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Evapotranspiration Basics and Estimating Actual Crop Evapotranspiration from Reference Evapotranspiration and Crop-Specific Coefficients

Suat Irmak, Professor and Soil-Water Resources and Irrigation Engineer, Department of Biological Systems Engineering

This publication presents some of the basics of evapotranspiration, evaporation, and transpiration processes and provides information about some of the influencing factors of these important variables. Additionally, it presents a method to estimate crop water use (actual crop ET) from reference evapotranspiration (ET_{ref}) and crop-specific coefficients (K_c) that can be used for irrigation management for numerous agronomic crops. Some of the publicly available ET_{ref} and K_c sources are also provided.

Evapotranspiration (ET) is a dynamic and critical variable in many disciplines, including agronomy, plant physiology, and plant sciences; hydrologic sciences; earth and atmospheric sciences; forestry; agricultural engineering; climate sciences; water sciences; and numerous other physical science disciplines. ET interacts with numerous processes at the plant, soil, and water interface and impacts many activities and plant responses to the environment. In general, ET can be defined as the transfer of water in the form of water vapor (very small water particles that cannot be visually seen) from the soil surface, a water body, vegetation, and other surfaces to the atmosphere. Water evaporates from any moist surface into the air unless the air is saturated. The rate and amount of ET from a surface depends on many factors. Evapotranspiration in agroecosystems is essentially the sum of two processes:

- Transpiration, in which water entering the plant roots is carried to stems and leaves for building plant tissue via photosynthesis and then passes through the leaves into the atmosphere in the form of water vapor.
- Evaporation, in which water evaporating from soil surfaces, water surfaces, or plant leaf surfaces that intercept water droplets from rain, irrigation, and/or dew formation.

Not in all cases, but usually evapotranspiration is the largest component of the hydrologic cycle, given that most precipitation that falls on land is returned to the atmosphere in the form of evaporation or transpiration. Globally, about 60 percent of the annual precipitation falling over the land surface is consumed by ET. On average, ET consumes about 70 percent of the United States annual precipitation, including more than 90 percent of the precipitation in the western and Midwestern United States and as much as 100 percent in some desert areas. In Nebraska, on average, 90–93 percent of precipitation is consumed for ET.

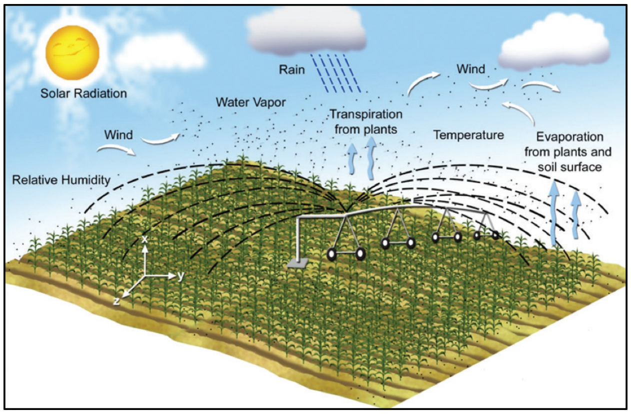

Figure 1. Depiction of evaporation and transpiration and some of the environmental factors that impact these processes in a center pivot-irrigated field.

Quantification of ET is necessary for many purposes, including crop production and determining crop productivity response to unit of water applied and/or used; water resources assessments, management, allocation, and forecasting; environmental assessment; natural system and ecosystem quality, etc. In agriculture, accurate quantification of ET is important for developing and implementing effective and efficient irrigation management practices. During a growing season when evaporative demand exceeds precipitation, plant growth and development as well as grain yield and quality may be adversely and significantly affected by soil water deficit in the absence of irrigation. In some areas, irrigation is used to supplement natural precipitation and minimize potential losses in crop production due to water deficits. A large part of the irrigation water applied to agricultural lands (*Figure 1*) is consumed by evaporation and transpiration.

In field measurements, it is a very difficult and expensive task to separate evaporation from transpiration, and the two evaporative loss processes are usually considered together as ET. Measurement or quantification of transpiration and evaporation requires extremely carefully designed and implemented apparatus and instrumentation, careful data collection, and expert interpretation. Thus, almost all separate evaporation or transpiration measurements are conducted in research settings due to extreme difficulties in implementing them in production fields in practice.

