Estimation of Actual Evapotranspiration using Eddy Covariance

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Abstract

Estimating the consumptive use (CU) of "high-elevation" grass hay fields and pastures is an important research topic, given that these lands dominate irrigated areas of the Upper Colorado River Basin. This region is experiencing ongoing drought and aridification, and there is an increasing need to accurately estimate CU on these fields during periods of severe water stress and reduced irrigation. To achieve this, a micrometeorological tower for collecting ground-based measurements was installed on a field where irrigation practices, soil conditions and grass species are considered representative of the surrounding areas. Irrigation on this field was curtailed for a full season in 2020 and then returned to historic irrigation practices in 2021. Measurements from the tower taken between June 18, 2020 and October 20, 2023 were used to estimate evapotranspiration (ET) through the eddy covariance (EC) technique. This data was then compared to ET estimates from remote sensing-based models. The conclusions drawn from this research are: (1) irrigation withdrawal significantly reduces ET rates during the growing season by as much as 67% compared with a prior year reference; (2) diminishment of ET is intensified as the season progresses into warmer months and then lessens as the surrounding environment cools; (3) conserved CU is possible to achieve at rates between 33-67% compared to reference conditions depending on the month of evaluation when full-withdrawal is applied; (4) overall, the EC method is a necessary resource for understanding ET rates on high-elevation pastures, since weather-based representations can overestimate ET when comparing to the EC method. Continued study of this field as well as other high-elevation pasture locations using the EC method should be included in planning for water conservation programs and CU inventory evaluations, as the installation of this tower in Kremmling, CO has been proven highly valuable to the estimation and verification of CU in the Upper Colorado Basin.

1. Introduction

Estimating the consumptive use (CU) of "high-elevation" grass hay fields and pastures is a critical research topic, given that these lands dominate irrigated areas of the Upper Colorado River Basin in the State of Colorado (MWH Americas, Inc., 2012; Cabot et al., 2017). The term "high-elevation" is applied to alpine pastures above 1,828 m (6,000 ft) MSL (Brummer et al., 2011). The need for additional research on this topic has been stated previously (URS, 2013). Given the importance of estimating CU in these managed ecosystems, particularly during severe water stress, micrometeorological instrumentation for collecting ground-based data was installed at a location where irrigation experienced a full season of withdrawal in 2020 and then a return to irrigation in 2021. Measurements were then applied to the eddy covariance (EC) technique for estimating evapotranspiration (ET) through water vapor fluxes in order to evaluate the results from remote sensing-based ET models. Having been observed to estimate ET less reliably when field data are unavailable (Al Zayed et al., 2016), geospatial models that use remotely sensed satellite data are improved by comparison with ground-based micrometeorological data.

Several EC flux tower sites exist in Colorado already, in some cases collecting data for grass hay fields and pastures under irrigated conditions (Wilson Water Group, 2015). This project was initiated with the intent to address an important knowledge gap, however, by obtaining EC data under the rare circumstance where three important conditions existed, those being: 1) high-elevation > 1,828 m (6,000 ft) MSL, 2) large areal coverage of an 82 ha (203 ac) irrigated pasture, and; 3) subjected to full-season irrigation cutoff. The combination of these conditions represents a likely tactic in the portfolio of management adaptations that are needed to address the shortage of water supply on the Upper Colorado River. Comparing EC data from this project's study location with remote sensing-based ET model results is intended to contribute to better estimation of CU rates on irrigated grass hay fields and pastures and verification of assumptions regarding the amount of CU conserved under irrigation withdrawal and foregone diversion programs.

2. Materials and Methods

An EC system measures the vertical water vapor flux from an ecosystem as the covariance of the vertical wind and water vapor density. Essentially, it measures the transport of water vapor by the up and down motions of turbulence above the surface. The vapor flux represents the evapotranspiration (ET) from the nearby upwind surface. The EC instrumentation for this project was installed on June 18, 2020 and operated through October 20, 2023 on the irrigated pasture surface in Kremmling, CO during a period of irrigation withdrawal. The system was hibernated during the winter months of 2020 – 2023 then restored to full operation in April-May after which data was collected until mid-October depending on access to the site. The system was installed where irrigation practices, soil conditions and grass species are considered representative of the surrounding area of interest to future water-sharing and drought resilience programs.

