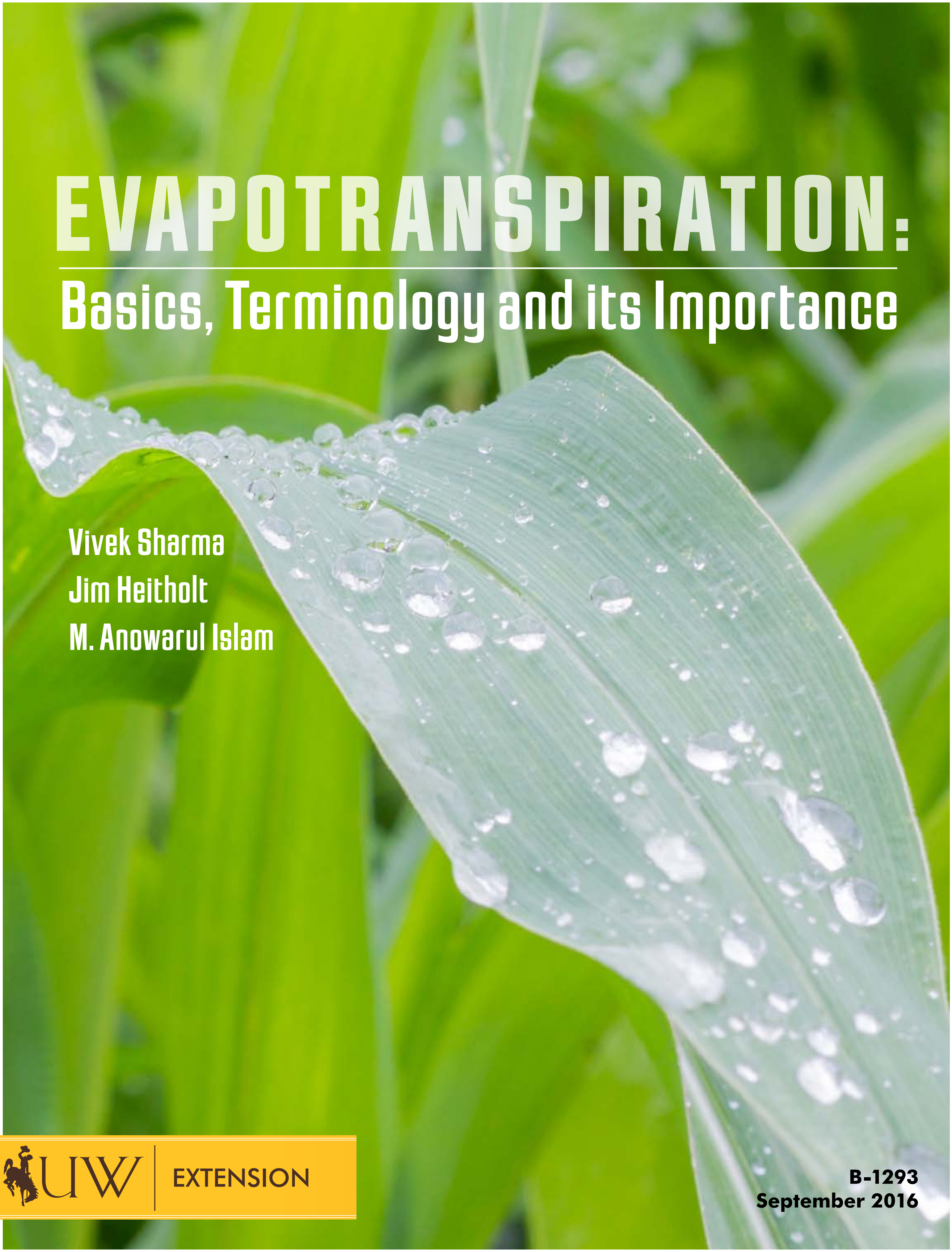
EVAPOTRANSPIRATION:

Basics, Terminology and its Importance



Vivek Sharma
Jim Heitholt
M. Anowarul Islam

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By Vivek Sharma, Jim Heitholt, M. Anowarul Islam

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EVAPOTRANSPIRATION: Basics, Terminology and its Importance

Vivek Sharma, University of Wyoming Extension, Irrigation Specialist
Jim Heitholt, Professor, Crop Physiology
M. Anowarul Islam, Associate Professor, Forage Agroecology

Increasing concerns have been expressed by crop producers, researchers, and policy makers about the impacts of changing climatic conditions on water supplies for agricultural regions of the United States. Although Wyoming currently has adequate water supply for agriculture, climate variability and an increasing number of extreme events (e.g., flood and drought) threaten our water quantity and quality and agriculture development. For example, in 2012, Wyoming was ranked as the number-one driest state, with most of the state under exceptional drought during its recorded history.