In a given agricultural field (for example, a center pivot-irrigated corn field, *Figure 1*), many soil, plant, and management factors will affect the ET process. Some of these factors can increase and some can decrease ET rates. Additionally, some of the same variables can have both increasing and decreasing impact on ET, depending on conditions and on the interactions of multiple variables. These factors include:

- plant species,
- canopy characteristics, including shading, leaf orientation, etc.
- stand density (plant population),
- degree of surface cover,
- plant growth stage,
- irrigation management (over-irrigation can either increase ET due to larger evaporation or can reduce ET due to plant lodging resulting from a very wet root zone that creates a reduced transpiration rate; under-irrigation can usually decrease ET),
- soil physical, hydraulic, and chemical characteristics,
- soil management, including tillage practice,
- planting and emergence date,
- maturity group of the plant variety/cultivar,
- soil water availability,
- irrigation method,
- disease pressure,
- geographic location, including elevation, latitude, and longitude.

While all these aforementioned factors can impact ET (and some of them substantially), ET is primarily driven by climatic conditions and plants' conditions (plant health and soil-water status) and interactions with the climate, such as air temperature, solar radiation, relative humidity of air, wind speed and direction, and vapor pressure deficit.

As the plants transpire water and evaporation occurs from the soil and/or plant surface, water moves to the surrounding atmosphere in the form of very small water vapor particles (shown by the small black dots in *Figure 1*). The movement of this water vapor within, from, or to a field from surrounding areas (e.g., if there is sprinkler irrigation in a neighboring field, water vapor particles can move to other fields as a function of wind speed and direction) is mainly determined by wind speed and direction although other climatic factors can also play an important role. For example, radiation and air temperature can play a role in evaporating some of the water vapor particles before they move within a field or to another field or intercepted by the canopy. Evapotranspiration increases with increasing air temperature and solar radiation—the two primary drivers of ET.

Wind speed usually causes ET to increase, but not always (Irmak and Mutiibwa, 2010). Above a certain wind speed the plant leaf stomata—the small pores on the top and bottom leaf surfaces that regulate transpiration—close. This reduces transpiration and ET due to the plants' inability to keep pace with the rate of evaporative loss (Irmak and Mutiibwa, 2010). In other word, plants may also close their stomata during a windy period if they are not able to maintain the evaporative demand of the surrounding air. Wind also can cause mechanical damage (lodging) to plants, which can reduce ET due to reduced leaf area and breakage in sap flow continuum to the evaporating surface (leaves). Similarly, hail can reduce the leaf area and ET due to the reduction in evaporating surface area.

Higher relative humidity reduces ET as the demand for water vapor by the atmosphere surrounding the leaf surface decreases. A reduction in relative humidity (dry air) increases ET. That is because low humidity increases the vapor pressure deficit (an indication of the dryness of the air) between the vegetative surface and air. Higher transpiration and evaporation will always need to occur to meet the evaporative demand of the air for moisture. The surrounding air's moisture demand always dictates surface to evaporate moisture to meet that demand. On a rainy day, incoming solar radiation decreases, relative humidity increases, and air temperature usually decreases, resulting in decreased ET. However, depending on climatic conditions, actual crop water use usually increases at a greater rate than usual in the sunny days after a rain event due to the increased availability of water in the soil surface and crop root zone.

In a given crop field, ET may not occur uniformly due to variations in crop germination, soil water availability, and other factors such as nonuniform water and nutrient applications and an uneven distribution of solar radiation within the canopy. Spatial variability in rainfall can also cause nonuniform soil-water status on the soil surface and in the crop root zone, which also contributes to nonuniform ET. Generally, the top leaves are more active in transpiration than the lower leaves because they receive more light. The leaves in the mid-canopy receive less light/radiation (shaded leaves) than the upper or top (sunlit) leaves and, therefore, have reduced transpiration rates as compared with the leaves on the upper canopy. Also, the bottom leaves mature and age earlier and may have lower transpiration rates than the greener and younger leaves in the upper layers of the canopy. Thus, there is a substantial spatial variability in transpiration (and ET) not only in different parts of the field, but also within the upper, middle, and lower canopy of the same plant as well.

