APPLYING THE FAO-56 DUAL K_c METHOD FOR IRRIGATION WATER REQUIREMENTS OVER LARGE AREAS OF THE WESTERN U.S.

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HIGHLIGHTS

- The FAO-56 dual crop coefficient procedure was applied over the entire agricultural areas of Idaho and Nevada to determine evapotranspiration (ET) and net irrigation water requirements (IWR).
- Basal crop coefficients were expressed as functions of normalized cumulative growing degree days.
- ET during dormant seasons was included in the estimates.
- The procedure was applied to a U.S. West-wide study of climate change effects on ET and IWR.

ABSTRACT. *The FAO-56 dual crop coefficient procedure was used to determine evapotranspiration (ET) and net irrigation water requirements for all agricultural areas of the states of Idaho and Nevada and in a western U.S. study on effects of climate change on future irrigation water requirements. The products of the applications are for use by state governments for water rights management, irrigation system planning and design, wastewater application system design and review, hydrologic water balances, and groundwater modeling. The products have been used by the U.S. federal government for assessing impacts of current and future climate change on irrigation water demands. The procedure was applied to data from more than 200 weather station locations across the state of Idaho, 200 weather station locations across the state of Nevada, and eight major river basins in the western U.S. for available periods of weather records. Estimates were made over daily, monthly, and annual time intervals. Methods from FAO-56 were employed for calculating reference ET and crop coefficients (K_c), with ET calculations performed for all times of the calendar year including winter. Expressing K_c as a function of thermal-time units allowed application across a wide range of local climates and elevations. The ET estimates covered a wide range of agricultural crops grown in the western U.S. plus a number of native plant systems, including wetlands, rangeland, and riparian trees. Evaporation was estimated for three types of open-water surfaces ranging from deep reservoirs to small farm ponds.*

Keywords. *Consumptive use, Dual crop coefficient, Evapotranspiration, FAO-56, Irrigation water requirements.*

Crop evapotranspiration (ET_c) is needed for design and management of irrigation systems, for water rights management and consumptive water rights transfers, and for hydrologic studies. In the western U.S., water rights have historically been based on estimates of ET_c that are based on historical weather data (ASCE, 2016). Daily timesteps using the FAO-56 dual crop coefficient (K_c) method (Allen et al., 1998) provide for the calculation of

evaporation of water from wet soil surfaces following precipitation or irrigation events and thereby increase the accuracy of estimates of both ET_c and effectiveness of precipitation. This article describes how dual K_c algorithms were prepared for widespread and automated application to weather data sets across statewide regions and how new algorithms to support general application, including during winter, were developed. Details on adaptations are given by Allen and Robison (2007) and Huntington et al. (2015, 2016).

The calculation procedure uses the K_c multiplied by reference ET method, in which the reference ET (ET_{ref}) represents ET from a defined, fully vegetated surface of clipped cool-season grass or full-cover alfalfa and incorporates the influence of weather on the ET quantity. The K_c is defined as the ratio of crop ET to ET_{ref} and incorporates plant and cultural factors that cause ET to vary from ET_{ref} . These factors are typically related to the vegetation development stage and wetting by irrigation or precipitation (Allen et al., 1998). The FAO-56 $K_c ET_{ref}$ method was selected for use due to its simplicity, reproducibility, relatively good accuracy, and transferability among locations and climates. The method, when applied carefully, can produce estimates of ET that are

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accurate for irrigation system design and operation and for water rights administration.

The objective of this article is to describe the steps and functions used to produce complete time series of ET and irrigation water requirements for crops common to a wide range of locations and geographic locations within western U.S. states, and to include ET during winter periods.

MATERIALS AND METHODS

The K_c ET_{ref} procedure follows the methodology introduced in FAO-56 (Allen et al., 1998) in which ET_{ref} is computed following standardized procedures, and the dual K_c approach is implemented.

REFERENCE EVAPOTRANSPIRATION

The Penman-Monteith (PM) standardized reference ET equation (ASCE, 2005) for both alfalfa and clipped grass references was used as the reference basis. The grass reference standardization of ASCE (2005) is patterned after the standardization of FAO-56 (Allen et al., 1998). The alfalfa reference ET (ET_r) was used in applications in Idaho for consistency with prior studies (Wright and Jensen, 1972; Allen and Brockway, 1983) that used an alfalfa reference. The clipped grass reference (ET_o) was used in applications in Nevada (Huntington and Allen, 2009) and in the western U.S. assessment of climate change impacts on irrigation water requirements (IWR) (Huntington et al., 2015, 2016). The alfalfa ET_r tends to run 1.2 to 1.4 times higher than the clipped grass ET_o, with the largest differences in dry, windy climates where the greater aerodynamic roughness and leaf area of full-cover alfalfa relative to clipped grass has greater interactions with wind speed and vapor pressure deficit (Wright et al., 2000; ASCE, 2016). The relatively rough aerodynamic properties of the alfalfa reference produce relatively consistent maximum values for K_c over a wide variety of crops and over a wide range of weather conditions due to the similarity of the energy exchange characteristics of alfalfa to those of many agricultural crops, and where the K_c values based on the alfalfa reference typically peak at 1.0 (Wright, 1982; ASCE, 2016). K_c for many full-cover agricultural crops, when based on the grass ET_o reference, can vary from 1.2 to 1.4 based on crop height and the magnitudes of wind speed and humidity (Allen et al., 1998). The ASCE PM ET_{ref} method was applied according to the guidelines and equations in FAO-56 (Allen et al., 1998) and ASCE (2005, 2016).

Data from a relatively dense network of weather stations are required to produce estimates for ET and IWR that are representative of local irrigated agriculture. To create the dense networks, weather data for both National Weather Service (NWS) and automated weather stations (AWS) were employed. The locations are shown in figures 1 and 2 for Idaho and Nevada and in figure 3 for eight large river basins in the western U.S. that were evaluated in the U.S. Bureau of Reclamation (USBR) West-Wide Climate Risks Assessment (WWCRA) study (Huntington et al., 2015). The 120 NWS stations in Idaho reported daily maximum and minimum air temperature and precipitation, along with observations of snowfall and snow cover depth. Thirty-three AWS

stations were used in Idaho, mostly from the USBR AgriMet network (USBR, 2005; Palmer, 2008; Palmer and Hamel, 2009), where full data sets of solar radiation, air temperature, humidity, and wind speed were measured hourly. The NWS data were officially collected and housed by the National Climatic Data Center (NCDC) of the National Oceanic and Atmospheric Administration (NOAA). In addition to the Idaho NWS and AWS stations, 28 NWS stations and 24 AWS stations outside of Idaho were processed that were close to state boundaries. In the Nevada applications, where agricultural AWS stations have historically been more sparse, 190 NWS stations and five AWS stations were used for calculating ET and IWR, as shown in figure 2. Wind measurements from AWS were used to develop monthly regional wind speed tables for use with the PM applications to NWS data sets. Wind, air temperature, and humidity data from airports were not used for direct ET calculations due to the typically arid, nonirrigated nature of airports and the tendency for their ET calculations to overstate ET from agricultural environments (Allen et al., 1998; ASCE, 2016; Blankenau et al., 2020; Allen et al., 2021).

In the WWCRA study, air temperature and precipitation data were processed from 12 km × 12 km grids that were downscaled and bias-corrected from the Coupled Model Intercomparison Project phase 3 (CMIP3) climate projections (Huntington et al., 2015). The CMIP3 data were served from the CMIP website (http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html). Quantile-quantile mapping was used for bias correction of the 12 km cell temperature and precipitation data to the NWS COOP station data. Available NWS station locations were used to select an overlying 12 km climate model cell and to bias-correct the gridded climate data to match the NWS COOP historical T_{max} , T_{min} , and precipitation. CMIP3 climate projections were used in the WWCRA study because they represented best available climate projections at the time of the study (Huntington et al., 2015). More description is given in the Results and Discussion section.

Application of the standardized PM equation using estimated weather data, when missing, is recommended in FAO-56 (Allen et al., 1998) and ASCE (2005, 2016) over the use of more empirical equations that require air temperature data only. These recommendations recognize the ability of estimated weather parameters to guide the reference ET estimates based on general conditions of high or low wind speed, clear or cloudy skies, and arid or humid climates (Allen et al., 1998; ASCE, 2005, 2016). The solar radiation, humidity, and wind speed data required in the ASCE PM equation were estimated following the guidelines in FAO-56 (Allen et al., 1998) and ASCE (2005), where solar radiation (R_s) was based on differences between daily maximum and minimum air temperature, and estimates for daily dewpoint temperature were based on daily minimum air temperature.

Daily Solar Radiation

In these studies, the Thornton and Running (1999) procedure was used for estimating R_s . The procedure has the form:

$$R_s = R_{so} \left[1 - 0.9 \exp \left(-B (T_{max} - T_{min})^{1.5} \right) \right] \quad (1)$$

Figure 1. Locations of National Weather Service (NWS) air temperature stations (diamonds) and automated weather stations (AgriMet, PN/INL, and RAWS) used for wind and dewpoint estimation at NWS (stars).

$$B = 0.023 + 0.1 \exp(-0.2 \Delta T_{month}) \quad (2)$$

where R_s is estimated daily solar radiation, R_{so} is theoretical solar radiation on a clear day (computed using exoatmospheric radiation computed as a function of latitude and date and the ASCE (2005) atmospheric transmissivity function), T_{max} is daily maximum air temperature ($^{\circ}\text{C}$), and T_{min} is daily minimum air temperature ($^{\circ}\text{C}$). Units for R_s and R_{so} are the same. Parameter ΔT_{month} in equation 2 represents long-term average values for T_{max} and T_{min} and, following Thornton and Running (1999), is computed on a monthly basis. The coefficients for equation 2 were developed by Allen and Robison (2007) using data from Thornton and Running (1999) for western U.S. locations and confirmed with comparisons against quality-controlled R_s data from USBR AgriMet weather stations in Idaho. Equations 1 and 2 produced more consistent and accurate estimates of R_s on a daily and monthly basis across southern Idaho than did the Hargreaves-Samani equation (Hargreaves and Samani, 1982) recommended in FAO-56 (Allen et al., 1998). An advantage

of equation 1 is that it is self-limited to a maximum value for R_s represented by R_{so} . An example for daily and monthly estimation of solar radiation is shown in figure 4 for an AgriMet weather station near Picabo, Idaho. The ratios of estimated R_s to measured and QA/QC'd R_s were 1.06 and 1.01 for the Hargreaves-Samani and Thornton-Running methods, respectively, and the RMSE of the daily estimates was 4.18 and 4.02 $\text{MJ m}^{-2} \text{d}^{-1}$, respectively.