Such conditions impose more challenges and demonstrate a pressing need to reduce unbeneficial water use through precise water resource planning, strategic water management, and equitable allocation on field, watershed, and regional scales.

In irrigated agriculture, producers, water resource planners, stakeholders, and managers must answer the following questions, such as how to maximize use of available water supplies and how much and at what time irrigation water is required. Addressing these and similar questions requires quantification, evaluation, and an understanding of crop water use, i.e., ***Evapotranspiration (ET)***, which represents the main consumptive use of water in agricultural production.

This bulletin gives an overview of the basic principles of the evapotranspiration process, factors affecting evapotranspiration, evapotranspiration terminology, information on quantification of evapotranspiration, and its importance in agro-ecosystems.

EVAPOTRANSPIRATION

Evapotranspiration (ET) is defined as the combined transfer of water from land surface to atmosphere in the form of water vapor by (i) ***evaporation*** and (ii) ***transpiration***. **Evaporation** is a non-biological process in which liquid water converts to water vapor in the atmosphere from water bodies such as lakes, reservoirs, oceans, the soil surface, and from water droplets on plant leaves. **Transpiration** is the biological associated evaporation of cellular water from within the plant leaves. It is defined as the process of movement of moisture through the plant roots to stems and leaves to the atmosphere through plant leaf stomata. Stomata are the microscopic pores on a leaf surface through which the plant transfers water and gas to the atmosphere. This process is important for leaf cooling.

ET has an important application in the land surface energy balance and water budgets. ET is one of the largest fractions of an ecosystem's water cycle. On average, about 55 to 60 percent of global