How Irrigation Affects ET

In water-deficit settings, ET will be less than in fully irrigated conditions. That's because deficit-irrigated plants cannot transpire water at the same rate as fully watered, healthy, and actively growing plants that transpire at the potential (maximum) rate. Under the same microclimatic conditions, irrigated crops will have higher ET rates than rainfed crops. Under rainfed, deficit, or limited irrigation, the plant leaf stomata will close when the soil cannot supply water at a sufficient rate, or the root system is not extensive and efficient enough to withdraw water from the soil system to meet the atmospheric demand.

In some cases, rainfed crops can have deeper and more extensive root systems than irrigated crops and can withdraw water from deeper soil layers. However, in the absence of rain when the available soil-water is depleted, rainfed plants will experience wilting and ET will be reduced. Also, in a given year, when plants that have deeper roots are planted, the soil-water in deeper soil layers can be mined or extracted. In water-deficit conditions in which deeper soil layers are not recharged via precipitation, the following year, the chance of producing a decent rainfed yield will be significantly reduced. This is because deep-rooted plants will have the opportunity to tap into the deeper soil layer soil-water that was depleted in the previous year. Thus, soil-water management, crop pattern and rotation, and soil/tillage management are more critical in rainfed settings than in irrigated conditions.

Crop water stress, disease stress, heat stress, wind stress, and other environmental stresses reduce transpiration and ET rates. Beyond a certain water stress threshold, crop yield quantity may decrease. Under rainfed conditions, seasonal ET of a crop usually will be close or equal to the sum of the available water in the soil profile and rainfall. But, this also depends on the timing and magnitude of precipitation.

In most cases, irrigation increases ET. In a long-term (2005–2010) full irrigation, limited irrigation, and rainfed corn ET, yield, and water use efficiency response field research, Irmak (2015a and b) found that ET linearly increased with increasing irrigation amounts. Irmak also observed that the increase in ET as a function of the same amount of increase in irrigation varied substantially from year to another (inter-annual variability). In other words, the same increase in irrigation amount resulted in a different amount of increase in corn ET. The reasons of this variation in irrigation amount vs. ET relationship from year to year are explained in Irmak (2015a and b).

Soil Evaporation

Similar to ET, water evaporation occurs due to potential vapor pressure deficit gradient (difference) between the evaporating surface and the surrounding microclimate/atmosphere. During the soil evaporation process, unlike transpiration, there is no plant resistance to water vapor transport (evaporation) into the atmosphere. The evaporation takes place primarily due to the vapor pressure deficit difference (gradient) between the soil surface and the surrounding microclimate. However, when soil-water vapor is being evaporated, there is soil resistance to water vapor transport due to water molecules being bounded with the soil particles. This reduces the rate of evaporation and is the primary reason why free water evaporation is usually greater than the soil evaporation. Thus, evaporation from the soil surface differs from free water evaporation that occurs from water bodies (ponds, lakes, reservoirs, wetlands, rivers, etc.).

Gradient in vapor pressure deficit is a function of numerous environmental variables, primarily due to atmospheric moisture content, air temperature, wind speed and direction, solar radiation, and air humidity. Evaporation in the field can occur from the crop canopy, from the soil surface, or from a free-water surface [e.g., ponded water after rainfall; during or after gravity (surface) irrigation; accumulation of water during or after sprinkler irrigation in different parts of a field, including in wheel-track areas, etc.]. Thus, evaporation due to irrigation applications can occur in gravity (surface) and sprinkler (including center pivot) irrigation. However, there is no evaporation directly from irrigation applications in subsurface drip-irrigated fields, because when drip irrigation is properly designed, installed, managed, and maintained, the top several inches of soil surface remain (and should remain) dry, eliminating evaporation losses due to irrigation.

When the soil surface is at least partially bare, evaporation can occur directly from the soil and plant surface. In conditions where the crop canopy reaches 100 percent closure, soil evaporation can still occur. This can constitute a considerable proportion of the seasonal total ET, in both irrigated and rainfed conditions. Evaporation is a process that, if uncontrolled, can cause considerable water losses. In Nebraska, depending on the soil, climate, crop growth stage, management practices, irrigation method, and several other factors, soil evaporation can be up to 20–30 percent (or more) of the seasonal total ET for irrigated crops.