Dewpoint Temperature

Dewpoint temperature (T_{dew}) was estimated from daily minimum air temperature:

$$T_{dew} = T_{min} - K_o \quad (3)$$

where T_{min} is the daily minimum air temperature ($^{\circ}\text{C}$), and K_o is an offset that varied monthly, as shown in table 1 and figure 5. The K_o offsets, which averaged 1.5°C during most of the growing season for Idaho, were based on long-term records of dewpoint and T_{min} derived from ten irrigated AgriMet AWS sites across southern Idaho and varied by

Figure 2. Locations of NWS air temperature stations (squares) for Nevada used to calculate ET and net irrigation water requirements and select stations (squares with circles) used to assign HUC 8 subbasin (black outlines) average net irrigation water requirements.

month. Location information for the ten sites is given by Allen and Robison (2007). Negative values during winter indicate that the 24 h average T_{dew} was higher than T_{min} due to condensation of moisture during nighttime as frost or dew, which allowed T_{min} to decline with a declining nighttime T_{dew} . Daytime increases in T_{dew} from evaporation caused the 24 h average winter T_{dew} to be greater than T_{min} .

The K_o values in table 1 were applied across Idaho by Allen and Robison (2007, 2011). In Nevada, north to south characteristics for K_o are large due to differences in climatic patterns and lower amounts of precipitation in the south. Southern Nevada locations have a larger mean difference between T_{min} and T_{dew} (i.e., larger K_o value) than northern Nevada locations, as shown in figure 6 for selected locations. This spatial trend in K_o is partially due to regional-scale advection of dry air, surface energy transport from low-elevation valley floor areas, and different origins of air masses. As a consequence, mean monthly K_o values were developed for geographic areas based on similarities in annual precipitation and elevation and availability of humidity data. Developed monthly K_o values were spatially interpolated using inverse distance weighting and then averaged over individual Hydrologic Unit Code (HUC) 8-sized hydrographic

areas. HUC 8 subbasins average about 1800 km² in size. Results are shown in figure 7 in terms of averaged annual values for K_o . The averaged values were assigned to NWS stations based on the hydrographic area (Huntington and Allen, 2009). The general K_o values and curves for northern (central latitude) Nevada stations shown in figure 6b were similar to the mean K_o curve developed for southern Idaho shown in figure 4.

Wind Speed

Long-term regional monthly average wind speed data were derived from weather stations that collected wind speed data. In southern Idaho, the nearest AgriMet station was used. In central and northern Idaho, the nearest NOAA airport weather station was used to develop monthly regional averages. For Nevada, mean monthly wind speed was developed by hydrographic areas. In all cases, values varied by month. Each set of twelve regional values were applied to every NWS station within a region.

Comparisons between NWS and AWS Station Data and Lysimeter Data

Comparisons were made between ET for full-cover Ranger variety alfalfa measured by a weighing lysimeter

Figure 3. Major river basin coverage for the U.S. Bureau of Reclamation (USBR) West-Wide Climate Risks Assessment (WWCRA) study where future ET and irrigation water requirements were estimated for a broad range of climate change scenarios using the FAO-56 dual K_c -based ETDemands model (from Huntington et al., 2015).

Figure 4. (a) Daily estimated R_s using Thornton-Running method (with eqs. 1 and 2) and (b) monthly estimates using Thornton-Running and Hargreaves-Samani methods versus measured R_s from a nearby AgriMet AWS near Picabo, Idaho, over the period of record.

operated by Wright (1982, 1988) near Kimberly, Idaho, and alfalfa ET_r calculated by the standardized PM equation using NWS air temperature and estimated dewpoint, solar

radiation, and wind speed data. The ET measurement data comprised daily measurements from a single lysimeter collected by Wright (1982) over a three-year period from 1969

Table 1. Temperature offsets (K_a , °C) used to estimate T_{dew} in Idaho.

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
-2	-1.5	0	1.5	1.5	1.5	1.5	1.5	1.5	1	-1	-2

to 1971. Results are summarized in table 2. The calculated ET_r using estimated T_{dew} , R_s , and wind speed compared favorably with the lysimeter measurements with a slope of 1.03, zero intercept, and RMSE values of 1.7 mm d⁻¹ for daily estimates and 0.90 mm d⁻¹ for five-day running averages (Allen and Robison 2007). This compares to a slope of 1.01 and RMSE values of 0.97 and 0.65 mm d⁻¹ by the ASCE PM equation for daily and five-day running averages when all weather data were measured locally. Five days is generally the shortest time between irrigations, and therefore the compensating error in daily ET during a five-day period is generally inconsequential to irrigation water management and design. The calculated ET_r using estimated weather data tended to preserve the variance of the measured population of reference ET.

In addition to the comparisons with measured ET, comparisons of estimated versus measured weather data were made by Allen and Robison (2007), Huntington and Allen (2009), and Huntington et al. (2015) at a number of AgriMet

and other agricultural weather stations. Results indicated good estimation accuracy of weather data and associated ET_r .

EVAPOTRANSPIRATION FROM CROPS AND OTHER LAND SURFACES

The crop coefficient (K_c) is defined as the ratio of ET from any particular surface to ET_{ref} . The K_c has been developed and applied over the past half-century to simplify and standardize the calculation and estimation of crop water use. The particular surface can be comprised of bare soil, soil with partial vegetation cover, or full vegetation cover. The K_c represents an integration of the effects of crop height, crop-soil resistance (including effects of depleted soil water), and surface reflectance that distinguish the surface from the ET_{ref} definition and value. The value for K_c often changes during the growing season as plants grow and develop, as the fraction of ground covered by vegetation changes, as the wetness of the underlying soil surface changes, and as plants age and mature.

This study applied the dual crop coefficient approach of FAO-56 due to its ability to quantify evaporation from precipitation and irrigation events. The dual K_c approach

Figure 5. Monthly differences between daily T_{min} and daily average T_{dew} at ten Idaho AWS stations in irrigated settings. Large blue circles represent the ten-station mean, and the thick blue line represents the statewide mean K_c used for all Idaho locations where humidity data were not measured.

Figure 6. Measured mean monthly K_o for (a) southern and (b) northern Nevada weather stations located in reference (irrigated agriculture) environments.

Figure 7. Spatially interpolated K_o (dewpoint depression) over Nevada averaged over annual periods and representing reference ET conditions (from Huntington and Allen, 2009).

Table 2. Statistical summary of comparison between lysimeter measurements of ET from full-cover alfalfa near Kimberly, Idaho, from 1969 to 1971 (data from Dr. James L. Wright, USDA-ARS (ref.)) and ET_r calculated by the ASCE PM method with all weather data measured and with T_{dew} , R_s , and wind speed estimated.

ET_r , Observation or Equation	Mean (mm d ⁻¹)	Ratio to Observed	SD (mm d ⁻¹)	Coeff. of Variation	Skew	RMSE (mm d ⁻¹)
Lysimeter measurement	6.36	-	1.99	0.31	-0.22	-
ASCE PM ET_r with measured weather data	6.41	1.009	1.77	0.28	-0.27	0.97
ASCE PM ET_r with estimated R_s , T_{dew} , and monthly wind speed	6.52	1.025	1.76	0.27	-0.33	1.67
Five-day lysimeter measurement	6.38	-	1.58	0.25	-0.47	-
Five-day ASCE PM ET_r with measured weather data	6.45	1.012	1.38	0.21	-0.36	0.65
Five-day ASCE PM ET_r with estimated R_s , T_{dew} , and monthly wind speed	6.53	1.024	1.28	0.20	-0.41	0.90

separates the K_c value into a basal crop coefficient (K_{cb}) and a separate component (K_e) that represents evaporation from the soil surface. The basal crop coefficient represents ET conditions when the soil surface is dry but with sufficient root zone soil water present to support full transpiration. The K_e component is calculated separately, according to actual or simulated wetting events, and is then added to the K_{cb} to produce the total K_c . Generally, a daily calculation time step is applied for the dual K_c method.

Actual ET_c may be less than potential ET_c when the soil water content is less than that able to sustain full rates of ET. In this case, ET_c is reduced by applying a stress coefficient (K_s). The form of the FAO-56 dual K_c equation for estimating actual ET_c is:

$$ET_{c \text{ actual}} = (K_s K_{cb} + K_e) ET_{ref} \quad (4)$$

where K_{cb} is the basal crop coefficient (0 to ~1.0 when used with $ET_{ref} = ET_r$ (alfalfa reference ET), and 0 to ~1.4 when used with $ET_{ref} = ET_o$ (grass reference ET); ASCE, 2005, 2016), K_e is a soil water evaporation coefficient (0 to ~1.0 when used with ET_r , and 0 to ~1.3 when used with ET_o), and K_s is a reduction coefficient that reduces the value of K_{cb} when the average soil water in the root zone is not adequate to sustain full plant transpiration ($K_s = 1.0$ when there is no water stress). All K terms are dimensionless.