2.1 Experimental Site and Instrumentation

Ground-based measurements were collected at a field north of Kremmling, CO coded as GPRT1H; 40°08'55.0" N, 106°27'11.0" W, nd 2,316 m (7,600 ft) MSL (Figure 2.1.1). The circle in this figure denotes a radius or "fetch" of 984 ft (300 m) around the tower on which the EC measurement sensors are installed. In this case there was adequate fetch from any wind direction, and fluxes could be calculated under any conditions.

The EC tower is equipped with instrumentation to directly observe the exchanges of gas, energy, and vapor between the Earth surface and the atmosphere (Figure 2.1.2). These observations are taken to measure the fluxes of sensible and latent heat by eddies in the lower atmosphere. In doing so, the EC technique can provide accurate estimates of ET over footprint areas of several acres (Allen et al., 2011; Glenn et al., 2015). The EC instrumentation enables estimates of water vapor fluxes and ET using: 1) an integrated open path infrared gas analyzer and three-dimensional sonic anemometer, commonly referred to as an IRGASON® (Campbell Scientific Inc., Logan, UT), 2) four way net radiometer (NR01, Hukseflux, Delftechpark, Netherlands), 3) aspirated unit for air temperature and humidity of (Apogee Instruments, E + E Elektronik, Logan, UT), 4) soil heat flux plates (REBS Inc.) and soil temperature and time domain reflectometer (TDR) water content probes (Acclima, Meridian, ID), 5) CR6 (Campbell Scientific) data logger, 6) tipping bucket rain gage (Texas Electronics), 7) solar panel-battery power system, and 8) cell signal telemetry. Hourly summary data are examined remotely by an experienced technician to identify problem data due to water drops, insects, or sensor malfunction. During early spring and late fall, the tower is surrounded with fencing to prevent damage from grazing cattle.

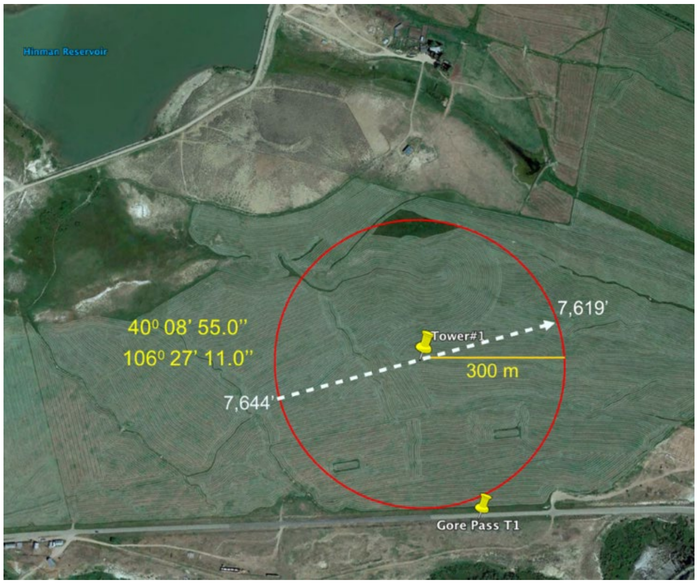

Figure 2.1.1. Eddy covariance tower location and surrounding fetch.

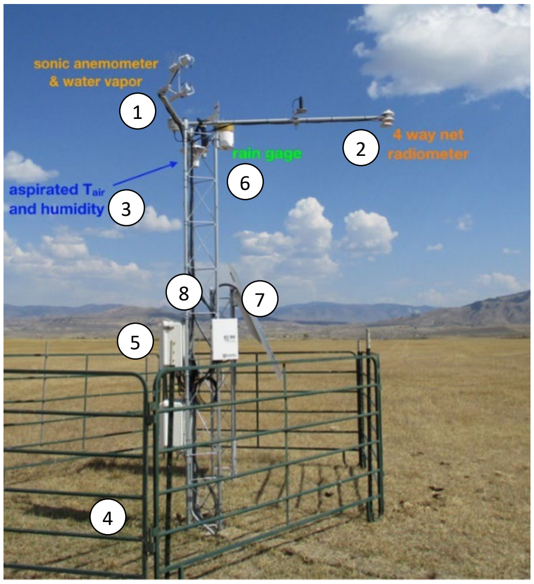

Figure 2.1.2. Eddy covariance tower instrumentation.

