Appendix D

Penman-Monteith

Agricultural Evapotranspiration and Net Irrigation Water Requirements for the Upper Colorado River Basin: 2020 ET Demands Model Summary

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(cover image taken from Google Earth Imagery near Duchesne, UT)

INTRODUCTION

This report summarizes application of the ET Demands model v1.1.0 to the Upper Colorado River Basin (UCRB) for the 2020 calendar year (Figure 1). The 2020 analysis builds upon previous model runs performed for 2017, 2018, and 2019. Model set-up and description sections contain recycled text from previous year reports for consistency. The ET Demands model was applied to develop daily, monthly, seasonal, and annual crop evapotranspiration (ET_c) and Net Irrigation Water Requirement (NIWR) estimates for irrigated croplands within the UCRB. ET Demands modeling was performed in collaboration with the Bureau of Reclamation and Wilson Water Group as part of a multiyear feasibility study to operationally estimate ET within the UCRB.

METHODS

ET Demands model application follows general workflows established during previous year analyses. Readers are encouraged to review previous year analysis reports (Huntington et al., 2018; Pearson et al., 2019; Pearson et al., 2020) for specifics on ET Demands model set-up and development for the UCRB ET feasibility study. Detailed descriptions of the ET Demands model and approach is included in Allen et al. (2005), Allen and Robison (2009), and Huntington et al. (2015). Specifics related to the Python ET Demands software and application can be found at: https://github.com/usbr/et-demands and https://et-demands.readthedocs.io/en/bminor_development/index.html

Reference ET

The ET Demands model is based on the American Society of Civil Engineers - Environmental & Water Resources Institute (ASCE-EWRI, 2005) Standardized Penman-Monteith reference ET (ASCE-PM) and Food and Agriculture Organization manual 56 (FAO-56) reference ET-crop coefficient approach (Allen et al., 1998), in which the reference ET (ET_r), is multiplied by crop coefficients (K_c) to estimate crop ET (ET_c). ET_r refers to the ET from a reference surface (alfalfa reference surface in this report) that is actively growing, not limited by soil moisture, and is at full cover and peak height. There are many methods available for estimating evaporative demand and ET_r, and while many of these methods are simple temperature-based techniques, others are more data intensive physically based models such as the ASCE-PM method. Estimates of ET_r vary widely among the methods, and until the last decade there was considerable debate as to the more correct and appropriate method. The professional and scientific communities now generally recognize the ASCE-EWRI and FAO-56 methods as the most appropriate and recommended ET_r methods for estimating crop ET.

Weather station measurements of solar radiation, air humidity, and wind speed are generally limited, but are required for the ASCE-PM method and other physically based reference ET methods. Difficulty in acquiring input data necessary for physically based reference ET methods has, in the past, led to the use of simpler and limited temperature-based methods to assess crop ET. In recent years, new gridded climate datasets have been expanded to include all the variables needed for the ASCE-PM equation (i.e. air temperature, solar radiation, humidity, and wind speed). Gridded climate datasets were used and applied in the ET Demands model in this study, and further described below.

Weather Station Data Quality Assurance and Quality Control, Comparison, and Bias Correction of Gridded Reference ET

Weather Station Data

Weather station datasets representative of agricultural conditions throughout the UCRB were acquired from local, state, and federal station networks including AgriMet, WACNet, CoAgMET, AgWeather, NMCC, and AZMet. In total, 68 were used for bias ratio development based on feedback by the Working Group and analysis being performed by the OpenET project. Stations were selected based on station location (i.e. representative of well-watered agricultural conditions with adequate fetch), Landsat derived Normalized Difference Vegetation Index (NDVI) values, and data quality (Table 1).

All weather station data was visually inspected and processed for Quality Assurance and Quality Control (QAQC) using custom Python software that can be found at the GitHub repository https://github.com/DRI-WSWUP/pyWeatherQAQC.

Weather variables were omitted or corrected as needed. The most common weather variable needing correction was measured solar radiation. Measured solar radiation is commonly under or over measured due to debris on the pyranometer window, non-level base plate, sensor miscalibration or drift, or shadowing from nearby obstructions. Corrections to measured solar radiation were made to each station using the theoretical clear sky solar radiation (ASCE-EWRI, 2005, equations D.1-D.6), where the average ratio of measured to clear sky solar radiation for the top 10 percentile of measured solar radiation during 60-day time windows was used to scale measured solar radiation for all days within respective 60-day time windows. Figure 2 illustrates correction of daily solar radiation for Granby, CO. See Table 1 for a summary of corrections developed for each station.

After QAQC and correction of individual weather variables, ASCE-PM ETr was computed at daily time steps for each station using Python software RefET (https://github.com/WSWUP/RefET), which was validated against the REF-ET program developed at the University of Idaho https://www.uidaho.edu/cals/kimberly-research-and-extension-center/research/water-resources/ref-et-software).

Gridded Reference ET Data

Gridded climate datasets used in this study were derived from gridMET, which has a spatial resolution of 4 km, and includes daily minimum and maximum air temperature, average solar radiation, average specific humidity, average wind speed, and computed ET_r (Abatzoglou, 2013). gridMET is a hybrid dataset of the North American Data Assimilation System (NLDAS) (Mitchell, 2004) and the Parameter Regression on Independent Slopes Model (PRISM) (Daly, 1994). ETr data included in gridMET are calculated following the ASCE-PM methodology (ASCE-EWRI, 2005) and was validated against Python RefET output. Daily time series were extracted for each gridMET 4 km grid cell, termed ET Cell, coincident with weather stations and agricultural land in the study area via the Northwest Knowledge Network data catalog (http://www.climatologylab.org/gridmet.html).

gridMET Bias Assessment and Correction

gridMET ET_r was compared to agricultural weather station computed ETr at 68 stations using each station's 2016-2020 data record to compare and bias correct gridMET ET_r (Figure 1). Unlike previous years that relied on a single year of data, a five-year average bias was used to avoid issues with missing values and station down times. Analysis of ratios calculated using a single year show relatively consistent bias throughout time with strong correlation to individual year results (Figure 3). At each weather station location, the coincident gridMET cell was identified to compare respective ET_r and associated weather data time series. Prior to this comparison, weather station variables of solar radiation, temperature, humidity, and wind speed were all QAQCed as described above.

Weather station and gridMET data were compared and bias correction factors were computed using 2016-2020 data as the ratio of mean monthly station ETr to mean monthly gridMET ETr using Python software gridwxcomp (https://github.com/WSWUP/gridwxcomp). A full list of 2016-2020 bias correction factors can be found in Table 2. Growing season average (April-October) bias factors for 2016-2020 ranged from 0.738 to 1.213. The gridMET and parent NLDAS datasets do not explicitly account for irrigation, increased actual ET, and near-surface boundary layer conditioning that occurs within irrigated areas, which results in gridMET having higher ETr that well-irrigated station based ETr. At some stations, gridMET ET_r was bias low due to low simulated wind speed compared to station measured wind speed. Further discussion of gridMET model bias can be found in the 2017- 2019 UCBR ET Demands summary reports (Huntington et al., 2018; Pearson et al., 2019; Pearson et al., 2020) as well as Abatzoglou (2013) and Huntington et al. (2016).

Spatially interpolated bias correction factors for each month were created from the monthly station ratios using the inverse distance weighting (IDW) approach with a power of 4, smoothing of 0, and the full study area domain as the search radius (Figure 3). IDW interpolation parameters were optimized so that bias corrected gridMET ETr would be similar to the ETr calculated at the station and surrounding agricultural lands, and to align with the interpolation approach being applied in Phase 1 of the OpenET project. All interpolations were performed at 400m resolution in the custom USBR UCRB Albers Equal Area projection and resampled to the 4km gridMET grid using bilinear interpolation to generate a set of 12 monthly correction factors for each ET Cell. Monthly bias correction factors were then multiplied by respective gridMET daily ET_r time series for each month within the ET Demands model run. Application of bias corrections ultimately remove bias of gridMET ET_r so that ETr estimates are more representative of irrigated agriculture within the UCRB.

Delineation of Irrigated Croplands

Reclamation provided an updated 2020 irrigated croplands layer consisting of polygons and crop type attributes for the UCRB. The 2020 layer was based on field and crop assignments from the 2019 irrigated crop layer for all states except Wyoming. 2020 crop layer information for Wyoming was based on data from 2018. Details about previous year crop layer development and data sources can be found in 2018 and 2019 summary reports (Pearson et al., 2019; Pearson et al., 2020).

2019 ET Demands Model Overview

Model Discretization

Similar to previous years, the UCRB study area was divided into 4km grid cells (i.e. ET Cells) based on the gridMET climate dataset (Figure 1). ET Cells included in the 2020 analysis were limited to those that contain irrigated croplands as defined by Reclamation (totaling 3,620 cells) and were used for extracting gridMET data, estimating crop types and soil properties, and parameterizing the ET Demands model across the UCRB. In total, 17 different crop types were simulated within the study area, however, only those crop types contained in each individual ET Cell were used to simulate ET and summarize output for respective ET Cells. Table 3 summarizes cross classification (i.e. cross walk) used to reclassify the 2020 BOR Crop Layer to ET Demands supported crop types. Crops with limited acreage (e.g. strawberry acreages of <10 acres) were cross walked to the dominant crop type within the surrounding grid cell to avoid unnecessary processing with limited to no impact on results.

Soils Data and Simulated Runoff

Soils attributes needed for ET Demands parameterization were obtained from the NRCS State Soil Geographic (STATSGO) database (USDA-NRCS, 1991). STATSGO is a spatial soils GIS database and contains attributes of the physical character of soils needed to estimate soil water holding capacity and runoff parameters in the ET Demands model's dual soil and root zone water balance and runoff modules. STATSGO attributes of available water holding capacity, and sand, silt, and clay fractions were used to estimate the spatial distribution of total evaporable water (TEW) and readily evaporable water (REW) used in the surface soil layer water balance, and total available water (TAW) and readily available water (RAW) used in the root zone water balance (Figure 4). These parameters affect the simulation of irrigation, soil evaporation, deep percolation, antecedent soil moisture, and runoff from precipitation. Soil attributes for available water holding capacity and sand and silt fractions were averaged over 0-150 cm depths and were then intersected with irrigated crop land areas, and then spatially averaged and attributed to each ET Cell (Figure 5).

Crop Coefficients

Alfalfa reference based basal crop coefficient (K_{cb}) curves outlined in Allen and Robison (2009) and Huntington et al. (2015) were in the application of ET Demands for this study. The K_{cb} curves are largely traceable to lysimeter-based K_{cb} curves of Wright (1982, 2001) and Reclamation's AgriMet program. Three methods were used to simulate the K_{cb} curve in time (1) normalized cumulative growing-degree-days from planting or green up to effective full cover, with this ratio extended until termination of the cropping period; (2) percent time from planting to effective full cover, with this ratio extended until termination; and (3) percent time from planting to effective full cover and then number of days after full cover to termination. These temporal K_{cb} simulation approaches allow for the stage and shape of crop specific K_{cb} curves to be a function of cumulative growing degree days (CGDD) and temperature dependent planting or green up estimates, such as 30 day moving average air temperature (T_{30}), rather than specified or fixed calendar dates. CGDD has previously been used for defining planting and green up times, crop coefficient development, scaling of development periods, and transferring K_{cb} curves among regions in a wide range of studies (Sammis et al. 1985; Slack et al. 1996; Howell et al. 1997; Snyder et al. 1999; Wright 2001; deTar 2004; Marek et al. 2006; Allen and Robison 2009). Allowing for variable green up, planting, effective full cover, harvest, and advancement of K_{cb} curves based on the weather and climate is an important aspect of simulating crop water use given the year-to-year variability, and wide range of climate across the UCRB.

Effective Precipitation

The dual crop coefficient approach and year-round daily soil water balance within ET Demands requires separate accounting of transpiration and evaporation and allows for separate estimation of evaporation from precipitation and evaporation from simulated irrigation events. Simulation and accounting of wintertime soil moisture gains often offset irrigation requirements during the beginning of the growing season. Accounting for off-season soil moisture gains and losses is important for accurate estimation of effective precipitation and NIWR. The NIWR is defined as the amount of water needed in addition to precipitation to grow a non-water limited crop, otherwise known as the precipitation deficit, and is estimated as the ET_c minus precipitation residing in the root zone, P_{rz}. P_{rz} is the amount of gross reported precipitation that infiltrates into the soil and that remains in the root zone for consumption by evaporation or transpiration. Although P_{rz} includes precipitation that is later evaporated and possibly not transpired by the crop, ET_c includes evaporation of precipitation, therefore ET_c minus P_{rz} represents the net irrigation water requirement, and not ET_c minus the P_{rz} portion that is effective toward transpiration only. P_{rz} is computed as P – Runoff – DPercp where P is gross reported precipitation. Runoff is estimated surface runoff, and DPercp is deep percolation of any precipitation below the maximum root zone for the crop or land-use condition. In this study, the ratio of annual effective precipitation to annual precipitation (PPT) was estimated and summarized as the crop area weighted average for each ET Cell and highlighted as an annual time series for grass hay (highlighted in Results Section). For more information on details of the ET Demands model and algorithm specifics see Allen et al. (2005), Allen and Robinson (2009), and Huntington et al. (2015).

2020 Model Calibration

2020 ET Demands model calibration utilized Landsat derived NDVI timeseries to determine growing season timing and crop phenology at key calibration sites throughout the basin. Specific focus was given to the eddy covariance comparison sites to assess the capability of satellite informed ET Demands modeling to capture actual ET timing and crop phenology. The following section highlights the use of satellite derived NDVI to inform ET Demands model calibration at the four eddy covariance monitoring sites.

Bloomfield, NM (Grass/Alfalfa Mix)

NDVI timeseries for the Bloomfield, NM site show a later than normal season start, not representative of typical full season, well-watered conditions (Figure 6). ET Demands simulated a mid-March green-up based on temperature, while NDVI data shows that green-up occurred in late-June. The disconnect between green-up date and temperature identifies an area where standard ET Demands modeling does not represent actual water use. ET Demands simulates consumptive use under optimal, well-watered conditions and without additional information from local stakeholders or satellite-based data cannot account for non-standard management practices. To demonstrate the capability of ET Demands to account for late-season startup, a site-specific model run was performed for the Bloomfield site. The site-specific run modified growth controls to match NDVI based phenology for the EC field.

Plots demonstrate the capability of ET Demands to capture field specific growth patterns; however, if “on average” conditions at the basin or watershed scale is desired, calibration of ET Demands to on average conditions is needed.

Big Piney, WY (Grass Hay)

Similar to Bloomfield, NM, Kcb simulations from ET Demands were compared to NDVI phenology for the Big Piney, WY grass hay site. Simulated phenology from ET Demands shows good agreement with NDVI in terms of green-up, mid-season cutting timing, grazing (i.e. reduced greenness and Kcb), and end of season timing (Figure 7). 2020 NDVI and ET Demands estimates are representative of a typical full grass hay growth season for the region.

