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

Giovanni Piccinni

Texas A&M University, Texas AgriLife Research, 1619 Garner Field Road, Uvalde, TX 78801

Jonghan Ko^{1,2}

USDA-ARS Agricultural Systems Research Unit, 2150 Centre Avenue, Building D, Suite 200, Fort Collins, CO 80526

Thomas Marek

Texas A&M University, Texas AgriLife Research and Extension Center, 6500 Amarillo Boulevard West, Amarillo, TX 79106

Daniel I. Leskovar

Texas A&M University, Texas AgriLife Research, Vegetable and Fruit Improvement Center, 1619 Garner Field Road, Uvalde, TX 78801

Additional index words. ET measurement, weighing lysimeter

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 $1.5 \times 2.0 \times 2.2$ -m deep soil monoliths, comprise the Texas AgriLife Research–Uvalde lysimeter facility. Six lysimeters, weighing ≈ 14 Mg, have been placed each in the middle of a 1-ha field beneath a linear low-energy precision application 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,

1999). 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 ≈ 660 mm/year of precipitation and has a growing season of ≈ 214 to 275 d. In 2000, growers in this region irrigated 40,000 ha (Texas Water Development Board, 2001). From preliminary studies carried on at the Texas AgriLife Research Center, it is estimated that ≈ 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 microclimatological data and crop coefficients enable growers the deter-

mination 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., 1980a, 1980b; Doorenbos and Pruitt, 1977). K_C is the ratio of the evapotranspiration of the crop (ET_C) to a reference crop (ET_O) (Allen et al., 1998). ET_O 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 ET_O and ET_C 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 ET_O 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 (ET_C) are local weather stations to determine ET_O and therefore solve the following simple equation:

$$ET_C = K_C \times ET_O \quad (1)$$

According to Allen et al. (1998), crop type, cultivar, and developmental stage affect ET_C . The objective of this multiyear research is to determine crop water use (ET_C) 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. $29^\circ 13'$ N, lat. $99^\circ 45'$ 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 1.5×2.0 m (length $\times$ 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 Calcisols with a pH of 8.1).

Microclimatological 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 $mV \cdot V^{-1}$ output of the load cell attached to a scale (Avery Weigh Tronix: model HSDS 6060, Fairmont, MN) beneath each lysimeter. The calibration of $mV \cdot V^{-1}$

Received for publication 19 Nov. 2008. Accepted for publication 10 Dec. 2008.

This study is a partial outcome of the Precision Irrigators Network (PIN) project funded by Texas Water Development Board (TWDB: Project No. 0603580596), Rio Grande Basin Initiative (RGBIRGBI: Grant No. 2005-34461-15661), and partial funding from USDA CSREES No. 2004-34402-14768 (“Designing Foods for Health”).

We thank the Texas Water Resources Institute (TWRI) for administrative project assistance. Current address: Monsanto Company, 700 Chesterfield Pkwy West, Chesterfield, MO 63017.

¹Research Agronomist.

²To whom reprint requests should be addressed; e-mail Jonghan.Ko@ars.usda.gov.

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 ET_O measured with the lysimeters (Lys ET_O) was determined as the difference between the lysimeter mass losses (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 rate data are not reported here). ET for each 24-h period was divided by 1.02 to adjust the lysimeter area to the midpoint between the two walls (10-mm air gap; 9.5-mm wall thickness; 9.18 m² area instead of the 9.00-mm lysimeter surface area) according to Howell et al. (2004).

Lysimeter field data. A tall fescue grass (*Festuca arundinacea* Schreb.) seed (cv. Emerald III; 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 sub-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:

$$K_C = ET_C / ET_O \quad (2)$$

where ET_O was determined either from direct measurement using the lysimeter (Lys ET_O) or from calculations using the ASCE Penman-Monteith equation (ASCE-EWRI, 2005) for grass (ASCE ET_O) and/or alfalfa (ASCE ET_R). K_C curves for the three methods (Lys ET_O , grass ET_O , and alfalfa ET_R) 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 Huttmacher, 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 version 9.1, Cary, NC). These methods were used to determine statistical differences of the measured lysimeter ET_O data from the ASCE Penman-Monteith calculated data.

Results

Onion evapotranspiration and crop coefficient. Daily onion ET_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 ET_C rates were variable depending on seasonal conditions (i.e., planting date, temperatures). Accumulated onion ET_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^{−1}) described by Doorenbos and Kassam (1986). The reference

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

Crop	Cultivar ^a	Planting year	Plant–harvest	Rainfall	Irrigation	GDD ^b
				(mm)		°C-d
Onion	Texas Legend	2002	21 Nov.–28 May	80	283	1,809
	Texas Legend	2004	8 Nov.–14 Apr.	166	215	1,219
Spinach	DMC 16	2002	21 Oct.–19 Jan.	205	39	840
	DMC 16	2003	20 Nov.–27 Feb.	60	130	822

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

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

Fig. 1. (A) Onion crop evapotranspiration (ET_C); (B) reference evapotranspiration (ET_O); 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 $K_C = 0.45 + 1.44 \cdot 10^{-3} \cdot DAP + 5.09 \cdot 10^{-5} \cdot DAP^2 - 2.76 \cdot 10^{-7} \cdot DAP^3$ ASCE $K_{co} = 0.45 + 2.95 \cdot 10^{-3} \cdot DAP + 3.85 \cdot 10^{-5} \cdot DAP^2 - 2.47 \cdot 10^{-7} \cdot DAP^3$ ASCE $K_{cr} = 0.40 + 2.36 \cdot 10^{-3} \cdot DAP + 3.94 \cdot 10^{-5} \cdot DAP^2 - 2.68 \cdot 10^{-7} \cdot DAP^3$.

