EC3005

EXTENSION

Winter Wheat (*Triticum aestivum* L.) Evapotranspiration (Crop Water Use) and Crop Coefficients

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Winter wheat is an important commodity grain crop in the United States and globally, and the third major crop grown in Nebraska. From emergence to harvest, effective water management is important at each stage of wheat growth. Water use can vary substantially on a daily basis, depending on climatic conditions and wheat health. Winter wheat water use (evapotranspiration, ETc) depends on variety; growth stage; canopy and leaf structure; population density; climatic conditions; and irrigation, soil, and crop management practices. This extension circular discusses the interannual variation in measured wheat ETc and presents measured grass- and alfalfa-reference crop coefficients (Kc) for each specific growth stage. Crop growth-specific crop coefficient tables were developed, which can be used in practical applications by wheat growers, their advisors, water management and agricultural agencies, and other professionals.

Winter wheat (*Triticum aestivum* L.) has been the mainstay of rainfed or dryland and irrigated cropping systems in arid and semiarid regions of the world, including the United States (U.S.). In the U.S., winter wheat is generally grown in the Midwestern states, including Nebraska, under a variety of practices and yield differences under irrigated and rainfed conditions. Globally, the U.S. is ranked third in production volume of wheat (both value and acreage), following China and India. Winter wheat accounts for 70 to 80 percent of total production in the U.S. In the last three decades, an increasing trend has been observed in winter wheat production in the U.S., with total production exceeding $12 billion (more than 1.80 billion bushels) in 2008 (United States Department of Agriculture-National Agricultural Statistics Service, USDA-NASS, 2012) (*Figure 1*).

The USDA defines eight official classes of wheat as durum, hard red spring, hard red winter, soft red winter, hard white, soft white, unclassed, and mixed. In Nebraska, winter wheat is the third major crop after corn and soybean. Within the U.S., Nebraska is the sixth largest wheat producer. In last 10 years, Nebraska producers have grown winter wheat on approximately 1.75 million acres annually. Of this acreage, approximately 12 percent or 209,000 acres were irrigated. As much as 50 percent of Nebraska's winter wheat is annually exported to international markets; e.g., in 2008 Nebraska's wheat production revenue was valued at over $490 million (USDA-NASS, 2012) (*Figure 1*).

The productivity of wheat can be limited by soil-water availability, in addition to other yield-limiting factors such as climate, diseases, nutrients, and soil properties. However, detailed information is still lacking on winter wheat water use (evapotranspiration, ETc) and crop coefficient (Kc), which are required for water resources demand, use, allocation, and management. Also, winter wheat ETc and Kc values have not been measured for modern cultivars in climatic, soil, and management conditions in Nebraska. This Extension Circular

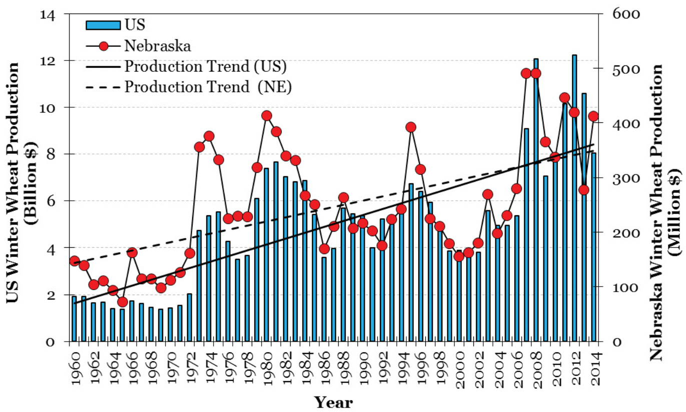


Figure 1. Long-term trend in winter wheat production ($) for the U.S. and Nebraska. Blue bars and the red marker line represent winter wheat production for the U.S. and Nebraska, respectively.

is based on the multiyear field research conducted by Irmak et al. (2015) and presents and discusses the measured inter-annual variation in winter wheat crop ETc and development of Kc specific to winter wheat growth stages.