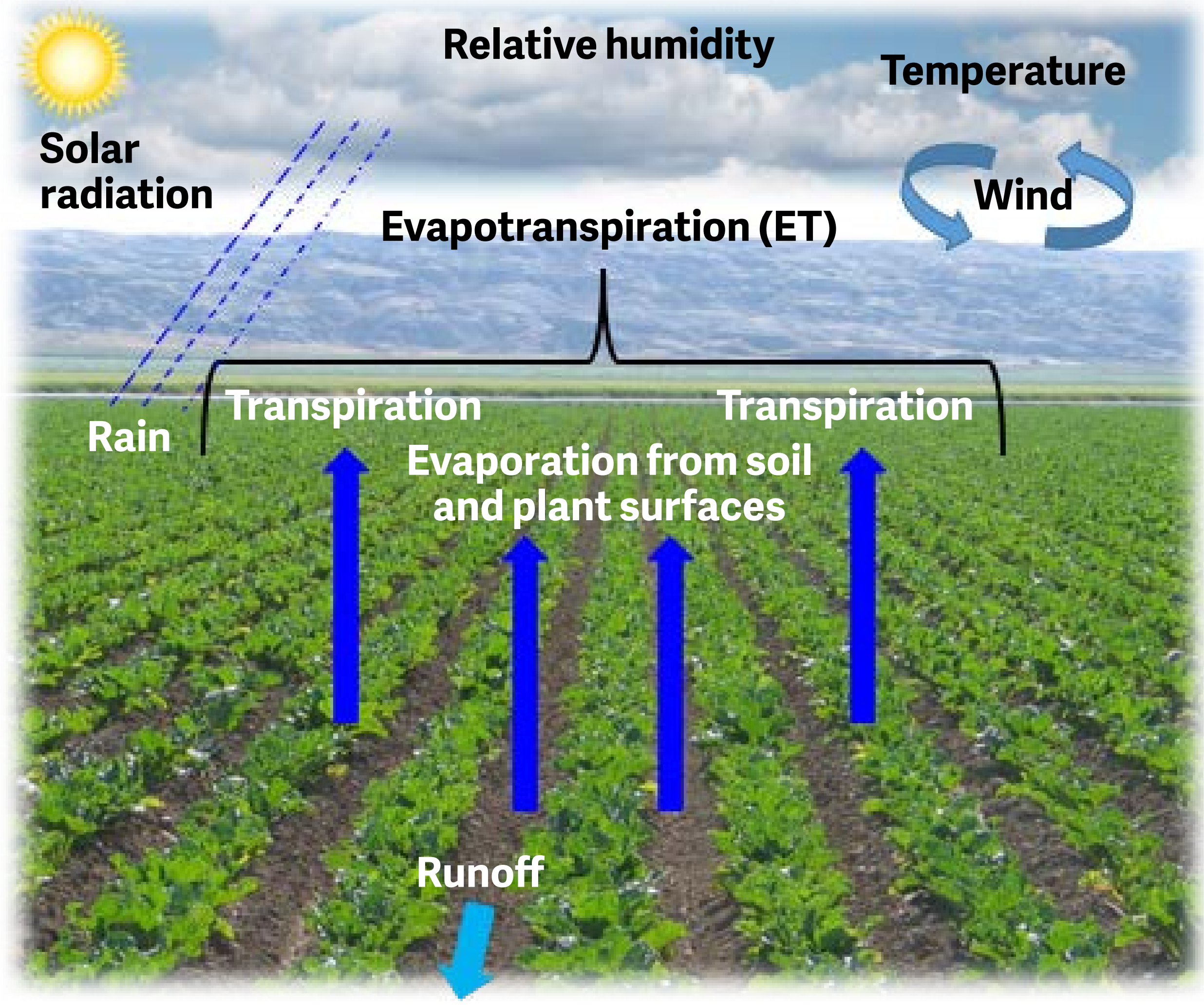

Figure 1. Basic representation of evapotranspiration (ET) concept and the factors affecting the ET process in a sugarbeet field.

precipitation, about 70 to 75 percent of precipitation in the U.S., and 85 to 90 percent of precipitation in Wyoming, goes back to the atmosphere via ET (Sanford and Selnick, 2013). Therefore, the accurate assessment of ET for water resources management and environmental assessments on field, watershed, and regional scales, is critical. In agro-ecosystems, reliable estimates of ET are vital to develop criteria for in-season water management, particularly in the context of crop production in irrigated agriculture such as scheduling irrigation, predicting soil water status, water allocation, efficient use, long-term estimates of water supply, demand and use, design and management of water management infrastructures, and assessing the impact of land use and management changes on water balances.

For example, when evaporative demand of the atmosphere exceeds precipitation, plant growth may be adversely affected by the soil water deficit. Under deficit conditions, supplemental irrigation is used to minimize the potential losses in crop production and to fulfill the atmospheric evaporative demand.

Figure 1 depicts the basic process and factors affecting ET under field conditions. As plant leaves transpire and evaporation occurs from soil and plant surfaces, water moves to the atmosphere in the form of very small water vapor particles. Evaporation constitutes a considerable part of ET. Evaporation of soil water is highest early in the growing season and gradually decreases as the crop canopy develops. Nearing the end of the growing season, evaporation increases again when plant leaves senesce (grow old).

Many management practices can reduce the evaporation of soil water, such as early planting, adoption of no-till/reduced till, narrow rows, and adoption of cover crops. Depending upon region and climatic conditions, cover crops can also deplete soil moisture. Water lost through soil evaporation does not contribute to crop yield.

Water lost through transpiration indirectly contributes to crop yield and biomass production. Transpiration is minimal early in the growing season when the crop canopy is small and requires less water. Transpiration increases as the crop canopy develops and decreases again at the end of the growing season. For irrigated crops, e.g., in the semi-arid west, transpiration is usually about 60-70 percent of the total seasonal actual crop evapotranspiration (ETc). The transpiration rate can be affected by the local climate, type of crop, and by management practices. Management practices that result in reducing evaporation (no-till, reduced tillage, cover crop adoption) makes more water available for plant transpiration.

