



Estimating Broccoli Crop Evapotranspiration Using Updated Crop Coefficients for Irrigation Scheduling in Yuma, Arizona

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Abstract

Broccoli is among the most economically significant cool-season vegetable grown in Yuma County, Arizona, where declining Colorado River allocations and elevated irrigation-water salinity place increasing pressure on agricultural water supplies. Accurate estimation of crop evapotranspiration (ET_c) is the foundation of efficient irrigation scheduling under these conditions. This publication presents updated, locally measured crop coefficients (K_c) for broccoli and demonstrates their use in a K_c-based scheduling framework, in which ET_c is calculated as the product of K_c and grass-reference evapotranspiration (ET_o) obtained from the Arizona Meteorological Network (2026). Because broccoli is planted across a broad September–December window and develops at temperature-dependent rates, growth-stage boundaries are defined using growing degree days rather than calendar days after planting. The updated K_c values increase from 0.52 during establishment to 0.80 at full canopy and are substantially lower than FAO-56 defaults, reflecting the periodic furrow irrigation typical of the region. Worked examples illustrate the calculation of net and gross irrigation requirements under representative application efficiencies. The methods provide growers and irrigation managers with a practical, regionally validated tool for matching water applications to actual broccoli water demand.

Introduction

Broccoli (*Brassica oleracea* var. *italica*) is one of the most economically significant cool-season vegetables produced in Yuma County, Arizona, with approximately 12,500 acres planted annually in the lower Colorado River

region between September and December, generating an estimated \$129 million in agricultural value (Yuma Center of Excellence for Desert Agriculture, n.d.; Duval et al., 2025). Continued reduction in Colorado River water allocations due to prolonged drought has placed sustained pressure on agricultural water supplies throughout the Yuma Valley (U.S. Bureau of Reclamation, 2022). Elevated salinity in delivered irrigation water compounds this challenge. Because broccoli is irrigated primarily by furrow after initial establishment using solid-set sprinklers, salt can accumulate at the soil surface during the season and must be managed through pre-season leaching before subsequent crops (Yuma Water Resources Research Center, 2024; Yuma Center of Excellence for Desert Agriculture, n.d.).

Accurate estimation of crop evapotranspiration (ET_c) is the foundation of effective irrigation scheduling in this environment. A crop coefficient (K_c)-based approach, in which ET_c is computed as the product of a locally measured K_c and the grass-reference evapotranspiration (ET_o) from the Arizona Meteorological Network (AZMet), provides the most operationally practical and scientifically validated framework for matching water applications to actual crop demand across each growth stage (Allen et al., 1998). This approach is well established for vegetable crops in the Yuma region; for a detailed treatment of ET_{ref} concepts and AZMet data access procedures, readers are referred to Mohammed (2025). The present publication extends that framework to broccoli. It introduces a broccoli-specific consideration not applicable to lettuce: the use of growing degree days (GDD) to define growth stage boundaries, which is necessary because broccoli development rates in Yuma vary substantially with planting date and ambient temperature.

Eddy covariance measurements at commercial broccoli production sites across Yuma County and the adjacent Bard Water District documented seasonal ETc values of 308–406 mm, equivalent to approximately 12–16 inches of water depth (French et al., 2023; Yuma Center of Excellence for Desert Agriculture, n.d.). Notably, French et al. (2023) demonstrated that existing U.S. Bureau of Reclamation evapotranspiration estimates underestimate actual broccoli ETc by approximately 21%, underscoring the importance of locally measured crop coefficients for accurate irrigation scheduling in the region.

Types of Evapotranspiration

Two forms of evapotranspiration are used in irrigation management. Reference evapotranspiration (ETref) quantifies the evaporative demand of the atmosphere independent of crop type. In Arizona, the grass-based reference(ETo)computedbythePenman-Monteithequation is the standard, and daily ETo values are available from AZMet for the Yuma Valley and other stations statewide (Allen et al., 1998; Food and Agriculture Organization of the United Nations, 2012). Crop evapotranspiration (ETc) is the actual water use of a specific crop under defined field conditions and is obtained by multiplying ETo by the crop-specific coefficient Kc. A comprehensive description of ETref types and ETo data access procedures is provided in Mohammed (2025).

