IRRIGATION MANAGEMENT SERIES

Agricultural Crop Water Use

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Crop water use, also referred to as evapotranspiration (ET), is the water used by a crop for growth and cooling. Crop water use, or crop water requirement, is the total amount of water needed for evapotranspiration from planting to harvest for a given crop in a specific climate, when adequate soil water is maintained by rainfall and/or irrigation so it does not limit plant growth and crop yield. Only a small fraction of the water a plant takes in is used for growth, often only about 1 percent; the majority of water is needed to allow the plant to cool itself. The movement of water into the plant is important, since this water carries essential nutrients needed by the plant for growth processes.

Evapotranspiration is the combination of two words: evaporation and transpiration. Evaporation refers to the water that moves from a wetted soil or leaf surface directly to the atmosphere, while transpiration refers to the water that the plant to be used in the growth process or released into the atmosphere. The term evapotranspiration was coined since the two processes can occur simultaneously and are difficult to measure separately.

Both evaporation and transpiration processes require energy or heat. This heat energy comes from the sun (solar radiation) or from advective heat, which is heat moved by air masses. Since this is a physical process, it can be predicted for a known crop using weather information. The common procedure for estimating the crop water use for a specific crop is to input weather data into an equation developed to predict the water use for a reference crop. The reference crop is often either grass or alfalfa of a specific height. The reference crop ET is often designated ETo for grass or ETr for alfalfa. The reference crop ET is then modified to the actual crop water use using a crop coefficient (Kco), which is unique for each crop species. The Kco's vary by crop and by the stage of growth of the specific crop. This process is more fully discussed in K-State Research and Extension publication MF2389, *What is ET?*.

Crop Water Use Fluctuations

Since crop water use is an energy-driven process, crop water use has a diurnal (daytime) cycle. The most commonly reported crop water use is the daily (total) crop water use. Daily use can have significant variation driven by the weather conditions, such as a hot and windy day versus cool and cloudy day.

Seasonal crop water use varies for a given crop based on the summation of the growing season conditions. During drought, reference crop ET rates are higher because the daily weather conditions are hotter and with clear skies, allowing more solar radiation to reach the crop leaf surface as contrasted with cooler and cloudy days. During drought, crop water use may be suppressed if the plants are stressed due to lack of adequate soil water from the lack of precipitation events and no irrigation.

Diurnal/Nocturnal Crop Water Use

The processes occurring internally in the plant are photosynthesis and respiration. Photosynthesis is unique to plants because chloroplasts in the plant cells give them the ability to capture light energy and produce sugar (energy) when carbon dioxide and water are available. Photosynthesis allows plants to convert light energy into a form that can be used to fuel plant growth. This growth process is called respiration, which is the metabolizing (burning of fuel) of sugar for plant growth and other life processes. Both plants and animals respire. Plants release oxygen during photosynthesis but require oxygen to complete respiration. Photosynthesis can only occur in the presence of light, while respiration can occur whether dark or light.

In a similar manner to respiration, soil water evaporation can occur throughout a 24-hour period; however, the rate of evaporation would likely increase with the additional solar radiation energy of the daytime hours. Soil evaporation also decreases as the soil surface dries. It also decreases under a crop canopy that shields the soil surface from sunlight and wind.

Figure 1 shows the generalized relationship between soil evaporation and transpiration for a location with wet soil and a crop canopy. The figure also shows the effect of irrigation on the transpiration and evaporation process. Notice that canopy evaporation greatly increased the water flux as soon as the canopy was wetted by sprinkler irrigation and stayed high until the irrigation ceased and the leaves dried. There was also a small water flux associated with droplet evaporation during the irrigation event. Transpiration through the plant occurs at a lesser rate than does direct evaporation from the plant canopy.

Daily Crop Water Use Fluctuations

Daily ET for a crop varies throughout the growing season as driven by two factors: (1) the weather conditions (reference ET) and (2) the stage of the crop's growth. These two factors are illustrated in Figure 2: the top line represents the typical crop water use rate for a reference crop as influenced by weather conditions of wind, temperature, solar radiation, and humidity. During the typical growing season in Kansas, the weather conditions cause ET demands to increase as spring turns into summer and then start decreasing as fall approaches. However, the crop also has to advance through its growth stages, so in the early season when the crop is small, its actual water use rate is also small, as represented by the lower line in Figure 2. Water use increases as plants add leaves and increase the total leaf area. It then gradually begins to

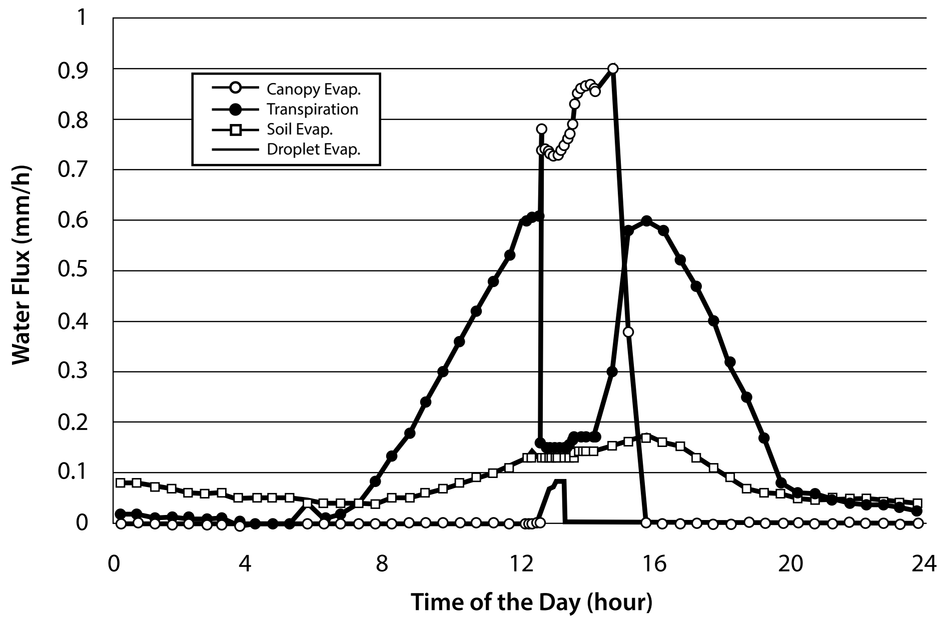

Figure 1. Water use for a rotator sprinkler placed on top of the pivot lateral irrigating at noon for 50 minutes. The figure illustrates, in addition to how water is lost during irrigation, that crop transpiration occurs during daylight hours, while soil water evaporation occurs throughout the entire day. (Martin et al. 2012)