Water lost through soil evaporation is a non-beneficial use as it does not contribute to crop growth and development or yield. Thus, reducing evaporation losses from agricultural fields should be a part of effective irrigation management. Soil evaporation is highest in the early growing season and gradually decreases as the plants develop, leaf area increases, and the canopy closes. It is minimal when the canopy completely shades the soil surface. As stated earlier, even under a fully closed canopy, some soil evaporation occurs. Soil evaporation increases toward the end of the season when leaf senescence and aging begin and transpiration is reduced. Several management practices can reduce soil evaporation. Early planting, when feasible, can result in early canopy closure, which will reduce soil evaporation. No-till and reduced-till practices also can reduce soil evaporation compared with conventional tillage. This is due to reducing the amount of solar radiation that is directly intercepted at the soil surface.

Plant Transpiration

In terms of crop productivity and yield, transpiration is the most beneficial use of water in irrigated and rainfed/dryland agriculture. Plants accumulate dry matter and yield due to transpiration. Thus, in reality, transpiration and crop yield are strongly and linearly correlated. However, because of the extreme difficulties, cost, and required high-level expertise in measuring and interpreting transpiration data, crop yields and ET still have a very strong and meaningful correlation in practices. In the transpiration process, the soil-water that is extracted by the plant roots is passed through the plant and is transpired from leaves via stomata (small pores at the upper and lower part of the leaves).

Unlike ET and evaporation, the transpiration process is driven by plant, soil, and climatic factors. In addition to soil resistance, there is always some level of resistance by the plant itself to transpire water vapor. Thus, the transpiration process is more complex and is impacted by more factors than evaporation. Water has three primary functions in plants:

- Water cools down the plants and helps them to maintain their turgidity (essentially keeping the plants hydrated) and is also essential for the transport of nutrients and micronutrients from the root system to the stem and leaves.

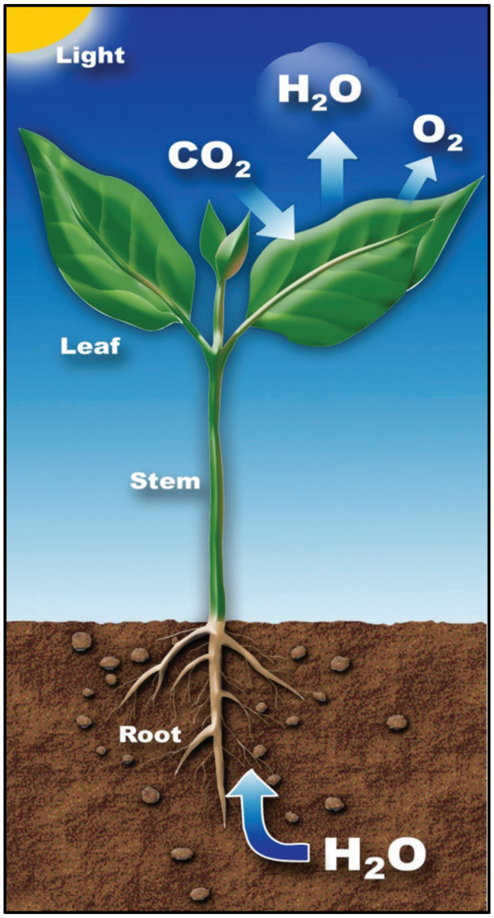

Figure 2. Depiction of soil-water uptake via plant roots and CO_2, H_2O, and O_2 exchange at the plant leaf level (adopted from: http://www2.estrellamountain.edu/faculty/farabee/biobk/BioBookPLANTANAT.html.