Generally, transpiration and evaporation are difficult to calculate independently, therefore, under field settings, the two processes are considered together as ET in many applications, including irrigation scheduling. In general, irrigated crops have greater evaporation and transpiration rates compared to dryland crops. For example, under dryland condition, the leaf stomata closes when the available soil moisture is depleted to meet the atmospheric demand. Under these conditions, plants will experience wilting and ET will be reduced. Seasonal ET of a crop under dryland condition will usually be close or equal to the sum of the available soil water and precipitation. Also, irrigation can affect the micro-climate of the crop field. The average air temperature near the canopy of an irrigated crop field may be as much as 8-10 degrees F lower than a non-irrigated field. This difference in air temperature and availability of more soil moisture and plant water affects the relative humidity and vapor pressure deficit and, hence, ET.

The rate and movement of water to the atmosphere by ET depends on many factors, which we can divide into three major categories: (i) climatic and edaphic variables; (ii) crop parameters; and (iii) management practices.

The movement is mainly determined by wind speed and direction. The rate of ET mainly depends on the climatic conditions, such as air temperature, relative humidity, solar radiation, and wind speed. For example, on a daily basis, ET rises with increases in temperature and solar radiation, which are the two primary drivers of ET. Wind speed generally increases ET, but not always. Above certain wind speeds, leaf stomata close due to wind stress reducing transpiration and ET. Wind can also cause mechanical damage to the plant leaves that can reduce ET due to reduced leaf area. Similarly, hail can also reduce leaf area and ET.

Increases in relative humidity generally decrease ET because the demand for water vapor by the atmosphere surrounding the plant decreases with increased humidity. Conversely, reduction in relative humidity (dry environment) increases ET because low humidity increases the vapor pressure deficit between the vegetative surface and the air. Higher transpiration and evaporation need to take place to meet the evaporative demand of the air for surface moisture. Because of this effect, the volume of water lost through ET can be significant when climate conditions are hot, dry, and windy. On a cloudy and rainy day, relative humidity increases and air temperature and solar radiation generally decrease resulting in a net reduction in ET; however, following the rainy day, ET usually increases due to increased availability of soil water in the soil surface and in the crop root zone.

Under field conditions, many agronomic/crop and management factors such as plant species, planting dates, plant growth stage, canopy characteristics, plant density, soil water availability, irrigation methods, crop residue cover tillage practices, and soil salinity, can also affect the ET rate at a given time. For example, in a given crop field, variations in soil type, soil water availability, nutrient application, crop germination, amount of residue on the surface and uneven distribution of solar radiation may lead to variation in ET. Generally, the upper leaves are greener and more active than lower leaves in transpiration as they are exposed to more sunlight. The lower leaves mature and age earlier due to lack of sunlight.

