Crop Coefficients Specific to Multiple Phenological Stages for Evapotranspiration-based Irrigation Management of Onion and Spinach

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Abstract. Weighing lysimeters are used to measure crop water use during the growing season. By relating the water use of a specific crop to a well-watered reference crop such as grass, crop coefficients (\(K_c\)) can be developed to assist in predicting crop needs using meteorological data available from weather stations. This research was conducted to determine growth stage-specific \(K_c\) and crop water use for onions (\(Allium cepa\) L.) and spinach (\(Spinacia oleracea\) L.) grown under south Texas conditions. Seven lysimeters, consisting of undisturbed 1.5 x 2.0 x 2.2-m deep soil monoliths, comprise the Texas AgriLife Research—Uvalde lysimeter facility. Six lysimeters, weighing \(\approx 14\) Mg, have been placed each in the middle of a 1-ha field beneath a linear low-energy precision irrigation system. A seventh lysimeter was established to measure reference grass reference evapotranspiration. Daily water use for onion and spinach was measured at 5-min intervals. Crop water requirements, \(K_c\) determination, and comparison with existing Food and Agricultural Organization (FAO) \(K_c\) values were determined over a 2-year period for each crop. The \(K_c\) values determined over the growing seasons varied from 0.2 to 1.3 for onion and 0.2 to 1.5 for spinach with some of the values in agreement with those from FAO. It is assumed that the application of growth stage-specific \(K_c\) will assist in irrigation management and provide precise water applications for a region of interest.

Agricultural water users must plan an annual water budget in arid to subhumid areas where water use is regulated as a result of ecological protection programs, limited resources, and competitive demand (Barrett, 2000). Determining crop water requirements specific to each crop is key in providing growers with information to 1) select which crops to grow; and 2) determine the timing and quantity of irrigation events.

The Wintergarden region of Texas, which is located on the South Texas Plains, receives \(\approx 660\) mm/year of precipitation and has a growing season of \(\approx 214\) to 275 d. In 2000, growers in this region irrigated 40,000 ha (Texas Water Development Board, 2001). From preliminary studies carried out at the Texas AgriLife Research Center, it is estimated that \(\approx 62\) million to 74 million m\(^3\) of groundwater could be conserved each year by implementing proper irrigation techniques and scheduling. To optimize irrigation events, crop water requirements throughout the growing season must first be determined.

The use of on-site micrometeorological data and crop coefficients enable growers the determination of crop water use in a reliable, usable, and affordable format. The concept of "crop coefficient" (\(K_c\)) was introduced by Jensen (1968) and further developed by the other researchers (Allen et al., 1998; Burman et al., 1980b; Doorenbos and Pruitt, 1977). \(K_c\) is the ratio of the evapotranspiration of the crop (\(E_{TC}\)) to a reference crop (\(E_{T0}\)) (Allen et al., 1998). \(E_{T0}\) may be measured directly from a reference crop such as a perennial grass (Watson and Burnett, 1995) or computed from weather data using temperature models (Doorenbos and Pruitt, 1977; Thornthwaite, 1948), radiation models (Doorenbos and Pruitt, 1977; Hargreaves and Samani, 1985), or combination models (Allen et al., 1998). Weighing lysimeters are used to measure \(E_{T0}\) and \(E_{TC}\) directly by detecting simultaneous changes in the weight of the soil/crop unit (Marek et al., 2006; Schneider et al., 1998). Weather data are used to compute \(E_{T0}\) by equations such as the ASCE Penman-Monteith (ASCE-EWRI, 2005). Once \(K_c\) values are determined, all that is needed to provide growers with real-time irrigation recommendations (\(E_{TC}\)) are local weather stations to determine \(E_{T0}\) and therefore solve the following simple equation:

\[E_{TC} = K_c \times E_{T0}\]  
(1)

According to Allen et al. (1998), crop type, cultivar, and developmental stage affect \(E_{TC}\). The objective of this multiyear research is to determine crop water use (\(E_{TC}\)) and develop \(K_c\) specific to multiple phenological stages for important vegetable crops such as onion and spinach.