A daily soil water balance is required to estimate K_s that incorporates the full effective root zone. A second and separate soil water balance is required to estimate K_e where only the water content in the upper 0.1 or 0.15 m of soil is simulated because this upper soil layer supplies water for direct evaporation from the soil surface. The daily water balance calculations for the full root zone and for the evaporation layer and the calculation of K_s and K_e directly followed the procedures established in FAO-56 (Allen et al., 1998) and extended by Allen et al. (2005). The Allen et al. (2005) procedures were further extended for the Idaho application to account for use of ET_r rather than ET_o , which is generally applied with the FAO-56 procedure. ET_o was used as the basis for the Nevada and U.S. West-wide applications. In addition, curvilinear K_{cb} curves, similar to those used by Wright (1982), were used for many crops rather than the piecewise linear-style curves used in FAO-56. Crop coefficients developed at Kimberly for the 1982 Kimberly Penman alfalfa reference method were converted for use with ASCE PM ET_r by Allen and Wright (2002) (ASCE, 2016, table F-1A). When used with alfalfa ET_r , no weather-based adjustments to $K_{c \text{ max}}$ nor K_{cb} were necessary.

Irrigation events are required in a daily soil water balance to estimate their influence on K_e , K_c , and ET_c . However, field-specific timings of irrigation events were unknown and were required to be generalized for each weather location. Therefore, irrigation events were simulated for irrigated crops where irrigations were specified when a management-allowed depletion (MAD) of soil water was reached in the daily soil water balance. Major soil types associated with each weather station were used to specify field capacity and wilting point using the SSURGO database (USDA, 2007). The simulation of irrigation produced a time series of irrigation and wetting events for the K_e calculation. Only one

realization of irrigation events was produced that represented each crop type. The MAD was generally set in the range of 30% to 50% to represent a mixture of high-frequency center pivot systems and low-frequency wheel-line and surface irrigation systems.

An SCS hydrologic soil group was determined from SSURGO for estimating surface runoff using the USDA-NRCS curve number method (USDA, 1985, 1993). Antecedent soil water conditions were estimated by the daily soil water balance for adjusting the curve number, as described by Allen and Robison (2007) and ASCE (2016). A dynamic sigmoidal root zone growth function was applied, following Borg and Grimes (1986).

CROP COEFFICIENT CURVE

The basal crop coefficient curve represents the changes in K_{cb} over the course of the growing season, depending on changes in vegetation cover and maturation. During the initial period of the growing season, shortly after planting of annuals or after the initiation of new leaves for perennials, the value for K_{cb} is small, often only 0.1 to 0.15 for a dry soil surface (with some soil water at greater depth) (Wright, 1982; Allen et al., 1998). When combined with soil evaporation, the total K_c value generally averages less than about 0.4 during the initial period. As the crop begins to develop more leaf area and covers more of the soil surface, the K_{cb} curve increases. Late in the growing season, the K_{cb} declines due to aging of leaves or senescence (dying) of leaves.

Application of K_{cb} Curves for a Wide Range of Locations and Periods of Record

In this study, the K_{cb} curves were expressed on relative time scales or relative thermal unit scales to allow the curves to be stretched differently each year, according to weather conditions. Normalized growing degree days (NGDD) were used as the time basis for most crops. The start of the growing season for many crops was determined by year according to mean air temperature over the 30-day period prior to the start date. In turn, the duration of the growing season was determined in proportion to the growing degree days following the start of the season. The growing season was terminated by the estimated maturation date for the crop or by a killing frost.

Estimating Beginning and End of Growing Season

The greening (greenup) of perennial vegetation in spring for perennial crops and the planting date for annual crops were used as initiation dates for the start of crop coefficient development. Planting dates are more commonly observed and reported than the germination or emergence of crops. Greenup date can be strongly impacted by short-term weather conditions, primarily by soil and air temperature and to some degree by wetting events and the amount of solar radiation. Planting date is strongly influenced by soil temperature at seed depth, and some predictive relationships of planting date from soil temperature have been established for some crops (Unger, 1980; Bollero et al., 1996; Ram et al., 2013). Therefore, both planting date and greenup dates can vary from year to year. Soil temperature is not commonly measured at cooperative NWS weather stations and is

generally available only at airports and occasionally for AWS stations. Therefore, 30-day average mean daily air temperature was used as a surrogate for soil temperature due to the strong correlation between soil temperature and air temperature over extended periods (Hu and Feng 2003).

The use of a 30-day running average mean air temperature (T_{30}) to estimate planting of annual crops was supported by lysimeter and cropping records at Kimberly, Idaho (Wright, 1982) and field observations made across southern Idaho between 1999 and 2005 (Allen and Brockway, 1983; Allen, 2005, personal communication). The use of T_{30} is similar to that used in SCS TR-21 (USDA, 1967), where mean monthly air temperature values signal planting and greenup of crops. However, contrary to the SCS method, the T_{30} here was the running average for the previous 30 days to better reflect the impact of prior 30-day weather on soil temperature. The SCS TR-21 method centers on the 30-day period. Specific T_{30} values developed by Allen and Robison (2007) are listed in table 3 based on records of Wright (2000, personal communication) associated with lysimeter crops (Wright, 1982) near Kimberly, Idaho.

Prior to calculating T_{30} , the air temperature data from the NWS stations were adjusted downward to compensate for any aridity bias in the NWS data relative to the air temperature expected for fully agricultural environments. Many NWS weather stations in the western U.S. are not located in agricultural areas. As a result, local aridity of a weather station and lack of evaporative cooling can elevate air temperature measurements (Allen et al., 2021). Aridity ratings for weather stations were computed following the procedures outlined by Allen and Brockway (1983) in which the station, local, and regional aridity was rated from 0 to 100 (0 = irrigated and 100 = completely arid), and a weighted aridity rating was computed as $0.4(\text{station aridity}) + 0.5(\text{local aridity}) + 0.1(\text{regional aridity})$. The qualitative analysis for assigning aridity ratings was based on NWS weather station photos and high-resolution imagery, where the station location was analyzed in terms of the degree of aridity or apparent lack of available soil water surrounding the station. The aridity rating was based on land use within the immediate area of the station (~50 m), the local aridity of the station (~1500 m), and the regional aridity of the station (50 km) following Allen and Pruitt (1986). The adjustment to temperature

subtracted the adjustment from both T_{max} and T_{min} . The aridity adjustment was made during calculation of T_{30} and cumulative growing degree days (CGDD, defined in the next section) but not during estimation of ET_{ref} or solar radiation because the estimation of T_{dew} from T_{min} using K_o from table 1 adjusted the T_{dew} estimate for any aridity artifacts in T_{max} and T_{min} (ASCE, 2005, 2016). The Allen and Brockway (1983) aridity adjustment values are listed in table 4. During a 2012 update to the Idaho calculations by Robison and Allen (2017), the aridity rating was correlated to the normalized difference vegetation index (NDVI).

During the estimation of planting (PL) or greenup (GU) dates for crops and natural vegetation, “no earlier than” and “no later than” dates were used to constrain the dates estimated using T_{30} to within reasonable ranges based on the anticipated behavior of farmers or the vegetation itself. For most crops, this was ± 40 days from the mean date based on a long-term average temperature.

Similar CGDD and T_{30} values were established for the Nevada and U.S. West-wide applications (Huntington and Allen, 2009; Huntington et al., 2015) based on computing T_{30} and CGDD at NWS stations located in irrigated valleys of Nevada, California, and Oregon where early spring photos were available, documented GU or PL dates were available from previous studies, or where verbal and written communication was obtained from phone interviews. The developed T_{30} , CGDD, killing frost temperature, and rooting depths are summarized in tables A1 and A2 in the Appendix from the three studies for the range of crops grown in the western U.S. These parameters were used to produce K_{cb} over time that varied each year according to air temperature records and to estimate soil evaporation K_e .

For the alfalfa forage crop, GU in spring was found to be estimated more consistently using CGDD accumulating since 1 January rather than using T_{30} . An analysis of CGDD, daily ET, and leaf area and height development data for

Table 4. Maximum aridity adjustment (°C) to average temperature for stations with aridity ratings of 100% following Allen and Brockway (1983). Proportional adjustment was applied to stations with <100% aridity.

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
0	0	0	1	1.5	2	3.5	4.5	3	0	0	0

Table 3. Mean air temperatures representing the 30-day period prior to the noted date for crops in southern Idaho associated with Wright (1982) dates for lysimeter crops near Kimberly, Idaho, with planting dates of Allen and Brockway (1983) and based on field notes taken by Allen (personal communication) between 1999 and 2005.

Crop	Observed Year	Observed Planting Date	30-Day Temp. Ending on Date (T_{30} , °C)	Equivalent 37-Year Mean Date	Recommended T_{30} to Use (°C)	Mean Date over 37 Years for Recommended T_{30}
Based on Wright (1982)						
Barley or spring wheat	1979	1 April	4.8	3 April	4.7	2 April
Peas	1977	10 April	4.4	31 March	5	4 April
Sugar beets	1975	15 April	2.1	12 March	5 (8) ^[a]	4 April (for 5°C)
Potatoes	1972	25 April	6.0	14 April	7	20 April
Corn	1976	5 May	7.9	29 April	8 (10) ^[a]	29 April (for 8°C)
Beans	1973 and 1974	22 May	12.5 and 12.3	30 May	12 (14) ^[a]	27 May (for 12°C)
Based on Allen and Brockway (1983)						
Pasture	Mean	3 April	4.8	-	5	4 April
Orchards	Mean	15 April	-	-	6	13 April
Vegetables	Mean	20 May	-	-	10	14 May
Onion	Mean	20 April	-	-	6.5	17 April

^[a] Values in parentheses were used in Allen and Robison (2007) calculations based on comparisons with METRIC results over the Magic Valley area of southern Idaho for the year 2000 and based on other local observations of planting dates across southern Idaho.