Field experiments were conducted for two consecutive winter wheat growing seasons (2008–2009 and 2009–2010) at the University of Nebraska–Lincoln South Central Agricultural Laboratory (40° 43′ N and 98° 8′ W, 552 m above mean sea level) near Clay Center, Nebraska, in a 34-acre subsurface drip-irrigated field (although there was no need for irrigation in any of the research years) (*Figure 2*). Detailed information on the primary agronomic management practices, including planting and harvest dates; variety; fertilizer and herbicide and their types, application dates, and amounts applied are presented in *Table 1*.

The soil at the research site is a Hastings silt-loam, which is a well-drained upland soil (fine, montmorillonitic, and mesic Udic Argiustoll) with water holding characteristics of 0.34 $m^3 m^{-3}$ field capacity, 0.14 $m^3 m^{-3}$ permanent wilting point, and 0.53 $m^3 m^{-3}$ saturation point. The soil particle size distribution is 15 percent sand, 65 percent silt, and 20 percent clay, with 2.5 percent organic matter content in the topsoil (0 to 0.30 m soil layer) (Irmak, 2010). In the 2008–2009 season, winter wheat grain yield ranged from 60 to 100 bu/ac with a field-average yield of 68.5 bu/ac. At harvest, about 34 percent, 47 percent, and 11 percent of the spatial yield data had 70, 80, and 90 bu/ac grain yield, respectively. In the 2009–2010 season, grain yield ranged from 50 to 100 bu/ac with the same field-average yield. About 15 percent, 34 percent, 30 percent, and 11 percent of the spatial yield data had 60, 70, 80, and 90 bu/ac grain yield, respectively.

Table 1. Detailed field agronomic management practices, variety, planting and emergence dates, harvest date, fertilizer and herbicide type, amount and application dates and yield for the 2008–2009 and 2009–2010 winter wheat growing seasons (Irmak et al., 2015).

Field Management	2008–2009 wheat growing season	2009–2010 wheat growing season
	ART variety (agronomic disease tolerance; Hard Red Winter variety, ArgiPro, Syngenta Seeds, Inc.)	ART variety (agronomic disease tolerance; Hard Red Winter variety, ArgiPro, Syngenta Seeds, Inc.)
Planting date	October 3, 2008	September 30, 2009
Seeding rate	110 lb/ac	109 lb/ac
Planting depth	0.5 inch (drilled into soybean residue)	0.5 inch (drilled into soybean residue)
Inter-row spacing	7.5 inches	7.5 inches
Emergence date	October 18, 2008	October 15, 2009
Planting direction	East-West	North-South
Nitrogen applied (N)	31 lb/ac	28.5 lb/ac
Nitrogen type	28–0-0 (Drilled)	28–0-0 (Drilled)
Phosphorous applied (P)	8.5 lb/ac	16 lb/ac
Phosphorous type	10–34–0 (Drilled)	10–34–0 (Drilled)
N and P application date	October 3, 2008	September 30, 2009
Urea amount applied	82 lb/ac (Broadcast)	92 lb/ac (Broadcast)
Urea application date	March 3, 2009	March 8, 2010
Herbicide	None	Roundup PowerMax®
Herbicide amount applied	None	1 qt/ac
Herbicide application date	None	September 17, 2009
Harvest Date	July 9, 2009	July 4, 2010
Field-average yield	4.5 ton/ha (69 bu/ac)	4.6 ton/ha (70 bu/ac)

Winter Wheat Evapotranspiration (ETc)

During the growing season, winter wheat ETc depends on variety, growth stage, canopy, population density, climatic conditions, irrigation, and crop management practices, etc. Crop water use and ETc are used interchangeably to describe the amount of water used by the crop for its growth under given climatic and soil conditions from emergence to physiological maturity. ETc comprises two terms: (i) evaporation from the soil surface and (ii) transpiration from plant leaves. To quantify ETc, a common practice is to use weather station climatic data to calculate potential (reference) ET (ETref) and then use a crop coefficient (Kc) to adjust the ETref of the crop of interest. A detailed description of crop ETc, ETref, and crop coefficient is presented in the Nebraska Extension publication *Estimating Crop Evapotranspiration from Reference Evapotranspiration and Crop Coefficients* (G1994).

