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Support vector machine based modeling of evapotranspiration using hydro-climatic variables in a sub-tropical environment

N.K. Shrestha, S. Shukla*

Department of Agricultural and Biological Engineering, University of Florida, 2685 State Road 29N, Immokalee, FL 34142

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ABSTRACT

Existing models and methods report crop coefficient (K_c) as a function of time but do not consider the variations due to surface conditions, wetting methods, meteorological conditions, and other biophysical factors. These limitations result in erroneous crop evapotranspiration (ET_c) estimates, especially for non-standard conditions (e.g. plastic mulch). We present Support Vector Machine (SVM), a data-driven model based on statistical learning theory, for predicting generic K_c and ET_c using a uniquely large dataset (10 seasons) from lysimeters for multiple crop-seasons combination under the plastic mulch conditions. The data used in this study were obtained from six years of lysimeter-based measurements (Shukla et al., 2006, 2012, 2014a, 2014b; Shukla and Knowles, 2011) for two distinctly different crop types (vine and erect) under two contrasting irrigation methods, drip and sub-irrigation. The SVM-based models predicted bell pepper (erect crop; $r^2 = 0.71$) and watermelon (vine crop; $r^2 = 0.82$) K_c as a function of time, water table depth, and number of rainfall events. The time since transplant represents the plant growth and, therefore, transpiration. The water table depth and rainfall events capture the effect of surface soil moisture on evaporation. The crop type-specific model is robust since it works for two different irrigation methods and growing seasons (spring and fall). The SVM model was superior to the Artificial Neural Network and Relevance Vector Machine models, two data-driven models used in hydrology. The errors in predicting ET_c from the SVM model were only 2.6% and 11.2% for watermelon and bell pepper, respectively, highlighting the model accuracy. For both crops, the SVM predicted K_c values were not statistically different from the actual K_c values. In contrast, the FAO-56 values were significantly lower than the actual K_c values for both bell pepper ($p = 0.016$) and watermelon ($p = 0.025$). When evaluated in the context of watershed-scale budgets, the SVM model improved the accuracy in ET_c estimates by 49.3 mm over the FAO-56 method, and this improvement represents 70% (70.7 mm) of the observed surface flow. Improved accuracy of the SVM model makes it useful in deriving local K_c using readily available hydro-climatic data for applications ranging from field-scale water management to watershed-scale modeling. The proposed model can be used to develop region-specific K_c to improve ET_c estimates. Future efforts should be made to explore the development of similar models for open-field crops.

1. Introduction

The crop coefficient (K_c) approach has been one of the most frequently used methods for estimating ET_c for the last 40 years (Allen et al., 1998; Tasumi et al., 2005). It has been used for the applications ranging from irrigation scheduling (Allen et al., 1998), simulating watershed-scale water balance components (Jaber and Shukla, 2012) to daily flux modeling (Payero and Irmak, 2013). Crop coefficient (K_c) is a ratio of crop evapotranspiration (ET_c) to reference evapotranspiration (ET_0). Literature K_c values (Doorenbos and Pruitt, 1977; Wright, 1981; Allen et al., 1998) are specific to crop type, climatic region, and type of soil wetting. The K_c developed for a specific production system and climatic region is likely to be different from other production systems and regions (Allen et al., 1998; Liu et al., 2002; Kang et al., 2003). The difference between literature and locally-developed K_c values has been reported for both agricultural crops (Simon et al., 1998; Kashyap and Panda, 2001; Kang et al., 2003; Lovelli et al., 2005; Orgaz et al., 2005; Shukla et al., 2012, 2014a, 2014b) and wetland vegetations (Wu and Shukla, 2013), and is to be expected. The differences become especially important when the surface cover condition is different (e.g. plastic mulch) from the standard open-field condition.

* Corresponding author. Tel.: +1 239 658 3425
E-mail address: sshukla@ufl.edu (S. Shukla).

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Crop production under plastic mulch has become a common production system for growing vegetable (e.g. pepper) and fruit (e.g. melons) crops worldwide including Florida. Covering raised beds with impermeable plastic mulch heats the soil through a greenhouse effect (Shinde et al., 2001). These effects combined with the additional benefit of reducing evaporation losses, nutrient leaching, and disease pressure and preventing weed competition make plasticulture an increasingly attractive production system. Almost 12 million hectares of plastic mulch covered farmland existed worldwide in 1999, a number which most likely has increased significantly by now (Miles et al., 2005). The water requirement of the crops grown with plasticulture is different than that in an open-field system, as it significantly alters the water and energy fluxes. Plastic mulch prevents rainfall entry and reduces overall evaporation but increases transpiration. Mulch increases the water flux and infiltration in the row-middle areas because of runoff from the raised beds. Allen et al. (1998) recommended reduction in K_c by 10–30% depending on wetting interval for the drip irrigation system under the plastic mulch. Studies show a difference in K_c values compared to FAO-56 for crops grown under plastic mulch (Amayreh and Al-Abed, 2005; Lovelli et al., 2005; Bryla et al., 2010; Moratiel and Martinez-Cob, 2012; Shukla et al., 2014a, 2014b). In Florida and elsewhere where plasticulture is practiced, wetting of soil prior to bed formation results in soil moisture to near saturation. Further wetting of the soil by rainfall and upflux from a shallow water table at the beginning of growing season keeps the soil moisture high in the row-middle areas, increasing evaporation, which can be 30–60% of the seasonal crop ET_c (Liu et al., 2002; Agam et al., 2012). The increased evaporation can significantly affect ET_c and K_c. With the current models and published methods, an accurate estimate of ET_c for the crops grown under plastic mulch remains a challenge.