The IRGASON® piece of equipment is used to simultaneously measure absolute carbon dioxide and water vapor, along with air temperature, barometric pressure, and three-dimensional wind speed and sonic air temperature. The system provides measurements of absolute densities of carbon dioxide and water vapor, while the sonic anemometer measures orthogonal wind components, thus, synchronizing gas and wind data for the calculation of fluxes using the eddy covariance method (Campbell Scientific, 2015). The net radiometer consists of four separate sensors arranged in a way that allows it to measure both incoming and outgoing radiation. Incoming and outgoing radiation measurements, combined with other meteorological data, serve as essential components in eddy covariance systems, enabling the estimation of evapotranspiration rates by contributing to the energy balance and Bowen ratio calculations. The aspirated unit improves the accuracy of air temperature and humidity measurements by actively drawing or aspirating air across temperature and humidity sensors to minimize the impact of various environmental factors, such as radiation, heat sources, or moisture. The soil heat flux plates measure the flow of heat energy into or out of the soil surface, helping to understand the energy balance and heat transfer processes within the soil.

The standard practice when using EC measurement is to mount the sensors at a height that ensures readings are taken within a representative local surface layer (Brutsaert, 1982; Schuepp, et al., 1990). The area of coverage monitored by the instrumentation is approximately 100 horizontal meters of surface layer for every 1 vertical meter of height that the sensors are mounted. In other words, a height to fetch (horizontal distance covered) ratio of 1:100 can be used when selecting a sensor mount height. In this study, an advanced footprint model developed by Kljun et al. (2015) was run to quantify the size and shape of the upwind footprint from which the EC measured the fluxes. Along with area, fetch requirements for reliable EC measurements are that the study fields should be homogeneous and flat, with no abrupt changes in vegetation height (Tanner, 1988), which are conditions to which this field easily adheres (Figure 2.1.3). These requirements were easily accommodated within this 82 ha (203 ac) study field which is large enough to allow a fetch distance of 300 m (984 ft) to cover a local surface layer of 28.2 ha (69.8 ac). The large area sensed by the tower used in this project, therefore, significantly improves the representativeness and credibility of the EC measurements of ET in this study, under irrigation withdrawal and subsequent resumption of watering (Figure 2.1.4).

Figure 2.1.3. Eddy covariance tower location in Kremmling, CO on a field where irrigation was stopped for the entire season in 2020.

Figure 2.1.4. Eddy covariance tower location in Kremmling, CO on a field where irrigation was stopped for the entire season in 2020, showing grass forage recovery.

2.2 Eddy Covariance Corrections

Other corrections to the flux calculations include: rotating the coordinate system to force the mean vertical wind to zero to address any tilt errors of the sonic anemometer, determining the correct value of various atmospheric properties, and considering buoyancy effects of water vapor on the fluxes. These are discussed in Massman and Lee (2002).

2.3 Energy balance closure of eddy-covariance measurements

In an ideal case, the energy fluxes at the surface follow the principle of conservation of energy, expressed by the surface energy balance equation (1):

$$R_n - G = LE + H \tag{1}$$

where R_n is the net radiation, LE is the latent heat flux, H is the sensible heat flux (both positive upwards), and G is the ground heat flux (positive downwards). All components are expressed in Watts/m^2. The minor flux terms such as canopy energy storage and photosynthetic energy conversion are neglected. Since each of these fluxes is determined independently, the energy balance equation can be checked, which provides useful information about the self-consistency and reliability of the flux estimates. In an ideal circumstance with no errors of measurements, the left side of (1) which represents available energy would balance the right side, which is the use of the energy to power heat flux and evaporation of water (ET). The ratio of interest is then depicted by equation (2):

$$\frac{H + LE}{R_n - G} \tag{2}$$

The ratio (2) would equal 1.0 in the ideal case. The actual ratio is usually < 1.0, however, since any error reduces a covariance, and the fluxes are covariances. Thus, some underestimation of the fluxes of H and LE is to be expected. When the value for (2) is < 1.0, the issue is whether to force it to close by adding to the underestimated fluxes. While estimates of ET from the EC technique are considered a highly reliable standard for reference data to compare against the results of remote sensing-based ET modeling (Miralles et al., 2011; Senay et al., 2020), the specific issues that arise due to inadequate energy balance closure and scale differences between the flux footprint and the model pixels must still be addressed. A common approach to “forcing” the balance of energy is to add to the value of H and LE according to their relative size (H/LE) to force (1) to be balanced.