Figure 8. (a) Simulated greenup (GU) dates for alfalfa for nine locations in Nevada using a CGDD value of 300 °C-days from 1 January versus reported or typical dates, and (b) simulated cutting dates for alfalfa using a CGDD value of 880 °C-days from GU to the first cutting and 740 °C-days for later cutting versus reported or typical dates (from Huntington and Allen, 2009).

lysimeter-grown alfalfa for the years 1969 to 1971 by Wright (1982, 1988) near Kimberly, Idaho, suggested that CGDD = 240 °C-days using a 0°C GDD basis most consistently estimated GU for Ranger variety alfalfa. Cuttings of alfalfa were estimated using CGDD = 700 and 850 °C-days from GU for the first growing cycle for, respectively, high-quality alfalfa production with frequent cutting and for common-quality alfalfa production. CGDD during subsequent growing cycles was 650 and 900 °C-days for high-quality and common-quality alfalfa, respectively, accumulated following a prior cutting event (Allen and Robison, 2007). In southern Idaho, high-quality alfalfa typically receives four to five cuttings per growing season, and common-quality alfalfa receives three cuttings. For southern Nevada, the best fit CGDD value from 1 January until GU was found to be 300 °C-days for high-quality alfalfa production, while the best CGDD value for time from GU until the first cutting was 880 °C-days, and CGDD was 740 °C-days from the first cutting until each following cutting (Huntington and Allen, 2009). Nevada CGDD values were developed from twelve observations reported by Nevada growers, with good estimation consistency in reproducing reported GU and harvest dates, as shown in figure 8.

GROWING DEGREE BASIS FOR K_{cb} CURVES

Plant functions of growth, photosynthesis, water and nutrient absorption and transport, enzyme activity, and other biological and chemical activities are regulated by temperature (Howell et al., 1997). Thus, crop development is more closely related to the amount of heat the crop is exposed to than to calendar days. As a result, CGDD since planting has been used as a basis for crop coefficient development (Sammis et al., 1985; Slack et al., 1996; Howell et al., 1997; Mitchell, 1997; Snyder et al., 1999; Wright, 2001; deTar, 2004; Marek et al., 2006; HPRCC, 2006). The use of CGDD facilitates the adjustment of growing period lengths to account for variation in temperature among years and facilitates transfer of crop coefficients among regions.

A wide range of computation methods for growing degree days (GDD) are in use. These include a standard method used for corn (maize):

$$\text{GDD}_{\text{corn}} = \left(\max \left[\min (T_{\text{max}}, 30), 10 \right] + \max \left[\min (T_{\text{min}}, 30), 10 \right] \right) \div 2 - 10 \quad (5)$$

where T_{max} is daily maximum air temperature (°C), and T_{min} is daily minimum air temperature (°C). The standard corn equation is often referred to as a heat unit equation and is also known as the 86/50 method, referring to the maximum threshold of 30°C and minimum threshold of 10°C, which are equivalent to 86°F and 50°F, respectively. The GDD equation for corn assumes no growth at air temperatures above 30°C and no negative penalty for growth if the minimum temperature goes below 10°C.

A common, basic formula for computing daily GDD for crops other than corn is to average the daily maximum and daily minimum air temperatures for each day and then subtract a minimum average daily temperature (base temperature) required for growth to proceed. For example, this formula has been used by Mitchell (1997), Wright (2001), and the Canola Council (2013). In contrast to the GDD for corn, there is no penalty applied when T_{max} exceeds a threshold, and no boost is given to T_{min} when it is lower than the minimum threshold. The basic equation for the general GDD is:

$$\text{GDD} = \max \left(\frac{T_{\text{max}} + T_{\text{min}}}{2} - T_{\text{base}}, 0 \right) \quad (6)$$

where T_{base} is the base temperature. When T_{min} is far enough below T_{base} to cause the average daily temperature to go below T_{base} , then GDD = 0. Days having high T_{max} but T_{min} below T_{base} are estimated to have lower growth rates by equation 6 than by equation 5, where T_{min} is boosted. Wright (2001) suggested that equation 6 is realistic for many crops in semi-arid climates such as Idaho, where cold nighttime

temperatures can retard growth during daytime even when midday temperatures are high. In a conversion of Wright (1982) K_c curves by Wright (2001) and Allen and Wright (2002) and reported in ASCE (2016), equation 5 was applied to corn for consistency with common usage in the U.S., and equation 6 was applied to all other crops. The CGDD was calculated by summing GDD from equations 5 or 6 from the PL or GU date.

NORMALIZATION OF GROWING DEGREE DAYS

In this study, a normalized cumulative growing degree days (NCGDD) method was used as the primary method to establish the development of K_{cb} over time due to its ability to adjust development by year according to accumulated air temperature. NCGDD was calculated by dividing the CGDD accumulated since the PL or GU date by the total CGDD at effective full cover (EFC):

$$\text{NCGDD} = \frac{\text{CGDD}_i}{\text{CGDD}_{\text{plant to EFC}}} \quad (7)$$

where CGDD_i is the CGDD for the i th day after PL or GU, and $\text{CGDD}_{\text{plant to EFC}}$ is the CGDD from PL or GU to EFC. The result is a NCGDD ratio that ranges from 0 at PL or GU to 1.0 at EFC.

Following Wright (2001), the NCGDD ratio was extended past EFC using ratios of CGDD_i to $\text{CGDD}_{\text{plant to EFC}}$ in equation 7 until termination of the growing season. Values for NCGDD therefore exceed 1.0 for periods beyond EFC. The NCGDD ratio was used as the basis for K_{cb} for the entire season, or for a cutting cycle in the case of alfalfa, until CGDD exceeded the value for CGDD at termination of the growing season ($\text{CGDD}_{\text{plant to terminate}}$) or earlier if a killing frost occurred. Values for $\text{CGDD}_{\text{plant to EFC}}$ and $\text{CGDD}_{\text{plant to terminate}}$ and killing frost temperatures are given in table A2 in the Appendix.

For some crops, three more traditional methods were used to express K_{cb} curves, depending on the crop type. These methods were: (1) the percentage time from PL (or GU) to harvest, (2) the percentage time from PL to EFC, with this ratio extended until termination, and (3) the percentage time from PL to EFC and then days after full-cover following Wright (1982). Basal crop coefficient curves were developed or re-organized for 42 crop and land cover types common to Idaho by Allen and Robison (2007) and expanded to 66 crops by Huntington et al. (2015) for application to the western U.S. All K_{cb} curves used in the WWCRA study are available in Appendix 5 of Huntington et al. (2015) for use with grass reference ET_o as a basis.

Many K_{cb} curves have a shape similar to those of Wright (1982). The K_{cb} curves of Wright (1982) for common crops in southern Idaho were converted to NCGDD. K_{cb} values for native Idaho species of sagebrush, cheatgrass, and bunchgrass were developed based on vegetation index trends from Landsat satellite imagery. The derived K_{cb} curves represent potential K_{cb} under conditions of readily available soil water. The K_{cb} values were reduced for nonirrigated vegetation or during nonirrigation periods using the K_s stress coefficient estimated from a soil water balance. The converted Wright (1982) K_{cb} curves for use with an alfalfa reference

Figure 9. K_{cb} curves of Wright (1982) converted to normalized cumulative growing degree day basis (NCGDD) for application with standardized ASCE PM method for alfalfa reference (from ASCE, 2016).

basis are described by Allen and Robison (2007) and ASCE (2016, table F-1A) and are plotted in figure 9. The use of the NCGDD basis causes the K_{cb} curves for the nine crops shown to follow similar patterns during the development periods.

Winter Wheat

Winter wheat crops are planted during fall and grow slowly or are dormant during winter periods in freezing climates. The estimation of ET in this study included winter months so that a winter K_{cb} development approach was developed for winter wheat. Adjustments were made periodically to the CGDD during winter, where the CGDD began accumulation on a prescribed sowing date of 1 October. Adjustments accounted for impacts of extremely cold weather that tends to retard growth on subsequent days or may even burn vegetation and set back the apparent CGDD used for crop and K_{cb} development. Reductions depended on the severity of the weather and were based on field observations over several years in southern Idaho. The following adjustments were made to winter wheat:

- When T_{min} was $< -25^{\circ}\text{C}$ and there was no documented snow cover present, 10% of the established canopy was assumed to be frostburnt each day of the occurrence, based on field observations near Twin Falls, Idaho. This impact was enacted by reducing any CGDD accumulated since 1 October for the winter wheat by 10% on the day following the low temperature.
- Whenever T_{min} was $< -10^{\circ}\text{C}$, the GDD for the following day, if greater than 0, was reduced by 5 GDD units. This was done as a sort of retardation penalty to the growth of winter wheat on the day after a cold freeze. GDD on all days was limited to 0 or greater.
- If T_{min} was $< -4^{\circ}\text{C}$ on a day, then GDD for that day was assumed to be zero, regardless of the value for T_{max} or T_{mean} . This was done as a delay penalty to the growth of winter wheat on the day of cold temperature, due to a "cold shock." No growth on days when

$T_{min} < -4^{\circ}\text{C}$ was based on observations by Wright (2002, personal communication).

Alfalfa Hay

For alfalfa hay, K_c versus NCGDD curves were established for individual cuttings using data from Wright (1981, 1982) and lysimeter records for 1969-1971 at Kimberly, Idaho. Separate K_c versus NCGDD curves were developed for the first growth period, for intermediate growth periods, and for the final growth period prior to frost. Unique K_{cb} versus NCGDD curve shapes were established for these three periods. The NCGDD values for the first growth cycle accumulated beginning at greenup of the crop in spring and from the time of cutting for all subsequent growth cycles. Greenup was estimated for alfalfa using CGDD since 1 January with a temperature base of 0°C . Figure 9 is a summary of the K_{cb} curves of Wright (1982) after conversion to NCGDD basis. NCGDD = 1.0 generally indicates the time of effective full cover.

In addition to transformation of the K_{cb} curves of Wright (1982) to NCGDD basis, additional K_{cb} curves were developed using NCGDD or relative time bases for cattail-bulrush wetlands; for poplar, cottonwood, and willow tree systems; for sagebrush, cheatgrass, bromegrass, and bunchgrass rangeland systems; and for additional crops of alfalfa seed, bluegrass seed, canola, safflower, sunflower, asparagus, apples, hops, melons, wine grapes, onions, mint, lentils, and turfgrass. Information on K_{cb} values for these additional land covers was taken from the general literature, university extension publications, and from the USBR AgriMet K_c database, as described by Allen and Robison (2007). Many of these are listed in the Appendix.