Materials and Methods

Lysimeter facility. The lysimeter facility at the Texas AgriLife Research Center in Uvalde, TX (long. 29°13' N, lat. 99°45' W; elevation 283 m), includes seven weighing lysimeters constructed between 2001 and 2006. Construction details and resolution are described by Marek et al. (2006). Each lysimeter is 1.5 x 2.0 m (length x width) and 2.2 m deep. The surface area (3 m\(^2\)) of the lysimeters accommodates common row spacings used in the region. The soil monoliths in the lysimeters contain a silty clay soil (fine-silty, mixed, hyperthermic Aridic Calciustolls with a pH of 8.1).

Micrometeorological data were collected by a standard Campbell Scientific, Inc. (Logan, UT) weather station every 6 s with 15-min outputs. These include solar radiation, wind speed, air temperature, dew point temperature, relative humidity, precipitation, and barometric pressure (Dusek et al., 1987; Howell et al., 1995). The weight of each lysimeter was sampled every 1 s with 5-min outputs. Weight changes in the lysimeters were measured in mV-V\(^-1\) output of the load cell attached to a scale (Avery Weigh Tronix: model HDS 6060, Fairmont, MN) beneath each lysimeter. The calibration of mV-V\(^-1\)
output to weight changes represented as millimeters of water is described in Marek et al. (2006). The load cell signal was composited to 30-min means and the lysimeter mass resolution was 0.01 mm. Daily $E_T_0$ measured with the lysimeters (Lys $E_T_0$) was determined as the difference between the lysimeter mass loss (evaporation and transpiration) and lysimeter mass gains (irrigation, precipitation, or dew) divided by the lysimeter area (9 m²). A pump (-10 kPa) provided vacuum drainage and the drainage effluent was weighed by load cells (drainage determined as the difference between the lysimeter mass (2006). The load cell signal was composited to 30-min means and the lysimeter mass (9.18 m²) was divided by 1.02 to adjust the effluent was weighed by load cells (drainage determined as the difference between the lysimeter mass (2006). The load cell signal was composited to 30-min means and the lysimeter mass (9.18 m²) was divided by 1.02 to adjust the

Results

Onion evapotranspiration and crop coefficient. Daily onion $E_T_c$ over the growing seasons 2002–2003 and 2004–2005 ranged between 1 and 7 mm and peaked at 160 d after planting (DAP) in 2002–2003 and 120 DAP in 2004–2005 (Fig. 1A). Daily $E_T_c$ rates were variable depending on seasonal conditions (i.e., planting date, temperatures). Accumulated onion $E_T_c$ was 362 mm in 2002–2003 and 438 mm in 2004–2005, respectively. These values are smaller than those obtained in Hawaii (Wu and Shimabuku, 1996), New Mexico (Al-Jamal et al., 2000; Sammis et al., 1985), and Utah (Drost et al., 1996). However, our values are within the range of the water requirements (350 to 550 mm) for optimum onion yield (35,000 to 45,000 kg/ha) described by Doorenbos and Kassam (1986). The reference

Table 1. Onion and spinach crop and seasonal conditions at the Texas AgriLife Research, Uvalde, TX.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Cultivar</th>
<th>Planting</th>
<th>Plant–harvest</th>
<th>Rainfall</th>
<th>Irrigation</th>
<th>GDD °C-d</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onion</td>
<td>Texas Legend</td>
<td>2002</td>
<td>21 Nov.–28 May</td>
<td>80</td>
<td>283</td>
<td>1,809</td>
</tr>
<tr>
<td></td>
<td>Texas Legend</td>
<td>2004</td>
<td>8 Nov.–14 Apr.</td>
<td>166</td>
<td>215</td>
<td>1,219</td>
</tr>
<tr>
<td></td>
<td>DMC 16</td>
<td>2003</td>
<td>20 Nov.–27 Feb.</td>
<td>60</td>
<td>130</td>
<td>822</td>
</tr>
</tbody>
</table>

* Texas Legend (Seminis Seed Co., St. Louis, MO) and DMC 16 (Del Monte Foods Co., San Francisco, CA).