2.4 Comparison to Potential ET (ETp)

Potential ET (ETp) was calculated using measured data from the CoAgMet station northeast of Kremmling, CO at 40°06’55.44” N,106°16’58.80” and 2,296 m (7,534 ft) MSL. The alfalfa reference crop ET (ET_r) was calculated in mm/day using the ASCE Standardized Reference Evapotranspiration Equation (ASCE-EWRI, 2005) shown below.

$$ET_r = \frac{0.408\Delta(R_n - G) + \gamma \frac{C_n}{T + 273} u_2(e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)} \tag{3}$$

The ET of grass hay was then estimated by multiplying reference crop ET by a crop coefficient (K_c = 0.87). The K_c is the fraction of the reference crop ET that is used by the actual crop.

3. Results

ET rates display seasonal patterns reflecting the irrigation withdrawal in 2020 and its resumption in 2021 through 2023 (Table 3.1). Table 3.1 reports average daily evapotranspiration (Avg ET, in/day) and total monthly evapotranspiration (Total ET, in/mo) for each month and year (2020–2023), allowing comparison of seasonal water use under restricted and fully irrigated conditions. Although June 2020 ET rates are reported, they include only data from June 18–30, the period following the EC tower's installation. Without a complete month, cumulative figures were not computed.

Table 3.1. Average and total monthly ET estimated by eddy covariance (Kremmling, CO).

Month	2020		2021		2022		2023	
	Avg ET *(in/day)*	Total ET *(in/mo)*	Avg ET *(in/day)*	Total ET *(in/mo)*	Avg ET *(in/day)*	Total ET *(in/mo)*	Avg ET *(in/day)*	Total ET *(in/mo)*
Apr			0.06	1.77	0.07	0.59		
May			0.09	2.71	0.11	3.27	0.16	2.49
Jun	0.13		0.20	5.98	0.21	6.44	0.22	6.62
Jul	0.10	3.16	0.21	6.41	0.21	6.59	0.23	7.28
Aug	0.06	1.91	0.18	5.72	0.17	5.29	0.19	5.86
Sep	0.04	1.16	0.07	2.12	0.09	2.63	0.08	2.52
Oct	0.02	0.34	0.04	1.02	0.07	2.07		

The average daily ET for each month (Avg ET) and the total ET for each month were calculated, along with the Δ Average ET comparing 2020 vs. 2021, 2022, and 2023. The restricted 2020 season showed markedly lower ET rates, particularly in July and August, when average daily ET was less than half the values observed in subsequent years. The reduction in actual evapotranspiration (ETa) during the water-use withdrawal illustrates the impact of decreased irrigation (Figure 3.1). In the following years, ETa rates remained subdued until the initial irrigation, likely due to lower-than-expected soil moisture compared to a fully irrigated season

By 2021, ET rebounded strongly, with July (+103%) and August (+200%) nearly doubling or tripling compared to 2020; September also rose sharply (+83%) and October more than tripled (+200%), reflecting a rapid response to resumed irrigation.

In 2022, ET levels stabilized, with mixed trends: July rose slightly (+3% over 2021), August declined (–7.5%), while September (+24%) and October (+103%) increased further. By 2023, midsummer ET strengthened again, with July (+10.5%) and August (+10.8%) higher than 2022, although September declined slightly (–4%). Relative to 2020, however, the recovery was striking, with July up +130% and August up +207%. Overall, these results highlight a sharp rebound following withdrawal, followed by gradual stabilization and continued variability shaped by seasonal and site-specific conditions.

Table 3.1 and Figure 3.1 together illustrate the strong contrast in evapotranspiration (ET) between the restricted 2020 season and subsequent recovery years. Average daily ET in 2020 remained well below later values, particularly in July and August when rates were less than half those observed from 2021 to 2023. With the reinstatement of irrigation, ET nearly doubled in 2021 and remained elevated in 2022 and 2023, with midsummer peaks consistently around 0.20–0.23 in/day. The consistent seasonal pattern, rising in spring, peaking in midsummer, and declining into fall, underscores both the suppressive effect of the 2020 withdrawal and the gradual recovery of crop water use in later years.