Vernal, UT (Alfalfa)

ET Demands Kcb estimates for the Vernal, UT alfalfa site show good alignment with Landsat derived NDVI. ET Demands estimated three cutting cycles with a fourth partial growth cycle for the Vernal, UT eddy covariance site (Figure 8). Results demonstrate the ability of ET Demands to capture growing season and cutting timing for alfalfa hay in this region. 2020 NDVI and ET Demands estimates are representative of a typical full well-watered alfalfa hay season.

Palisade, CO (Peach Orchard)

ET Demands simulated crop phenology for the Palisade, CO Peach Orchard (orchard with groundcover) site shows good agreement with Landsat derived NDVI. ET Demands simulated growing season start-up in early April and senescence in late October (Figure 9). Kcb values show a mid-season reduction in line with NDVI signals. 2020 NDVI and ET Demands estimates for the Palisade, CO orchard site are representative of a typical full orchard growing season for the region.

Incorporating satellite-based information into the ET Demands calibration workflow allows for improved estimation of growing season start and end dates as well as harvest timing throughout the basin. Proper estimation of crop phenology and development is critical for accurate estimation of crop ETc and water demand. Future improvements should focus on establishing regional benchmark NDVI processing workflows (i.e., HUC level averages) in order calibrate ET Demands to representative management practices.

ET Demands Model Application and Post Processing

The ET Demands model was executed with bias corrected gridMET climate time series representative of observed agricultural climate during 2020 for calculation of ET_r, K_c curves, ET_c. and NIWR. For consistency with previous years, the full 1979-2020 period was simulated using 2020 crop layer distributions. The ET Demands model was executed for each ET Cell within irrigated agricultural areas of the UCRB (Figure 1), and daily output of simulated ET_r, K_{cb}, runoff, irrigations, growing-season and non-growing-season flags, and ET_c and NIWR, were saved and visualized for each crop type within each ET Cell (Figures 10 and 11). ET_r, ET_c, NIWR, and PPT rates for each crop type and ET Cell were summarized by month, growing season (as determined by ET Demands), and calendar year. Total ET_c and NIWR volumes for each ET Cell and period were computed using respective crop type rates and areas derived from irrigated croplands layers provided by Reclamation. Crop area weighted growing season and annual ET_c and NIWR rates for each ET Cell and period were computed as the total seasonal and annual ET_c and NIWR volume for all crops divided by the total crop acreage within each ET Cell.

RESULTS

Similar to previous reports, this section presents an overview of results of ET Demands model components for the 2020 UCRB analysis. Results include spatial maps and time series of reference evapotranspiration (ET_r), crop evapotranspiration (ET_c), and net irrigation water requirement (NIWR) as well as other components of the ET Demands model. The full package of results is available upon request including daily, monthly, and annual time series and summary map packages of model components and result aggregations for the 2020 study period. Figures 12-14 visualize the spatial variability of growing season start day of year, end day of year, and season length for ET Cells containing grass hay. Figures 15-18 illustrate the crop area weighted ET_c and NIWR for both annual and growing season timeframes.

Crop-weighted ET_c rates for ET Cells modeled in 2020 ranged from 605 - 1851 mm/yr (1.98 – 6.07 ft/yr), and NIWR ranges from 357 - 1740 mm/yr (1.17 – 5.71 ft/yr), respectively. The 2020 growing season ET_c ranged from 465 - 1798 mm/yr (1.53 – 5.90 ft/yr), and growing season NIWR ranges from 361 - 1745 mm/yr (1.18 – 5.73 ft/yr), respectively. Annual crop weighted ETc estimates throughout the UCRB follow general temperature patterns related to elevation and latitude gradients with higher ETc rates occurring in lower latitude, lower elevation areas (Figure 19). Similar to results in 2019, a significant amount of ETc variability in the UCRB can be explained by elevation and latitude (R^2=0.647). The remaining variability is likely driven by management controls such as crop acreage, irrigation shortages, and other non-climate related management practices.

Crop weighted effective precipitation estimates expressed as a fraction of the total annual precipitation (Peft_fraction = PefT/ PPT) ranged from 0.17 – 0.88 for the 2020 calendar year (Figure 20). Lower PefT fractions (i.e., Peft_fraction < 0.3) generally occur in areas of high elevation where large precipitation totals enhance deep percolation. The Peft_fraction corresponds to the fraction of precipitation that is effective in reducing irrigation water requirements. It is important to note that effective precipitation estimates are a function of crop type, precipitation timing and amounts, and soil. Time series of P_rz and P_eft effectiveness fractions from 1979-2020 for grass hay at four grid cells throughout the basin show temporal variability in relation to both total annual precipitation and deep percolation (Figure 21). Deep percolation can exceed total annual precipitation due to contributions from irrigation when precipitation is low, and irrigation is high.

Results demonstrate the capability for ET Demands to simulate spatial variability in ETc and NIWR throughout the UCRB. Inclusion of satellite-based crop phenology information allows for more accurate model calibration and growing season estimation. ET Demands provides an estimate of potential ET and net irrigation water requirements under optimal growth and well water conditions. Estimates provided by ET Demands represents potential consumptive use and can serve as a theoretical limit for actual crop ET. Combining estimates from ET Demands with actual ET measurements from ground stations or satellite-based ET models provides validation and context for management and planning.

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TABLES

Table 1: Summary of weather stations evaluated for inclusion in the 2020 bias correction analysis. 68 stations, including the four eddy covariance validation sites, were approved for development of 2020 monthly bias correction surfaces. All available station data from 2016-2020 was included in the bias correction analysis.

State	Station Name	Latitude	Longitude	Elevation (m)	Location	Source	DRI_ID	2020-Specific Correction Notes
AZ	Safford	32.812972	-109.679263	901.903	Outside UCRB	AZMet	004_AZ	Removed temperature outliers through median-based z-score approach. Used relative humidity data for humidity record. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
AZ	Mohave	34.967462	-114.611077	147.828	Outside UCRB	AZMet	014_AZ	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
UT	Circleville	38.15133	-112.251	1884	Outside UCRB	SCAN	1087_UT	Removed temperature outliers through median-based z-score approach. Used relative humidity data for humidity record. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
UT	Green River	39.01825	-110.163	1281	UCRB	SCAN	1089_UT	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
UT	Split Mountain	40.39136	-109.353	1491	UCRB	SCAN	1093_UT	Removed temperature outliers through median-based z-score approach. Used relative humidity data for humidity record. Solar radiation was corrected through a 60-day-bracket percentile

								approach, but no data required more than a 20% correction.
CO	Carbondale, Roaring Fork Valley	39.3623	-107.208	1918.11	UCRB	COAGM	203_CO	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
CO	Collbran	39.1993	-107.9899	1998	UCRB	COAGM	204_CO	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
CO	Clark	40.7043	-106.9341	2201	UCRB	COAGM	207_CO	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
CO	Crowdrey	40.8659	-106.336	2406.396	Outside UCRB	COAGM	209_CO	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
CO	Center #2	37.8288	-106.038	2317	Outside UCRB	COAGM	211_CO	Removed temperature outliers through median-based z-score approach. Used relative humidity data for humidity record. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.

CO	Durango	37.1125	-107.8806	1891	UCRB	COAGM	214_CO	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
CO	Eckert	38.8398	-107.973	1683.11	UCRB	COAGM	217_CO	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
CO	CSUFruitaExptStation	39.1803	-108.699	1377.39	UCRB	COAGM	218_CO	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction. Station moved late 2020, data from new location not considered due to date of move.
CO	Granby	40.1047	-105.9433	2411	UCRB	COAGM	224_CO	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
CO	Gunnison	38.6135	-106.901	2406.09	UCRB	COAGM	227_CO	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
CO	Gypsum	39.6344	-106.9469	1972.06	UCRB	COAGM	228_CO	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.

CO	Hebron	40.5455	-106.388	2490.22	Outside UCRB	COAGM	229_CO	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, with some data requiring a greater than 20% correction.
CO	Hayden	40.499	-107.181	1967.18	UCRB	COAGM	236_CO	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
CO	Ignacio	37.1383	-107.7072	2017	UCRB	COAGM	239_CO	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
CO	Kline	37.1261	-108.1465	2059	UCRB	COAGM	242_CO	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
CO	Kremmling	40.1154	-106.2829	2296	UCRB	COAGM	244_CO	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
CO	Larand	40.6126	-106.2997	2515.2096	Outside UCRB	COAGM	251_CO	Removed temperature outliers through median-based z-score approach. Relative Humidity shifted down by 2% for the year of 2020. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.

CO	Mancos	37.3212	-108.339	2051.3	UCRB	COAGM	258_CO	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
CO	Montrose	38.547	-107.9143	1722.42	UCRB	COAGM	259_CO	Removed temperature outliers through median-based z-score approach. Manually removed two bad sections of humidity data in 2020. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
CO	Norwood	38.151	-108.2835	2134	UCRB	COAGM	260_CO	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
CO	Salida	38.5713	-106.0427	2202.79	Outside UCRB	COAGM	274_CO	Removed temperature outliers through median-based z-score approach. Used relative humidity data for humidity record. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
CO	SiltMesa	39.5667	-107.6934	1712.98	UCRB	COAGM	275_CO	Removed temperature outliers through median-based z-score approach. Used relative humidity data for the humidity record. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
CO	Towaoc	37.1891	-108.9351	1621.23	UCRB	COAGM	279_CO	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.

CO	Westcliff	38.1504	-105.4988	2357.32	Outside UCRB	COAGM	283_CO	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
CO	YellowJacket	37.5428	-108.7398	2103.12	UCRB	COAGM	291_CO	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
WY	Cokeville	42.07783	-110.95611	1887.02	Outside UCRB	AgriMet	317_ID	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged, although RHMax and RHMin were missing for the entire record. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
NM	Farmington	36.687	-108.31	1719.99	UCRB	NMCC	615_NM	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
UT	CastleDale	39.22013	-111.07003	1720.6	UCRB	AgriMet	885_UT	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
UT	Castle Valley, near Moab	38.6483	-109.39897	1428.6	UCRB	AgriMet	886_UT	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.

UT	Duchesne	40.18068	-110.36013	1674.57	UCRB	AgriMet	888_UT	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
UT	Elmo	39.42126	-110.83798	1743.46	UCRB	AgriMet	889_UT	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
UT	Flowell	38.9571	-112.42	1429	Outside UCRB	AgriMet	891_UT	Removed temperature outliers through median-based z-score approach. Used relative humidity data for humidity record. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
UT	Ferron	39.07555	-111.15426	1829.41	UCRB	AgriMet	892_UT	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
UT	Huntington	39.3079	-110.97399	1753.51	UCRB	AgriMet	894_UT	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
UT	Monroe	38.63419	-112.158	1633	Outside UCRB	AgriMet	898_UT	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.

UT	Pelican Lake	40.17426	-109.66665	1466.7	UCRB	AgriMet	903_UT	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
UT	Pleasant Valley	40.1663	-110.09471	1611.48	UCRB	AgriMet	904_UT	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
UT	San Pete Valley	39.48575	-111.53721	1710.84	Outside UCRB	AgriMet	909_UT	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
UT	Tropic	37.62747	-112.04642	1892.5	UCRB	AgriMet	912_UT	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
UT	Venice	38.8235	-112.00037	1597.76	Outside UCRB	AgriMet	913_UT	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
UT	Bluebell, Neola area	40.373	-110.209	1885.49	UCRB	AgWeather	916_UT	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.

WY	Evanston	41.19713	-111.02937	2079.96	Outside UCRB	AgriMet	920_UT	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
UT	Loa	38.383	-111.636	2168.96	UCRB	AgWeather	924_UT	Removed temperature outliers through median-based z-score approach. Used relative humidity data for humidity record. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
UT	Manila	40.99	-109.654	1942.8	UCRB	AgriMet	925_UT	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
UT	Nephi	39.68942	-111.87678	1710.84	Outside UCRB	AgriMet	926_UT	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
UT	Panguitch	37.86858	-112.42177	1995.83	Outside UCRB	AgriMet	929_UT	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
UT	Spanish Fork	40.0672	-111.62912	1438.96	Outside UCRB	AgriMet	933_UT	Removed temperature outliers through median-based z-score approach. Used relative humidity data for the humidity record. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.

WY	Afton	42.732683	-110.94136	1892.81	Outside UCRB	AgriMet	956_WY	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
WY	Baggs 2E	41.03809	-107.61192	1922.98	UCRB	WACNet	968_WY	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, and had to remove approximately 60 days of bad Rs data.
WY	BigPiney 11W	42.54106	-110.33352	2259.18	UCRB	WACNet	969_WY	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
WY	Burlington	44.46105	-108.39329	1352.09	Outside UCRB	WACNet	970_WY	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
WY	Daniel 10NW	42.94333	-110.2387	2262.23	UCRB	WACNet	971_WY	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
WY	Farson 5S	42.03636	-109.45527	2009.85	UCRB	WACNet	973_WY	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.

WY	Lonetree	41.05099	-110.12453	2276.55	UCRB	WACNet	975_WY	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
WY	Pavillion 2N	43.27505	-108.67837	1665.12	Outside UCRB	WACNet	976_WY	Removed temperature outliers through median-based z-score approach. Used relative humidity data for humidity record. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
WY	Lyman 1SW	41.31671	-110.31064	2044.9	UCRB	WACNet	979_WY	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
WY	LaBarge 2S	42.24051	-110.18793	1961.69	UCRB	WACNet	980_WY	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
WY	Elk Mountain	41.5981	-106.4501	2167.74	Outside UCRB	WACNet	981_WY	Removed temperature outliers through median-based z-score approach. Manually removed a spike in humidity data. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
CO	Orchard Mesa CSU Research Station	39.0441	-108.4673	1432.56	UCRB	COAGM	NEW_004_CO	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.

WY	Big Piney EC+Wx	42.54	-110.195	2130.86	UCRB	AgWeather	NEW_005_WY_EC	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
NM	Bloomfield EC+Wx	36.691	-107.914	1694.08	UCRB	AgWeather	NEW_006_NM_EC	No data present for the first half of 2020. Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.
CO	Palisade EC+Wx	39.094	-108.37	1417.02	UCRB	AgWeather	NEW_007_CO_EC	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction. Station is in an orchard so the wind data was modified using Rick Allen's wind translation paper to convert observations to reference conditions.
UT	Vernal EC+Wx	40.458	-109.562	1665.43	UCRB	AgWeather	NEW_008_UT_EC	Removed temperature outliers through median-based z-score approach. Vapor pressure and relative humidity left unchanged. Solar radiation was corrected through a 60-day-bracket percentile approach, but no data required more than a 20% correction.

Table 2: Summary of monthly ETr bias correction factors for each station, grid cell combination. Factors from 68 approved stations were used to develop bias-wide correction surfaces.