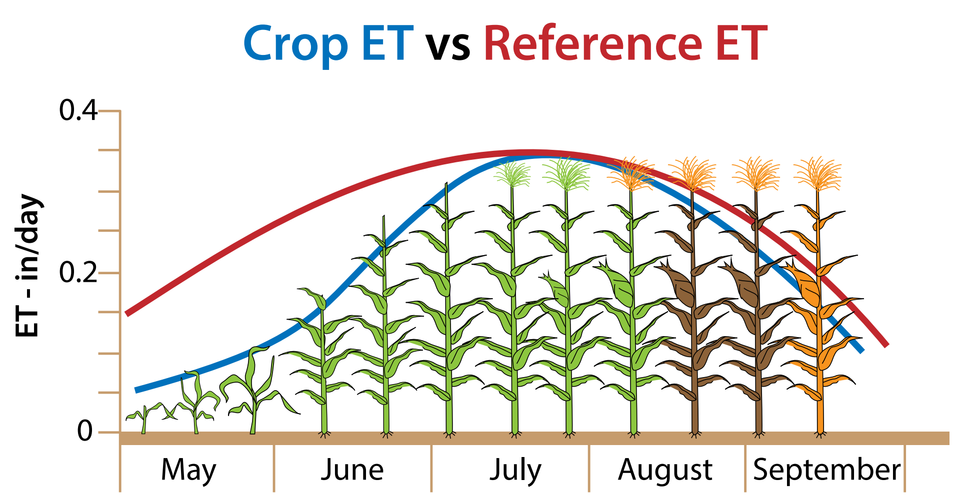

Figure 2. Generalized Crop ET versus Reference ET. (Rogers 2007)

decrease once the plant completes it reproductive life and begins to lose green leaf area.

The day-to-day variation is much more dramatic than what is shown by the generalized curve illustrated in Figure 3. The solid line represents the average crop water use for 1972 to 2003. While not completely as smooth as the generalized curve of Figure 2, it is very smooth as compared to the daily values plotted for 2003. Notice the daily values can greatly exceed or be much less than the long-term average. The large day-to-day variations reflect the wide swings in weather conditions common in Kansas. The peak daily water use rates of crops are similar, typically averaging 0.3 to 0.35 inches per day, but single-day values can be about 0.5 inches, as is the case for one day as shown in Figure 3. Examples of peak values from various studies and locations are shown in Table 1a.

Several of the reported maximum daily crop water use values are listed at much less than the values noted above. This would indicate the weather conditions for the period were likely not severe or the water supply available to the crop was somewhat lacking, or long-term mean weather data were used as opposed to specific daily values. Maximum peak daily values are not often measured due to the difficulty of measuring daily values and therefore there are not many reported values.

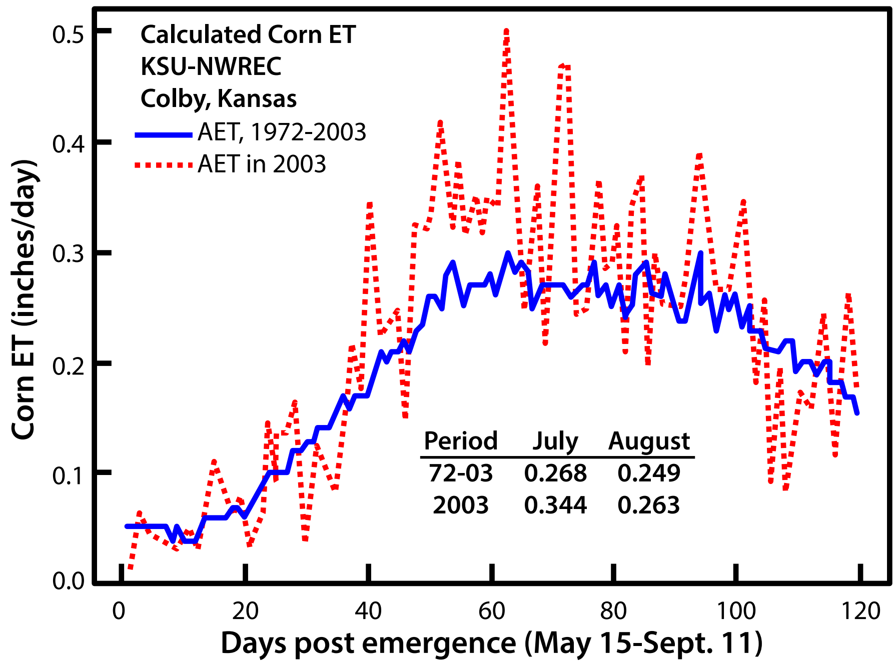

Figure 3. Actual seasonal daily ET and long-term average ET rate for corn. (Lamm 2004).