ETref was calculated using the climate data measured from an energy flux tower (Bowen Ratio Energy Balance System, BREBS) installed in the middle of the research field, which is also part of the larger Nebraska Water and Energy Flux Measurement, Modeling and Research Network (NEBFLUX; Irmak, 2010). A BREBS [Radiation and Energy Balance Systems (REBS), Bellevue, Wash.] was used to measure surface energy balance variables, including ETc and other climatic variables (precipitation, maximum and minimum air temperature, maximum and minimum relative humidity, incoming shortwave radiation, net radiation, sensible heat flux, soil heat flux, soil temperature, and wind speed). All variables were sampled every 60 seconds, averaged and recorded every hour. A detailed description of the measurement of the microclimatic and climatic variables using BREBS was presented by Irmak (2010). In this research, actual winter wheat ETc was taken directly from BREBS-measured ETc data, which were assumed to represent the average field ETc.

Visual wheat growth stages are presented in *Figure 3*. Winter wheat has two peak water use periods: fall and spring. During the initial stage (fall) of the winter wheat, BREBS-measured daily ETc values were low and much lower during the winter period due to extremely low air temperatures, minimal evaporative demand and transpirative losses, high relative humidity, short sunshine periods, and low incoming shortwave radiation. ETc during this period mainly results from soil water evaporation. Daily ETc in 2008–2009 varied from 0 inch/day on extremely cold days to 0.38 inch/day during the summer period [229 days after planting (DAP) (May 19, 2009)] with a seasonal average of 0.08 inch/day. It ranged from 0 to 0.42 inch/day [237 DAP (May 24, 2010)] with a seasonal average of 0.06 inch/day in 2009–2010. The seasonal total ETc was 23.6 inches and 19.2 inches during the 2008–2009 and 2009–2010 growing seasons, respectively (*Figures 4a and 4b*).

Figure 2. A winter wheat research field at the South Central Agricultural Laboratory near Clay Center, Nebraska (Photo by Suat Irmak, June 3, 2009)

Daily ETc was lowest during the extreme cold period of December through the end of February when the plants were in dormancy. From crop emergence to early December, ETc was reduced primarily to soil water evaporation during the winter due to the extreme cold temperatures and the frozen surface. During that period, ETc depended mainly on the aerodynamic variables and low air temperature, which restrict wheat growth, while low radiation and low vapor pressure deficit result in low soil-water evaporation rates.

Winter wheat requires a cold period or chilling (vernalization) during early growth for normal heading during long days. Productivity is largely limited by soil water availability, in addition to other yield-limiting factors such as variety, growth stage, nutrients, soil properties, disease, climatic conditions, and irrigation and crop management practices. Winter wheat in its early stages of development exhibits a strong resistance to frost (down to -4°F). This resistance is lost in the active growth period in the spring and during head development and flowering.

If the vernalization requirement is only partially met in the fall because of late planting or other factors, it will result in a delay in maturity the following summer, as reproductive growth will eventually be triggered by day length. Once spring green up occurs, ETc increases to the maximum value at the full crop development and reproductive stages that usually coincide with the second half of May and early June in Nebraska. At this point, the plant begins to turn the solar energy it receives into grain production. Although grain is

Table 2. Growth stages (Miller, 1999) and cumulative winter wheat evapotranspiration (ETc) for the 2008–2009 and 2009–2010 growing seasons (Irmak et al., 2015).