Depending on the irrigation methods and climate (Allen et al., 2005; Zhou and Zhou, 2009), K_c and ET_c can vary for the same crop. Sub-irrigation and drip irrigation systems are two common irrigation methods in Florida. The sub-irrigation method in Florida involves surface application of water into ditches similar to surface irrigation. The water is applied at a high rate on the surface, which artificially raises the water table within 0.6 m from the surface. Although sub-irrigation has relatively low efficiency (50%; Smajstrla et al., 1991) compared to drip irrigation (>80%, Lamm and Trooien, 2003), its low cost makes it an attractive option for farmers. Considerable volume of water is lost through evaporation for flood irrigation compared to drip (Lazzara and Rana, 2010), where flood and sub-irrigation have similar efficiency. Drip irrigation under plastic mulch increases its efficiency further because it reduces unproductive evaporation. Existing models and methods lack the robustness and accuracy to differentiate between drip and sub-irrigated crops to calculate ET fluxes. The uncertainty associated with the K_c approach arising from literature K_c values that do not represent the climate and production method of the system being simulated can result in poor calibration and validation of hydrologic models (Kienzle and Schmidt, 2008; Zhao et al., 2012), and often leads to transferring the errors to other water balance components. The differences need to be quantified, which necessitates the development of a model to estimate K_c for the type of wetting for a plasticulture production system.

For a plasticulture system, the soil is wetted to near saturation for preparing the firm raised beds with a tractor-driven machine. Due to excessive wetting, the evaporation is high compared to transpiration at the initial crop stage for both sub- and drip-irrigation methods as the soil is wetted to the same level. When the soil moisture is not limiting, the evaporation rate is close to ET_0 during the early crop stage (Liu et al., 2002). The evaporation is also affected by the crop cover or structure. The effective full cover for an erect crop such as bell pepper is about 40% (Miranda et al., 2006), which results in high evaporation from the wide-open bare row-middles. The vine crop such as watermelon affects the row-middle evaporation differently than an erect crop. Evapotranspiration for a vine crop during the early crop growth stage predominantly occurs in the form of soil evaporation when the crop cover is low. As the crop grows, greater shading from its canopy reduces bare soil evaporation (Johnson, 2002). Ground cover for a vine crop is both larger and spreads faster than that for an erect crop. Most vine crops achieve almost complete ground cover (>95%; Akintoye et al., 2009) at full growth, resulting in diminished soil evaporation and increased transpiration. During this stage, wetting of row-middles by rainfall and/or irrigation does not have much effect on evaporation. Evaporation of rain or irrigation from a vine crop, therefore, is likely to be different from an erect low canopy crop due to differences in bare soil evaporation as well as direct evaporation of the intercepted rainfall. In addition to fraction of ground cover (Williams and Ayars, 2005), the crop height also affects K_c (Allen and Pereira, 2009). Since vine and erect crops are distinctly different in crop height and ground cover, significant difference in ET_c and K_c between the two types of crop is expected.

Many regions in the world including Florida have multiple cropping seasons (e.g. gradually warming, gradually cooling) where the same crop is grown for more than one season within a year that are distinctly different in climatic conditions. The seasonal difference in climate variables and crop growth (Went, 1953) can result in a difference in ET_c and K_c between the seasons. In absence of local K_c values, same literature K_c values have been used for the meteorologically different seasons despite the fact that they are mostly derived under specific climatic conditions. This adds further uncertainty in crop water use estimates.

Past studies report K_c as a function of time, but do not consider the variation in K_c for the factors such as hydrologic conditions, weather, wetting methods (e.g. drip, sub-irrigation), and surface conditions (e.g. plastic mulch, open-field, partial or complete cover). The majority of literature K_c values have been derived from lysimeter studies (Allen et al., 1998; Ko et al., 2009; Shukla et al., 2012, 2014a, 2014b) and are specific to crop, irrigation method, surface condition, and climatic region and season. The effects of such variables on ET_c and K_c values have been reported. Doorenboss and Pruitt (1977) emphasized the need for local calibration of K_c under given climatic conditions. Allen et al. (1998) proposed adjustment on mid and late stage K_c for relative humidity, wind speed, and crop height. Zhou and Zhou (2009) performed regression analysis for modeling ET_c for reed marsh in northern China, and found air temperature, relative humidity, and net radiation as the most explanatory variables for explaining variations of K_c. They also observed increased ET_c after rain events. Li et al. (2003) conducted lysimeter studies for maize and wheat in China where ET_c was strongly affected by rainfall, irrigation, and leaf area index (LAI). Rijal et al. (2012) analyzed the effects of subsurface drainage on corn and soybean ET_c and K_c in North Dakota and found that ET_c values were mainly affected by the water table level. A similar effect of water table on ET_c is reported in Nachabe et al. (2005). Therefore, there is a need to develop a model that accounts for hydrologic and meteorological conditions to predict K_c in order to reduce uncertainty in ET_c estimates.

Current science of ET is not mature enough to accurately simulate the effect of type of surface wetting, season, and hydrologic condition on ET_c using physically-based models. ET_c modeling using current physically based models use simplified assumptions and have difficulty and extensiveness of the parameter estimation (Farahani and Ahuja, 1996). The complexities in the physically based models (Beven, 1989; Kirchner, 2006) and difficulties associated with the data acquisitions such as lysimeter-based K_c development (Bryla et al., 2010; Shukla et al., 2014a) along with the associated high costs have also limited the development of