Understanding the Crop Coefficient (Kc) for Broccoli

The Kc values presented here were produced through a multi-year, multi-site study led by Drs. Sanchez (University of Arizona) and French (USDA-ARS), and the Yuma Center of Excellence for Desert Agriculture, using eddy covariance instrumentation and satellite remote

sensing across commercial fields spanning the principal irrigation districts of Yuma County and the Bard Water District in California (French et al., 2023; Yuma Center of Excellence for Desert Agriculture, n.d.). The resulting values are substantially lower than the FAO-56 default Kc values for broccoli (Allen et al., 1998) because FAO-56 defaults assume high-frequency irrigation that keeps the soil surface wet—conditions that do not reflect the periodic furrow sets used in Yuma, which allow inter-row soil to dry between irrigations and markedly reduce the soil evaporation component of ETc (French et al., 2023).

A critical distinction between broccoli and lettuce (Mohammed, 2025) is that broccoli's growth-stage progression in Yuma is best tracked using growing degree days (GDD) rather than calendar days after planting (DAP). Because broccoli is planted across a broad window from September through December, crops experience markedly different thermal environments depending on planting date, and a fixed DAP schedule cannot reliably identify when stage transitions occur (Yuma Center of Excellence for Desert Agriculture, n.d.). GDD for Yuma broccoli is computed using a base temperature of 4.4°C (39.9°F) and a ceiling temperature of 28°C (82.4°F); daily minimum and maximum temperatures are clipped to these thresholds before averaging. The daily GDD is calculated as:

Daily GDD = [(Tmax + Tmin) / 2] – 4.4°C

where Tmax is capped at the ceiling temperature of 28°C (82.4°F), and Tmin is raised to the base temperature of 4.4°C (39.9°F) before averaging; any negative daily value is set to zero. The equivalent calculation in Fahrenheit units is Daily GDD = [(Tmax + Tmin) / 2] – 39.9°F. Because the stage boundaries in Table 1 are expressed in °C-day, Fahrenheit-based GDD accumulations must be divided by 1.8 before they are compared with Table 1. Growers can

Table 1. Growing degree day (GDD) stage boundaries and crop coefficient (Kc) values for broccoli grown in the lower Colorado River region near Yuma, Arizona (French et al., 2023; Yuma Center of Excellence for Desert Agriculture, n.d.).

Growth Stage	GDD Range (°C-day)	Approximate DAP	Kc
Initial	0 – 456	0 – 25	0.52
Crop Development	456 – 1,005	25 – 65	0.52 → 0.80
Mid-season	1,005 – 1,407	65 – 105	0.80
Late-season	1,407 – 1,543	105 – 120	0.80

calculate cumulative GDD from AZMet minimum and maximum temperature data and compare results against the stage boundaries in Table 1.

The growing season is divided into four phases (Table 1). Kc_{ini} is 0.52, reflecting low crop water use during early establishment when bare soil between young plants accounts for a substantial fraction of ET. Kc_{dev} increases linearly from 0.52 to 0.80 as canopy cover expands. Kc_{mid} is 0.80, corresponding to full canopy cover and maximum crop water demand. Late-season ends at approximately GDD = 1,543 °C-day, after which the crop is harvested (French et al., 2023; Yuma Center of Excellence for Desert Agriculture, n.d.).

For any cumulative GDD within the crop development stage (456–1,005 °C-day), Kc is estimated by linear interpolation between Kc_{ini} and Kc_{mid}:

$$Kc = 0.52 + [(GDD - 456) / (1,005 - 456)] \times (0.80 - 0.52)$$

Adapting Kc Values for Specific Production Conditions

The Kc values in Table 1 represent averages from fields managed under the standard Yuma system of solid-set sprinkler germination followed by furrow irrigation (Yuma Center of Excellence for Desert Agriculture, n.d.). Conditions that deviate from this approach—such as additional sprinkler irrigations during vegetative growth may shift actual ETc above the values predicted by Table 1. Salinity management does not necessarily increase ETc, but it may require additional applied water beyond the ETc-based net irrigation requirement to maintain an adequate leaching fraction. Growers are encouraged to:

- Verify growth stage using GDD: Compute cumulative GDD from AZMet minimum and maximum temperature data and compare against the boundaries in Table 1. Direct field observation of canopy development should take priority where the GDD-predicted and observed stages differ.
- Account for leaching requirements: Where irrigation water salinity necessitates additional water for salt leaching beyond the ETc-based net requirement, the gross irrigation depth must be increased accordingly. Procedures for computing the required leaching fraction and adjusting gross irrigation applications are described in Allen et al. (1998).
- Monitor inter-row soil moisture: Fields receiving more frequent irrigations than typical may need a modestly higher effective Kc during the development stage, as more frequent surface wetting increases soil evaporation.
- Consult University of Arizona Cooperative Extension:

Local specialists can provide updated variety-specific Kc guidance and site-specific irrigation recommendations.