Wheat growth stages	Cumulative ETc (2008–2009) (inches)	Cumulative ETc (2009–2010) (inches)	Average cumulative ETc (inches)
Emergence to Feekes 1: One shoot	5.10	2.43	3.77
Feekes 1 to Feekes 2: Tillering begins	0.31	0.32	0.32
Feekes 2 to Feekes 3: Tillers formed	0.59	0.52	0.56
Feekes 3 to Feekes 4: Leaf sheaths lengthen	0.85	0.95	0.90
Feekes 4 to Feekes 5: Leaf sheaths erected	1.44	1.03	1.23
Feekes 5 to Feekes 6: First node visible	1.50	1.01	1.25
Feekes 6 to Feekes 7: Second node visible	1.32	0.92	1.12
Feekes 7 to Feekes 8: Last leaf visible	1.90	1.09	1.50
Feekes 8 to Feekes 9: Ligule of last leaf visible	1.64	1.73	1.69
Feekes 9 to Feekes 10: In boot	2.56	2.73	2.65
Feekes 10 to Feekes 10.1: Head visible	0.99	1.53	1.26
Feekes 10.1 to Feekes 10.5: Flowering	0.85	0.87	0.86
Feekes 10.5 to Feekes 11: Ripening	2.90	3.59	3.24

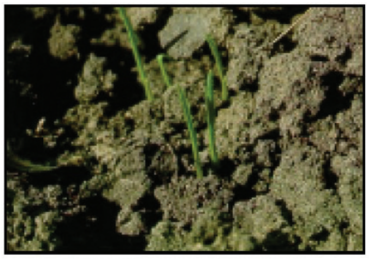
being produced, water use begins to decline at nearly the same rate as it increased. At four weeks after peak water use, the winter wheat nears maturity.

Relative to thermal units (growing degree days), wheat growth can be divided into three periods: (i) active growth performance, (ii) dormancy, and (iii) post-dormancy, during which 12 percent, 21 percent, and 67 percent of ETc occurred in 2008–2009 and 11 percent, 10 percent, and 79 percent of ETc occurred in 2009–2010, respectively, indicating that wheat water use for the same growth stages can vary substantially between years. Average daily ETc during these periods was, respectively, 0.05, 0.04, and 0.17 inch/day for the 2008–2009 growing season and 0.3, 0.02, and 0.16 inch/day for the 2009–2010 growing season.

Winter wheat was in dormancy during the period from December 2 to April 9 in 2008–2009 (61 to 186 DAP) and during December 4 to March 29 in 2009–2010 (66 to 181 DAP). The 2008–2009 winter was warmer than the 2009–2010 winter with higher vapor pressure deficit (VPD; atmospheric demand for evaporative losses), and consequently, there was greater seasonal evapotranspiration in the 2008–2009 growing season (*Figure 4*). Lower ETc values during the 2009–2010 growing season are attributed to lower VPD, which was very low from the beginning of December through the end of February, and with almost negligible reference (potential) evapotranspiration.

To further analyze the winter wheat ETc, cumulative ETc was calculated for each growth stage from emergence to harvest (*Table 2*). Several growth scales describe the growth and development of cereal crops, including wheat. Commonly used scales include the Feekes, Haun, BBCH, and Zadoks. Each scale differs in the level of detail it uses to describe the crop growth stages. For this study, we used the Feekes scale, which is the most widely used scale in the U.S. The Feekes scale is numerical. It begins at Feekes 1.0 (which describes emergence) and ends at 11.4 (which describes a mature plant that is ready for harvest). The Feekes scale uses decimal subdivisions to describe development stages during head emergence to maturity (Feekes 10.0 through 11.4). A detailed description of winter wheat growth stages from emergence to harvest is presented in Miller (1999) and the Texas A&M AgriLife Extension article *Growth Stages of Wheat: Identification and Understanding Improve Crop Management* (SCS-1999–16).

Higher ETc values from emergence to Feekes stage 1 in both growing seasons (*Table 2*) were due to a longer duration between emergence and Feekes stage 1, including the dormancy period. For example, in the 2008–2009 season, the winter wheat emerged on October 18, 2008, and the first shoot (Feekes stage 1) was observed on March 11, 2009. Overall, ETc values were higher in the 2008–2009 growing season over different growth stages, with maximum ETc occurring in the booting, flowering, and ripening stages.