State	Station ID	GRIDMET_ID	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec	GS	JJA	Ann
AZ	004_AZ	258158	1.006	1.005	0.961	0.946	0.961	0.931	0.968	0.929	0.884	0.827	0.904	1.030	0.927	0.942	0.939
AZ	014_AZ	330112	0.920	0.858	0.783	0.767	0.816	0.770	0.779	0.755	0.782	0.798	0.846	0.923	0.780	0.769	0.798
CO	203_CO	475819	0.712	0.858	0.941	0.949	0.922	0.863	0.938	0.858	0.826	0.799	0.829	0.733	0.880	0.887	0.874
CO	204_CO	470257	0.633	0.768	0.782	0.847	0.810	0.843	0.895	0.847	0.805	0.757	0.757	0.666	0.835	0.861	0.821
CO	207_CO	520178	0.477	0.644	0.690	0.721	0.751	0.699	0.739	0.772	0.758	0.706	0.590	0.513	0.738	0.737	0.719
CO	209_CO	525736	0.822	1.025	0.972	0.961	0.948	0.857	0.802	0.849	0.856	0.909	0.843	0.902	0.872	0.836	0.880
CO	211_CO	424565	0.951	1.013	1.170	1.137	1.101	1.115	1.133	1.067	1.073	1.071	0.980	0.998	1.104	1.108	1.094
CO	214_CO	400959	0.746	0.896	0.847	0.939	0.868	0.892	0.953	0.898	0.848	0.853	0.830	0.812	0.896	0.913	0.886
CO	217_CO	459169	0.714	0.862	0.955	0.950	0.908	0.874	0.881	0.848	0.755	0.755	0.773	0.738	0.852	0.868	0.847
CO	218_CO	470240	0.626	0.765	0.818	0.857	0.870	0.871	0.922	0.848	0.748	0.644	0.609	0.605	0.834	0.880	0.812
CO	224_CO	500798	0.681	0.814	0.857	0.927	0.873	0.879	0.945	0.933	0.867	0.838	0.700	0.554	0.897	0.918	0.877
CO	227_CO	450879	0.784	0.884	0.944	0.975	0.947	0.834	0.846	0.858	0.874	0.805	0.782	0.718	0.874	0.845	0.871
CO	228_CO	485528	0.826	0.978	0.989	0.952	0.899	0.901	0.924	0.869	0.831	0.815	0.825	0.791	0.884	0.899	0.883
CO	229_CO	514647	0.970	0.950	0.981	0.958	0.973	0.971	0.960	1.001	0.968	0.988	1.020	0.956	0.974	0.977	0.975
CO	236_CO	513242	0.624	0.712	0.834	0.845	0.827	0.819	0.834	0.840	0.814	0.735	0.710	0.635	0.820	0.831	0.808
CO	239_CO	402349	0.740	0.885	0.849	0.947	0.875	0.826	0.904	0.876	0.829	0.838	0.815	0.750	0.868	0.867	0.861
CO	242_CO	400953	1.068	1.111	0.979	1.032	0.967	1.020	1.117	1.127	1.121	1.118	1.179	1.154	1.069	1.085	1.073
CO	244_CO	500790	0.649	0.791	0.784	0.842	0.830	0.777	0.805	0.792	0.786	0.765	0.637	0.560	0.797	0.792	0.782
CO	251_CO	517421	1.059	1.071	1.099	1.056	1.030	1.036	1.028	1.009	1.032	1.099	1.120	0.979	1.036	1.024	1.043
CO	258_CO	407878	1.108	1.116	0.965	0.989	0.932	0.897	0.968	0.962	0.916	0.952	1.014	1.092	0.941	0.940	0.958
CO	259_CO	449468	0.980	1.038	1.089	1.086	1.045	1.057	1.048	0.933	0.910	0.926	0.935	0.938	1.007	1.017	1.008
CO	260_CO	435600	0.792	0.814	0.843	0.954	0.969	0.985	1.083	1.101	1.070	0.963	0.936	0.860	1.032	1.058	1.001
CO	274_CO	449513	0.965	1.036	1.036	1.037	0.994	0.942	0.940	0.910	0.878	0.907	0.838	0.948	0.943	0.932	0.949
CO	275_CO	482738	0.675	0.769	0.859	0.847	0.809	0.827	0.853	0.848	0.755	0.741	0.734	0.728	0.816	0.842	0.808
CO	279_CO	403706	1.565	1.482	1.305	1.173	1.052	1.084	1.181	1.169	1.160	1.279	1.443	1.591	1.145	1.141	1.191
CO	283_CO	435666	1.099	1.076	1.033	1.020	0.990	0.962	1.007	1.025	0.969	0.930	0.964	1.030	0.986	0.993	0.998
CO	291_CO	414799	0.780	0.903	0.980	0.993	0.979	0.991	1.004	1.019	0.934	0.941	0.948	0.842	0.984	1.003	0.970

CO	NEW_004_CO	464701	0.830	1.124	0.972	0.999	0.914	0.935	1.035	0.928	0.893	0.893	1.044	1.032	0.939	0.965	0.955
CO	NEW_007_CO_EC	467476	1.074	1.184	1.083	1.048	0.935	0.897	0.908	0.878	0.837	0.820	1.161	1.145	0.898	0.895	0.934
ID	317_ID	565819	0.487	0.590	0.701	0.797	0.839	0.830	0.847	0.827	0.787	0.730	0.609	0.521	0.815	0.834	0.781
NM	615_NM	387089	1.111	1.233	1.156	1.101	1.073	1.021	1.066	1.007	0.990	0.979	1.070	1.121	1.039	1.031	1.060
NM	NEW_006_NM_EC	387098	1.108	1.058	0.914	0.933	0.905	0.903	0.992	0.960	0.913	0.886	1.012	1.097	0.932	0.950	0.945
UT	1087_UT	435504	0.893	1.042	1.035	0.987	0.919	0.957	0.918	0.931	0.886	0.939	0.890	0.909	0.934	0.936	0.942
UT	1089_UT	464660	0.815	0.949	0.937	0.985	0.966	0.894	0.885	0.819	0.753	0.761	0.804	0.882	0.872	0.868	0.876
UT	1093_UT	510418	0.732	0.850	0.917	0.970	0.977	0.979	1.012	1.004	0.882	0.902	0.956	0.879	0.970	0.998	0.958
UT	885_UT	471569	0.837	0.981	0.987	1.050	0.975	0.983	0.975	0.952	0.913	0.873	0.877	0.887	0.964	0.971	0.958
UT	886_UT	452205	0.898	0.980	0.892	0.887	0.865	0.863	0.935	0.902	0.811	0.830	0.901	0.952	0.875	0.898	0.882
UT	888_UT	503464	1.206	1.361	1.240	1.202	1.080	1.097	1.050	1.009	1.031	1.122	1.314	1.334	1.077	1.054	1.108
UT	889_UT	478504	0.799	0.857	0.891	0.964	0.857	0.857	0.841	0.818	0.757	0.713	0.718	0.751	0.832	0.839	0.828
UT	891_UT	461834	0.869	0.951	0.984	0.951	0.989	0.935	0.875	0.802	0.800	0.929	1.042	0.868	0.887	0.871	0.897
UT	892_UT	466023	0.944	1.090	1.098	1.136	1.072	1.143	1.135	1.135	1.101	1.027	1.039	1.005	1.114	1.138	1.103
UT	894_UT	474343	0.738	0.833	0.884	0.946	0.872	0.860	0.835	0.815	0.740	0.718	0.727	0.755	0.833	0.838	0.828
UT	898_UT	452139	0.811	1.051	1.022	0.951	0.907	0.990	0.975	0.964	0.924	0.872	0.879	0.754	0.951	0.977	0.950
UT	903_UT	503480	0.911	1.064	1.069	1.097	1.079	1.040	1.001	0.970	0.946	1.026	1.142	1.112	1.019	1.005	1.027
UT	904_UT	502084	1.255	1.421	1.359	1.298	1.207	1.187	1.173	1.175	1.191	1.400	1.674	1.601	1.213	1.179	1.246
UT	909_UT	479874	0.676	0.793	0.846	0.882	0.878	0.904	0.931	0.942	0.868	0.798	0.747	0.670	0.895	0.925	0.872
UT	912_UT	417491	0.863	0.963	0.909	0.909	0.859	0.896	0.892	0.890	0.875	0.846	0.821	0.857	0.883	0.893	0.883
UT	913_UT	457686	0.651	0.940	0.894	0.915	0.827	0.886	0.854	0.798	0.789	0.790	0.758	0.680	0.839	0.848	0.834
UT	916_UT	509011	0.809	0.901	0.984	1.005	0.961	0.933	0.971	0.963	0.932	0.962	0.928	0.918	0.959	0.956	0.954
UT	920_UT	536712	0.768	0.792	0.870	0.950	0.925	0.968	0.994	1.052	0.977	0.971	0.881	0.925	0.983	1.005	0.959
UT	924_UT	443835	1.155	1.267	1.110	1.124	1.010	0.994	1.018	0.997	1.028	1.098	1.169	1.260	1.028	1.003	1.053
UT	925_UT	529813	0.822	0.825	0.847	0.908	0.859	0.846	0.816	0.831	0.812	0.876	0.764	0.605	0.844	0.830	0.833
UT	926_UT	486795	0.781	0.873	0.945	0.921	0.872	0.884	0.871	0.847	0.828	0.884	0.882	0.869	0.870	0.868	0.873
UT	929_UT	425798	0.801	0.918	0.930	0.917	0.842	0.810	0.835	0.830	0.797	0.811	0.800	0.763	0.832	0.824	0.837
UT	933_UT	499275	0.651	0.749	0.820	0.803	0.811	0.796	0.817	0.789	0.727	0.708	0.677	0.660	0.788	0.801	0.778
UT	NEW_008_UT_EC	511799	0.990	1.015	1.055	0.997	0.951	0.954	1.004	1.002	1.030	1.098	1.332	1.211	0.996	0.986	1.010
WY	956_WY	587996	0.488	0.605	0.718	0.854	0.804	0.819	0.843	0.822	0.773	0.697	0.551	0.477	0.809	0.829	0.774
WY	968_WY	531250	0.748	0.781	0.924	1.003	0.942	0.932	0.946	0.924	0.916	0.955	0.947	0.895	0.941	0.935	0.928

WY	969_WY	581080	1.139	1.075	1.063	1.102	1.018	1.040	1.025	1.127	1.194	1.269	1.237	1.204	1.094	1.064	1.101
WY	970_WY	644883	1.055	1.047	1.099	1.084	1.007	1.044	1.110	1.068	1.033	1.134	1.217	1.152	1.065	1.075	1.072
WY	971_WY	594943	0.625	0.675	0.790	0.880	0.919	0.922	0.910	0.944	0.928	0.913	0.819	0.657	0.918	0.923	0.880
WY	973_WY	564469	0.855	0.867	0.997	1.007	0.996	0.952	0.945	0.942	0.922	1.002	1.009	0.822	0.960	0.946	0.956
WY	975_WY	532575	1.137	1.171	1.014	1.048	0.967	0.965	0.953	1.019	0.977	1.104	1.149	1.209	0.995	0.978	1.018
WY	976_WY	606068	0.898	0.923	1.100	1.028	0.908	0.971	0.993	0.974	0.985	1.041	1.196	1.025	0.982	0.980	0.994
WY	979_WY	540887	1.144	1.126	1.079	1.025	1.014	1.085	1.090	1.161	1.199	1.206	1.224	1.149	1.108	1.111	1.114
WY	980_WY	571382	0.671	0.890	0.985	1.006	0.880	0.878	0.836	0.927	0.860	0.886	0.855	0.726	0.889	0.879	0.883
WY	981_WY	550682	1.197	1.015	1.028	1.053	1.040	1.152	1.206	1.272	1.316	1.269	1.356	1.356	1.191	1.211	1.185
WY	NEW_005_WY_EC	581084	0.694	0.745	0.937	0.910	0.866	0.821	0.800	0.873	0.894	0.874	0.798	0.638	0.854	0.831	0.844

Table 3: 2019 Reclamation to ET Demands crop type cross classification table.

USRB Crop Assignment	ET Demands Crop Number	ET Demands Crop
Alfalfa Hay	3	Alfalfa Hay
Corn Silage	8	Silage Corn (field corn but with truncated season)
Field Corn	7	Field Corn (moderate length season)
Field Corn or Sorghum	7	Field Corn (moderate length season)
Garden Vegetables (general)	21	Garden Vegetables - general
Grapes	25	Grapes--wine
Grapes - Wine	25	Grapes--wine
Grass Hay	4	Grass Hay
Grass Hay/Pasture	4	Grass Hay
Hemp	7	Field Corn (moderate length season)
Orchards no Ground Cover	20	Orchards - Apples and Cherries no ground cover
Orchards with Ground Cover	19	Orchards - Apples and Cherries w/ground cover
Pasture	4	Grass Hay
Potatoes (early harvest)	29	Potatoes--processing (early harvest)
Safflower	38	Safflower -irrigated
Snap and Dry Beans (fresh)	5	Snap and Dry Beans - fresh
Sorghum	60	Sorghum
Spring Grain	11	Spring Grain - irrigated
Strawberry	3	Alfalfa Hay
Sunflower	36	Sunflower -irrigated
Sweet Corn (late)	10	Sweet Corn--late plant
Turfgrass (lawns)	17	AgriMET Turfgrass
Winter Grain	13	Winter Grain - irrigated

FIGURES

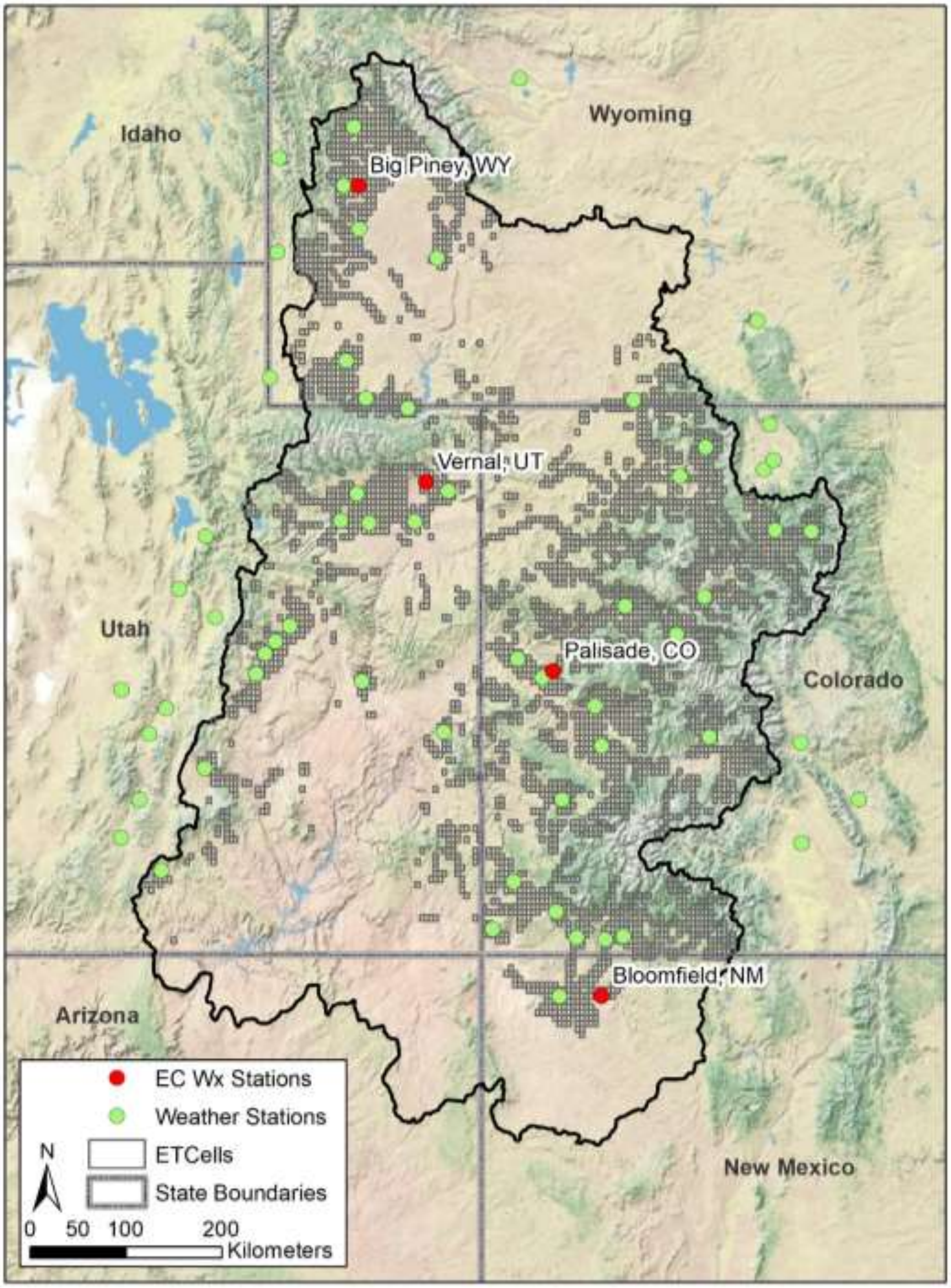


Figure 1. Map of Upper Colorado River Basin study area illustrating the hydrographic basin boundary (USGS HUC-14) and 2020 ET Demands model cells (ET Cells) for which the ET Demands model was executed to simulate crop ET and the Net Irrigation Water Requirement

assuming well-watered conditions. Three weather stations located further outside of the UCRB Basin (1 in WY, 2 in AZ) are not shown for display purposes.