- Water is essential for the transpiration process, which is a very complex process. Transpiration is minimal early in the growing season when plants are small and do not require much water, but increases with greater leaf area until complete closure of the canopy occurs. For irrigated crops, transpiration is usually the dominant water consumer (i.e., 65–70 percent of the seasonal total ET). Studies have revealed that transpiration accounts for about 10 percent of the moisture in the atmosphere, with oceans, seas, and other bodies of water (lakes, rivers, streams) providing nearly 90 percent. (A small amount comes from sublimation when ice changes into water vapor without first becoming liquid).
- Transpiration and photosynthesis are linked, but they are also significantly different processes. Plants lose water vapor through transpiration, photosynthesis, which is a biochemical pathway that takes place in plant cells in which CO_2, H_2O, and light (radiant) energy are used to produce carbohydrates, sugar, and O_2, which ultimately enables plants to produce biomass and yield. While very little (1–2 percent) of the total water that is extracted from the soil via plant roots and passes through the plant is actually used for the photosynthesis process, this is a crucial process for crop growth and productivity. The remaining significant majority of absorbed water is consumed through transpiration, which is also a crucial process for crop productivity. Water does not flow from the soil into the crop roots automatically. Several very complex processes take place to enable plants to extract water from the soil particles to be used for various purposes in the plant. A general water uptake and gas exchange at the leaf level is depicted in *Figure 2*.

Factors Affecting the Transpiration Rate

The transpiration rate of a given crop is influenced by many factors, including crop type, soil and plant management practices, irrigation regime, climatic conditions, plant growth stage, plant genetic characteristics, leaf characteristics and orientation, leaf age, and other factors. Reducing soil evaporation can result in more water availability for plant transpiration. This, in turn, may increase the crop's water use efficiency, because transpiration and crop yield are linearly and strongly correlated.

However, when more water is available to plants, it does not automatically mean that plants will use the extra available water. Irrigation management practices should be designed to reduce soil evaporation and make the most of the water available for plant transpiration to increase plant water use efficiency. Each plant type has a unique transpiration rate. For example, corn usually uses more water per growing season than soybean and sorghum under the same climatic, soil, and management conditions. Thus the total transpiration rate for corn will usually be higher than that for soybean and sorghum under the same climatic conditions. However, the biomass, dry matter, and yield production per unit of transpired water can vary significantly from one crop to another. When a unit of crop yield is determined per unit of transpiration, it is called *transpiration use efficiency*, which is the ultimate and most meaningful and proper way of determining a crop's water productivity and true response to water. Although water is consumed by plants via transpiration, the ET rate (transpiration plus soil evaporation) should be considered in determining the total water use of a given plant to estimate irrigation requirements. That's because, in practice, it is practically impossible or economically infeasible to completely eliminate evaporation losses from large scale production fields.

Estimating Evapotranspiration for Determining Crop Water Use and Irrigation Management

The main purpose of an effective irrigation management is to deliver the proper amount of water to the crop root zone at the proper time with acceptable uniformity to meet crop water requirements to optimize crop productivity. With some of the irrigation methods (e.g., gravity/surface irrigation, center pivot or other forms of sprinkler irrigation, surface drip irrigation), it is not possible to deliver water directly to the crop root zone and some portion of topsoil needs to be wetted to achieve the proper amount of water retention in the crop root zone. With subsurface drip irrigation and subirrigation (note that subirrigation and subsurface drip irrigation are substantially different irrigation methods), it is feasible to deliver irrigation water directly to the crop root zone. In areas where rainfall supplies some of the seasonal crop water (irrigation) requirement, irrigation should be used as a supplement. Rainfall should be taken advantage of in water management as effectively as possible to reduce the irrigation requirement and energy use for pumping irrigation water.

In humid, subhumid, and tropical climates, rainfall usually (not always) provides a good portion of the seasonal crop irrigation requirement. In arid and semiarid regions, rainfall in most cases is significantly less than the seasonal irrigation requirement so crop production without irrigation may not be possible. In drought years, rainfall in humid and subhumid climates may also be significantly less than the seasonal crop water requirement.

It should be noted that in many cases, the within-season distribution of rainfall is more important than the total seasonal rainfall for meeting part of the crop water requirements. In some cases, while seasonal rainfall amount may be large, the timing/distribution of the rainfall may not be adequate to contribute to the crop's water requirement. Rainfall may occur right after (or during) an irrigation event or it may occur with very high density and short duration, which may not be very beneficial or effective due to the low probability of infiltration. Thus automatic rain shut-off devices and closely monitoring the weather forecast should be part of effective irrigation management. The within-season timing/distribution of the rainfall is critically important. That is because rainfall during or after crop senescence, or very early in the growing season during planting, or right after emergence, may not be as beneficial in meeting the crop water requirements.