OPEN-WATER EVAPORATION

Evaporation from open water is a common component of hydrologic systems and of irrigation supply systems and was an important estimation product. In this study, evaporation was estimated for three classes of open water to cover general cases and types of water bodies:

- Small, shallow stock ponds: $K_c = 0.7$ for the ET_r basis and $K_c = 0.85$ for the ET_o basis were used for all months based on FAO-56 (Allen et al., 1998).
- Large, shallow water bodies or deep water bodies that have high turbidity: $K_c = 0.6$ for all months for the ET_r basis and $K_c = 1.05$ for the ET_o basis based on FAO-56 (Allen et al., 1998). This class may be generally applicable to relatively shallow (<4 m in depth) ponds, reservoirs, and streams.
- Deep systems (relatively clear lakes and reservoirs deeper than 4 m): this class used aerodynamic algorithms developed for the American Falls reservoir (Allen and Tasumi, 2005).

A special study of evaporation from the American Falls reservoir near Aberdeen, Idaho, was conducted by the University of Idaho during 2003-2005; micrometeorological, Bowen ratio, and eddy covariance equipment was set up on the reservoir (Allen and Tasumi, 2005). Measurements from that study were used to calibrate a standard aerodynamic procedure that was manipulated to be applied with air temperature and wind speed data:

Table 5. Monthly differences between estimated mean daily water surface and air temperatures ($T_s - T_a$) developed from American Falls reservoir, Idaho, by Allen and Tasumi (2005).

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
4	3	1	0	0	0	0.5	1	1	3	4	4

$$E = \frac{\rho C_E u (q_w - q_a)}{86400} \quad (8)$$

where E is evaporation (mm d^{-1}), q_w is the specific humidity for the water surface (kg kg^{-1}), q_a is the specific humidity of the air (kg kg^{-1}), C_E is the bulk transfer coefficient for water vapor (dimensionless) taken as $C_E = 0.0015$ based on Pond et al. (1973), ρ is the air density (kg m^{-3}), and u is the wind speed at 2 m height (m s^{-1}).

The water surface temperature, on which q_w was based, was estimated by Allen and Robison (2007) as $T_s = T_{mean} + (T_s - T_a)$, where the water-air temperature difference ($T_s - T_a$) was based on observations of water surface temperature from infrared thermometry and reservoir outflow temperature by Allen and Tasumi (2005) from the American Falls reservoir and daily mean air temperature data from the Aberdeen NWS COOP weather station. Monthly values for ($T_s - T_a$) are listed in table 5. The q_a estimate was based on measured humidity when applied at AWS sites or was estimated for COOP stations from dewpoint temperature estimated from T_{min} using K_o values from table 1. Wind speed data were based on measurements at AWS sites and were based on long-term, regional mean monthly values for COOP stations.

The evaporation estimates for small, shallow stock ponds were the highest of the three categories and account for the impact of shallow water on radiant energy absorption close to the surface and thus the generally higher surface temperatures for these systems. In addition, shallow ponds tend to have more turbidity and thus higher surface temperatures. The evaporation estimates assume that no freezing occurs. If water systems are known to freeze, then the evaporation rate would tend toward zero during periods of ice cover, and users should adjust the evaporation estimates.

EVAPORATION DURING WINTER

Quantification of winter evaporation is important when performing hydrologic water balances and when estimating the effectiveness of winter precipitation in recharging the soil profile to supply water to vegetation during the subsequent growing season. Evaporation during nongrowing or winter periods varies widely, based on availability of soil water, freezing of soils, snow cover, impacts of surface organic mulches (dead vegetation), and availability of energy for evaporation. Evaporation losses following soil wetting events during winter reduce the effectiveness of precipitation in recharging soil profiles.

Few studies have measured and documented winter evaporation. Wright (1991, 1993) conducted a series of winter measurements of evaporation using the dual precision weighing lysimeter system at Kimberly, Idaho, over a six-year period from 1985 to 1991 (figs. 10 and 11). The lysimeter surface conditions included clipped fescue grass on one lysimeter that was dormant during the winter period and various bare soil conditions on the other lysimeter, representing

Figure 10. Mean monthly K_c measured by Wright (1993) for a grassed (dormant) lysimeter during nongrowing periods at Kimberly, Idaho, converted for use with the ASCE PM alfalfa reference ET_r equation.

Figure 11. Mean monthly K_c measured by Wright (1993) for a bare ground surface during nongrowing periods at Kimberly, Idaho, for various types of surface conditions, converted for use with the ASCE PM alfalfa reference ET_r equation.

soil conditions occurring between annual agricultural crops. The bare soil conditions included disked wheat stubble, disked alfalfa, disked soil, alfalfa, and winter wheat.

The basis for the mean K_c values in figures 10 and 11 is the ASCE PM alfalfa reference ET_r . The ASCE PM ET_r standard is a hypothetical reference that represents 0.5 m tall green alfalfa, even during dormant periods in winter, so that, even under wet conditions, the K_c during winter is not expected to reach 1.0. However, the mean K_c (K_{cm}) data measured by Wright (1993) approached or exceeded 0.8 during December 1988 to March 1989 for the disked soil, a period having a nearly continuous distribution of precipitation.

The K_c measurements from Wright (1993) were used to guide the development of procedures for computing daily K_c using the FAO-56 dual K_c procedure. The nongrowing (winter) period was defined as the period beginning at the termination of a K_{cb} curve at the end of the growing cycle or by the occurrence of a killing frost. The nongrowing period was defined as ending at greenup or planting of the same crop the following year (or on 1 Oct. for winter wheat).

In estimating K_c for nongrowing periods, a basal $K_{cb} = 0.1$ was used to represent bare soil conditions, for surfaces covered with some amount of mulch, and for dormant turf or sod systems. That K_{cb} value represented conditions when these surfaces had a dry soil surface but with sufficient soil water at depth to supply some diffusive evaporation. The evaporation (K_e) component of the FAO-56 dual K_c method was estimated separately in the daily soil water balance, where $K_{c\max}$ during the nongrowing period was set to 0.9 for bare soil, to 0.85 for mulched surfaces, and to 0.8 for dormant

Figure 12. Mean monthly winter K_c estimated for ground surface covers that most closely matched those shown in figure 11 at Kimberly, Idaho (BS = bare surface, M = mulched).

Figure 13. Mean monthly winter estimated K_c versus measured K_c for ground surface covers shown in figure 11 at Kimberly, Idaho (BS = bare surface, M = mulched).

grass cover when used with the alfalfa reference. The lower value for grass was to account for the insulative effects of dormant grass and its higher albedo. The use of a low value for K_{cb} permitted the K_e function in the daily calculations to increase the value for total K_c according to the wetting frequency by rain and snow. An effective rooting zone of 0.10 m was used to represent the contribution of the upper evaporation layer of soil, following FAO-56. For all surfaces, a daily soil water balance was conducted, and a stress coefficient was applied when the soil water content dropped below a critical value. Thus, actual K_c was reduced below K_{cb} when both the ground surface and subsurface soil were dry and in a stressed state. All land use types, including agricultural, landscape, horticultural, and natural vegetation, were assigned one of the three winter cover conditions (dormant grass, bare soil, or mulch) when assembling a complete daily time series for each calendar year.

Results from the K_c calculations for dormant periods for the same six years, as shown in figure 11, are presented in figure 12 for the same Kimberly, Idaho, weather station in the form of monthly averages. Estimated monthly K_c has similar range and magnitudes as the measured values in figure 11. Figure 13 shows the same data in the form of a scatter plot, with means over the six winter periods showing some disagreement between the estimates and measurements but in general showing correspondence between the estimates and measurements, with a slope of 0.92 and $r^2 = 0.93$.

ADJUSTMENT OF K_c DURING SNOW COVER

Snow cover information collected at NWS COOP weather sites was used to reduce the K_c and $K_{c\max}$ values to account for the higher albedo of snow and absorption of heat by melting. This was done by multiplying the computed K_c by a $K_{c\text{ multiplier}}$ developed by Allen and Robison (2007). The following algorithm was applied:

$$K_{c\text{ multiplier}} = 1 - K_{\text{rad term winter}} + \frac{(1 - \text{albedo}_{\text{snow}})}{(1 - \text{albedo}_{\text{surface}})} K_{\text{rad term winter}} \quad (9)$$

where $K_{\text{rad term winter}}$ represents the weighting of (or contribution to) winter reference ET estimates by the radiation term of the Penman-Monteith method, $\text{albedo}_{\text{snow}}$ is the mean albedo of snow cover, and $\text{albedo}_{\text{surface}}$ is the mean albedo of the bare surface. The albedo of snow was set to 0.8 in the calculations, and the albedo of the surface was set to 0.25. The $K_{\text{rad term winter}}$ term is equivalent to:

$$K_{\text{rad term winter}} = \frac{\Delta}{\Delta + \gamma \left(1 + \frac{r_s}{r_a} \right)} \quad (10)$$

where Δ is the slope of the saturation vapor pressure-temperature curve, γ is the psychrometric constant, r_s is the surface resistance to vapor flow, and r_a is the aerodynamic resistance to heat and vapor flow above the surface. The intent of equation 9 is to adjust for the ET_{ref} estimates by the Penman-Monteith method, which is parameterized to estimate ET for a vegetated surface, to those that would have occurred with snow cover. The primary adjustment is for the surface albedo, which is higher for snow cover. For ease of calculation, $K_{\text{rad term winter}}$ was calculated as a function of day of year based on a relationship derived using full years of weather data for Kimberly, Idaho, and the FAO-56 and ASCE standardized PM equation:

$$K_{\text{rad term winter}} = 2.2 \times 10^{-8} (J^3) - 2.42 \times 10^{-5} (J^2) + 0.006 (J) + 0.011 \quad (11)$$

where J is the day of year. An additional reduction in evaporation of 30% was made, in the presence of snow cover, to account for absorbed latent heat of fusion of any melting snow prior to evaporation, as determined by Allen and Robison (2007)

ADJUSTMENT OF K_{cb} FOR ALFALFA DURING FALL

An additional adjustment was made to the computed K_{cb} for alfalfa hay during fall periods to account for the effects of cold nighttime temperatures and occasional light but non-killing frosts. The killing frost temperature used to terminate the growing period for alfalfa was -7°C . The adjustment reduced the value for K_{cb} following the first occurrence of -3°C in the fall by 0.005 each day following a -3°C temperature. This reduced the value for K_{cb} , for example, by 0.10 by the 20th day following a light frost to reflect the reduced vigor of damaged but still functioning alfalfa vegetation.