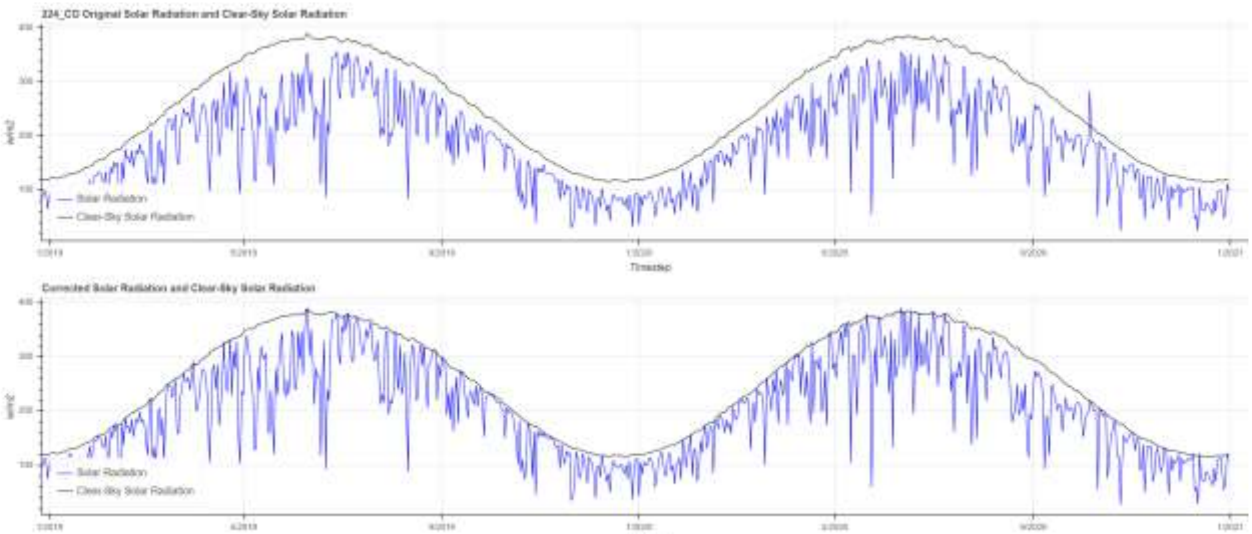


Figure 2. Example plot of measured solar radiation (R_s) and computed clear sky solar radiation (R_{so}) for pre- (top) and post-correction (bottom) datasets for Granby, CO. Notice that in both 2019 and 2020 the pre-correction measured R_s never approaches the R_{so} curve for the majority of the growing season. This sensor drift was automatically corrected for and is illustrated in the bottom graph. Also, notice the removal of a data spike in early October of 2020.

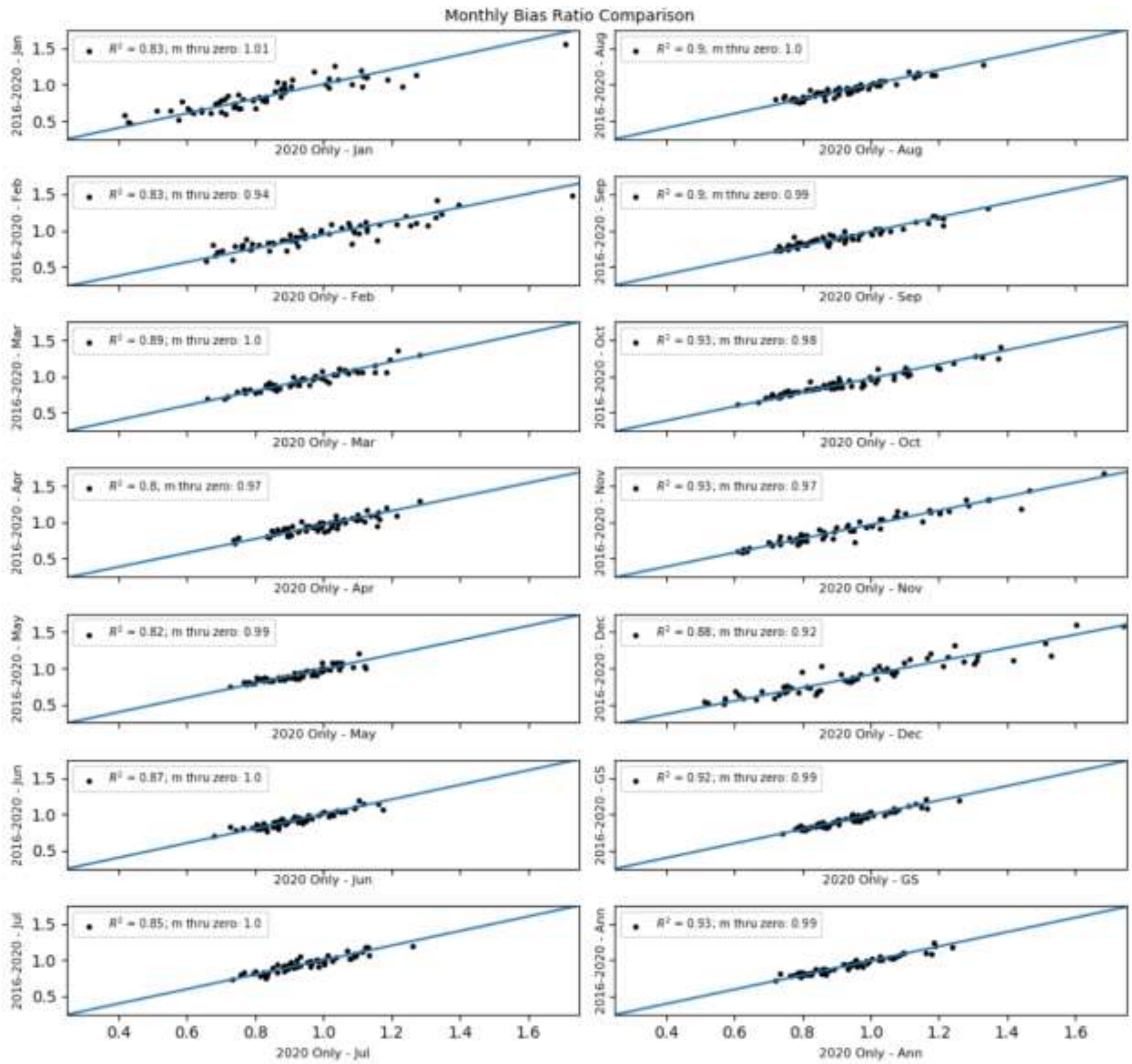


Figure 3: Comparison of ETr bias correction ratios estimated using 2020 station data and 2016-2020 data. Ratios calculated using the multiyear station record show good correlation with ratios estimated using a single year of station data and avoid issues with outliers or data gaps in shorter term records.

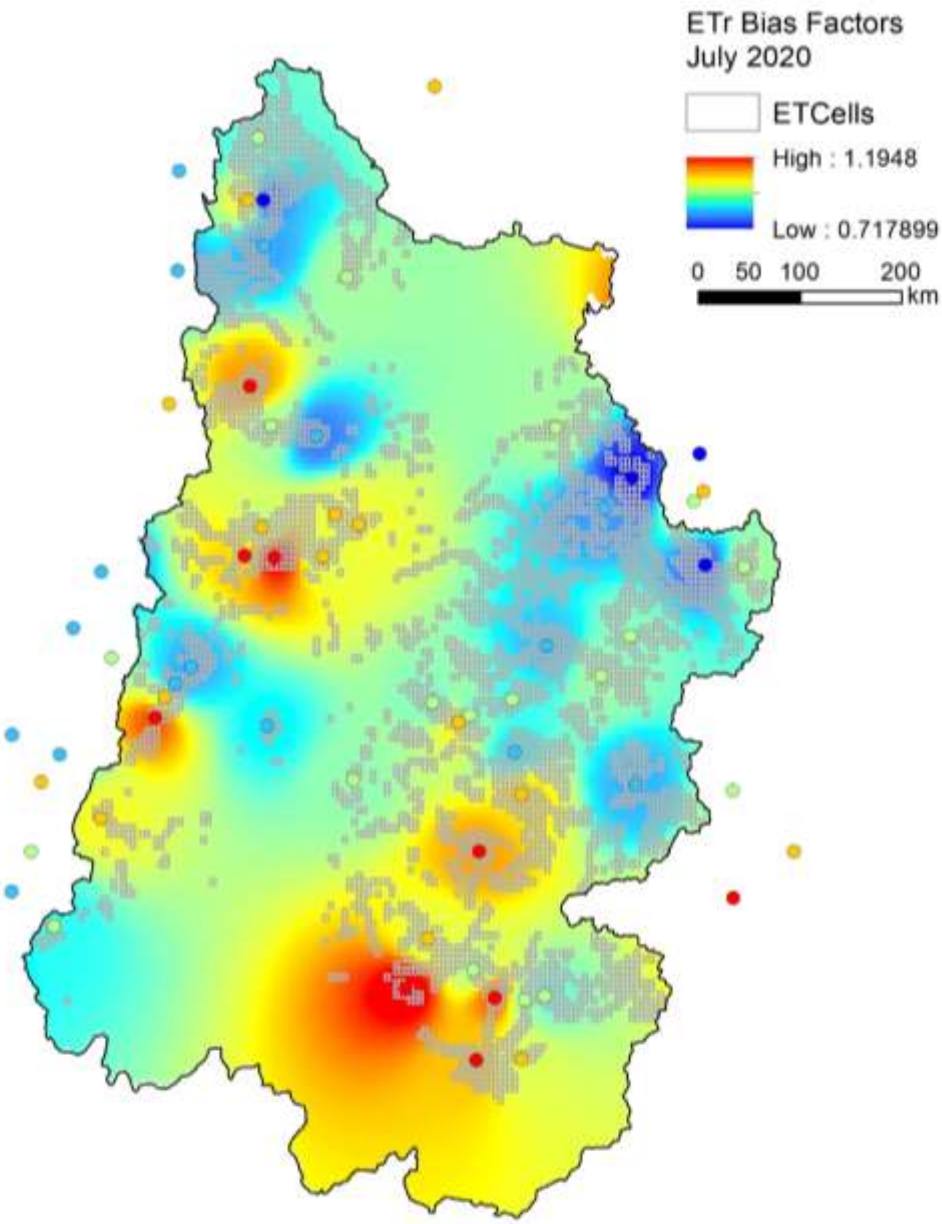


Figure 3. Map of ETr bias correction layer for July 2020. ETr bias correction layers were developed for each month by comparing agriculture weather station data from 2016-2020 with gridded weather data from gridMET. Spatial interpolation throughout the Upper Colorado Basin was based on data from 68 stations using inverse distance nearest neighbor (p=4, s=0). Three weather stations located further outside of the UCRB Basin (1 north, 2 south) are not shown for display purposes.

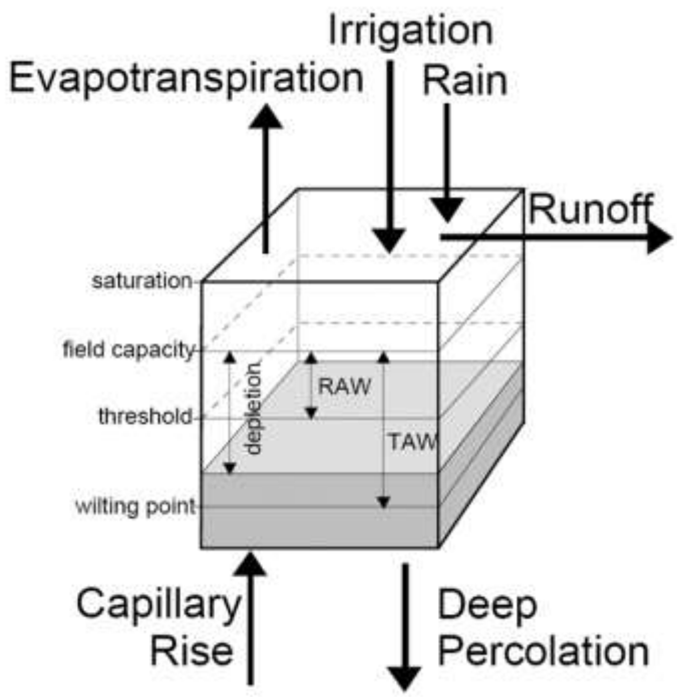


Figure 4. Schematic of the FAO-56 soil and root zone water balance adopted and used by the ET Demands model. Capillary rise in this study was assumed to be negligible. Modified from Allen et al. (1998). STATSGO attributes of available water capacity (AWC), and sand, silt, and clay fractions were used to estimate the spatial distribution of total evaporable water (TEW) and readily evaporable water (REW) used in the soil water balance, and total available water (TAW) and readily available water (RAW) used in the root zone water balance.