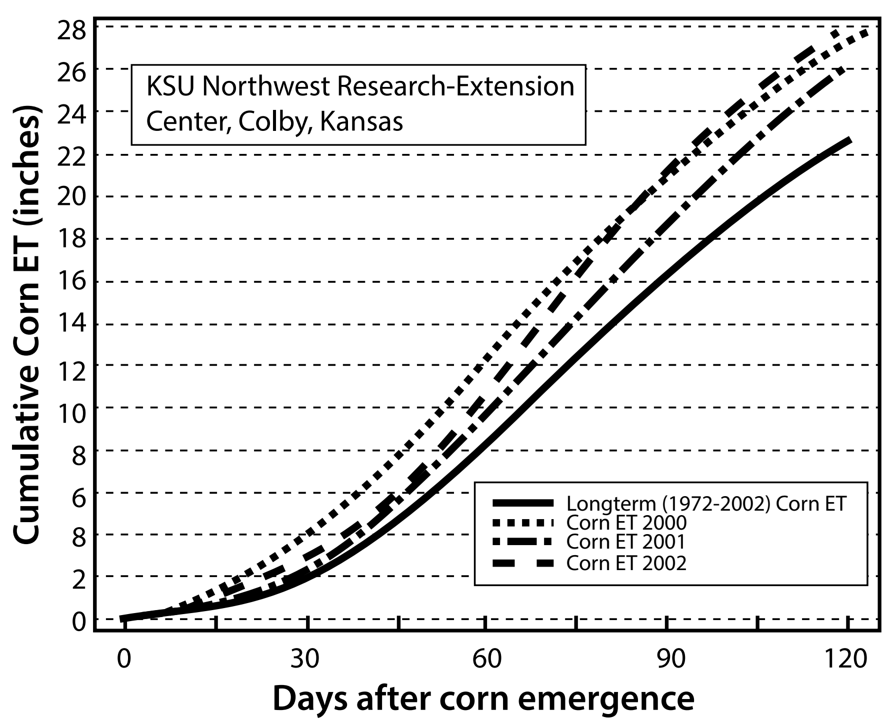

Figure 4. Actual corn ET versus 30-year average corn ET for three drought years. (Lamm 2003).

Seasonal Crop Water Use Fluctuations

Seasonal crop water use variations for a specific crop occur due to differences in year-to-year weather conditions and due to the specific variety or hybrid for a given crop, especially as related to the maturity length. Seasonal crop water use fluctuations due to climatic variations are illustrated in Figure 4. Long-term average corn ET at Colby, Kansas, is about 23 inches, but during 2000 to 2003, corn ET was about 3 to 5 inches greater than the long-term seasonal average. Typical ranges of seasonal and daily crop water use values and ranges from numerous studies are shown in Table 1a.

Table 2 shows results that reported the ratio of the maximum

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Table 1a. Ranges of seasonal and daily crop water use values for selected crops in Kansas.

Crop	Seasonal Crop Water Use (ET) (Inches)	Generalized and Reported Maximum Daily Peak Crop Water Use (ET) (Inches)	Study Location	References (See Table 1b for letter designations)
Alfalfa	31.5–63	----	Generalized — World	E
Alfalfa	32–48	0.55	Regional — Central Plains	A, D, P
Alfafa	----	0.32*	Kansas	G
Alfalfa	32.6–44.76	----	Garden City, KS	B
Corn (Maize)	19.69–31.5	----	Generalized — World	E
Corn	22–30	0.50	Regional — Central Plains	D, K
Corn	----	0.49	Bushland , TX	H
Corn	22.6–28.6	---	Colby, KS	F
Corn	22.0–29.1	----	Colby, KS	I
Corn	Avg 25.4, 20.2–31.6	---	Tribune, KS	J
Corn	4-yr Avg, 29.58	---	Tribune, KS	N
Corn	21.69–22.99	---	Manhattan and Tribune, KS	C
Corn	20.12–26.89	----	Garden City, KS	M
Corn	15.6–17.7	0.49	China	T
Soybeans	17.72–27.56	----	Generalized — World	E
Soybeans	18–24	0.32*	Regional — Central Plains	D
Soybeans	20–26	0.48	Regional — Nebraska	L
Soybeans	17.36–23.46	----	Manhattan and Tribune, KS	C
Grain Sorghum	17.72–25.59	----	Generalized — World	E
Grain Sorghum	16–22	0.40	Regional — Central Plains	D
Grain Sorghum	----	0.40	Bushland , TX	H
Grain Sorghum	17.76–20.59	----	Manhattan and Tribune, KS	C
Grain Sorghum	Avg 26.1, 21.2–30.6	---	Tribune, KS	J
Grain Sorghum	18.3–22.8	---	Garden City, KS	M
Grain Sorghum	21.5–28.0	0.51	Bushland , TX	S
Sunflowers	23.62–39.37	----	Generalized — World	E
Sunflowers	16–20	0.28*	Regional — Central Plains	D
Sunflowers	18.74–22.99	----	Manhattan and Tribune, KS	C
Sunflowers	Avg 22.7, 21.4–24.8	---	Tribune, KS	J
Wheat	17.72–25.59	----	Generalized — World	E
Wheat	16–24	0.40	Regional — Central Plains	D, Q
Wheat	---	0.54	Bushland , TX	H
Wheat	15.4–23.4	---	Garden City, KS	M
Wheat	15.8–18.2	0.35	China	T
*Value appears low; see Table 2 discussion.				

Table 1b. References associated with letter designations of Table 1a.