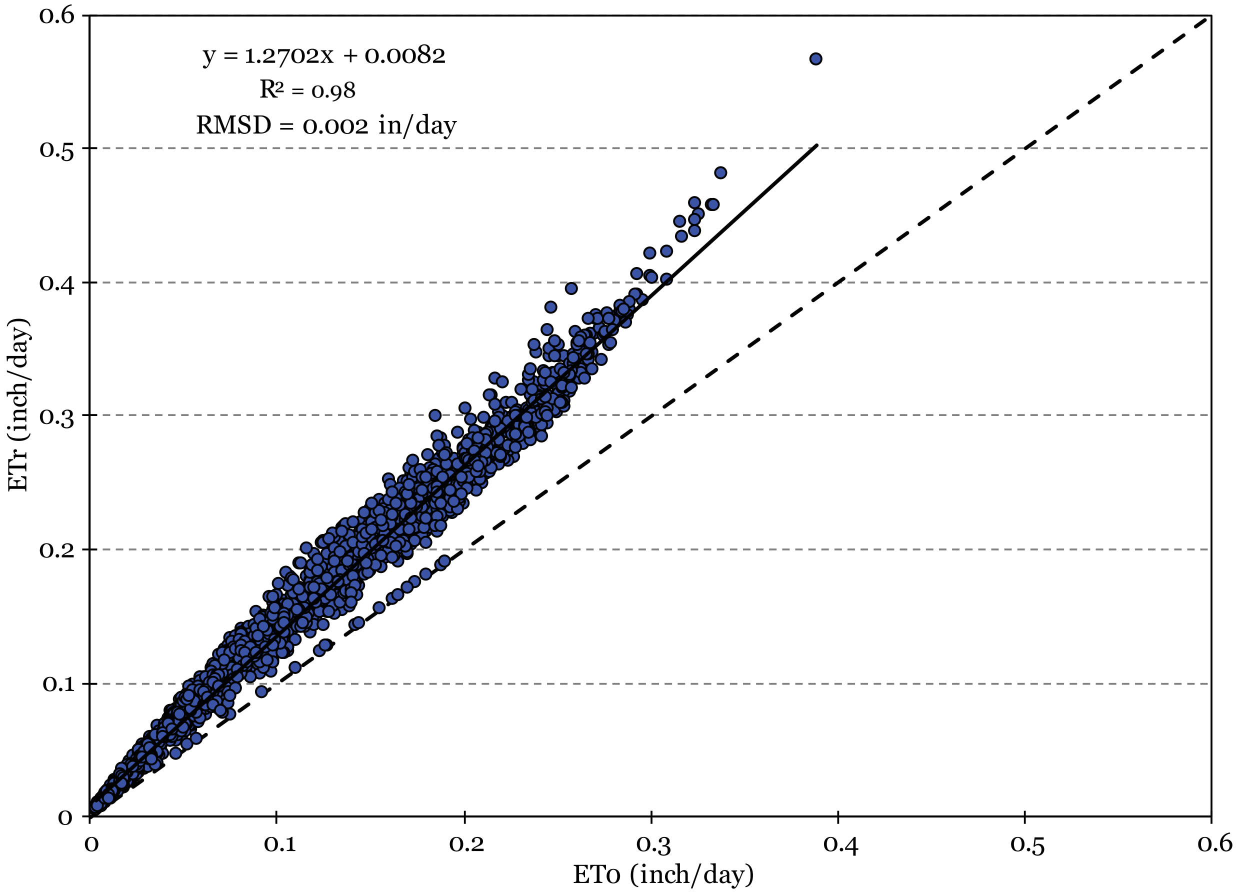

Figure 2. Long-term (2010-April, 2016) relationship between daily grass-reference (ETo) and alfalfa-reference (ETr) evapotranspiration values for Powell Research and Extension Center (PREC), Powell Wyoming.

EVAPOTRANSPIRATION TERMINOLOGY

Researchers over the last seven decades have introduced various ET definitions to understand its concept and applications in agricultural water management. This section provides the descriptions and differences in various terms associated with ET and their uses in agricultural water management, mainly potential evapotranspiration (PET), reference evapotranspiration (ETref), and actual crop evapotranspiration (ETc), as it can introduce difficulties for many practitioners who wish to understand and compare various terms.

Potential evapotranspiration (PET): The term was first introduced in 1948 by botanist and climatologist C.W. Thornthwaite, who introduced crop water requirements in the calculation of the drought index (effect of drought on water supply and demand) by using PET. Thornthwaite (1948) defined this term as "the loss of water by a canopy if soil never limits evapotranspiration." In the same year, Penman (1948) published his approach for modeling evaporation from short-saturated crops. He defined this term as "the rate of water vapor loss from a short green crop under the following conditions: grown in a large surface, during an active growth stage, completely covering the soil (sunlight reaching the ground was negligible), of homogeneous height, in unlimited water and nutritional status." In both definitions of PET, the term "potential" is equivalent to maximum possible level of ET under unlimited soil water supply and actual climatic conditions.