Estimating Crop Evapotranspiration

Once the appropriate Kc is identified from Table 1, ETc is estimated by multiplying the cumulative ETo for the irrigation interval by that Kc value:

$$ETc = ETo \times Kc$$

ETo values are retrieved from AZMet using the Penman-Monteith Cumulative column in the ETo Special Reports (Arizona Meteorological Network, n.d.). Weekly (7-day) intervals are a common and practical scheduling period for furrow-irrigated broccoli in Yuma. In dry periods with negligible rainfall, the resulting ETc is a practical estimate of the net irrigation requirement (NIR) that must be replenished at the next irrigation event. If rainfall occurs or soil water storage changes substantially, those amounts should be accounted for before determining the irrigation depth.

Measuring Application Efficiency in Crop Production

Application efficiency (Ea) is the fraction of applied irrigation water that is used by the crop (i.e., consumed as ETc rather than lost to surface runoff or deep percolation):

$$\text{Application Efficiency (Ea) (\%)} = [(ETc) / (\text{Total Irrigation Water Applied})] \times 100$$

Furrow irrigation achieves application efficiencies of 50–75%, depending on furrow length, inflow rate, soil texture, and cutoff time management (Allen et al., 1998). In Yuma, application efficiency is often higher because laser leveling and other field practices improve water distribution. The gross irrigation requirement (GIR) is therefore calculated as GIR = NIR / Ea to ensure adequate water reaches the root zone despite field application losses.

Example 1

A broccoli crop planted on October 1 in Yuma Valley has reached the mid-season (Kc_{mid}) growth stage by early January. The 7-day cumulative reference evapotranspiration (ETo) from the AZMet Yuma Valley station for January 1–7, 2025, is 0.76 inches (Penman-Monteith). Determine the 7-day ETc and the net irrigation depth required to replenish the water consumed, assuming 100% application efficiency.

Solution:

Access the 7-day cumulative ETo from AZMet:

1. Go to the Arizona Meteorological Network at <https://>

azmet.arizona.edu/azmet/az-data.htm.

2. Select the Yuma Valley weather station.
3. Under Special Reports, click ETo and enter the desired date range.
4. Record the Penman-Monteith Cumulative (CUM) column value for the last day of the period.

Given:

ETo (January 1–7, 2025, Yuma Valley AZMet, Penman-Monteith) = 0.76 inches

Growth stage: mid-season — Kc = 0.80 (Table 1)

Application efficiency (Ea) = 100%

Calculation:

$$ETc = ETo \times Kc$$

$$ETc = 0.76 \times 0.80 = 0.61 \text{ inches}$$

At 100% efficiency, the net irrigation requirement equals ETc:

$$\text{Irrigation needed} = 0.61 \text{ inches}$$

Example 2

Using the ETc from Example 1, determine the gross irrigation depth required when the same broccoli field is irrigated by furrow at a measured application efficiency of 60%. Note: The application efficiency in Yuma is substantially higher due to laser leveling and other techniques that the growers utilize.

Solution:

Given:

Net Irrigation Requirement (NIR) = ETc = 0.61 inches

Application efficiency (Ea) = 60% = 0.60

Formula:

$$\text{Gross Irrigation Requirement (GIR)} = NIR / Ea$$

Calculation:

$$GIR = 0.61 / 0.60 = 1.02 \text{ inches}$$

To replenish the 0.61 inches consumed by the crop, approximately 1.02 inches must be applied through the furrow system. The 0.41-inch difference between GIR (1.02 inches) and NIR (0.61 inches) represents water lost to surface runoff, deep percolation, and non-uniform distribution. Where salinity management requires a leaching fraction, the GIR should be further adjusted accordingly (Allen et al., 1998).

These examples estimate irrigation depth from ETc only. Final irrigation decisions should also consider soil moisture observations, rainfall, salinity management, irrigation set time, field slope, and local Extension guidance.

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