Several approaches can be used to manage irrigation. These vary from soil water measurements to the more complicated observation and measurement of plant water status and/or plant physiological parameters (i.e., plant temperature, relative water content of leaf, stem diameter, etc.) or a combination of both. Perhaps the most commonly used irrigation management approach is to measure soil moisture in the crop root zone and trigger irrigation at certain levels of depletion of soil water, which is a strong function of soil characteristics. A detailed description of using soil moisture for irrigation management in different soil types is discussed in the Nebraska Extension Circular EC783, *Principles and operational characteristics of Watermark granular matrix sensor to measure soil water status and its practical applications for irrigation management in various soil textures*.

Determination of soil water status to schedule irrigations probably dates back to the origin of irrigated agriculture when advanced sensors and instruments were not readily available, but people still irrigated their fields with some level of frequency and made decisions when to irrigate. However, the amount of water that needs to be applied probably was not considered as ancient irrigation practices usually diverted large amounts of water from rivers, creeks, etc., without any controlled amount of delivery. Sometimes, growers or their advisers (e.g., independent crop consultants) use the "hand-feel" method to determine when to irrigate. This method is generally inaccurate and usually provides false information about irrigation timing, leading to under- or over-estimations of the irrigation amount. It is a qualitative rather than a quantitative indicator. Now, numerous advanced, accurate, durable, economical, and scientifically based tools and technologies are available and can be used for irrigation management. These tools should be used instead of the hand-feel method for accurate irrigation management decisions.

Another approach for irrigation management is to use ET information to determine the crop water requirement (crop water use) and replenish the soil profile to meet the amount of ET that is consumed by plants in a given period. Currently, one of the common practices for estimating the actual crop ET rate (or actual crop water use rate) for a specific crop (ET_c) requires first calculating reference evapotranspiration (ET_{ref}) and then applying the crop-specific coefficients (K_c) to estimate actual crop ET as:

$$ET_c = ET_{ref} \times K_c$$

where ET_c is the actual crop ET (inches/day, inches/week, inches/month) and ET_{ref} is the alfalfa-reference ET (inches/day, inches/week, inches/month). The ET_{ref} can represent either grass or alfalfa-reference ET. Since alfalfa-reference ET is more commonly used in the Midwest, including Nebraska, in this publication ET_{ref} represents alfalfa-reference ET. Grass-reference ET is commonly used mostly in the eastern, southern, southeastern, and western U.S.

Alfalfa-reference ET is defined as the ET rate from an extensive, uniform surface of dense, actively growing alfalfa that is about 20 inches tall with adequate soil water, no disease, and is actively growing without any physiological or environmental stresses. The terms "reference ET" and "reference crop ET" often are used interchangeably, and they both represent the same ET rate from a tall alfalfa surface.

Crop Coefficient Concept

While ET_{ref} accounts for variations in weather and is used as an indicator of atmospheric demand for water, K_c values account for the difference between ET_{ref} and ET_c and link them. K_c is the crop coefficient for a given crop, varies with the growth stage, and is usually determined experimentally. Each agronomic crop has a set of specific crop coefficients used to predict water use rates at different growth stages. An example of a K_c curve as a function of days or weeks after planting is presented in *Figure 3*.

In general, there are four main crop growth stages: initial, crop development, mid-season, and late season. The length of each stage depends on the climate, latitude, elevation, planting date, crop type, maturity group of different varieties, hybrids, or cultivars, and management practices.

Early in the growing season during the crop germination and establishment stage, most ET occurs as evaporation from the soil surface. As the crop canopy develops and covers the soil surface, evaporation from the soil surface decreases and transpiration increases. Early in the season when the plant is small, the water use rate and K_c value also are small (K_c initial stage).