The use of PET in agricultural water management, i.e., in agronomy and irrigation sciences, to determine the crop water requirement has resulted in some criticism, as the evapotranspiration rates from well-watered agricultural crops (tall crop, e.g., corn) may be as much as 10 to 30 percent greater than that occurring from a short green crop. Also, in the definition of PET, the evapotranspiration rate is not related to a specific crop, and there are many types of agronomic and horticultural crops that fit into the description of a short, green crop. Choosing a short, green crop species is a challenge

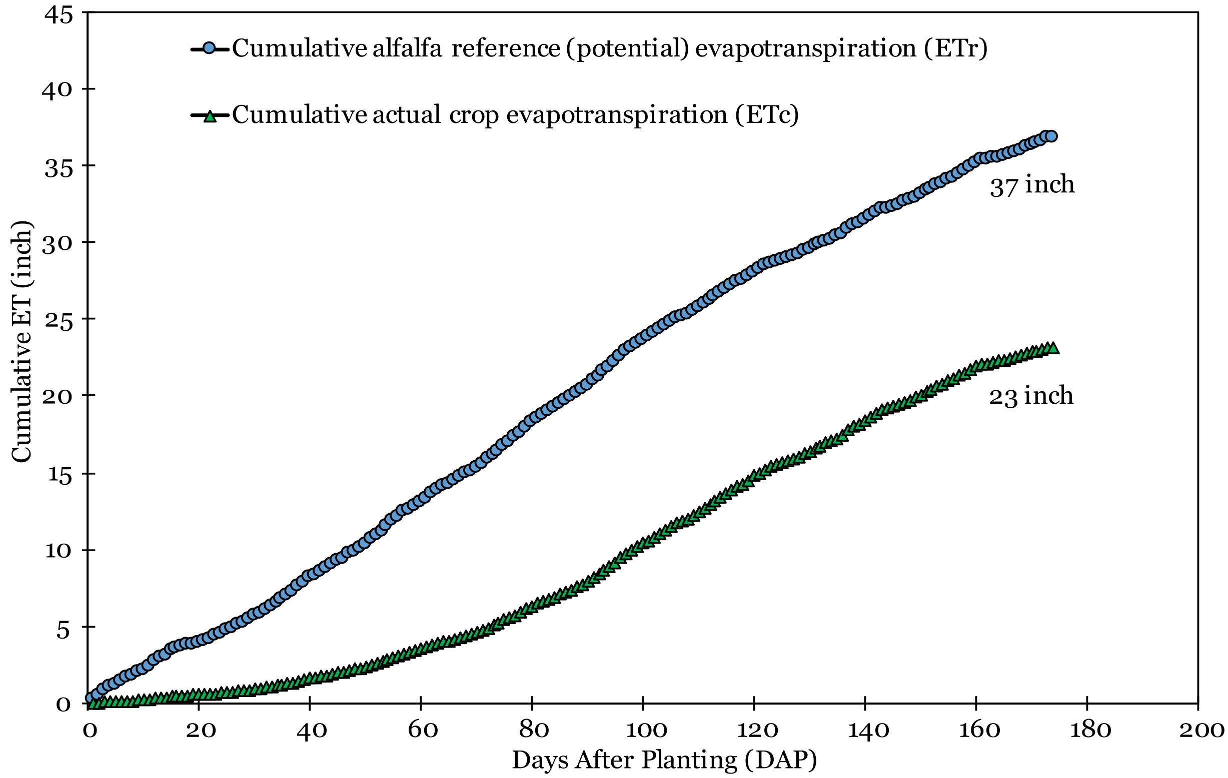

Figure 3. Comparison of seasonal cumulative alfalfa based reference (potential) and actual sugarbeet crop evapotranspiration for 2014 growing season at Powell, Wyoming.

for researchers and producers. Consequently, irrigation specialists suggested abandoning the concept of PET and replacing it with the concept of "reference crop evapotranspiration (ETref)" (Doorenbos and Pruitt 1976).

Reference evapotranspiration (ETref): This is defined as "the rate of water loss by evaporation and transpiration from a healthy (free from water stress and diseases) hypothetical reference crop, i.e., grass, with an assumed crop height of 4.72 inches (0.12 m), a fixed surface resistance to water transport of 21.87 sec ft^{-1} (70 sec m^{-1}) and an albedo of 0.23, closely resembling the evapotranspiration from an extensive surface of green grass of uniform height, actively growing, well-watered, and completely shading the ground." An alternative reference crop is alfalfa, with assumed crop height of 19.7 inches, with a fixed resistance to water vapor of 14.06 sec ft^{-1} (45 sec m^{-1}).