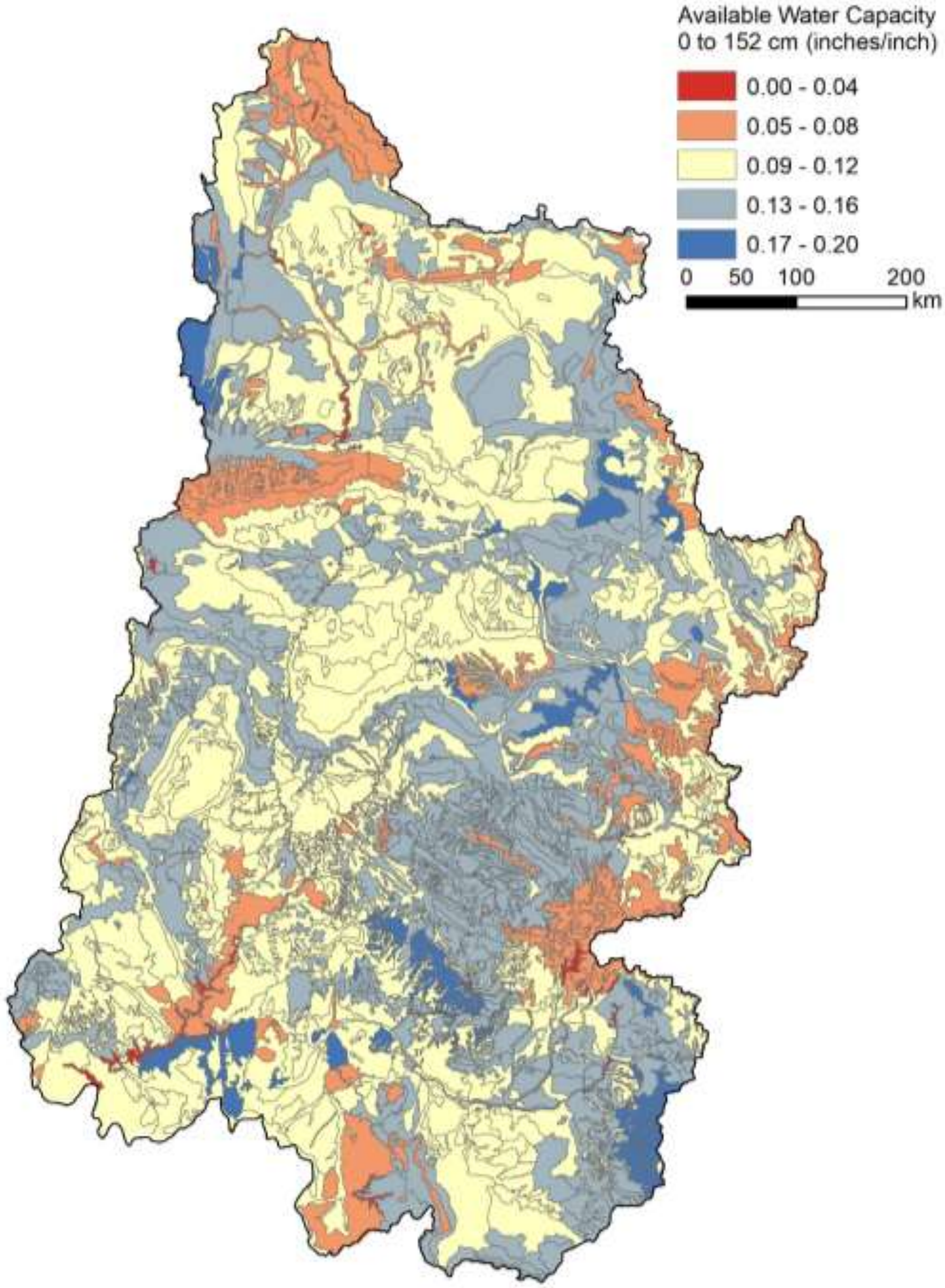
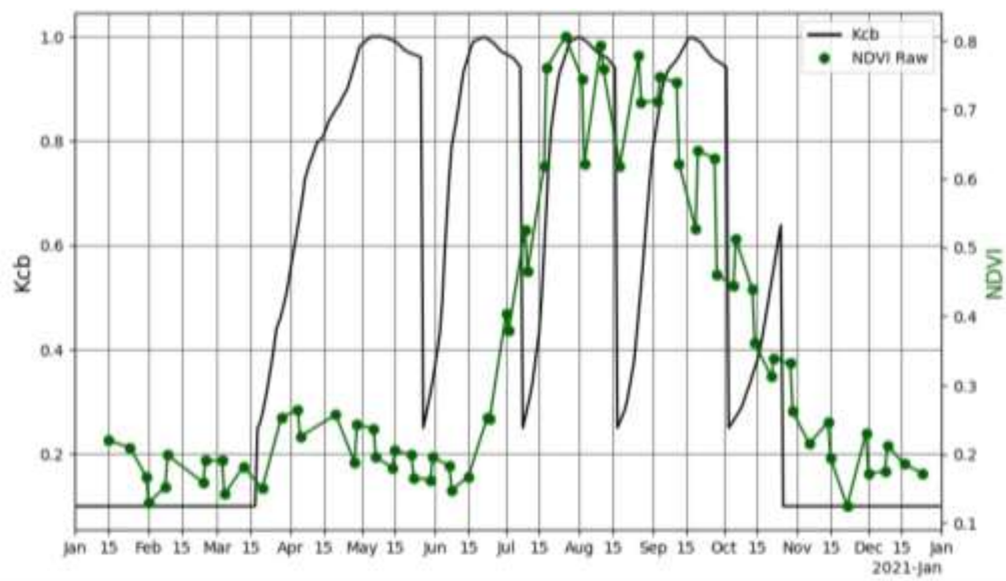


Figure 5. Spatial distribution of depth averaged (0-152cm) Available Water Capacity (AWC) from the STATSGO database.



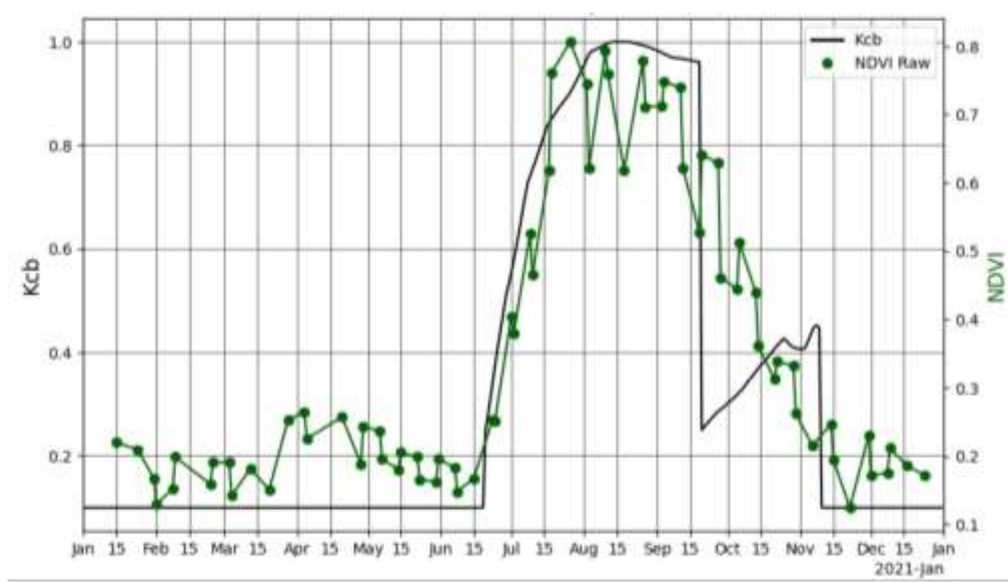


Figure 6: Top) Typical full-season ET Demands simulated Kcb timeseries alongside Landsat derived NDVI for the Bloomfield, NM eddy covariance site. Bottom) Site specific ET Demands simulation adjusted to capture non-standard growing season practices at Bloomfield, NM during the 2020 season.

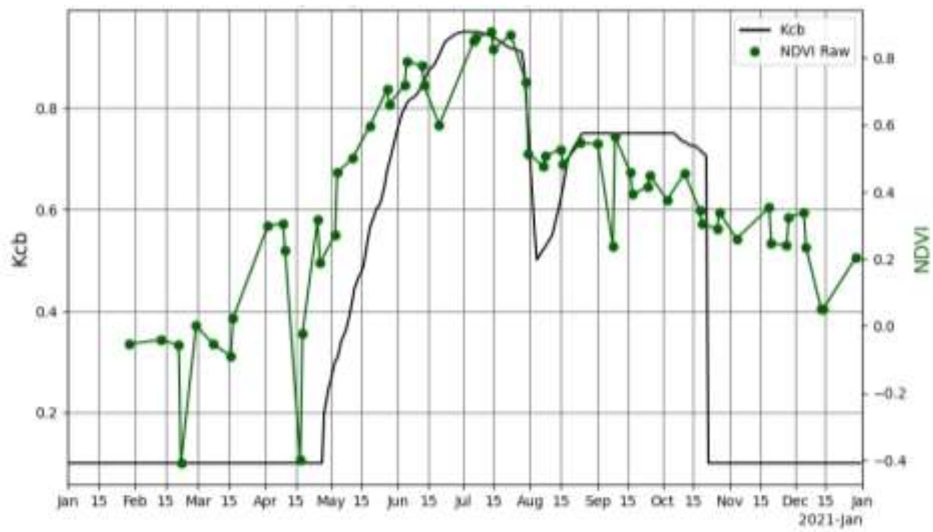


Figure 7: 2020 ET Demands simulated Kcb and Landsat derived NDVI timeseries for the Big Piney, WY grass hay eddy covariance site. Results show good agreement between NDVI and estimated Kcb crop development and timing.

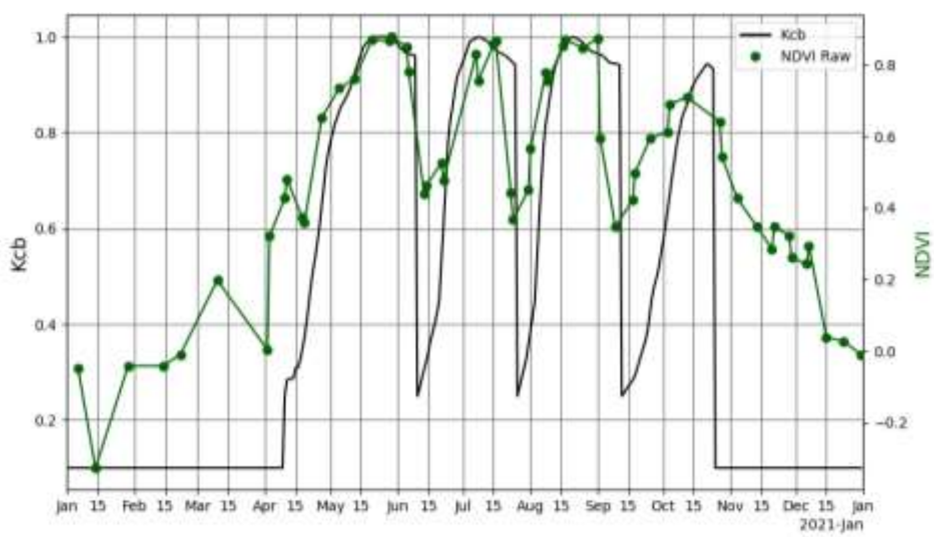


Figure 8: 2020 ET Demands simulated Kcb and Landsat derived NDVI timeseries for the Vernal, UT alfalfa hay eddy covariance site. Results show good agreement between NDVI and estimated Kcb crop development and timing.

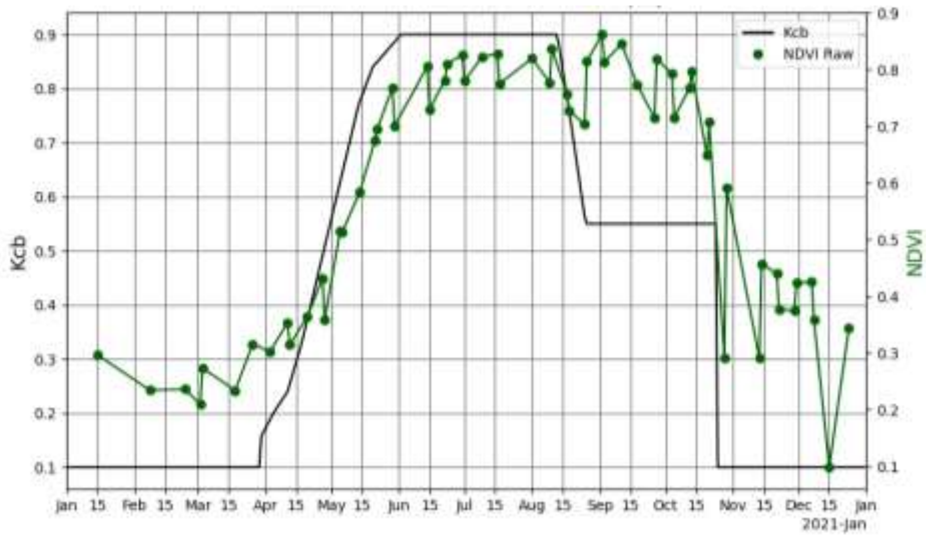


Figure 9: 2020 ET Demands simulated Kcb and Landsat derived NDVI timeseries for the Palisade, CO peach orchard eddy covariance site. Results show good agreement between NDVI and estimated Kcb crop development and timing.