Reference Designation	Reference
A	Rogers, D.H. and M. Alam. 1998. "Irrigating Alfalfa." Chapter 4 of the *Alfalfa Production Handbook*. Kansas State University Research and Extension bulletin C-683 (revised) Manhattan, KS. 5 pgs.
B	Klocke, N.L., R.S. Currie and J.D. Holman. 2013. "Alfalfa Response to Irrigation from Limited Water Supplies." In press: *Transaction of ASABE*.
C	Hattendorf, M.J., M.S. Redelfs, B. Amos, L.R. Stone, and R.E. Gwin, Jr. 1988. "Comparative Water Use Characteristics of Six Row Crops." *Agron. J.* 80:80-85 (1988).
D	Shawcroft, R.W. 1989. "Crop Water Use." In proceedings of the 1989 Central Plains Irrigation Work-shop. Colby, KS. 6 pgs.
E	FAO. 1986. *Irrigation Water Management Training Manual,* no. 3, Chapter 3, "Crop Water Needs." Rome, Italy. 20 pgs.
F	Lamm, F.R., R.M. Aiken, and A.A. Abou Kheira. 2009. "Corn Yield and Water Use Characteristics as Affected by Tillage, Plant Density and Irrigation." *Trans. of ASABE*. Vol. 52(1): 133-143.
G	Stone, L.R., A.J. Schlegel, A.H. Kahn, N.L. Klocke. 2006. "Water supply: yield relationships developed for study of water management." *Journal of Natural Resources and Life Sciences Education*. 35:161-173.
H	Howell, T.A., J.L. Steiner, A.D. Schnieder, S.R. Evett, and J.A. Tolk. 1994. *Evapotranspiration of Irrigated Winter Wheat, Sorghum and Corn.* ASAE Paper no. 94-2081
I	Lamm, F.R. and R.M. Aiken. 2007. *Conventional, Strip and No Tillage Corn Production under Different Irrigation Capacities*. CPIA 2007.
J	Stone, L.R., A.J. Schlegel, R.E. Gwin, Jr. and A.H. Khan. 1996. "Response of corn, grain sorghum, and sunflower to irrigation in the High Plains of Kansas." *Agricultural Water Management* 30 (1996) pp. 251-259.
K	Rogers, D. H. 2007. "Irrigation." Chapter of *Corn Production Handbook*. Kansas State University Research and Extension. C-560. pp. 30-36.
L	Kranz, W.L., R.W. Elmore, and J.E. Specht. 2005. *Irrigating Soybean*. NebGuide G1367. University of Nebraska – Lincoln. 4 pgs.
M	Klocke, N.L. 2014. "Corn and Forage Sorghum Response to Limited Irrigation, Drought, and Hail." Manuscript SW-10810-2014.R1. Accepted for *Applied Engineering in Agriculture*.
N	Schlegel, A., L. Stone, and T. Dumler. 2010. "Managing Irrigation with Diminished-Capacity Wells." In *2010 SWREC Field Day Report of Progress 1034*. Kansas State University Research and Extension. pp. 35-39.
O	Rogers, D. H., J. P. Schneekloth, and M. Alam. April 2009. "Irrigation Management," chapter of the *High Plains Sunflower Production Handbook*. Kansas State Research and Extension. Bulletin MF-2384. pp.12-17.
P	Alam, M. and D.H. Rogers. March 2009. *Irrigation Management for Alfalfa*. Kansas State Research and Extension. Irrigation Management Series MF-2868.
Q	Rogers, D.H. 1997. "Irrigation Management." *Wheat Production Handbook*. K-State Research and Extension. C-529. pp 29-31.
R	Rogers, D.H. 1997. "Irrigation." *Soybean Production Handbook*. C-449. K-State Research & Extension. C-449. pp 15-19.
S	Tolk, J.A. and T.A. Howell. 2001. "Measured and Simulated Evapotranspiration of Grain Sorghum with Full and Limited Irrigation in Three High Plains Soils." *Transactions of ASAE*. Vol. 44(6):1553-1558.
T	Lui, C., X. Zhang, Y. Zhang. 2002. "Determination of daily evaporation and evapotranspiration of winter wheat and maize by large-scale weighing lysimeter and micro-lysimeter." *Agricultural and Forest Meteorology* 111 (2002) 109-120.

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value of crop ET to a reference ET value. In this study, sunflowers had the largest ratio, indicating that crop had the largest daily peak water use rate. Table 2 also reported seasonal water use amounts, which are discussed in the next section.

Crop water use variations for a given crop based on maturity length are illustrated in Figure 5. In the example, five maturity lengths of corn were planted at the same date and population. The crop water use for a longer maturity length, as might be expected, has a higher water use requirement than for a shorter maturity length. In this example, the water use variation from the shortest maturity to the longest maturity was approximately 4 inches. Normally, the crop water use value cited for an area is for the longest maturity group that can be reliably grown in an area. Extremely detrimental yield losses can occur if a too long of maturity group crop is planted and growth is stopped by frost before the crop has reached yield maturity.

Plant population, or the number of plants per unit area, is an important consideration due to the influence on yield; however, it normally has only a small affect on water use. A measurement associated with plant population is the leaf area index (LAI).

LAI is the leaf area of the crop per unit of land area. An LAI of 1 indicates there is one unit of leaf area for each unit of land area. An LAI of 3 means three units of leaf area for each unit of land area. It takes an LAI of about 2.7 for a standing crop to completely shade the ground, meaning no direct sunlight would hit the ground. Since the ET process is an energy-driven process, if all sunlight is intercepted by the leaves, then the photosynthetic process — from an available energy standpoint — would be at its maximum. The optimum plant population for optimum yield is generally greater than an LAI of 2.7.

Table 2. Comparative Water Use of Crops. (Hattendorf et al., 1988)

Crop	Seasonal Water Use (inches)	Max Value of Measured ET/ Reference ET	Mean Daily Water Use Rate (in/day)
Corn	22.2	1.15	0.19
Grain Sorghum	19.1	1.05	0.19
Pinto Bean	16.7	1.13	0.19
Soybean	21.3	1.09	0.19
Sunflower	21.5	1.35	0.24

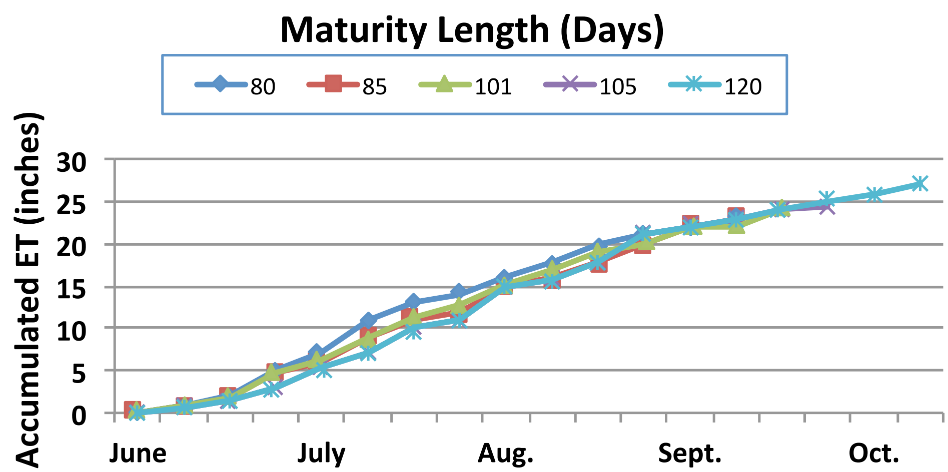

Figure 5. Seasonal water use for five corn maturity lengths. (Watts, 1982 — unpublished data)