The chart illustrates how ET recovered after the 2020 curtailment and shows subtle year-to-year shifts at the start of the growing season. In 2021, 2022, and 2023, ET rates increased slightly earlier and more strongly each spring, with May and June values progressively higher across the three years. This suggests that as soil moisture and crop vigor improved following the restriction year, fields not only reached higher midsummer peaks but also began ramping up ET earlier in the season, reflecting quicker canopy development and greater water use.

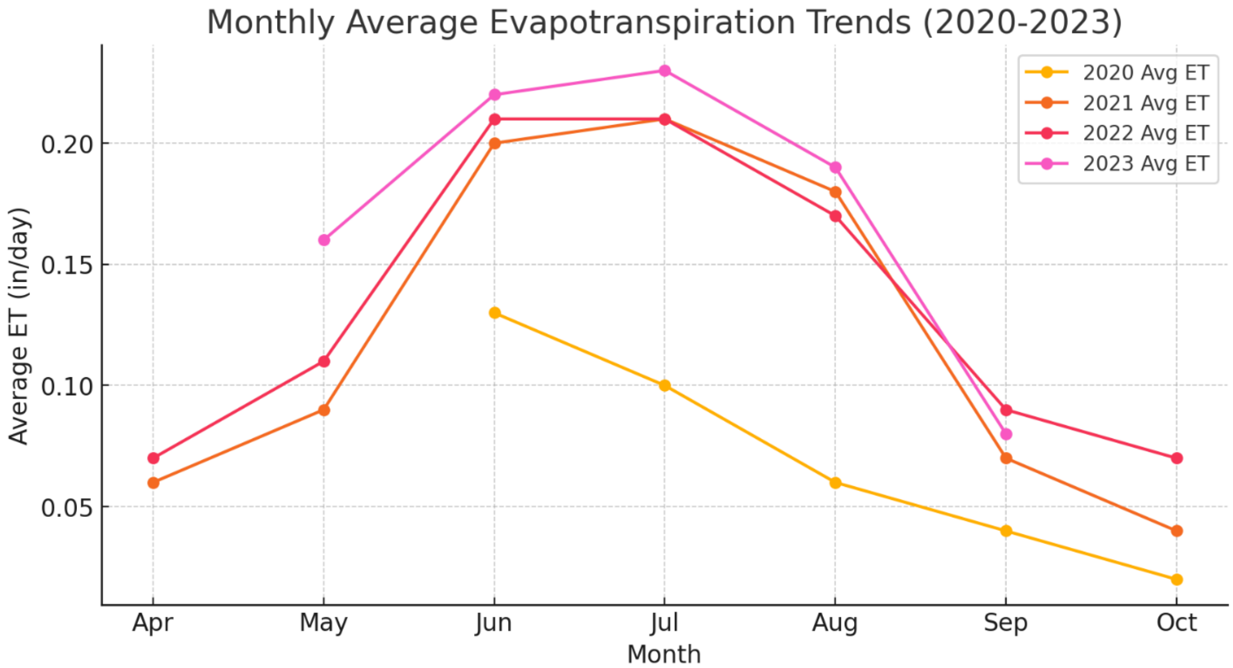

Figure 3.1. Seasonal evapotranspiration dynamics under irrigation withdrawal and recovery (2020–2023).

Research on EC technique uncertainty suggests that under ideal conditions (adherence to best practices at optimal sites), accuracy within 10 percent can be achieved for daily, monthly, and seasonal measurements (Foken et al., 2012). This aligns with reported EC Tower measurement uncertainty of 10 to 15 percent compared to actual values (Allen et al., 2011).

The comparison between PET and energy balance ET estimates highlights clear seasonal differences in crop water use. PET values for grass hay remained consistently higher throughout the season, often by several millimeters per day, reflecting the atmospheric demand under fully watered conditions. In contrast, both closed and unclosed energy balance ET estimates showed a lower trajectory, particularly after late June, as field conditions transitioned away from peak growth and water availability became limiting. The energy balance closure analysis for 2020 reveals a strong average daily value of 0.92, indicating high acceptability