* GDD = growing degree days was based on a minimum base temperature of 7.0 °C for onion and 4.0 °C for spinach.

Fig. 1. (A) Onion crop evapotranspiration ($E_T_c$); (B) reference evapotranspiration ($E_T_0$); and (C) crop coefficient as a function of days after planting (DAP) in 2002–2003 and 2004–2005. A third polynomial equation for each $K_c$ is as follows: Lys $K_c = 0.45 + 1.44 \times 10^{-2} \times DAP + 5.09 \times 10^{-4} \times DAP^2 - 2.76 \times 10^{-6} \times DAP^3$, ASCE $K_c = 0.45 + 2.95 \times 10^{-3} \times DAP + 3.85 \times 10^{-5} \times DAP^2 - 2.47 \times 10^{-7} \times DAP^3$, ASCE $K_c = 0.40 + 2.36 \times 10^{-3} \times DAP + 3.94 \times 10^{-5} \times DAP^2 - 2.68 \times 10^{-7} \times DAP^3$.  

where $E_T_0$ was determined either from direct measurement using the lysimeter (Lys $E_T_0$) or from calculations using the ASCE Penman-Monteith equation (ASCE-EWRI, 2005) for grass (ASCE $E_T_0$) and/or alfalfa (ASCE $E_T_0$). $K_c$ curves for the three methods (Lys $E_T_0$, grass $E_T_0$, and alfalfa $E_T_0$) were fitted to third-order polynomials. Other studies demonstrate that $K_c$ curves can be fitted to third- and up to fifth-order polynomials (Ayars and Hutnacher, 1994; Sammis and Wu, 1985; Stegman, 1988; Wright, 1982).

The load cell signal was composited to 30-min means and the lysimeter mass (9.18 m²) was divided by 1.02 to adjust the effluent was weighed by load cells (drainage determined as the difference between the lysimeter mass (9.18 m²) was divided by 1.02 to adjust the

Lysimeter field data. A tall fescue grass (Festuca arundinacea Schreb.) seed (cv. Emerald II; Sharp Bros. Seed Co., Healy, KS) was hydromulched in late Fall 2001 on the weather station plot after completing installation of a lysimeter located in the center of 1.0 ha, a field that had a surface drip irrigation system. The grass height was ~0.1 m after mowing and varied from 0.12 to 0.15 m before mowing.

Two vegetable crops, onion cv. Texas Legend and spinach cv. DMC 16, were grown during 2002 to 2005 in the crop lysimeter fields, each located in the center of ~1.0 ha, which were used in the determination of $K_c$ (Table 1). All field operations were performed using standard 1.0-m wide row-crop field equipment, except inside each lysimeter where hand-cultural methods were applied. Fertility and pest control practices were uniformly applied following standard production practices in the Wintergarden (http://aggie-horticulture.tamu.edu/extension/vegetable/cropguides). Every year fields were furrow-diked (dike spacing at ~1.5 m) to minimize field runoff and rainfall and irrigation redistribution. Irrigation was provided with a three-span lateral move sprinkler system (Lindsay Manufacturing Co., Lindsay, NE). The system was equipped with goose-neck fittings and spray heads (Senninger Super Spray 360E, Clermont, FL) with medium grooved spray plates on drops located ~1.5 m above the ground and 1.0 m apart. The drops could be converted to low-energy precision application (LEPA) heads placed ~0.3 m above the ground. Fields were managed under full irrigation, which was scheduled based on measured daily crop water use (ET).