The effect of plant population on LAI is generalized in Figure 6, which shows the LAI of corn by stage of growth for four populations. Higher plant populations reach the full ET threshold LAI of 2.7 more rapidly, and stay above this level longer, than lower plant populations. This means more photosynthesis can take place and have more yield potential. Since yield and water use are linearly related, lowering plant population to reduce water use results in loss of yield. In good dryland production areas or irrigated crop production areas, planting a low population level to reduce water use results in a disproportional yield loss to the potential water savings. Figure 7 shows the LAI values for a 120-day maturity corn for four populations; the two low plant populations never exceed the full ET threshold value of 2.7.

Crop Water Use and Yield

It should be clear that the plant growth process is water intensive. Plants that fully shade the ground are intercepting all the solar radiation energy that drives transpiration and are using water at their maximum rate. Another energy source that can increase water use is the energy derived from advective heat

— energy transported to a crop by wind. Since taller plants can potentially intercept more of this energy, a taller plant canopy could have a higher water use rate then a short plant canopy. However, on hot, sunny days with calm winds, a lawn water use rate is about the same as a corn field at its peak. Water use has been quantified as inches per day. Implied in this unit of measure is an area of coverage.

In crop fields, the area of coverage normally used is an acre, meaning the water use rate is actually in terms of acre-inches per acre per day. One acre-inch is the volume of water needed to cover 1 acre of land area to the depth of 1 inch. An acre-inch is equivalent to 27,154 gallons of water. Recall that a peak daily water use rate for a crop is about 0.35 inches per day, meaning a home lawn of ¼ acre may transpire about 2,400 gallons of water in a day.

Similarly, crop production is water intensive as well. From Table 1, corn might have a seasonal water use of 24 inches per year. To get optimum yield, a typical plant population may be around 30,000 plants per acre, with one ear of corn per plant. This means it takes about 22 gallons of water to grow each ear of corn or about 50 gallons per pound of grain.

Table 3 lists the estimated water requirement for the production of various food items on a worldwide basis. This production requirement varies considerably because of local conditions. For example, the water requirement from Table 3 for corn is more than twice the estimate given above.

Yield and crop water use are closely linked and linearly related; meaning the more crop ET, the

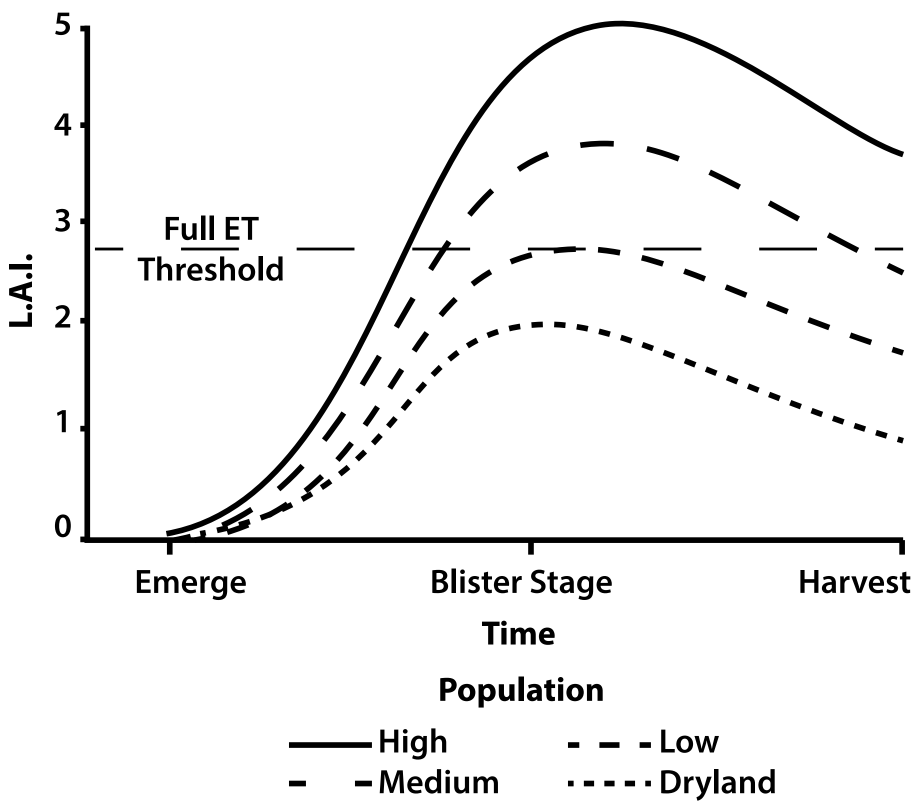

Figure 6. Effect of stage of growth on Leaf Area Index for various plant populations. (Watts and Klocke, Irrigation Chapter 6 – Crop Water Use – Plant and Soil Sciences)