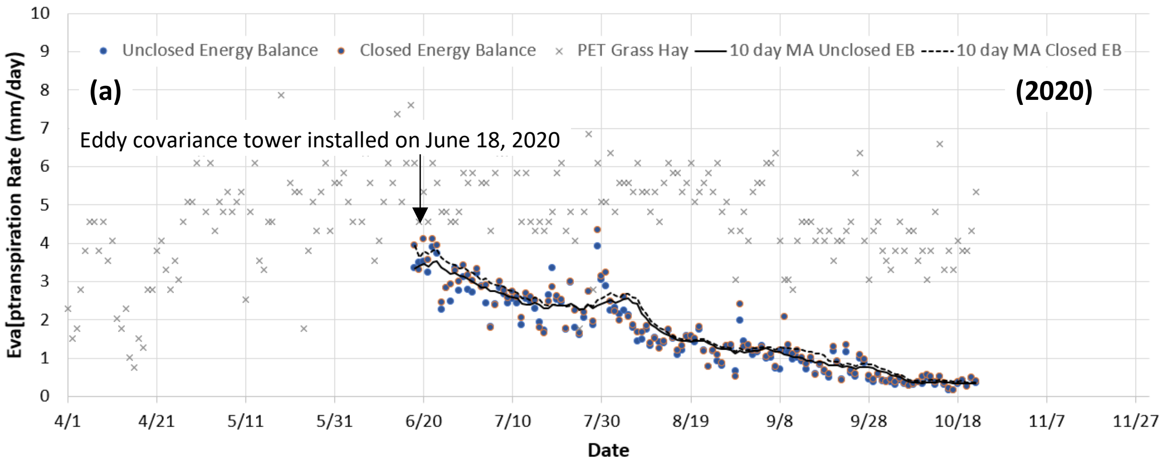

Figure 3.2a. Evapotranspiration rate modeled from the closed and unclosed energy balance in 2020 (a), 2021 (b) and 2022 (c) represented using a 10-day moving average (MA) over the period of measurement.