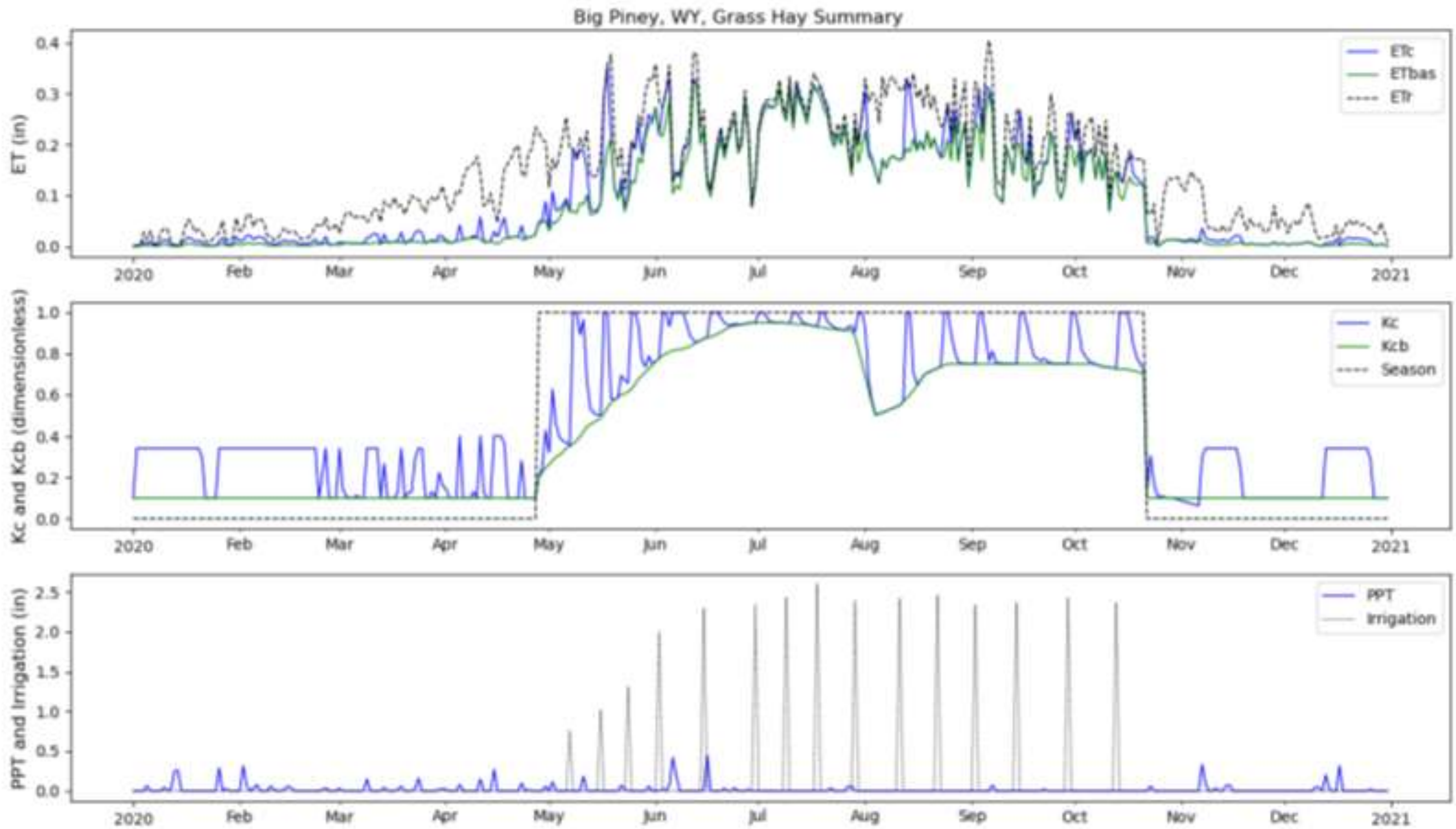


Figure 10. 2020 ET Demands model simulation of ETr, Grass Hay crop ET (ET_{act}) and basal ET (ET_{bas}) (top panel), basal crop coefficient curve (K_{cb}), total crop coefficient curve (K_c), and growing season (middle panel), and simulated irrigations and precipitation for ET cell 581084, located near Big Piney, WY. The simulated Kc curve, irrigations, and estimated precipitation are shown to illustrate the development of the Kc curve, and response of the K_c curve and ET_{act} due to wetting events from precipitation and simulated irrigation events.

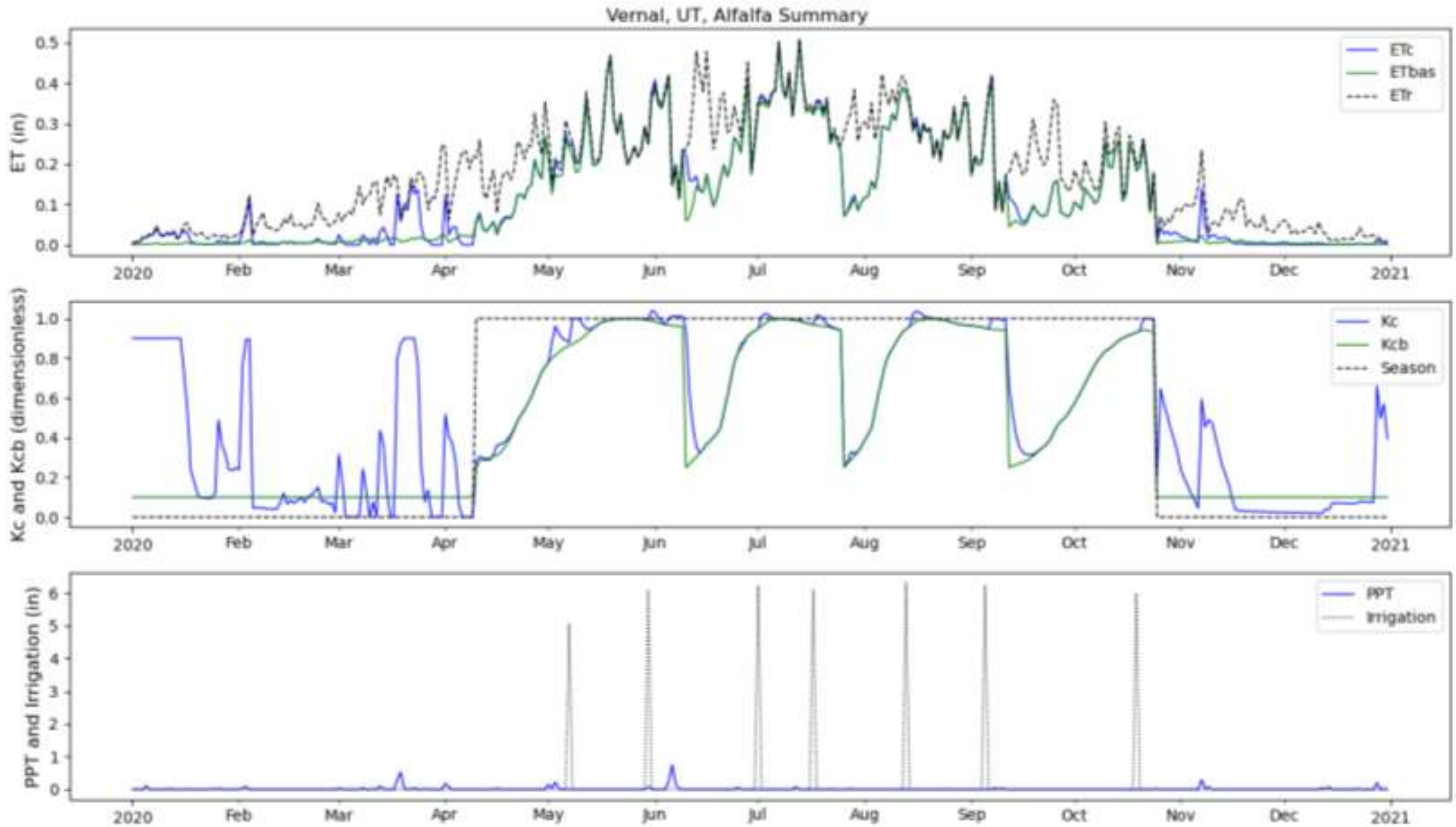


Figure 11. 2019 ET Demands model simulation of ETr, Alfalfa crop ET (ET_{act}) and basal ET (ET_{bas}) (top panel), basal crop coefficient curve (K_{cb}), total crop coefficient curve (K_c), and growing season (middle panel), and simulated irrigations and precipitation for ET cell 511799, located near Vernal, UT. Note the progression of Kcb curve shape throughout the season (see pg. 49 of [Evapotranspiration and Net Irrigation Water Requirements for Nevada](#) report).

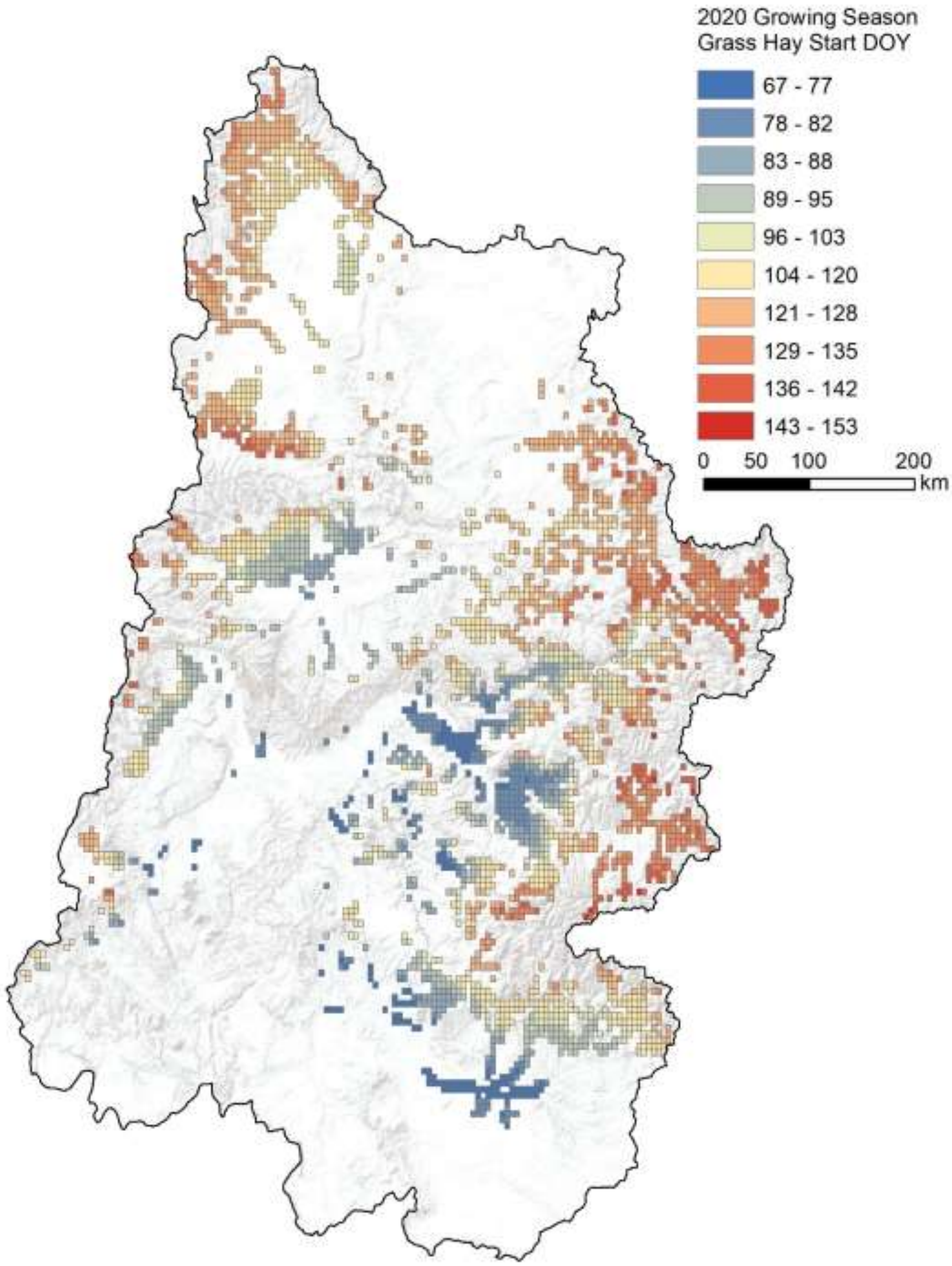


Figure 12. Map of 2019 growing season start dates as Day of Year (DOY) for grass hay.

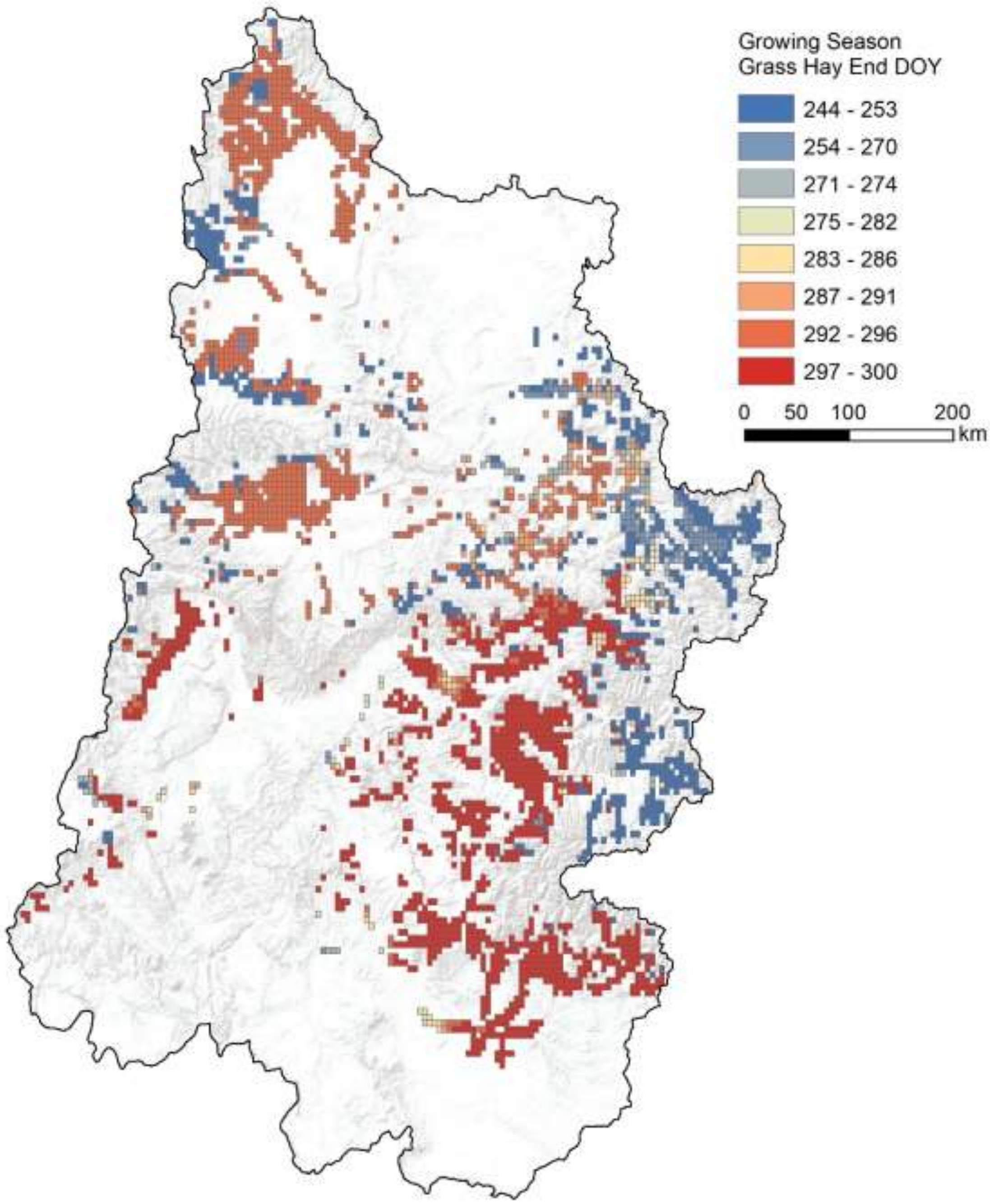


Figure 13. Map of 2019 growing season end date as Day of Year (DOY) for grass hay.