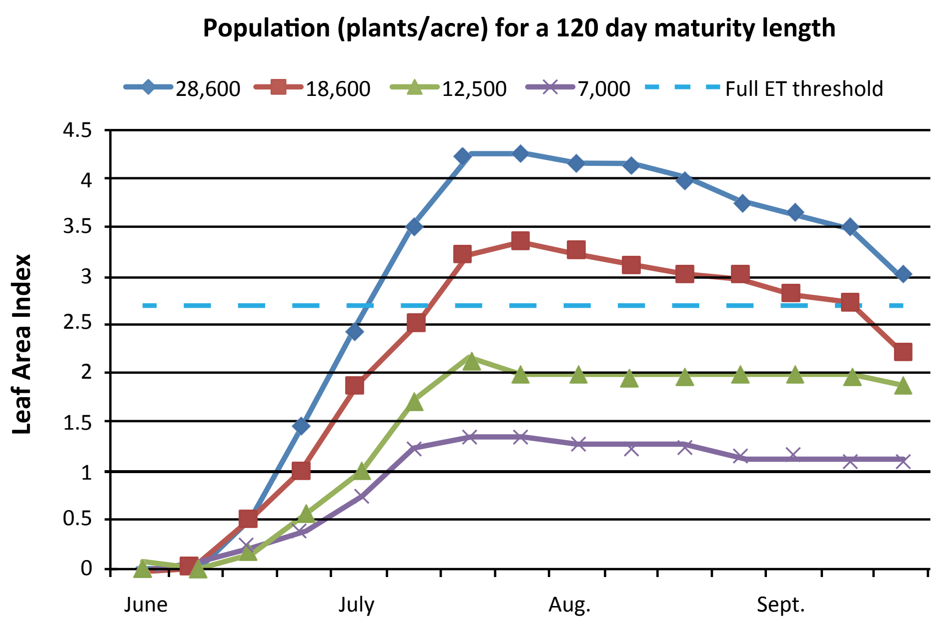

Figure 7. Example of the effect of population on Leaf Area Index for various plant populations. (Watts, 1982 – unpublished data)

more yield until the production limit is reached. This is illustrated in Figure 8. Threshold ET is the amount of crop water use needed to grow the crop until the seed-producing segment of the yield. In forage crops, when the entire above-ground portion of the crop is harvested, the threshold ET would be zero, and the y axis would be the weight of dry matter production. Often the crop water production function is referred to as the crop water use curve, which

Table 3. Water requirement for the production of various food items.
(Adapted from: *www.waterfootprint.org/Reports/Hoekstra-2008-WaterfootprintFood.pdf*).

Food Item	Gallons per unit	Unit
Lettuce	16	1 lb
Tomato	22	1 lb
Cabbage	24	1 lb
Cucumber or pumpkin	29	1 lb
Potato	30	1 lb
Orange	55	1 lb
Apple or pear	84	1 lb
Banana	103	1 lb
Corn	108	1 lb
Peach or nectarine	144	1 lb
Bread (from wheat)	156	1 lb
Sugar (from sugar cane)	180	1 lb
Mango	192	1 lb
Chocolate	288	1 lb

Food Item	Gallons per unit	Unit
Dates	359	1 lb
Groundnuts (in shell)	371	1 lb
Rice	407	1 lb
Chicken	467	1 lb
Olives	527	1 lb
Pork	575	1 lb
Cheese	599	1 lb
Beef	1,857	1 lb
Beverage Item		
Beer (from barley)	20	8 oz
Tea	30	8 oz
Wine: 1 glass of 125 ml	32	4 oz
Coffee: 1 cup of 125 ml	37	4 oz
Milk	66	8 oz

is the curvilinear line of Figure 8. This line includes the ET amount plus additional water applied to a field either by rainfall or irrigation but was lost to runoff, drainage, or evaporation. Drainage water also is called deep percolation and is water that moves past the crop root zone and therefore cannot be accessed by the plant. The water use curve represents the average long-term yield response of a crop for a particular location. The crop's root depth and the soil water holding capacity determine the amount of water that can be held in the soil for the crop to use. (See L935 *Important Agricultural Soil Properties* for more information.)

When rainfall and/or irrigation water is added to the field in amounts that keep this water availability in the upper range for optimum growth, there is less room for water storage in the soil; also, wetter soils have slower infiltration rates. Both of these factors increase the potential loss of water due to drainage or runoff when it rains.

Irrigation water applications should be scheduled so no water is applied unless there is sufficient root zone soil water storage available for the application; however, every irrigation system has an associated efficiency, which means some applied water may not be used by the crop. The general objective of irrigation is to keep the soil water in the optimum range, so less storage of rainfall after an irrigation event may occur, since perfect weather forecasts are not possible.

Crop yield and water use relationships for important Kansas crops are shown in Figure 9, with the threshold ET values and yield slope shown in Table 4. Corn, soybeans, grain sorghum, and sunflowers are all spring-planted, summer-grown crops, while winter wheat is fall-planted, grows until winter dormancy, resumes growth in spring, and matures in early to mid-summer. Corn and grain sorghum are generally used as feed grains, although they are also stock for ethanol production. Corn tends to be grown in areas with irrigation or higher rainfall instead of grain sorghum due to higher yield potential. Grain sorghum initiates grain yield at a lower ET threshold, which can give it a production advantage over corn in lower rainfall areas under dryland or limited irrigation conditions.

The crop water production functions are useful planning tools but represent the long-term response of crops to growing conditions. As shown previously, crop water use varies based on the seasonal weather conditions. This is illustrated by a long-term water use study on corn at Garden City. The study had six levels of irrigation treatment, ranging from dryland to full irrigation, as shown in Table 5. Figure 10 shows the yields for each of the six irrigation treatments for each of the seven years of the study. The precipitation ranged from above normal to extreme drought at the site during the study period. Yield for the higher water treatments were generally good, although in some years, yield was suppressed due to hail.

In general, notice the variation of yield decreases with increasing irrigation. This is more easily seen in Figure 11, which shows the relative yield of the study. Relative yield is the yield of an individual treatment divided by the maximum yield of the year multiplied by 100 to make it a percentage. This removes the year-to-year yield variation effect. The irrigation application depths for the highest yield level ranged from about 8 inches to about 19 inches (the seven 100 percent yield data points of Figure 11), which dramatically illustrates the need to schedule irrigation using current-year conditions versus long-term averages.