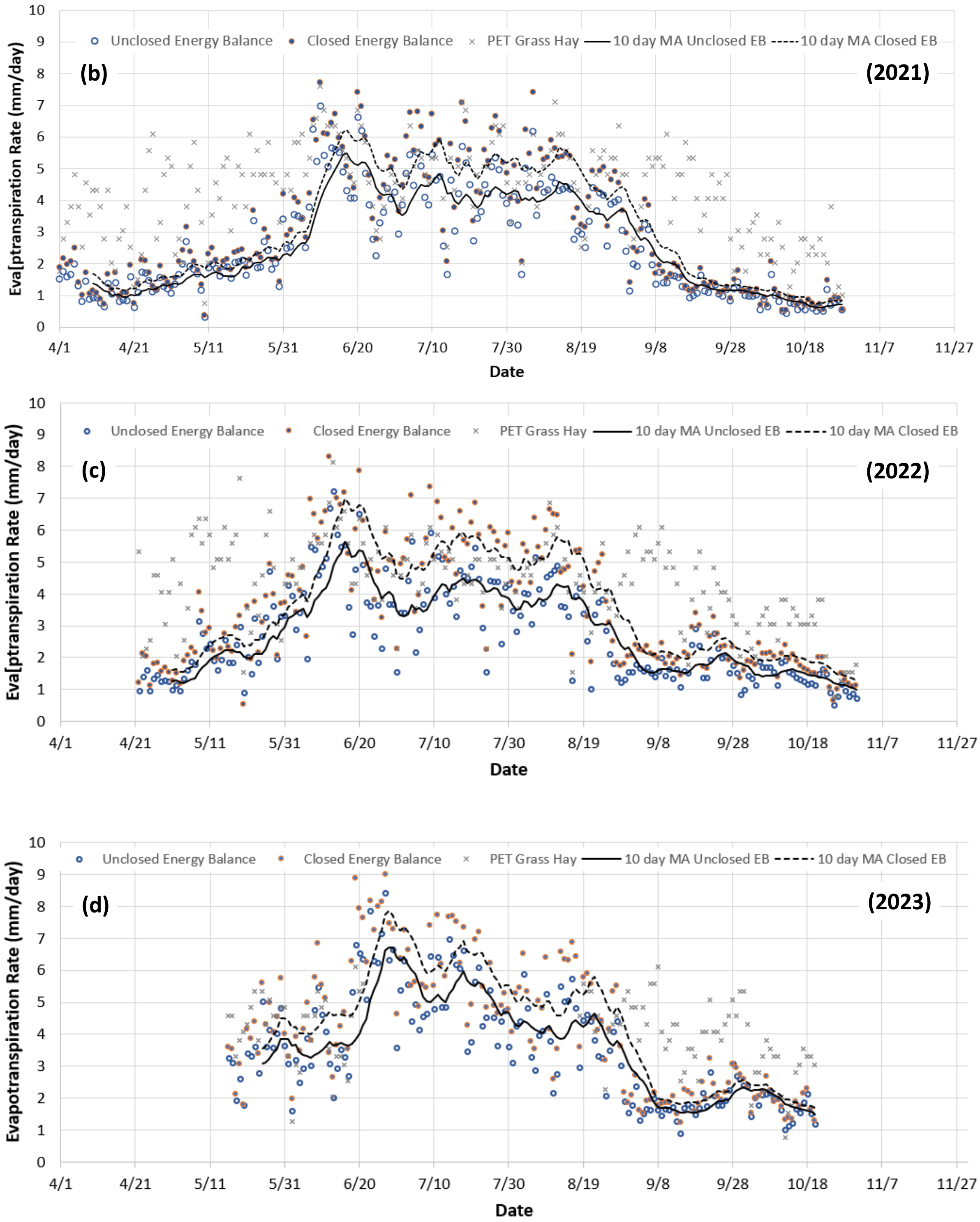

Figure 3.2 b, c, and d. Evapotranspiration rate modeled from the closed and unclosed energy balance in 2020 (a), 2021 (b) and 2022 (c) represented using a 10-day moving average (MA) over the period of measurement.

Across all years, PET values were consistently higher than the ET estimates derived from energy balance modeling. This gap reflects the distinction between atmospheric demand (PET) and actual crop water use

(ET), which is constrained by soil moisture availability, plant growth stage, and management practices. PET traces the theoretical maximum evapotranspiration if water were non-limiting, while the energy balance ET values capture the realized fluxes in the field. The energy balance estimates tracked seasonal crop dynamics closely, showing distinct peaks in late June and July and gradual declines into the fall, whereas PET remained elevated for longer periods. The relatively close agreement between closed and unclosed energy balance estimates underscores the robustness of the method, but their consistent position below PET highlights the influence of water stress and field conditions in limiting crop evapotranspiration relative to atmospheric demand. In 2021, 2022, and 2023, closure values were somewhat lower but remained elevated, averaging 0.84, 0.76, and 0.83 respectively. These values demonstrate robust accuracy according to this methodology. The results are highly dependable, with potential alterations in fluxes due to closure adjustments negligible.

4. Discussion

The grassland environment at high elevation pasture locations is unique to the Upper Colorado River Basin, heavily influenced by regional climatic factors and the dynamic interplay of water and energy inputs. These inputs undergo significant shifts as the growing season kicks off in late May and extends until early September. Changes in local temperature and vapor pressure deficit (VPD) due to irrigation withdrawals, coupled with broader regional climate shifts, can potentially modify the ET process. These changes have implications for the water and energy balances of fields enrolled in water sharing agreements. However, there is limited existing knowledge regarding the impacts of altered irrigation regimes on energy and water movement within high elevation pasturelands.

This study aimed to lessen this knowledge gap by evaluating ET rates for specific fields during full-season and partial-season periods of reduced irrigation, which are approximately 5 and 2 months in the Grand County, CO area. This is significant for this area, which is characterized by an approximately 70 day period between the 50% likelihood for last and first frosts of the growing season, and about 35 days between the 10% likelihood for first and last frost. During this period in 2020, the field relied solely on natural precipitation. This data was compared with conditions of irrigation resumption in subsequent years 2021 and 2022.

During the summer months, daily ET exhibited noteworthy variations, with a gradual decline observed in 2020 due to reduced irrigation and the depletion of stored soil moisture. Minimal increases in ET were attributed to sporadic natural rainfall events. As 2021 commenced, daily ET rates for the early months from January to April were unexpectedly lower. This discrepancy was likely a result of the substantial soil moisture deficit caused by the previous season's irrigation suspension, leaving limited residual moisture for grass consumption. Following the reinstatement of irrigation, ET rates recovered swiftly, notably in late May 2021.