Allen and Robison (2007) and ASCE (2016) report estimated killing frost temperatures for a range of crops and vegetation grown in the western U.S.

RESULTS AND DISCUSSION

Examples of calculated K_{cb} and what Allen and Robison (2007) referred to as actual crop coefficient ($K_{c\text{ actual}}$) curves are shown in figure 14 for spring wheat and potato crops during the 2004 calendar year near Ashton, Idaho. The $K_{c\text{ actual}}$ traces were calculated using the previously described procedures and represent best estimates of actual daily K_c under conditions of no water stress for irrigated crops and under actual conditions that may include water stress for nonirrigated, dryland crops. The $K_{c\text{ actual}}$ values include the evaporation (K_e) component and appear as spikes above the K_{cb} curves following precipitation and irrigation events. The $K_{c\text{ actual}}$ during winter peaked at about 0.6 for the spring wheat crop, prior to sowing, when the surface was assumed to have an organic mulch (fig. 14a). The $K_{c\text{ actual}}$ decreased to about 0.4 when snow cover was present (January to February) to account for higher reflectance of the snow. $K_{c\text{ actual}}$ was below K_{cb} when low soil water content was estimated to occur during the nongrowing season or prior to initiation of irrigation (generally begun when $K_{cb} > 0.22$). The relatively high frequency of irrigation for potatoes (fig. 14b), caused by a shallower root zone than for the spring wheat crop, created more evaporation losses from the soil surface, as evidenced by the large number of K_e spikes above the K_{cb} curve. The duration of the K_e spikes tended to increase during spring and fall when air temperatures were cooler and more days were required to dry the soil surface. Although the estimated $K_{c\text{ actual}}$ was relatively high during the nongrowing season, the actual ET rate was relatively low (fig. 14c) due to the low values for reference ET that represent the drying power of the atmosphere and energy available for evaporation.

COMPARISON OF CROP ET ESTIMATES WITH REMOTELY SENSED ESTIMATES

Comparisons were made between seasonal ET_c calculated during the Idaho application and seasonal ET reported by Allen et al. (2007b) for crops in the Magic Valley of south-central Idaho during the year 2000 as determined using the METRIC satellite-based energy balance processing system (Allen et al., 2007a). The METRIC procedure estimates actual ET for specific fields of crops using shortwave and thermal imagery from the USGS Landsat satellite. Comparisons were additionally made with ET_c estimates reported by the USBR AgriMet system for 2000, where AgriMet ET_c was based on mean (single) K_c values traceable to Wright (1981). Figure 15 shows comparisons for weather stations located near Twin Falls and Jerome, Idaho, which are 30 km apart. The year 2000 was the focus of an intensive application of the METRIC satellite-based energy balance method for estimating ET over large areas (Allen et al. 2007b).

The values shown for METRIC in figure 15 were sampled from a large number of fields in Jerome and Twin Falls counties of southern Idaho from METRIC images of ET (and K_c)

Figure 14. Example basal crop coefficient (K_{cbasal}) and final crop coefficient ($K_{cactual}$) curves for (a) spring wheat and (b) potato crops near Ashton, Idaho, during 2004 for an alfalfa reference ET basis. Simulated irrigation events are shown as vertical bars. The K_c traces include the evaporation component (K_e) and appear as spikes above the K_{cb} curves following precipitation and irrigation events. Also shown (c) is daily actual ET_c for the spring grain crop.

between 15 March and 17 October (Tasumi et al., 2005). The METRIC derived images were integrated monthly and over the period from 1 March to 31 October. The “Allen-Robison

(2007)” values in figure 15 represent ET_c determined in this study for the March to October 2000 period and are presented for ET_c calculations based on the Twin Falls 7E and

Figure 15. Growing season evapotranspiration (ET) during year 2000 for major crops grown in the Twin Falls County and Jerome County area of Magic Valley, Idaho, from four sources: (1) METRIC satellite-based energy balance, (2) Allen and Robison (2007) for Twin Falls 7E and Jerome NWS stations, (3) USBR AgriMet ET reports, and (4) this study using the Twin Falls AgriMet AWS station data. The black triangles represent ET_c summed for spring and winter grain for the March to July 2000 period only. The “AgriMet - Twin Falls - 2000” values were taken from the USBR AgriMet website for year 2000 and represent calculations by the USBR.

Jerome NWS weather stations as well as based on data from the Twin Falls AgriMet weather station. The Twin Falls AgriMet weather station is collocated with the Twin Falls 7E NWS station at the USDA-ARS center near Kimberly. The Allen-Robison ET_c calculations for the AgriMet station were made using alfalfa reference ET_r based on a full complement of AgriMet weather data (solar radiation, air temperature, humidity, and wind speed), while the Twin Falls 7E NWS ET_r calculations were based on daily air temperature and long-term mean monthly wind speed. The “AgriMet - Twin Falls - 2000” values in figure 15 represent growing season ET_c reported by the USBR AgriMet website.

The growing season ET_c from the Allen and Robison (2007) computations (this study) compared relatively closely with that determined by METRIC for alfalfa hay, sugar beets, and spring grain. The FAO-56 dual K_c -based computations exceeded those by METRIC by about 10% for dry beans and sugar beets. The dual K_c -based computations were about 10% lower than those by METRIC for corn, early and late potatoes, and winter grain. Growing season ET_c from the dual K_c -based computations (averaged over the Twin Falls and Jerome stations) were within 7% of METRIC estimates for alfalfa hay, sugar beets, and spring grain and were within 16% of METRIC ET_c for all crops.

Reasons for the lower ET_c estimation by Allen and Robison (2007) for corn and potatoes, relative to METRIC, arise partly from the assumption of relatively low-frequency irrigation scheduling when simulating irrigation schedules for estimation of soil evaporation. Corn crops tend to be irrigated by center pivot systems, and potato crops tend to be irrigated by center pivots or by solid set sprinklers. Both types of systems tend to be operated so that irrigations are spaced more closely together in time than for wheel-line or

gravity systems. The consequence of this is more frequent wetting of the soil surface and somewhat higher total ET_c . The estimates from this study would be closer to those from METRIC if a smaller value for MAD were used in the simulation of irrigation events. This may explain some of the 10% to 15% difference between the two estimating approaches (this study vs. METRIC). The 16% underestimation of ET_c for winter wheat as compared to METRIC-produced ET_c appears to be primarily due to estimation of earlier crop development during early spring and earlier maturity and harvest in this study for the year 2000 than observed by METRIC.

The AgriMet ET_c that was produced by USBR AgriMet using a single K_c curve estimated about 7% below the METRIC-derived growing season ET_c for alfalfa hay and 13% to 15% below METRIC for dry bean and early potato crops. AgriMet ET_c estimated 20% to 30% below METRIC for the remainder of crops (sugar beets, corn, late potatoes, spring grain, and winter grain). AgriMet estimated shorter growing periods for sugar beets and field corn, as reflected in the K_c curves for Magic Valley than observed by METRIC and as estimated in this study using T_{30} and NCGDD. Earlier growing periods were estimated by AgriMet for winter and spring grain. An additional reason for the lower seasonal ET_c estimates by AgriMet is that its ET_c calculations do not begin until emergence (or greenup) and are discontinued at estimated harvest for annual crops. Therefore, evaporation from precipitation prior to and following the specific growing periods is neglected.

STATISTICS AND TIME SERIES

In applications to Idaho, Nevada, and to the USBR WWCRA study, time series for ET_c estimates were

summarized statistically by processing over historical periods of daily data to compute information for monthly and annual time periods. This information was made available via the internet. Tables of statistics describing 30-year normals (means) for ET_c on monthly, growing season, and annual bases were developed. Those tables included means, standard deviations, and 20% and 80% exceedance values that describe the expected variation within the populations of ET_c . The statistics were computed for time period lengths of 3, 7, 15, and 30 days within each month. Those period lengths were selected to encapsulate expected lengths of irrigation intervals or drying periods that are of interest in irrigation system design and operation.

The statistics were computed over the most recent 30 years of valid (nonmissing) data or over shorter periods if less than 30 years of valid data were available. The 30-year normal periods were used to generate statistics describing the behavior of the ET data rather than using the entire periods of record for two reasons. First, the lengths of records varied widely from station to station, ranging from as few as eight years to 120 years. Second, some trends in air temperature and consequently ET estimates have occurred over long periods of time. Some of these trends were caused by changes in relative dryness of the local or regional environment due to irrigation development or by land use change, by station location or relocation, or by change in overall climate. The last 30 years of usable record were considered to be the more representative of anticipated future conditions than were prior periods and conform to the use of 30-year normals by the National Weather Service. The full records for each station were preserved in the daily, monthly, and annual time series files. Statistics for the full periods of record can be computed as needed from these series.

Time series and statistics were compiled for the following four basic ET or precipitation parameters: (1) actual ET, (2) potential crop ET, (3) basal ET, and (4) precipitation deficit, also termed the net irrigation water requirement. Potential crop ET was calculated as $K_c ET_{ref}$. Actual ET values lie below potential crop ET values during periods of soil water stress in rainfed conditions, during nongrowing periods, and occasionally early in growing seasons prior to initiation of irrigation, when estimated $K_s < 1.0$. The basal ET values represent ET when little or no water evaporation from the soil surface occurs. The precipitation deficit represents the amount of irrigation in excess of any effective precipitation needed to sustain the potential ET rates. The precipitation deficit was calculated following procedures described in ASCE (2016) as “the difference between potential crop ET and the precipitation residing in the root zone that is available for transpiration (rather than for evaporation).” This calculation was made considering only the components of precipitation that were effective in reducing irrigation requirements for transpiration because evaporation losses from precipitation are generally not effective in reducing the irrigation water requirement.