For non-stressed, disease-free grass and alfalfa, ETref is equal to PET. Ideally, using grass-reference (ETo) or alfalfa-reference (ETr) ET results in similar values (Figure 2). However, there is no consensus on which reference surface should be chosen for a particular region, but the choice could be a function of climate characteristics of a local region or location (Irmak et al., 2008).

For example, alfalfa may be preferable for semiarid or arid climates, including Wyoming, because alfalfa tends to transpire water at potential rates even under advective environments. Also, alfalfa has a vigorous and deeper root structure and is less likely to suffer water stress compared with a shallow-rooted grass crop. In places such as humid, subtropical climates where alfalfa is not commonly grown, the grass reference may be preferable. Given the prevailing conditions of the Intermountain West, it is recommended the alfalfa-based ETref concept be used for irrigation scheduling and water management studies in Wyoming.

Actual Crop Evapotranspiration (ETc): The actual evapotranspiration is the amount of water actually transpired from plants and evaporated from soil surface under actual climatic conditions, under non-optimal soil, biological, management, and environmental conditions. It is different from PET (standard conditions), since in actual field conditions the crop may encounter soil water shortage or waterlogging, diseases, or soil salinity. Figure 3 represents the comparison of alfalfa-based reference evapotranspiration and actual sugarbeet crop evapotranspiration for the 2014 sugarbeet growing season at Powell, Wyoming.

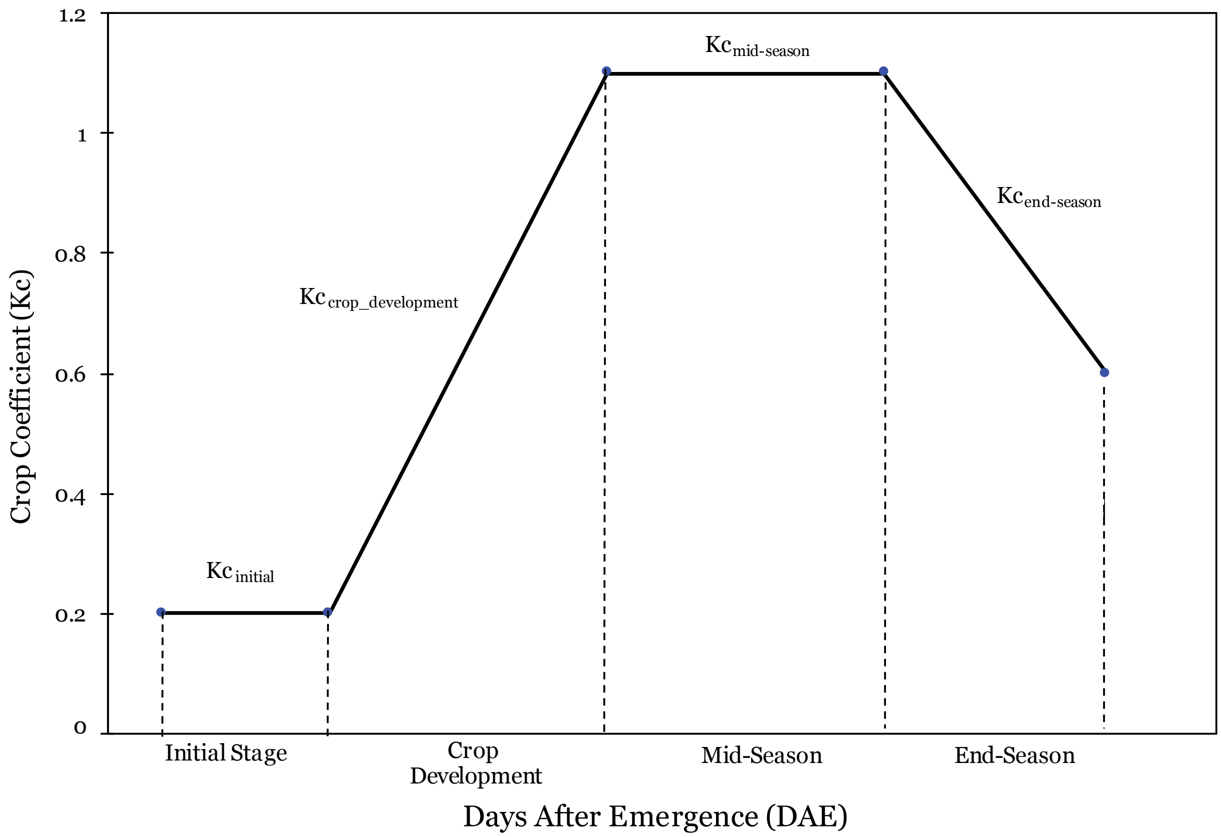

Figure 4. Crop coefficient curve according to different growth stages.