Crop coefficient ($K_c$) was calculated using the following equation:

$$K_c = \frac{E_T_c}{E_T_0} \quad (2)$$

where $E_T_0$ was determined either from direct measurement using the lysimeter (Lys $E_T_0$) or from calculations using the ASCE Penman-Monteith equation (ASCE-EWRI, 2005) for grass (ASCE $E_T_0$) and/or alfalfa (ASCE $E_T_0$). $K_c$ curves for the three methods (Lys $E_T_0$, grass $E_T_0$, and alfalfa $E_T_0$) were fitted to third-order polynomials. Other studies demonstrate that $K_c$ curves can be fitted to third- and up to fifth-order polynomials (Ayars and Hutnacher, 1994; Sammis and Wu, 1985; Stegman, 1988; Wright, 1982).

Data were analyzed by paired $t$ test using PROC TTEST, analysis of correlation using PROC CORR as well as PROC REG (SAS Institute, Cary, NC). These methods were used to determine statistical differences of the measured lysimeter $E_T_0$ data from the ASCE Penman-Monteith calculated data.
ET0 during the corresponding crop seasons ranged between 1 and 7 mm for both lysimeter measured ET0 (Lys ET0) and calculated ET0 using ASCE Penman-Monteith equation for grass (ASCE ET0) (Fig. 1B). The ASCE ET0 matched well with Lys ET0 with a Pearson’s correlation coefficient (r) of 0.81 and root mean square error (RMSE) of 1.13 mm (Fig. 2).

Throughout crop development, daily onion Kc varied from 0.2 to 1.3 for all lysimeter-based Kc (Lys Kc), ASCE grass-based Kc (ASCE Kc0), and Kc based on ASCE Penman-Monteith equation for alfalfa (ASCE Kc) (Fig. 1C). Growth stage-specific Kc for onion determined in this study was 0.40 at emergence, 0.90 at bulb development, and 0.70 at dry leaf stage (Table 2). These values were determined based on the third polynomial Kc curve (see Fig. 1C). The values are smaller at initial and midgrowth stages than those from the Food and Agricultural Organization (FAO) (Allen et al., 1998).

### Spinach evapotranspiration and crop coefficient
Daily changes of spinach ETc during 2002–2003 and 2003–2004 seasons were between 0.5 and 5.0 mm (Fig. 3A). Daily ETc rates varied from 0.5 to 3.0 mm during fall (0 to 35 DAP) and seldom exceeded 2.0 mm between 35 and 50 DAP. Accumulated spinach ETc was 160 mm in 2002–2003 and 156 mm in 2003–2004, respectively. To our best knowledge, there is no comparable report on spinach ETc or crop water use. However, our values are less than the vegetable water requirements (250 to 500 mm) described by Doorenbos and Kassam (1986). ETc during the corresponding crop seasons was between 0.5 and 5.0 mm for both Lys ETc and ASCE ETc (Fig. 3B). ASCE ETc matched well with Lys ETc with an r-value of 0.76 and RMSE of 0.64 mm (Fig. 4).

Spinach Kc ranged between 0.2 and 1.5 for all of Lys Kc, ASCE Kc0, and ASCE Kc (Fig. 3C). Growth stage-specific Kc estimates for spinach based on the third polynomial Kc curve were 0.35 at emergence, 1.0 at 13 to 15 leaves, and 1.05 at 19-harvest stages (Table 3). The values are smaller at initial and greater at end growth stages than those from FAO (Allen et al., 1998).

### Discussion
The aim of this research was the determination of Kc for two major winter vegetable crops and to determine their plant water use or crop ETc. Once Kc are determined, irrigation scheduling can then be improved for applications by private consultants and growers to avoid water overuse and to more precisely meet the crop water demand to produce greater yields, crop quality, and enhanced water productivity. From these studies, accumulated ETc estimates for each crop during the growing season were 400 mm for onion and 158 mm for spinach. The seasonal Kc values varied from 0.2 to 1.3 for onion and 0.2 to 1.5 for spinach. On the other hand, the present stage-specific Kc values were determined based on Kc curves that represent the distribution of Kc over time throughout the season. The results in this study showed that some of the Kc values were in accordance with FAO, whereas those during crop establishment and early growth were smaller than FAO (Allen et al., 1998).