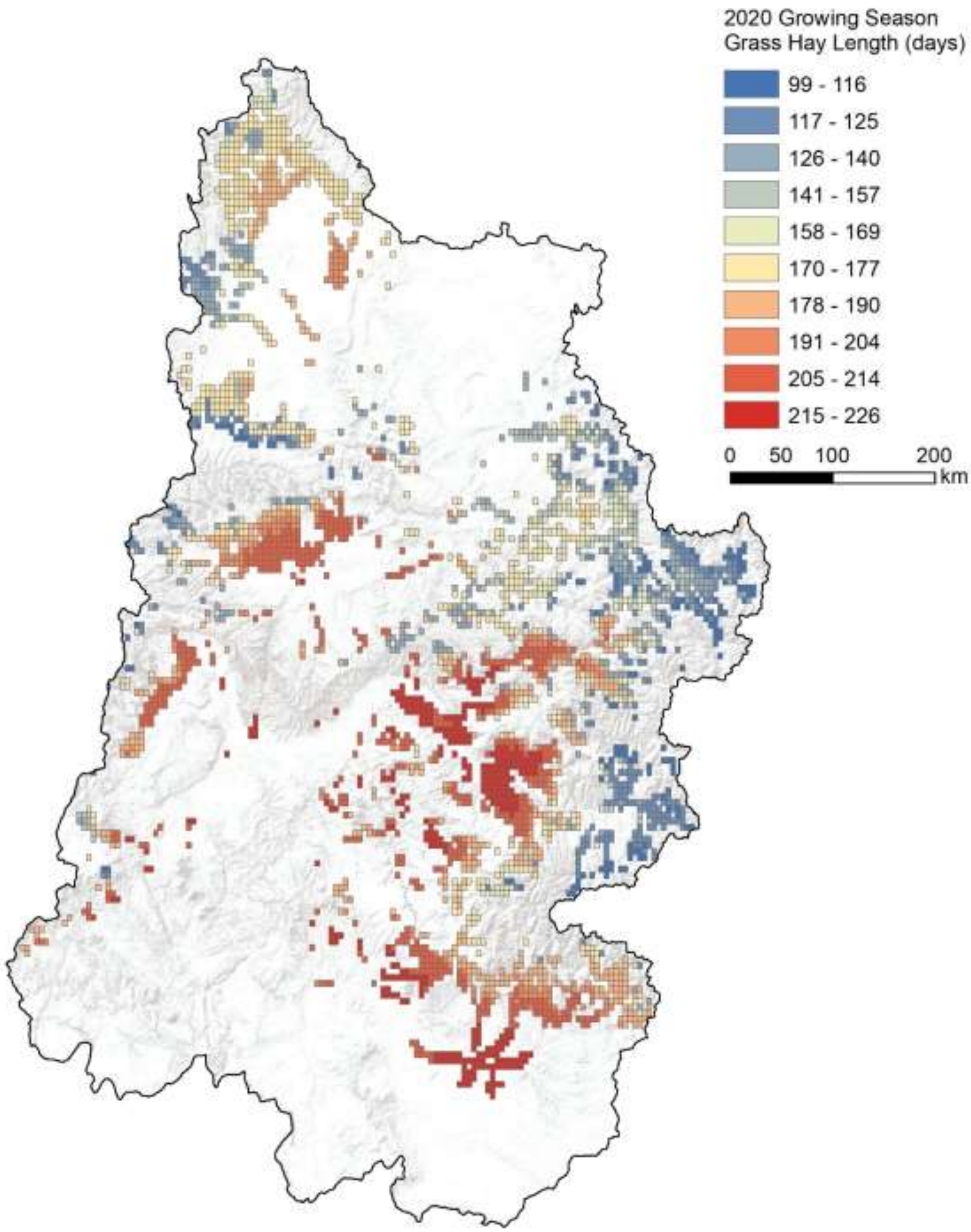


Figure 14. Map of 2019 growing season length (# of days) for grass hay.

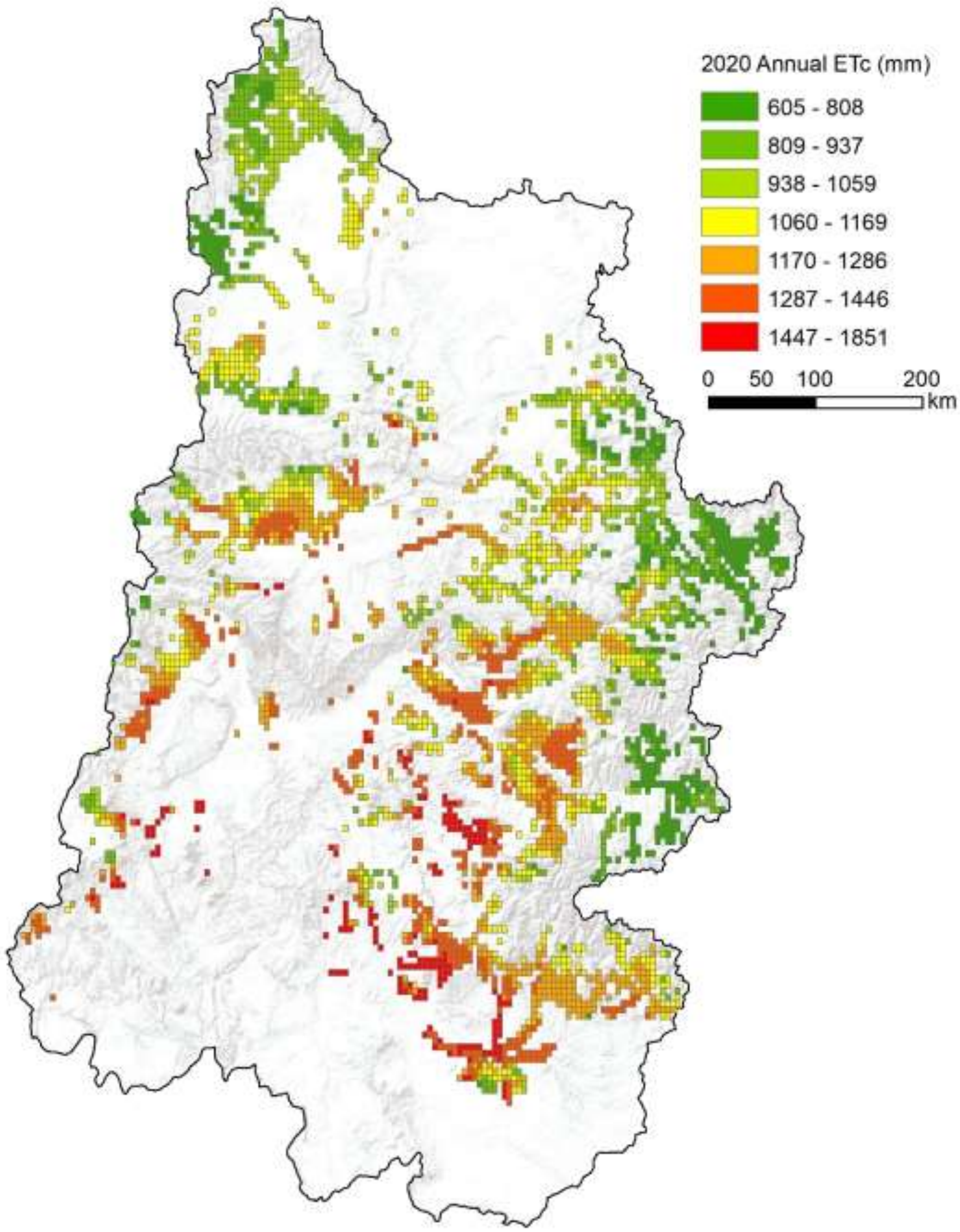


Figure 15. Spatial distribution of annual crop weighted actual crop ET (ETc) for 2020.

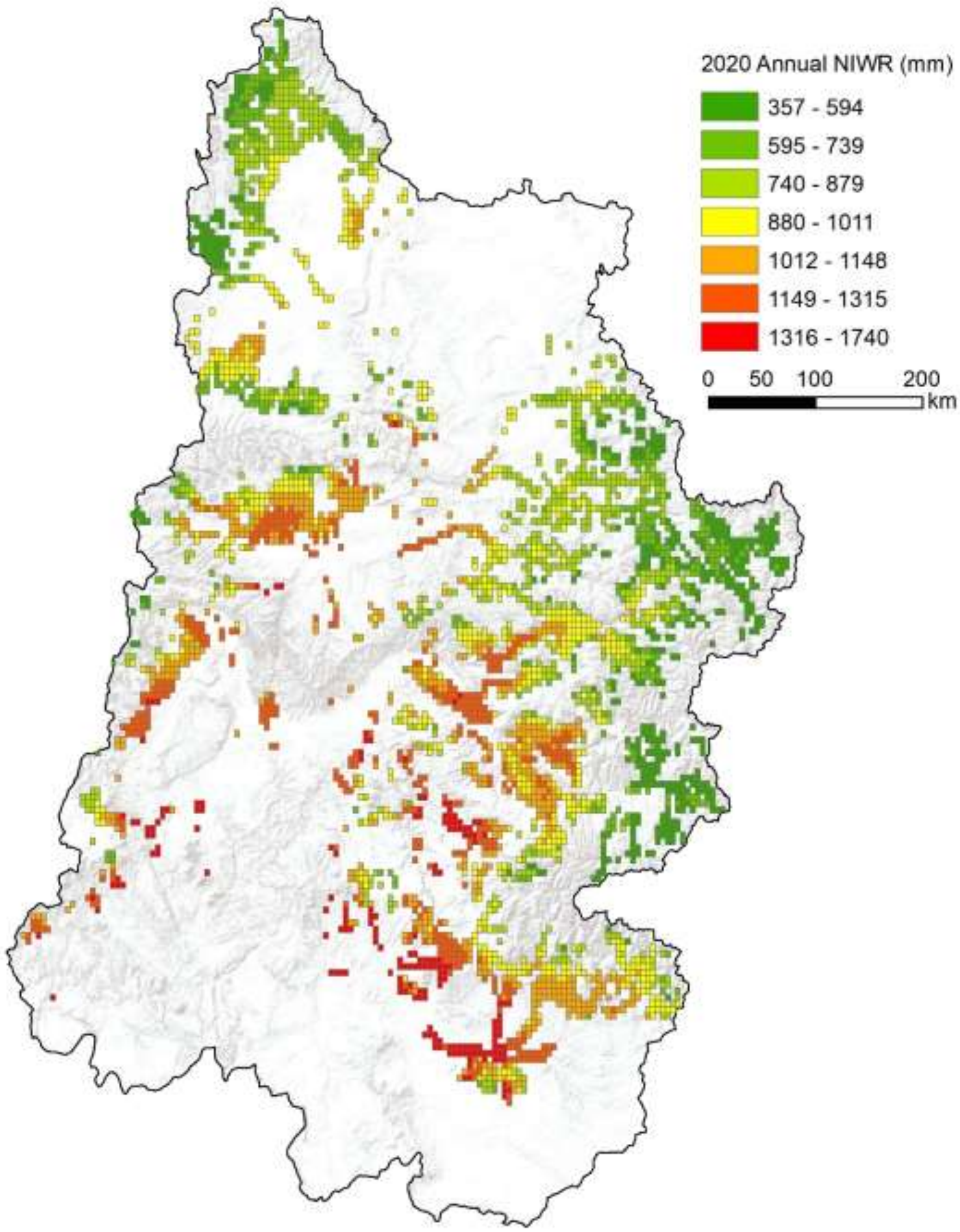


Figure 16. Spatial distribution of annual crop weighted NIWR for 2020.

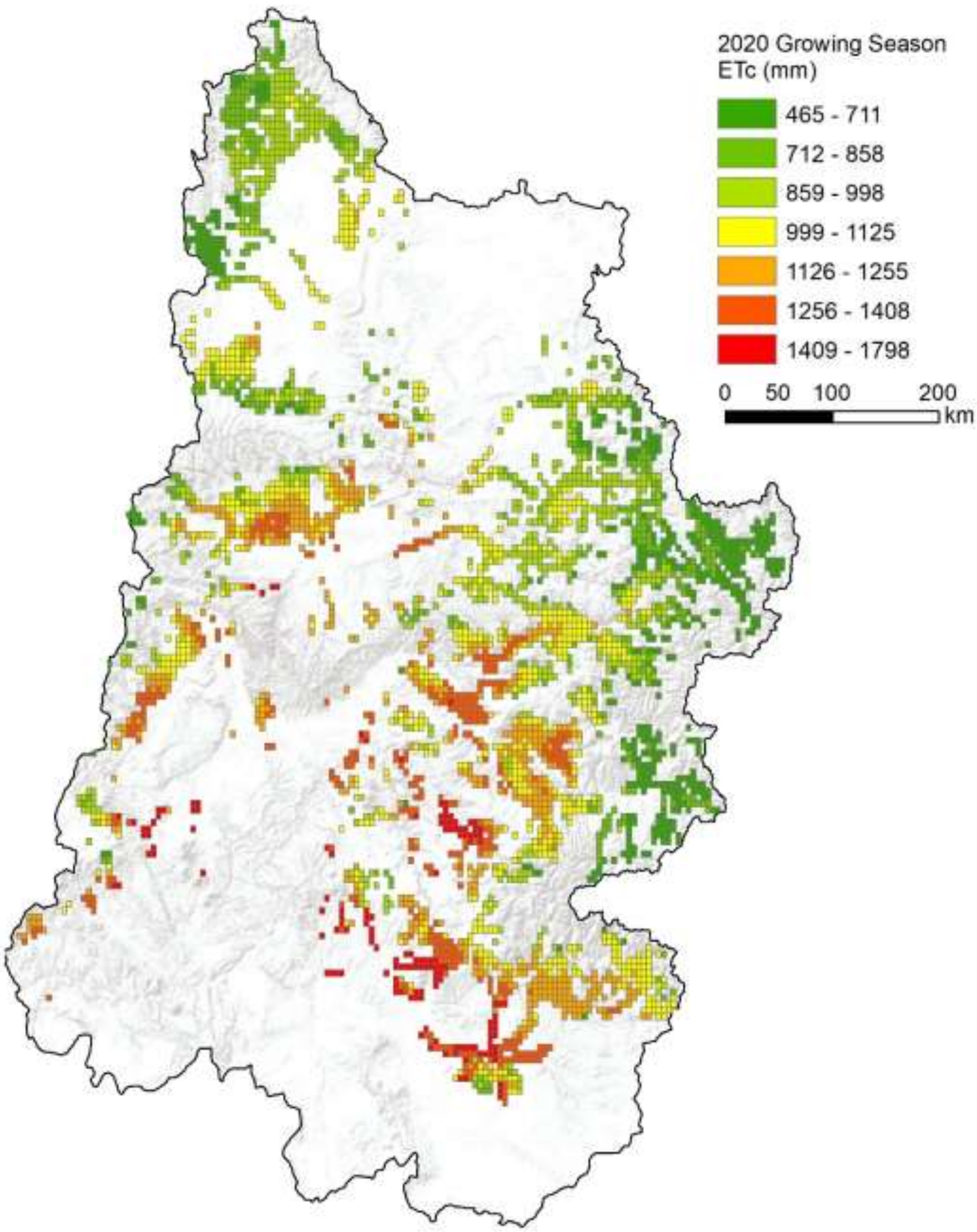


Figure 17. Spatial distribution of growing season actual crop ET (ETc) for 2020.