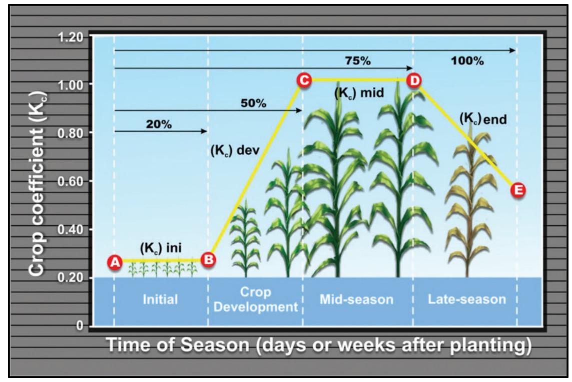

Figure 3. Depiction of crop coefficients (K_c), which vary according to plant growth stages [$(K_c)_{ini}$: crop coefficient for initial plant growth stage; $(K_c)_{dev}$: coefficient for plant development stage; $(K_c)_{mid}$: coefficient for mid-season; and $(K_c)_{end}$: coefficient towards the end of the season].

As the plant develops, the crop ET rate increases (*Figure 3*). For agronomic plants, the crop ET rate is at the maximum level when the plant is fully developed (K_c mid-season). Note that *Figure 3* is not drawn to scale and the K_c values can be greater than 1.0. The ET rate decreases again towards the end of the season when the plant reaches physiological maturity (K_c end season). The plant growth stage (leaf area), soil-water status, plant turgidity, plant stress level, and climatic conditions (radiation, vapor pressure deficit, air temperature, wind speed, relative humidity) drive the rate of crop ET.

Source of Crop Coefficient Data for Different Crops

K_c values for many crops are publicly available. One of the sources for crop coefficients is the High Plains Regional Climate Center (HPRCC: http://www.hprcc.unl.edu/). The alfalfa-reference crop coefficients for six major agronomic crops are presented in *Table I* and are based on the plant growth stages.

After determining ET_{ref} on a daily or weekly basis, the ET_{ref} value is multiplied with the proper K_c value to estimate actual crop water use. For example, if the ET_{ref} for July 20–24 is 1.20 inches for corn at the silking stage (K_c = 1.10 from *Table I*), the actual crop water use is 1.32 inches ($ET_c = ET_{ref} \times K_c$ = 1.20 x 1.10 = 1.32 inches). If the application efficiency of a center pivot is considered to be 85 percent, then 1.55 inches needs to be applied [1.32 inches ÷ 0.85 =

Table I. Alfalfa-reference crop coefficients (K_c) for major agronomic crops based on the growth stages [K_c values are as reported by the High Plains Regional Climate Center (HPRCC, http://www.hprcc.unl.edu/)].

Corn		Soybean		Alfalfa		Winter wheat		Grain sorghum		Dry beans	
Growth stage	K_c	Growth stage	K_c	Growth stage	K_c	Growth stage	K_c	Growth stage	K_c	Growth stage	K_c
2 leaves	0.10	Cotyledon	0.10	Stage 1	0.10	Emergence	0.10	Emergence	0.10	Emergence -10% cover	0.06
4 leaves	0.18	First node	0.20	Stage 2	0.41	Visual crown	0.50	3 leaves	0.15	10–50% cover	0.06
6 leaves	0.35	Second node	0.40	Stage 3	0.54	Leaf elongation	0.90	5 leaves	0.31	50–80% cover	0.48
8 leaves	0.51	Third node	0.60	Stage 4	0.66	Jointing	1.03	8 leaves	0.56	80%-full cover	0.81
10 leaves	0.69	Beginning bloom	0.90	Maturity	0.85	Boot	1.10	Final leaf	0.87	Full cover	1.00
12 leaves	0.88	Full bloom	1.00	Full cover	1.00	Heading	1.10	Boot	1.10	Pod elongation	1.00
14 leaves	1.01	Beginning pod	1.10			Flowering	1.10	Half bloom	1.10	Pod fill	0.83
16 leaves	1.10	Full pod	1.10			Grain fill	1.10	Soft dough	1.10	Dry down	0.59
Silking	1.10	Beginning seed	1.10			Stiff dough	1.00	Hard dough	0.84	Senescence	0.30
Blister	1.10	Full seed	1.10			Ripening	0.50	Full maturity	0.10	Full maturity	0.09
Dough	1.10	Beginning maturity	0.90			Full maturity	0.10				
Beginning dent	1.10	Full maturity	0.20								
Full dent	0.98										
Black layer	0.60										
Full maturity	0.10										

1.55 inches] to account for losses from the irrigation application and to meet crop water requirements.