APPLICATION OF FAO-56 PROCEDURE TO ASSESS IMPACTS OF CLIMATE CHANGE

The WWCRA study was authorized by the USBR to evaluate the risks and impacts of climate change in 13 major

USBR river basins and project areas in the western U.S. (Huntington et al., 2015, 2016). The purpose of the study was to evaluate the potential future water demands within each river basin and to identify adaptation and mitigation strategies for potential impacts of climate change. The coverage of the study is shown in figure 3. Agricultural weather station data were used from 564 NWS weather stations and 14 agricultural and research weather networks representing each HUC 8 to bias correct gridded T_{max} , T_{min} , and precipitation in the CMIP3 data set (Huntington et al., 2015). The standardized PM equation was applied to the CMIP3 12 km grid cell data, as was the calculation of T_{30} and CGDD to estimate the initiation and lengths of growing periods under a range of climate change projections. R_s and T_{dew} were estimated using equations 1, 2, and 3, and wind speed was assigned from long-term monthly averages developed from 567 AWS stations, many of which had less than 30 years of record (Huntington et al., 2015). In the extended Huntington et al. (2016) study, R_s , T_{dew} , T_{max} , T_{min} , and windspeed data were taken from the gridded GridMET climate data system (Abatzoglou, 2013) following adjustment for bias, as described by Huntington et al. (2016). The dual K_c method was applied so that impacts of changing precipitation amounts on total ET could be assessed.

The wide range of climates among the eight river basins required a broader range in K_o in equation 3 to estimate T_{dew} than was experienced for the Idaho and Nevada stations. As an example, figure 16 shows mean monthly K_o for four agricultural weather stations spanning a broad range of climatic zones (Klamath Falls, Ore.; Twin Falls, Ida.; Fallon, Nev.; and Aguila, Ariz.). These K_o values, representing conditions anticipated within irrigated settings, were used by Huntington et al. (2015) to estimate T_{dew} from the projected gridded weather data sets. Regional and local humidity levels substantially impacted the seasonal values for K_o in irrigated environments, as expected, producing higher estimates for ET_o in the very arid Arizona region, where entrainment of dry air from regional air masses into boundary layers over irrigated fields is substantial. Lower estimates for ET_o were produced in the less arid Klamath region.

Future impacts on irrigation demands were analyzed for five climate change scenarios (warm-dry, warm-wet, hot-dry, hot-wet, and central tendency or ensemble median) that were informed by 112 BCSD-CMIP3 projections (USBR, 2011; Maurer et al., 2007) for three future periods: the 2020s (years 2010 to 2039), 2050s (years 2040 to 2069), and 2080s (years 2070 to 2099). The period from 1950 to 1999 was used as the baseline period for comparison (Huntington et al., 2015). The ETDemands model, employing the FAO-56 dual K_c procedure and thermal-based K_{cb} curves described previously, played a central role in estimating ET_c for the various scenarios, which were implemented by modifying known time series of weather data at hundreds of weather station locations. ET was simulated for all crops common to each major river basin, and percentage changes from baseline conditions were analyzed. Greenup and planting dates were projected to occur earlier for the climate change scenarios, and the growing periods for annual crops were often shortened due to more rapid accumulation of growing degree days.

Figure 16. Mean monthly K_o ($K_o = T_{min} - T_{dew}$) for four example agricultural weather station locations in the Klamath (Klamath Falls, Ore.), Columbia (Twin Falls, Ida.), Lower Colorado (Aguila, Ariz.), and Truckee (Fallon, Nev.) river basins (from Huntington et al. 2016).

Huntington et al. (2015) provide a number of summary figures showing forecast changes in weather parameters, in ET_o , and in ET_c for the eight river basins under the range of climate change scenarios. An example is shown in figure 17 for the Colorado River basin, where the projected percentage change in ET_c is greater for higher elevations of the basin. As anticipated, increases in ET_c were greatest for the hot-dry and hot-wet scenarios. Growing period lengths for indiscriminate perennial crops such as alfalfa, orchards, and grass hay were projected to lengthen and contributed to the increase in ET_c . The estimated changes in the growing period timing and length are uncertain due to lack of knowledge regarding how farmers will react to warmer climates regarding planting dates and whether there will be shifts to crops with longer growing seasons to take advantage of the longer potential growing periods.

CONCLUSIONS

The FAO-56 dual K_c procedure (Allen et al., 1998) has provided a consistent and accurate means to estimate daily, monthly, growing season, and annual ET and irrigation water requirements (IWR) for hundreds of weather station locations for statewide and regionwide applications. The dual K_c procedure captured impacts of evaporation from wetting events including both precipitation and irrigation and was applied both during growing seasons and during dormant and winter periods to assess total annual evaporation and accumulation of effective precipitation. This resulted in dependable estimates that are traceable to physical descriptions of soils, crop growth, and potential ET demands. The ET estimates and statistical summaries have proven useful to the western U.S. states of Idaho and Nevada for managing water rights and water transfers and for computing hydrologic water balances, and to the U.S. Bureau of Reclamation for projecting future irrigation water demands. The expression of K_{cb} curves as functions of normalized cumulative growing degree days and the estimation of starts of growing seasons using 30-day mean air temperature provided a flexible and responsive means to assess the effects of historical and

projected climatic properties on ET and net IWR under conditions in which air temperature characteristics vary from year to year and from decade to decade.

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Figure 17. Spatial distributions of projected percentage change in crop evapotranspiration for HUC 8 sub-basins within the Colorado River basin for different climate scenarios and time periods: S1 = warm-dry, S2 = warm-wet, S3 = hot-dry, S4 = hot-wet, and S5 = central tendency (from Huntington et al., 2015).

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APPENDIX

Table A1. Crop rooting, MAD, and height parameters for crops common to western U.S. (from Allen and Robison, 2007, and Huntington et al., 2015).

Crop or Cover Type	Rooting Depth		End of Root Growth as a Fraction of Time from Planting to EFC	MAD (%)		Crop Height	
	Initial (m)	Maximum (m)		Initial and Development Stage	Midseason and Late Season	Initial (m)	Maximum (m)
Alfalfa hay, typical style	0.7	1.8	0.5	60	60	0.1	0.5
Alfalfa hay, frequent cut	0.7	1.8	0.5	60	60	0.1	0.6
Grass hay	0.3	1.1	0.4	50	50	0.1	0.6
Snap and dry beans, fresh	0.12	1.2	1.2	60	50	0.05	0.35
Snap and dry beans, seed	0.12	1.2	1.2	60	50	0.05	0.35
Field corn (moderate length season)	0.12	1.5	1.2	70	50	0.1	3
Silage corn (field corn with truncated season)	0.12	1.5	1.2	70	50	0.1	3.5
Sweet corn, early	0.12	1	1.2	60	50	0.1	1.5
Sweet corn, late	0.12	1	1.2	60	50	0.1	1.5
Spring grain, irrigated	0.25	1.8	1.2	60	50	0.05	1
Winter grain, irrigated	0.25	1.8	1.2	60	50	0.05	1
Grass pasture, high management	0.3	1	0.4	60	50	0.1	0.25
Grass pasture, low management	0.3	1	0.4	60	50	0.1	0.15
Turfgrass (lawns), irrigated	0.3	0.6	0.4	65	50	0.05	0.1
Apples and cherries with ground cover	1.5	1.5	0.5	50	50	4	4
Apples and cherries with no ground cover	1.5	1.5	0.5	50	50	4	4
Garden vegetables (general)	0.12	0.6	1.2	60	50	0.1	0.4
Carrots	0.12	0.6	1.2	60	50	0.1	0.5
Onions	0.25	0.8	1.2	60	50	0.1	0.4
Melons	0.2	1.2	1.2	60	50	0.05	0.3
Grapes, wine	1	2	1	70	70	1.5	1.5
Alfalfa seed	0.7	1.5	0.5	70	70	0.1	0.6
Peas, fresh	0.2	1	1	65	50	0.05	0.3
Peas, seed	0.2	1	1	65	50	0.05	0.3
Potatoes, processing (early harvest)	0.3	0.8	1	50	40	0.05	0.4
Potatoes, baking (late harvest)	0.3	0.8	1	50	40	0.05	0.4
Sugar beets	0.15	1.3	1.2	60	50	0.05	0.35
Hops	1	1.5	1	50	50	1	6
Mint	0.5	1.3	0.8	50	50	0.1	0.5
Poplar (third year and older)	1.5	1.5	1	60	50	6	6
Lentils	0.15	0.9	1.2	60	50	0.05	0.5
Sunflower, rainfed	0.2	2.5	1.2	60	60	0.1	2
Safflower, rainfed	0.2	2.5	1.2	60	60	0.1	1
Canola	0.2	1.6	1.2	60	60	0.1	1

Table A1 (continued). Crop rooting, MAD, and height parameters for crops common to western U.S.