Research has repeatedly shown that proper irrigation management is key to achieving profitable crop yields. Potential evapotranspiration (PET) network is a group of meteorological stations to acquire weather data to compute PET (Howell, 1998). The PET networks (Brock et al., 1995; Howell,
Cornic and Massacci, 1996), impeding plants to transpire at its full potential. In addition, different environmental conditions between regions allow variation in variety selection and crop developmental stage, which affect $K_c$ (Allen et al., 1998). In the Wintergarden region, the use of $K_c$ generalized (Allen et al., 1998) or developed in other regions (e.g., Al-Jamal et al., 2000) will result in overwatering and consequently increased production costs and reduced profits. At the same site, Leskova and Piccinni (2005) demonstrated that $ET_0$-based irrigation management for spinach can be efficiently applied. They concluded that it is possible to reach a maximum of 25% water-saving in one season using the irrigation scheduling based on crop evapotranspiration.

In conclusion, the development of regionally based $K_c$ is critical to assist growers optimizing irrigation management and to further provide precise water applications in those areas where high irrigation efficiencies are achieved by center pivot with LEPA systems or subsurface drip irrigation systems.

**Literature Cited**


Table 3. Spinach crop coefficients ($K_c$) determined using the data of two seasons (2002-2003 and 2003-2004) at Uvalde, TX (A) in comparison with those from FAO (Allen et al., 1998) (B).

<table>
<thead>
<tr>
<th>Growth stage</th>
<th>DAP*</th>
<th>$K_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emergence</td>
<td>18</td>
<td>0.35</td>
</tr>
<tr>
<td>Two to three leaves</td>
<td>29</td>
<td>0.50</td>
</tr>
<tr>
<td>Four to six leaves</td>
<td>42</td>
<td>0.70</td>
</tr>
<tr>
<td>Seven to nine leaves</td>
<td>51</td>
<td>0.85</td>
</tr>
<tr>
<td>Ten to 12 leaves</td>
<td>62</td>
<td>0.80</td>
</tr>
<tr>
<td>Thirteen to 15 leaves</td>
<td>72</td>
<td>1.00</td>
</tr>
<tr>
<td>Sixteen to 18 leaves</td>
<td>82</td>
<td>1.00</td>
</tr>
<tr>
<td>Nineteen to harvest</td>
<td>93</td>
<td>1.05</td>
</tr>
<tr>
<td>(B) $K_c$ ini</td>
<td>0-20</td>
<td>0.70</td>
</tr>
<tr>
<td>$K_c$ mid</td>
<td>50-90</td>
<td>1.00</td>
</tr>
<tr>
<td>$K_c$ end</td>
<td>90-100</td>
<td>0.95</td>
</tr>
</tbody>
</table>

*DAP = days after planting.

1998) and crop simulation models (Guerra et al., 2005, 2007; Santos et al., 2000) have proven to be reliable, inexpensive, and effective tools for estimating crop water needs in research settings. Networks of weather stations have been established in many diverse growing regions for the purpose of supporting predictions of crop ET. To support predictions of crop evapotranspiration, generic crop coefficients will not fulfill the need for precise irrigation applications.

The need for regionalized $K_c$ is demonstrated by the comparison between the $K_c$ described in FAO 56 (Allen et al., 1998) and those obtained at Uvalde, TX. For example, the onion and spinach $K_c$ values were smaller at initial growth stages than the $K_c$ values described in FAO 56 and respective crop coefficients will not fulfill the need for precise irrigation applications.

In conclusion, the development of regionally based $K_c$ is critical to assist growers optimizing irrigation management and to further provide precise water applications in those areas where high irrigation efficiencies are achieved by center pivot with LEPA systems or subsurface drip irrigation systems.