May temperatures showed little disparity between the two years, averaging at 8.4°C for 2020 and 7.7°C for 2021, as recorded by a meteorological station in Kremmling, CO (Latitude: 40°6'55.44", Longitude: 106°16'58.8", Elevation: 7534 ft). These slight temperature variations influenced the marginal difference in average May ET rates for grass hay, estimated at 4.6 mm/day (0.18 in/day) in 2020 compared to 4.8 mm/day (0.19 in/day) in 2021 using the ASCE Standardized Equation (ASCE-EWRI; 2005). These values notably surpass the 2021 May ET rate of 2.3 mm/day (0.09 in/day) projected by the EC method, illustrating the variance between ETp and ETa under these conditions. However, as June arrived during the recovery year, the average ET rate rose to 5.1 mm/day (0.20 in/day), which is comparable yet slightly lower than the potential ET rate of 5.3 mm/day (0.21 in/day).

In this context, any shifts in precipitation patterns due to climate variability and alterations in ET flows because of irrigation withdrawals would exert more pronounced effects on soil moisture, ecosystem productivity, and forage yield compared to regions at lower elevations with longer growing seasons. These findings directly substantiate that fields subjected to substantial irrigation reductions experience gradual recovery as soil moisture deficits are replenished by winter precipitation and water availability is reinstated during the post-withdrawal year.

In 2020, the study field experienced a full withdrawal of water, significantly reducing evapotranspiration (ET) levels compared to subsequent years when full irrigation was restored (2021 onward). To assess how ET responded post-withdrawal, we conducted a paired t-test comparing monthly ET values from 2020 with those from 2021, 2022, and 2023. This statistical test allowed us to determine whether ET increased significantly after irrigation was reinstated.

The results indicate a strong recovery trend, with ET levels increasing consistently each year after 2020. In 2021, the first year after irrigation was restored, ET values showed an increase (T-stat = -3.07, P-value = 0.092), though the statistical significance was just above the conventional 0.05 threshold. This suggests that ET rebounded but had not yet fully stabilized. By 2022, however, the difference between 2020 and post-withdrawal ET became much more pronounced (T-stat = -4.28, P-value = 0.051), indicating a strong return toward normal conditions. While the P-value was slightly above 0.05, it suggests a meaningful recovery, particularly during peak ET months (June-August). In 2023, the trend remained stable (T-stat = -3.52, P-value = 0.072), reinforcing the conclusion that the field's ET levels had largely returned to normal but with some interannual variation.

Overall, the findings suggest that ET recovery was not immediate but rather gradual over multiple growing seasons. The increase in ET from 2021 to 2023 likely reflects improving soil moisture conditions, plant regrowth, and enhanced water availability following the withdrawal. The strongest recovery signal appeared in 2022, when ET levels approached pre-withdrawal norms. This trend highlights the resilience of the system but also suggests that it takes multiple seasons for ET to fully stabilize after a prolonged water deficit. Future analyses could explore whether other factors, such as soil characteristics or precipitation patterns, influenced the rate of recovery.

5. Conclusion

This study presents ET estimates based on EC measurements conducted over two consecutive growing seasons in Kremmling, CO. The research spanned an initial year characterized by full irrigation withdrawal, followed by a subsequent year (2020) marked by the resumption of irrigation in the following two years (2021-2023). The acquired data facilitates a comparative analysis between field measurements and remote sensing-based modeling to quantify ET flux across various temporal scales, including daily, monthly, and seasonal intervals. The use of data in geospatial modeling techniques is notably limited for landscape-scale studies in higher-elevation pastures. Consequently, this dataset is pivotal in evaluating modeled ET rates at important locations in water the Upper Colorado River Basin.

The study's findings demonstrate the following: (1) Imposition of irrigation withdrawal led to a substantial reduction in ET rates during the 2020 growing season, reaching up to 67% compared to the subsequent years following irrigation resumption. (2) The decline in ET becomes more pronounced as the season advances into warmer months and tapers as environmental temperatures decrease. (3) Implementation of full irrigation withdrawal allows for a potential conservation of consumptive use (CU) ranging between 33% and 67% relative to reference conditions, contingent on the month of assessment. (4) Overall, the EC method emerges as a pivotal asset in comprehending ET rates within higher-elevation pastures, as predictions rooted in weather-based models tend to overestimate when compared to EC measurements. Given the evident value of the tower installation in Kremmling, CO, for CU estimation and validation in the Upper Colorado Basin, it is recommended that the ongoing investigation of this site and other analogous higher-elevation pasture locations be integrated into strategies for water conservation initiatives and CU inventory assessments.

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