Crop or Cover Type	Rooting Depth		End of Root Growth as a Fraction of Time from Planting to EFC	MAD (%)		Crop Height	
	Initial (m)	Maximum (m)		Initial and Development Stage	Midseason and Late Season	Initial (m)	Maximum (m)
Mustard	0.2	1.4	1.2	60	60	0.1	1
Bluegrass seed	0.3	1	0.4	60	50	0.1	0.3
Garlic	1	1	1	60	60	0.1	1
Range grasses, early short season (cheatgrass, etc.)	0.3	0.6	0.3	60	60	0.05	0.3
Range grasses, long season (bunchgrass, wheatgrass)	0.6	1.8	0.3	60	60	0.05	0.7
Range grasses (bromegrass)	0.6	1.2	0.3	60	60	0.05	0.7
Sagebrush	3	3	1	60	60	1	1
Wetlands, large stands	1	2	1	60	60	0.3	1.5
Wetlands, narrow stands	1	2	1	60	60	0.3	1.5
Cottonwoods	2	2	0.5	60	60	10	10
Willows	2	2	0.5	60	60	5	5
Cotton	0.25	0.9	1.2	60	50	0.05	0.5
Peppers	0.25	0.6	1.2	60	60	0.1	0.7
Sorghum	0.25	1.2	1.2	60	50	0.1	1.5
Olives	1.5	1.5	0.5	50	50	4	4
Strawberries	0.25	1	0.8	50	50	0.1	0.3
Blueberries	0.7	1.2	0.5	50	50	0.5	0.5
Raspberries	0.7	1.2	0.5	50	50	0.5	0.5
Rice	0.25	1.2	1.2	60	50	0.05	0.5
Soybeans	0.25	1.2	1.2	60	50	0.05	0.35
Peanuts	0.25	1.2	1.2	60	50	0.05	0.35
Millet	0.25	1.8	1.2	60	50	0.05	1
Tomatoes	0.3	0.8	1	60	40	0.05	0.4
Oranges	1.5	1.5	0.5	50	50	4	4
Lettuce, single crop	0.25	0.6	1.2	60	40	0.1	0.4
Lettuce, first planting	0.25	0.6	1.2	60	40	0.1	0.4
Lettuce, second planting	0.25	0.6	1.2	60	40	0.1	0.4
Nuts	1.5	1.5	0.5	50	50	4	4
Cranberries	0.7	1.2	0.5	50	50	0.5	0.5
Sugarcane	0.25	1	1.2	60	50	0.1	1.5
Field corn after another crop	0.25	1.5	1.2	65	50	0.1	3
Sorghum after another crop	0.25	1.2	1.2	65	50	0.1	1.5
Cotton after another crop	0.25	0.9	1.2	65	50	0.05	0.5
Cabbage	0.25	0.6	1.2	60	40	0.1	0.4
Sudan	0.7	1.8	0.5	60	60	0.1	1.5
Christmas trees	1.3	1.3	0.5	50	50	3	3
Melons after another crop	0.2	1.2	1.2	60	50	0.05	0.3
Grain after another crop	0.25	1.2	1.2	60	50	0.1	1.5
Soybeans after another crop	0.25	1.2	1.2	60	50	0.05	0.35

Table A2. Crop T_{30} , CGDD, T_{base} , and timing parameters for crops common to the western U.S. for estimating planting date (PL), greenup date (GU), date of effective full cover (EFC), and termination of growing seasons (from Allen and Robison, 2007, and Huntington et al., 2015; lower ranges for T_{30} and CGDD are from Allen and Robison, 2007).

Crop or Cover Type	Means to Estimate PL or GU (1 = CGDD, 2 = T_{30} , 3 = date)	T_{30} or CGDD for PL or GU (°C or °C-d)	Month ^[a] of PL or GU	T_{base} for NCGDD Based Curves (°C)	CGDD for EFC (°C-d)	CGDD for Termination (°C-d)	Time of EFC (days after PL or GU)	Time of Harvest (d) ^[b]	Killing Frost Temp. (°C)	Winter Surface Cover (1 = bare, 2 = mulch, 3 = sod)
Alfalfa hay, typical style	1	240-310	-	0	900	850	-	-240 ^[c]	-7	2
Alfalfa hay, frequent cut	1	240	-	0	700	650	-	-240	-7	1
Grass hay	2	5-12	-	0	1300	4500	-	-250	-5	3
Snap and dry beans, fresh	2	14	-	5	670	950-1200	-	-	-2	1
Snap and dry beans, seed	2	14	-	5	670	1350	-	-	-2	1
Field corn (moderate length season)	2	10-15	-	10 ^[d]	540-700	1400-1750	-	210	-5	2
Silage corn (field corn with truncated season)	2	10-15	-	10 ^[d]	540-700	1100-1200	-	210	-4	2
Sweet corn, early	2	10-12	-	10 ^[d]	500-540	1000-1100	-	210	-4	2
Sweet corn, late	2	12	-	10 ^[d]	500-540	1000	-	210	-5	2
Spring grain, irrigated	2	4-7	-	0	840-880	2040-2160	-	180-210	-40	2
Winter grain, irrigated	3		10	0	1100-1150	2000-2600	-	-	-40	2
Grass pasture, high management	2	5-10	-	-	-	-	30-50	-220	-5	3
Grass pasture, low management	2	7-10	-	-	-	-	40-50	-220	-5	3
Turfgrass (lawns), irrigated	2	5-10	-	-	-	-	60	-270	-5	3
Apples and cherries with ground cover	2	6-8	-	-	-	-	55	260-320	-5	2
Apples and cherries, no ground cover	2	6-8	-	-	-	-	55	260-320	-5	1
Garden vegetables, general	2	10-20	-	-	-	-	80	200	-2	1
Carrots	2	6-9	-	-	-	-	80	200	-2	1
Onions	2	6-20	-	-	-	-	70-80	200	-2	1
Melons	2	10-20	-	-	-	-	70	190-270	-2	1
Grapes, wine	2	8-10	-	-	-	-	80-120	180-270	-3	1
Alfalfa seed	1	240-310	-	0	-	-	80	100	-7	2

Table A2 (continued). Crop T_{30} , CGDD, T_{base} and timing parameters for crops common to the western U.S. for estimating planting date (PL), greenup date (GU), date of effective full cover (EFC), and termination of growing seasons (from Allen and Robison, 2007, and Huntington et al., 2015; lower ranges for T_{30} and CGDD are from Allen and Robison, 2007).

Crop or Cover Type	Means to Estimate PL or GU (1 = CGDD, 2 = T_{30} , 3 = date)	T_{30} or CGDD for PL or GU ($^{\circ}\text{C}$ or $^{\circ}\text{C-d}$)	Month ^[a] of PL or GU	T_{base} for NCGDD Based Curves ($^{\circ}\text{C}$)	CGDD for EFC ($^{\circ}\text{C-d}$)	CGDD for Termination ($^{\circ}\text{C-d}$)	Time of EFC (days after PL or GU)	Time of Harvest (d) ^[b]	Killing Frost Temp. ($^{\circ}\text{C}$)	Winter Surface Cover (1 = bare, 2 = mulch, 3 = sod)
Peas, fresh	2	5-10	-	0	640	1000-1300	-	-	-4	1
Peas, seed	2	5-10	-	0	640-800	1650-2200	-	-	-4	1
Potatoes, processing (early harvest)	2	6-10	-	5	700-800	1600	-	-	-2	1
Potatoes, baking (late harvest)	2	7-10	-	5	740-800	1800-2150	-	-	-2	1
Sugar beets	2	8-11	-	0	970	2700	-	-	-4	1
Hops	1	600	-	0	-	-	100	200	-2	1
Mint	1	600	-	0	1400	4000	-	-	-4	2
Poplar, third year and older	2	8-10	-	-	-	-	20	-200	-5	2
Lentils	2	5-10	-	0	935	2160	-	-	-4	1
Sunflower, rainfed	2	10-13	-	-	-	-	70	190	-4	1
Safflower, rainfed	2	8-11	-	-	-	-	70	190	-4	2
Canola	2	8	-	-	-	-	55	170-190	-4	2
Mustard	3	11	4.8	-	-	-	55	190	-4	2
Bluegrass seed	2	5-10	-	-	-	-	35	-230	-5	3
Garlic	2	10	-	-	-	-	80	170	-2	2
Range grasses, early short season (cheatgrass, etc.)	2	5-10	-10	-	-	-	-	-	-5	2
Range grasses, long season (bunchgrass, wheatgrass)	2	5-10	-10	-	-	-	-	-	-5	2
Range grasses (brome grass)	2	5-10	-10	-	-	-	-	-	-5	2
Sagebrush	2	5-10	-10	-	-	-	-	-	-5	2
Wetlands, large stands	2	11-15	-	-	-	-	45	-200	-2	2
Wetlands, narrow stands	2	11-15	-	-	-	-	45	-200	-2	2
Cottonwoods	2	6-8	-	-	-	-	60	-260	-4	2
Willows	2	4-8	-	-	-	-	60	-260	-6	2
Cotton	2	20	-	12.5 ^[d]	800	1950	-	-	-2	1
Peppers	2	19	-	10 ^[d]	1490	2280	-	-	-2	1
Sorghum	2	20	-	7 ^[d]	-	-	35	105	-3	1
Olives	3	-	1	-	-	-	60	-100	-40	1
Strawberries	1	600	-	0	1400	4000	-	-	-4	2
Blueberries	3	-	1	-	-	-	60	-100	-40	1
Raspberries	3	-	1	-	-	-	60	-100	-40	1
Rice	2	15	-	0	880	2190	-	-	-40	2
Soybeans	2	21	-	5	850	2000	-	-	-2	2
Peanuts	2	21	-	5	850	2000	-	-	-2	1
Millet	2	21	-	0	1000	2800	-	-	-40	2
Tomatoes	2	10	-	5	900	2100	-	165	-5	1
Oranges	3	-	1	-	-	-	40	-100	-10	1
Lettuce, single crop	2	10	-	0	1000	2300	-	-	-5	1
Lettuce, first planting	2	10	-	0	800	1800	-	-	-5	1
Lettuce, second planting	2	27	-	0	800	2000	-	-	-5	1
Nuts	2	11	-	-	-	-	45	330	-3	1
Cranberries	3	-	1	-	-	-	60	-100	-40	1
Sugarcane	2	16	-	10 ^[d]	540	1000	-	-	-4	1
Field corn after another crop	2	19	-	10 ^[d]	540	1400	-	-	-5	2
Sorghum after another crop	2	19	-	7 ^[d]	-	-	60	70	-3	2
Cotton after another crop	2	20	-	-12 ^[d]	800	1800	-	-	-2	2
Cabbage	2	11	-	0	1000	2300	-	-	-5	1
Sudan	1	300	-	0	1860	3010	-	-	-7	2
Christmas trees	3	-	1	-	-	-	1	-100	-50	1
Melons after another crop	2	27	-	-	-	-	70	190	-2	2
Grain after another crop	2	27	-	7 ^[d]	-	-	60	90	-3	2
Soybeans after another crop	2	13	-	5	755	1690	-	-	-2	2

^[a] A negative value is an offset to the prior column; a positive value is months.

^[b] A negative value is the time to extend until frost.

^[c] Use as maximum length for CGDD crops.

^[d] Use the special corn growing degree day calculation; others use standard method.