ET_O during the corresponding crop seasons ranged between 1 and 7 mm for both lysimeter measured ET_O (Lys ET_O) and calculated ET_O using ASCE Penman-Monteith equation for grass (ASCE ET_O) (Fig. 1B). The ASCE ET_O matched well with Lys ET_O 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 K_C varied from 0.2 to 1.3 for all lysimeter-based K_C (Lys K_C), ASCE grass-based K_C (ASCE K_{co}), and K_C based on ASCE Penman-Monteith equation for alfalfa (ASCE K_{cr}) (Fig. 1C). Growth stage-specific K_C 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 K_C 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 ET_C during 2002–2003 and 2003–2004 seasons were between 0.5 and 5.0 mm (Fig. 3A). Daily ET_C rates varied from 0.5 to 3.0 mm during fall (0

Fig. 2. Lysimeter measured evapotranspiration (Lys ET_O) versus calculated ET_O using the ASCE Penman-Monteith equation for grass (ASCE ET_O) during the onion crop seasons in 2002–03 and 2004–05. The dashed line was generated by the fitted linear regression equation.

Table 2. Onion crop coefficients (K_C) determined using the data of two seasons (2002–2003 and 2004–2005) at Uvalde, TX (A) in comparison with those from FAO (Allen et al., 1998) (B).

Growth stage	DAP ^z	K _C
(A)		
Emergence	25	0.40
Two leaves	75	0.55
Three to four leaves	105	0.75
Five to six leaves, beginning of bulbing	130	0.85
Seven to nine leaves, bulb development	152	0.90
Bulb fully developed	175	0.85
Dry leaf stage	190	0.70
(B)		
K _C ini	0–20	0.70
K _C mid	55–165	1.05
K _C end	165–210	0.75

^zDAP = days after planting.

Fig. 3. (A) Spinach crop evapotranspiration (ET_C); (B) reference evapotranspiration (ET_O); and (C) crop coefficient as a function of days after planting (DAP) in 2002–2003 and 2003–2004. A third polynomial equation for each K_C is as follows: Lys K_C = 0.31 + 0.01·DAP + 6.07·10⁻⁵·DAP² – 9.34·10⁻⁷·DAP³ ASCE K_{co} = 0.45 + 6.12·10⁻³·DAP + 9.37·10⁻⁵·DAP² – 8.70·10⁻⁷·DAP³ ASCE K_{cr} = 0.18 + 0.01·DAP – 9.40·10⁻⁵·DAP² + 2.55·10⁻⁷·DAP³.

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

Spinach K_C ranged between 0.2 and 1.5 for all of Lys K_C, ASCE K_{co}, and ASCE K_{cr} (Fig. 3C). Growth stage-specific K_C estimates for spinach based on the third polynomial K_C 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 K_C for two major winter vegetable

crops and to determine their plant water use or crop ET_C. Once K_C 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 ET_C estimates for each crop during the growing season were 400 mm for onion and 158 mm for spinach. The seasonal K_C 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 K_C values were determined based on K_C curves that represent the distribution of K_C over time throughout the season. The results in this study showed that some of the K_C 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,

Fig. 4. Lysimeter measured evapotranspiration (Lys ET₀) versus calculated ET₀ using the ASCE Penman-Monteith equation for grass (ASCE ET₀) during the spinach crop seasons in 2002–03 and 2003–04. The dashed line was generated by the fitted linear regression equation.

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).

Growth stage	DAP ^a	K _C
(A)		
Emergence	18	0.35
Two to three leaves	29	0.50
Four to six leaves	42	0.70
Seven to nine leaves	51	0.85
Ten to 12 leaves	62	0.90
Thirteen to 15 leaves	72	1.00
Sixteen to 18 leaves	82	1.00
Nineteen to harvest	93	1.05
(B)		
Kc ini	0–20	0.70
Kc mid	50–90	1.00
Kc end	90–100	0.95

^aDAP = 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 from FAO. In addition, the onion K_C values are smaller at the midgrowth stage and greater at dry leaf stage than those reported by Al-Jamal et al. (2000) at Farmington, NM. This site has annual average temperature of 11.2 °C, which is cooler than that (20.5 °C) at Uvalde, TX. It is assumed that the differences of K_C between the two regions are the result of elevated air temperatures and water vapor pressure deficit over the growing season that caused temporal and transient leaf stomata closure (Baker et al., 2007; Bunce, 1997;

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, Leskovar and Piccinini (2005) demonstrated that ET_C-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.

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