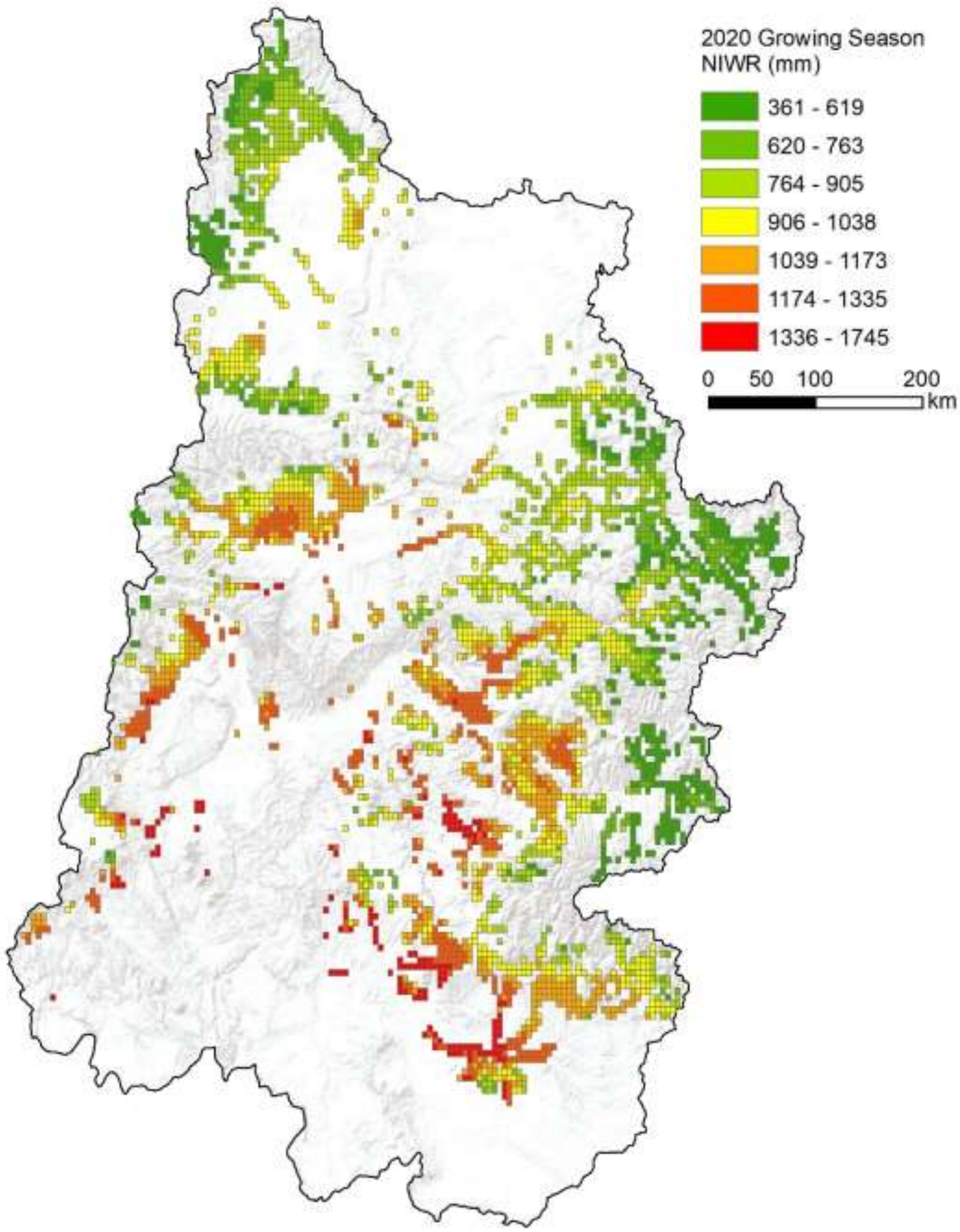


Figure 18. Spatial distribution of growing season NIWR for 2020.

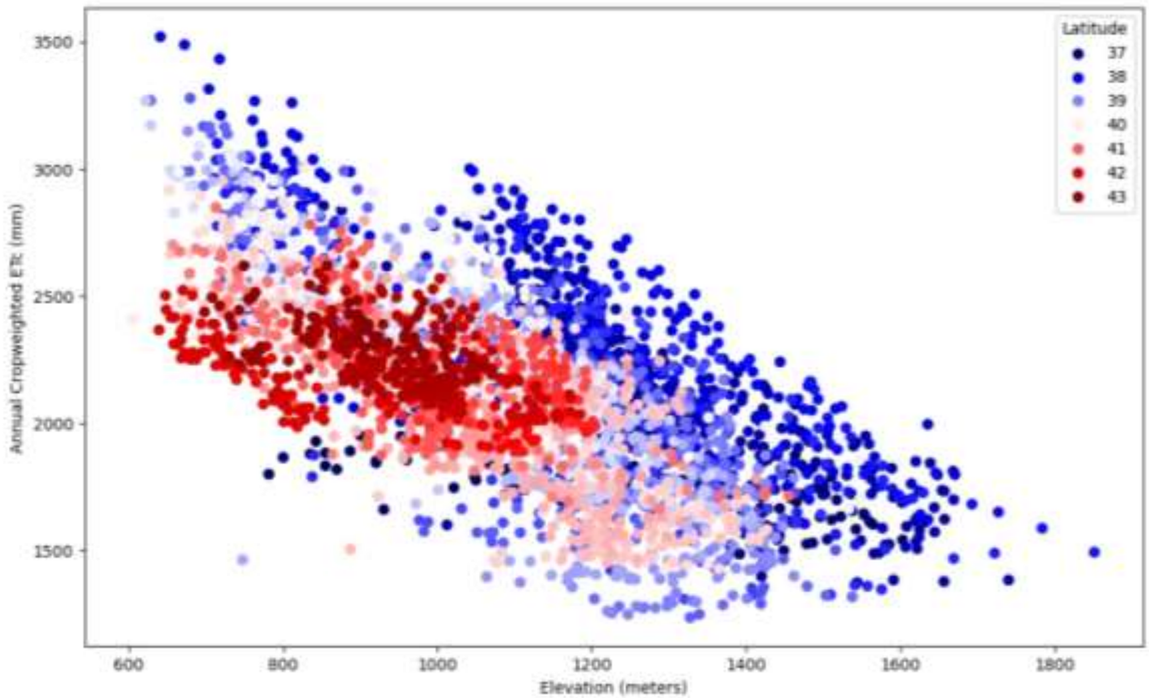


Figure 19: Figure of annual crop weighted ETc versus Elevation + Latitude. Multiple linear regression between ETc ~ Elevation + Latitude shows that approximately 64% of ETc spatial variability throughout the UCRB can be explained by elevation and latitude alone (r-squared=0.647).

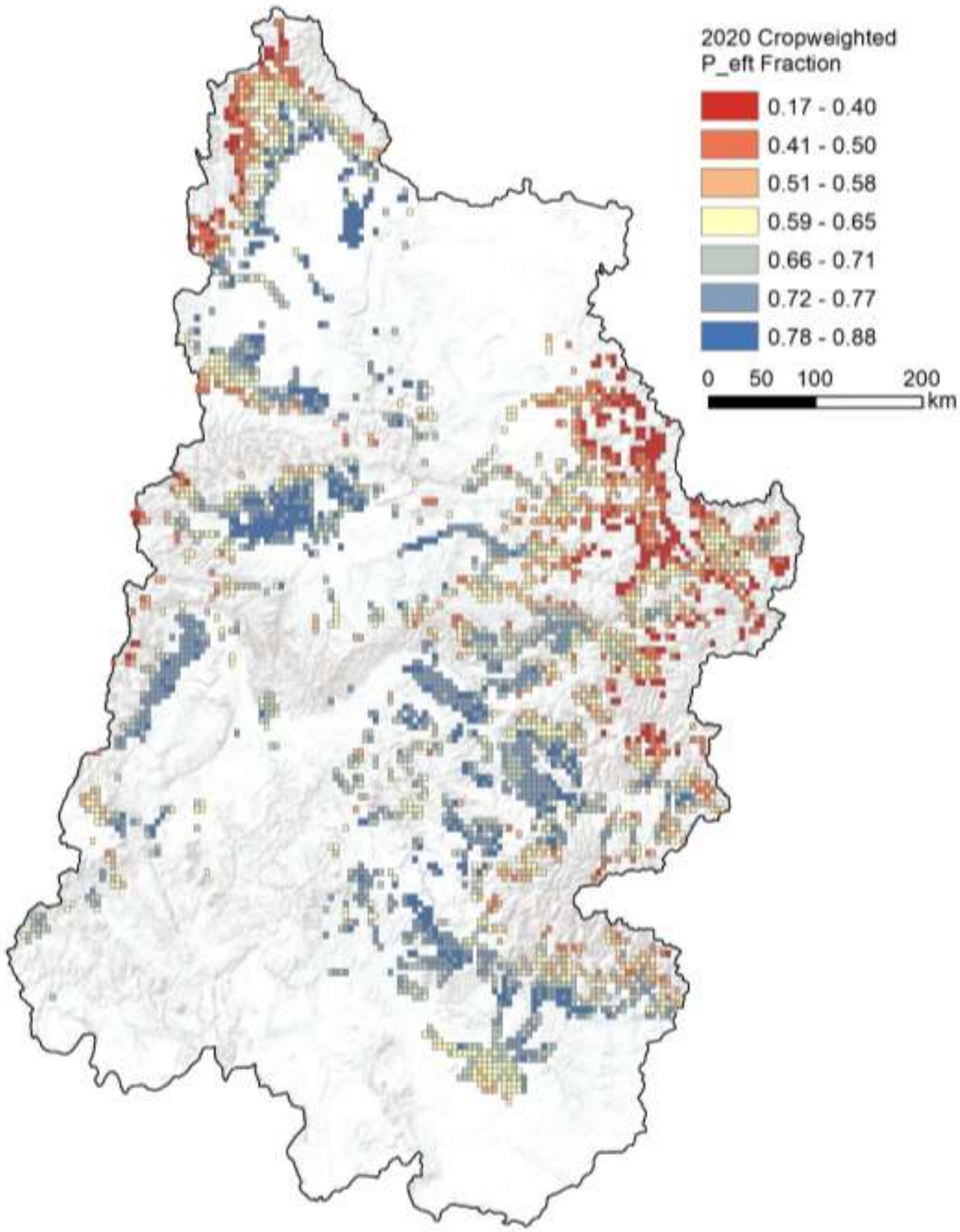


Figure 20: Map of crop weighted P_eft effectiveness fraction for 2020 calendar year. The P_eft fraction represents the fraction of total annual precipitation that is available for transpiration.

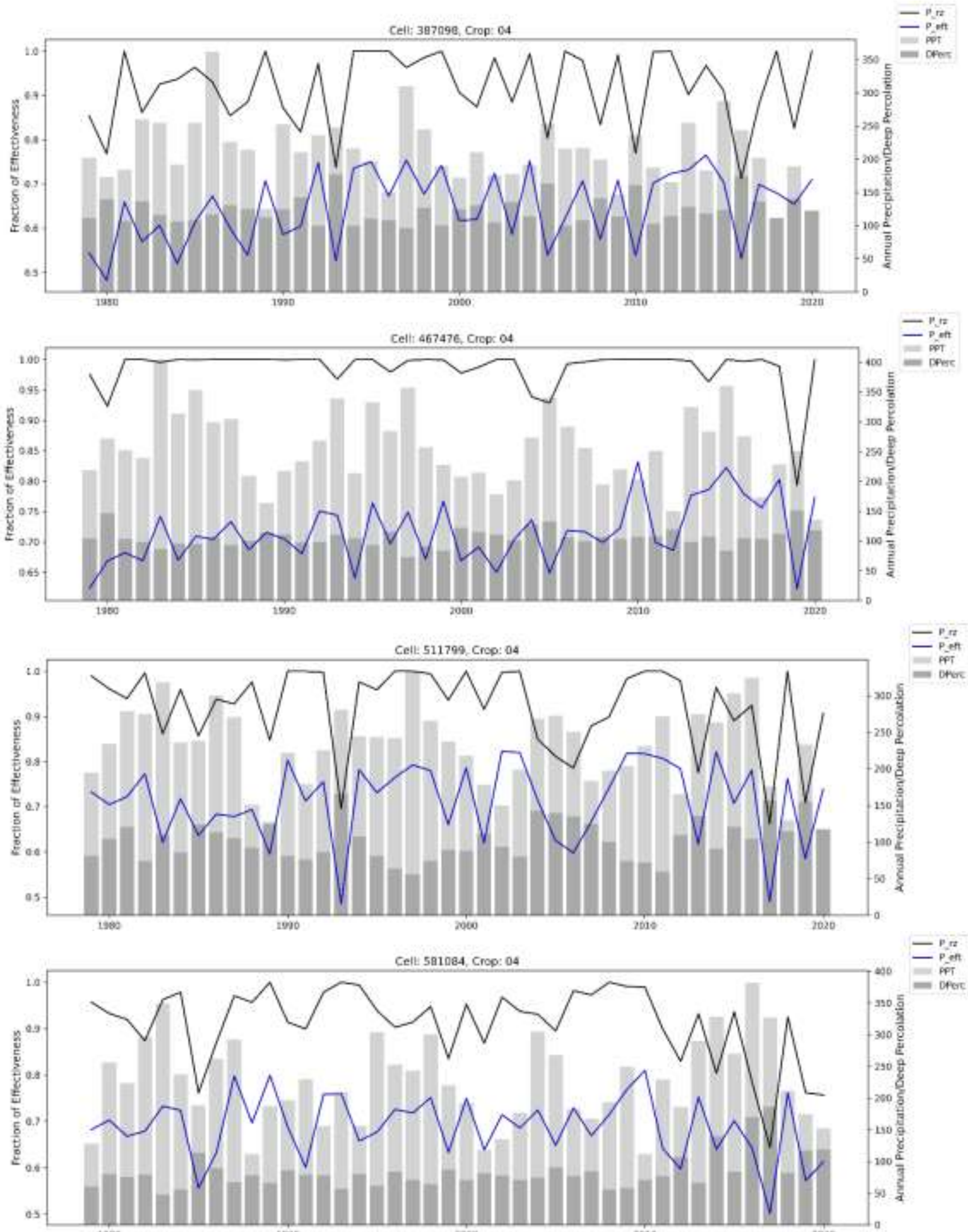


Figure 21: Time series of annual precipitation (PPT), deep percolation (DPerc), and effective precipitation fractions (P_rz: precipitation residing in the root zone, P_eft: precipitation residing in the rootzone available for transpiration) for grass hay (Crop 04) at the ET Demands model grid cells coincident with consumptive use study eddy covariance stations. From top to bottom, plots represent Bloomfield, NM, Palisade, CO, Vernal, UT, and Big Piney, WY ET Cells. Note that precipitation is not shown in years where deep percolation is greater than precipitation.