The individual year relative yields are shown in Figure 12; note the yield response curve of 2011, the drought year. This was the only year with yield failure at the dryland treatment level. Over 7 inches of irrigation was needed to achieve 20 percent relative yield level, just slightly less than the full irrigation treatment application in 2009.

The range of full irrigation treatment application depth demonstrates the need to use some form of irrigation scheduling to account for the day-to-day variation in water use as discussed previously which, when combined with seasonal rainfall variations, can result in wide fluctuation of the annual irrigation requirement. KanSched, an ET-based irrigation scheduling program, is available to assist producers in scheduling irrigation (see KanSched in the reference list).

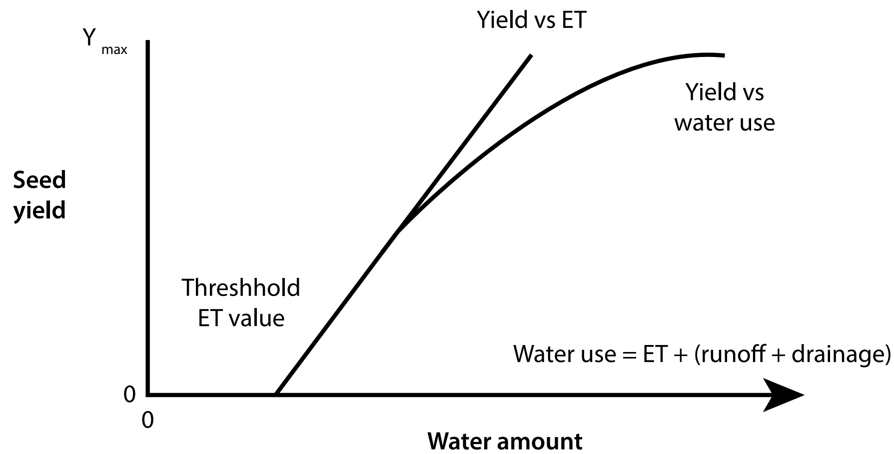

Figure 8. Generalized relationship between yield and water amount (ET or water use). (Stone and Schlegel 2006)

Table 4. Yield versus ET relationship for crops of the central High Plains. (Stone et al. 2006)

Crop	Max ET for full-season variety (inches)	Threshold ET (inches)	Slope of yield vs ET (bushels/acre/inch)	Slope of yield vs ET* (bushels/acre/inch)
Corn	25	10.9	16.9	13.3
Soybean	24	7.8	4.6	3.8
Grain Sorghum	21	6.9	12.2	9.4
Sunflower	22	5.4	218**	150**
Winter Wheat	24	10.0	6.0	4.6
* Long-term (multi-year) slope is less than full slope due to yield reducing factors other than water stress such as hail, freeze damage, insects, diseases, and lodging.				
** (pounds/acre/inch)				

Table 5. Irrigation frequency and application depths for a long-term water use study on corn. (Klocke, et al., 2014)

Irrigation Treatment	Irrigation Frequency (days)	Total irrigation (inches)	Percent of Full Irrigation
1	5	13	100
2	7	10	80
3	8	8	65
4	11	6	47
5	16	4	33
6	22	2	20

Summary

Plants require a lot of water to grow, but the amount varies considerably on a seasonal basis and a daily basis. Their use rate also changes based on their stage of growth. It is important to understand the range of water use by crops to better manage the crops, particularly when crops are being irrigated.

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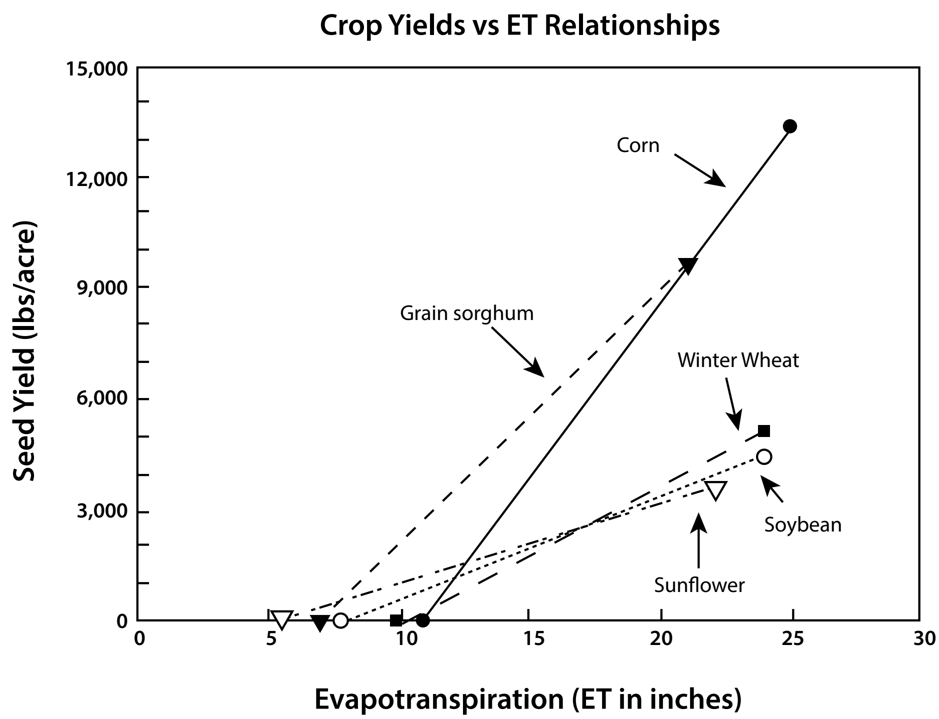

Figure 9. Yield versus ET for various crops. (Stone et al., 2006. Crop Yield as Related to Evapotranspiration).

