i) Ambia bahar (Feb flowering), ii) Mrig bahar (Jun flowering), and iii) Hast bahar (Oct flowering). Due to limited water supplements, farmers of this region prefer Mrig Bahar that demands less water during summer (initial stage) and more water during monsoon (growth stage). Citrus trees of the experimental fields are matured (8 years old) with 2.5 to 3 m height and 70% ground cover, healthy (free from Phytophthora spp.), and planted at 5 m spacing. Water requirement of citrus trees is generally met through flood system during flowering and early growth stages (for the ease with fertilizer application), and through drip system during late growth stage (due to limited resources). Irrigation is given at a frequency of 10–15 days with a ponding depth ranging from 6 mm to 40 mm depending on crop growth stage and antecedent precipitation/soil moisture conditions. The soil of the region is classified as vertisol having high water holding capability with rich in clay content (Peddinti et al., 2018). Hydro-geologically, the study area forms part of Deccan plateau characterized by multiple layers of solidified flood basalt resulting from volcanic eruptions. Groundwater is available under phreatic conditions with water drawn from upper weathered to fractured aquifers (Peddinti et al., 2016). Depth to groundwater in the study area is ranged from 12 m (pre-monsoon) to 6 m (post-monsoon) (CGWB, 2013; Central Ground Water Board, 2013).

2.2. Eddy covariance data collection and processing

EC flux tower was installed to measure fast and slow response meteorological parameters during the crop cycle (DOY: 62–365, 2017). Carbon (CO_2), water (H_2O) fluxes were measured at 5 m height using an open path fast response infrared gas analyzer (IRGASON-EB-IC, Campbell Sci. Inc., USA) and a 3D sonic anemometer. Flux data was sampled at 10 Hz frequency and averaged over 30 min interval using a data logger (CR1000, Campbell Sci. Inc., USA). Additionally, slow response meteorological variables including precipitation (TE525-L-PTL, Tipping Bucket, Campbell Sci. Inc., USA), soil heat flux (HFP01SC-L-PT-L, Campbell Sci. Inc., USA), solar radiation (CNR 4, Campbell Sci. Inc., USA), and soil moisture (CS616-L-PT-L, Campbell Sci. Inc., USA) were obtained at 30-min interval. Crop characteristics within the flux footprint were observed to be homogeneous (for at-least 500 m in the