EVAPOTRANSPIRATION QUANTIFICATION AND ITS IMPORTANCE

In arid to semi-arid climatic conditions, such as Wyoming, annual rainfall varies significantly ranging from 7.6 to 25.4 inches. Extensive irrigation is practiced because of the uneven and limited distribution of rainfall over the growing season, drought conditions, and high water requirement of the field crop produced. Effective irrigation management requires the efficient use of water resources in agriculture through adequately quantifying the crop water use, i.e., ETc, which represents the main consumptive use of water in agricultural production.

Crop water requirement is defined as the amount of water required to compensate the ET loss from the crop field. Accurate quantification of crop water requirement requires the accurate determination of soil water in the crop root zone. Various methods can be used to measure soil moisture ranging from the use of advanced soil moisture sensors to use of the hand-feel method to the water balance approach.

The water balance approach uses the actual crop ET (ETc) information to calculate the soil moisture deficit and, hence, the crop water requirement. Different approaches and instruments can be used to quantify ET such as Eddy Covariance Systems (ECS), Bowen Ratio Energy Balance Systems (BREBS), or Lysimeters, to a commonly used method that requires first the determination of ETref and then adjusting it by a specific crop coefficient to calculate ETc as:

$$ETc = Kc * ETref$$

Where ETc is the actual crop evapotranspiration (inch/day, inch/week, inch/month), ETref is the alfalfa or grass reference ET (inch/day, inch/week, inch/month), and Kc is the crop coefficient. ETref accounts for the variation in climate and is used as an indicator of atmospheric water demand. ETref can be computed from the climate data using the standardized Penman-Monteith equation (ASCE-EWRI, 2005). Climate data (maximum and minimum temperature, relative humidity, solar radiation, wind speed) from nearby weather stations can be used to quantify ETref. An atmometer, commonly known as an ET gauge, is another source of ETref.

The crop coefficient (Kc) incorporates the crop canopy characteristics and management practices. Each crop has different sets of specific Kc values depending upon the growth stages of the crop and field/crop management practices. Figure 4 represents the typical crop coefficient curve as a function of development stages. For Kc purposes, crop growth is divided into four stages: initial stage, crop development stage, mid-season, and later season. The length of each stage depends on the climate, location (elevation, latitude), planting dates, crop type, crop varieties, and various management practices. Early in the crop growing season, (i.e., during the initial stage when the plant is small) crop water use and Kc values are small. As the crop develops, Kc values increase, reaching the maximum value when the crop fully develops and reaches mid-season and decreases again toward the end-season, when the crop reaches physiological maturity (Figure 4).

After determining the ETref value, the ETref is multiplied by the crop Kc value to estimate the ETc. For example, if the ETref for August 15 is 0.24 inch/day and the Kc value for sugarbeet at mid-season is 1.1, then the actual water use, or ETc, is 0.24 inch/day * 1.1 = 0.26 inch/day. Considering the application efficiency of a center pivot system to be 85 percent, the total irrigation application required to meet the crop water requirement is 0.31 inch/day (0.26 inch/day ÷ 0.85).

SUMMARY:

The efficient use of water resources in agriculture requires adequately quantifying the water use, i.e. ET, which represents the main consumptive use of water in agricultural production. ET represents direct response in terms of water losses from the field as a function of soil, water, and crop management and climatic conditions and is a powerful indicator of crop water productivity. Therefore, it is important to understand and accurately quantify ETc, which further can help farmers to use reliable information and tools to make better irrigation decisions. This bulletin describes the basic concept of evapotranspiration and defines the major difference between commonly used ET terms, mainly PET, ETref, and ETc. A common understanding of these terms will help to understand the fundamental ET process and to better communication among producers, extension educators, and researchers.

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