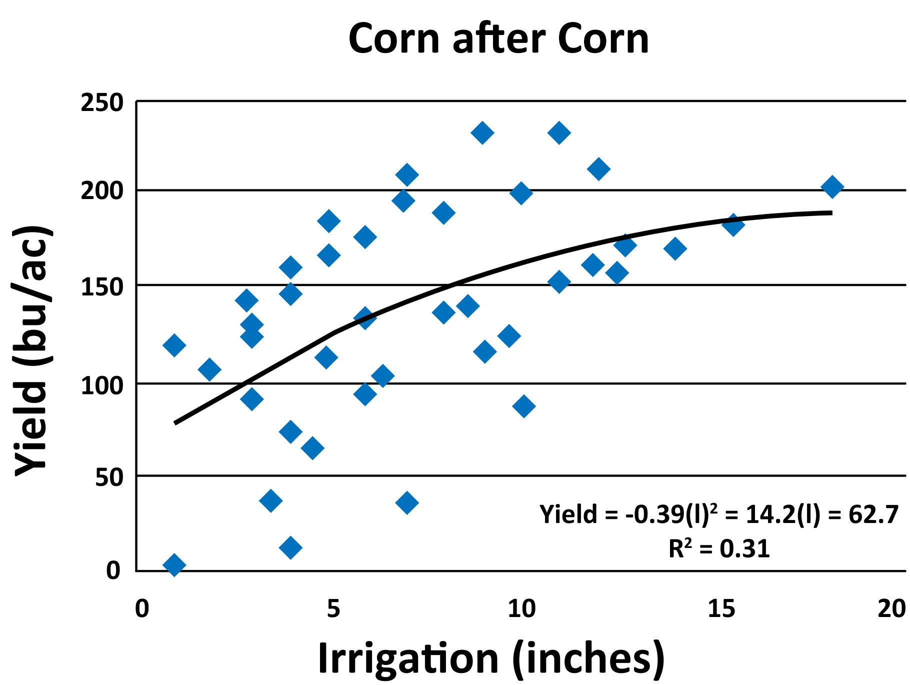

Figure 10. Corn yield as related to irrigation amount for Garden City, Kansas. (Klocke, et al. 2014).

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Related bulletins and software:

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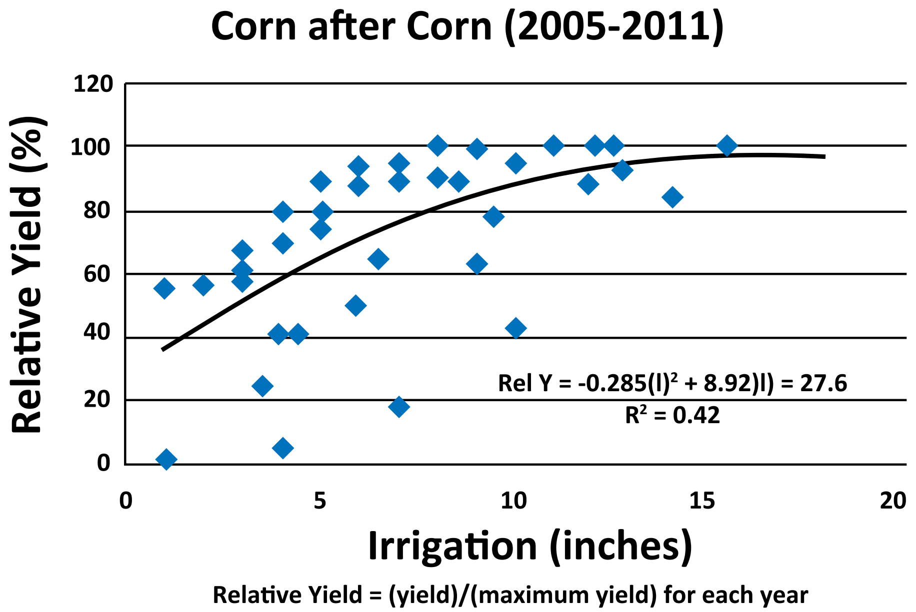

Figure 11. Relative corn yield as related to irrigation amount for Garden City, Kansas. (Klocke, et al. 2014).

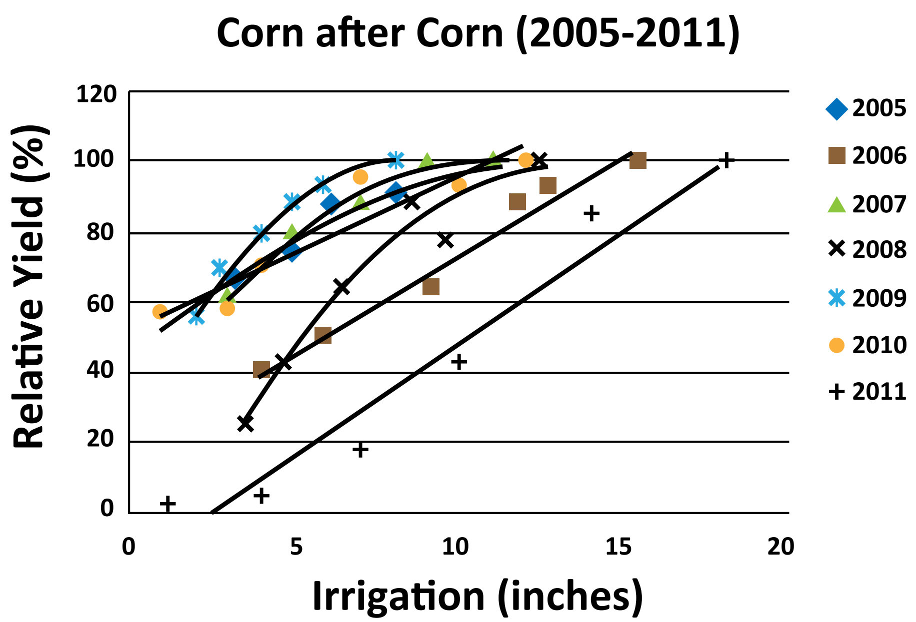

Figure 12. Relative corn yield as related to irrigation amount by year for Garden City, Kansas. (Klocke, et al. 2014).

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