Seeding Emergence - Feekes 1.0


Beginning of tillering - Feekes 2.0


Tillers formed - Feekes 3.0


Beginning of erect growth
- Feekes 4.0


Leaf sheaths strongly erect
- Feekes 5.0


First node visible - Feekes 6.0


Second node visible
- Feekes 7.0


Flag leaf visible - Feekes 8.0


Ligule of flag leaf
visible - Feekes 9.0


Boot stage
- Feekes 10.1


Beginning flowering
- Feekes 10.5.1


Wheat mature and harvest-ready - Feekes 11.4

Figure 3. Wheat growth stages (photos by Travis D. Miller, 1999)

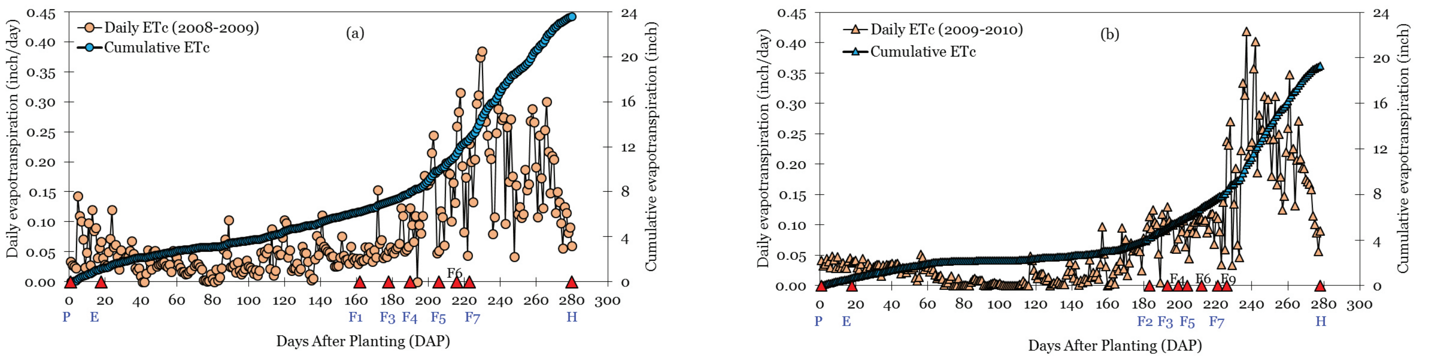


Figure 4. Winter wheat daily and cumulative crop evapotranspiration (ETc; inches) and observed phenological growth and development stages for the (a) 2008–2009 and (b) 2009–2010 growing seasons. Crop growth and development stages are marked with letters and blue squares on the x-axes: P=planting, E=emergence, H=harvest, and F=Feekes stage (research results from Irmak et al., 2015).

Winter Wheat Grass- and Alfalfa-Reference Single (normal) and Basal crop coefficient (Kc and Kcb)

Crop growth stage-specific coefficients can be used to determine crop water use at various crop growth stages. To develop the winter wheat single (Kc) and basal (Kcb) crop coefficients, measured ETc and estimated values of ETref from BREBS were used. In this research, single (normal) and basal crop coefficient (Kc and Kcb, respectively) values were developed for both grass (Kco, Kcbo) and alfalfa (Kcr, Kcbr)-based reference. Single crop coefficient (Kc) is defined as the ratio of actual crop ET to the well calibrated grass or alfalfa reference ET (ETref) under the same conditions. *Figure 5* represents the typical winter wheat crop coefficient as a function of DAP.

In general, Kc values were high in the early-season stages, gradually decreased toward the start of the winter season (i.e., ~200 DAP), gradually increased again in spring, and reached minimum values toward harvest. The two-year average Kco values were 0.60, 1.30, and 0.30 for the early season, mid-season, and late-season crop growth stages, respectively. Kcr values varied from 0.14 to 1.40 with average values of 0.40, 1.05, and 0.20 for the early-season, mid-season, and late-season stages, respectively.