It should be noted that an average application efficiency of 85 percent for a center pivot was used in the example. The application efficiency of any given system in the real world is not a fixed number and changes according to how the system is managed. Two exact center pivot systems that have the exact design application efficiency will have different efficiency values when they are managed differently in operation. Local field observations to determine the actual crop growth stage are best for choosing the proper K_c values from *Table I*.

Sources of Local Reference Evapotranspiration (ET_{ref}) Data

Two main sources of daily ET_{ref} values are available for Nebraska. One of the sources is the High Plains Regional Climate Center (HPRCC, http://www.hprcc.unl.edu/). It operates about 60 automated weather stations in Nebraska and other stations in North Dakota, Kansas, South Dakota, and Colorado as part of an automated weather network. The main climatic data reported by HPRCC include maximum and minimum air temperature, maximum and minimum relative humidity, solar radiation, rainfall, wind speed and direction, growing degree days, soil temperature, and ET_{ref}, on a daily and hourly basis. Users can subscribe to an HPRCC service to receive daily ET_{ref} information from the weather station closest to their fields for which the ET_c estimates are being made. The long-term historical data are also available for most stations.

Another source for ET_{ref} is an atmometer (ET_{gage}™). Information about operational characteristics, installation, maintenance, data interpretation, and how it can be used to measure ET_{ref}, and its use for irrigation management are described in detail in the Nebraska Extension NebGuide G1579, *Using Modified Atmometers (ET_{gage}™) for Irrigation Management*.

As part of a large effort to implement newer tools and technologies for irrigation management, the Nebraska Agricultural Water Management Network (NAWMN: water .unl.edu/cropswater/nawmdn) gathers weekly totals from ET_{gages} at several hundred locations scattered across Nebraska. On the NAWMN website users can view ET_{ref} data from the ET_{gage} location closest to their fields to estimate crop water use for their location. The NAWMN also provides K_c values for various cropping systems based on growth stages. Using weather station ET_{ref} data is very helpful for practical applications. However, in many cases, the weather station can be 20–30 miles, or more, from the field location in which ET_{ref} data are being used to manage irrigations. In this case, the weather station may not be able to represent the climatic conditions of the field due to the long distance.

The advantage of using ET_{gage} installed nearby or at the side or edge of a field is that it can provide local ET_{ref} data that are well-representative of that field. In long distances when the weather station and the production field under consideration are far from each other, some of the climatic variables can change substantially, especially precipitation, which can have a large spatio-temporal characteristic. Thus, ET_{gage} would account for the effects of local climatic conditions on ET_{ref} and can provide more local and appropriate ET_{ref} data for the production fields under consideration.

Another source of ET_{ref} is solving the empirical or combination-based energy balance equations (e.g., Penman, Penman-Monteith, and other equations that are a derivation of these equations) to estimate ET_{ref} from climatic data (solar radiation, maximum and minimum air temperature, relative humidity, and wind speed). This process requires expert knowledge and experience. The process includes determining several variables and coefficients that are not readily available. Experts in this field can be contacted for assistance to estimate ET_{ref} for a given location.

REFERENCES

Irmak, S., and D. Mutiibwa. 2010. On the dynamics of canopy resistance: Generalized-linear estimation and its relationships with primary micrometeorological variables. Water Resources Research 46:1–20, W08526, doi: 10.1029/2009WR008484.

Irmak, S. 2015a. Inter-annual variation in long-term center pivot-irrigated maize evapotranspiration (ET) and various water productivity response indices: Part I. Grain yield, actual and basal ET, irrigation-yield production functions, ET-yield production functions, and yield response factors. J. Irrigation and Drainage Engineering, ASCE 141(5):1–17. 04014068. doi:10.1061/(ASCE) IR.1943–4774.0000825.

Irmak, S. 2015b. Inter-annual variation in long-term center pivot-irrigated maize evapotranspiration (ET) and various water productivity response indices: Part II. Irrigation water use efficiency (IWUE), crop WUE, evapotranspiration WUE, irrigation-evapotranspiration use efficiency, and precipitation use efficiency. J. Irrigation and Drainage Engineering, ASCE 141(5):1–11. 04014069. doi: 10.1061/(ASCE)IR.1943–4774.0000826.

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