Basal crop coefficients (Kcb) represent the condition when soil evaporation is minimal, but the availability of soil water within the root zone does not limit plant growth and transpiration. It can be adjusted to depict a higher proportion of evaporation from the wet soil following irrigation or precipitation. Thus, in theory, Kcb values are assumed to represent primarily the transpiration component of the wheat ETc. The two-year average Kcbo values were 0.45, 1.30, and 0.20 for the early-season, mid-season, and late-season, while the average Kcbr values were 0.30, 1.05, and 0.20 for the same growth stages, respectively.

For practical application by users, *Table 3* represents the two-year average Kco, Kcr, Kcbo, and Kcbr values for each winter wheat growth stage. On average, the seasonal average grass-reference basal crop coefficient (Kcbo) is about 87 percent of Kco, and the alfalfa-reference basal crop coefficient (Kcbr) is 89 percent of Kcr. Therefore, transpiration is expected to be about 87 percent to 89 percent of ETc, and evaporation represents about 11 percent to 13 percent of ETc. However, it should be noted that the Kcb values are assumed to represent transpiration losses, which should be verified through additional field research. In general, soil-water evaporation accounted for only a small proportion of evapotranspiration (primarily due to uniform and relatively vigorous wheat residue cover on the soil surface), decreased with DAP, and decreased with crop growth and development. In most cases, single (normal) Kc values are used in practical applications. For example, if producers have ETgages with either #54 alfalfa canvas cover or #30 grass canvas cover or have other sources of either alfalfa- or grass-reference (potential) ET information, they can use single (normal) alfalfa- or grass-reference Kc values (Kcr or Kco) in *Table 3* to calculate actual winter wheat water use.

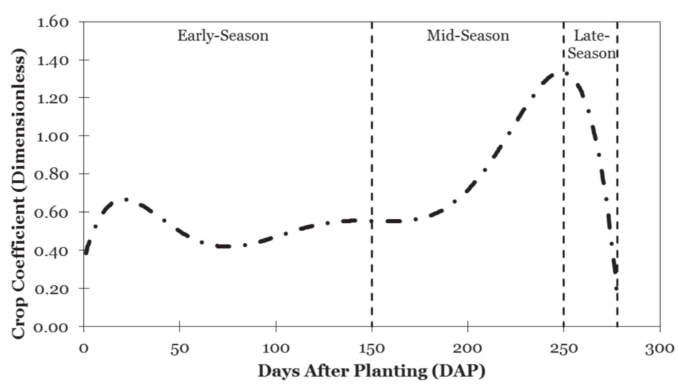


Figure 5. General crop coefficient curve for winter wheat in Nebraska.

Table 3. Two-year average crop growth stage-specific grass- and alfalfa-reference single (normal) crop coefficients (Kco and Kcr, respectively) and grass- and alfalfa-reference basal crop coefficients (Kcbo and Kcbr, respectively) for wheat.

Wheat growth stages	**Crop coefficient**			
	Kco	Kcr	Kcbo	Kcbr
Feekes 1: One shoot	0.63	0.43	0.44	0.27
Feekes 2: Tillering begins	0.59	0.41	0.44	0.37
Feekes 3: Tillers formed	0.57	0.46	0.49	0.42
Feekes 4: Leaf sheaths lengthen	0.75	0.66	0.69	0.47
Feekes 5: Leaf sheaths strongly erected	0.84	0.78	0.78	0.67
Feekes 6: First node visible	0.86	0.64	0.63	0.54
Feekes 7: Second node visible	0.91	0.65	0.63	0.63
Feekes 8: Last leaf visible	1.00	0.78	0.90	0.68
Feekes 9: Ligule of last leaf visible	1.28	1.06	1.23	0.95
Feekes 10: In boot	1.22	1.02	1.18	1.00
Feekes 10.1: Head visible	1.33	1.09	1.21	1.00
Feekes 10.5: Flowering	1.33	1.06	1.27	1.00
Feekes 11: Ripening	0.98	0.67	0.78	0.60

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