Field Evaluation of Near-Surface Soil Moisture Content using Time Domain Reflectometry Sensors: Relevance to Irrigation Withdrawal in High-Elevation Hayfields and Grass Pastures

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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need to understand the patterns of soil moisture exhibited by these fields during periods of severe water stress and withdrawn irrigation. To accomplish this goal, continuous soil moisture measurements were taken between 2020-2022 in 10 fields in Grand County around Kremmling, CO using in-situ time domain reflectometry (TDR) sensors. Sensors were installed at 6, 18, 30 and 42 cm depths to represent identical 12 cm sub-zones of 0-12, 12-24, 24-36, and 36-48 cm below the soil surface within the effective root zone. These sensors were installed to evaluate a low-cost method for comparing an in-field soil water balance approach based on soil moisture depletion over specified time intervals against modeled evapotranspiration (ET) rates from remote sensing data. During the evaluation period, there were 28 distinct time intervals identified during which a one-dimensional soil water balance (SWB) could be assessed. These intervals occurred when irrigation was not taking place and the soil volumetric water content (VWC) was below the field capacity (FC), using a practical determination method to identify intervals between FC and permanent wilting point (PWP). Estimations of total ET using the soil water balance approach averaged 33.3% lower than the modeled estimates derived from eeMETRIC over the same time intervals. One possible reason for this variation could be that the effective root zone for these fields extends below 48 cm in depth, which means that the sensors did not accurately account for the total soil moisture depletion. The sensors performed more usefully for assessing the soil moisture levels before and after the periods when water was withdrawn and during periods of conventional irrigation. These assessments showed that after the 2020 season, conventionally irrigated fields had an average post-season volumetric water content (VWC) of approximately 25%, while fields where irrigation had been withdrawn had an average VWC of 16%. Before the subsequent 2021 irrigation season, winter precipitation, estimated at 8.2 cm based on local weather data, contributed to an increase in VWC levels on all evaluation fields. As a result, all fields in 2021 began the season with VWC levels exceeding 30% in the estimated 48 cm root zone, although the VWC for fields affected by irrigation withdrawals was on average lower and also more variable.

1. Introduction

For shallow water table environments, continuous soil moisture measurements and water table estimation have been found to accurately determine ET from a hydrologic balance (Fares and Alva, 2000; Robock et al., 2000; Mahmood and Hubbard, 2003; Nachabe et al., 2005). The approach used herein involves the use of soil moisture and water table data measurements at specific locations within hayfields and grass pastures subjected to various irrigated conditions.

2. Materials and Methods

2.1 Experimental Site and Soil Conditions

This report focuses on sensor data collected at field locations where data was collected for other objectives of the project "Evaluating Conserved Consumptive Use in the Upper Colorado," primarily forage sub-sampling. These sensor locations are described in Table 2.1 using an alpha-numeric code based on the ranch name and research condition (i.e., reference or treatment). For example, GPR R1 designates the 3-letter code for the ranch, 1-letter designation for R or T (Reference = conventional irrigation or Treatment = irrigation withdrawal), and 1-number designation for field name. These sites were equipped with sensors as a potential approach for ground-checking modeled actual evapotranspiration (ET_a) estimates from remote sensing data. Sensors were installed at locations identified by landowners as having "high" production yields, designated by H, based on landowner knowledge about harvest patterns from previous years.

Table 2.1. Sites evaluated for CU and CCU in Kremmling, CO

Site Name	Irrigation Withdrawal Practice	Acres	Hectares
GPR T1 H	Full season, no irrigation	203.7	82.4
GPR T2 H	Full season, no irrigation	344.9	139.6
RCR T2 H	Split Season, no irrigation after June 15	36.7	14.9
RSR T1 H	Split Season, no irrigation after June 15	122.8	49.7
SBR T1 H	Full season, no irrigation	70.2	28.4
SPR T1 H	Full season, no irrigation	220.6	89.3
GPR R1 H	Reference, historical irrigation	94.5	38.2
RSR R1 H	Reference, historical irrigation	20.1	8.1
SBR R1 H	Reference, historical irrigation	28.5	11.5
SPR R1 H	Reference, historical irrigation	30.0	12.1

2.2 Experimental Sites Instrumentation

The evaluation utilized Acclima TDR-315 sensors and Solar DataSnap SDI-12 data loggers (Acclima, Inc., Meridian, ID) at 10 field locations near Kremmling, CO. The sensors were chosen based on comparisons of performance between various soil moisture measuring tools (Varble and Chavez, 2011). Time Domain Reflectometry (TDR) sensors for soil moisture measurement operate by sending electromagnetic pulses into the soil through metal rods, along which changes in the soil dielectric constant are encountered. The time it takes for the reflected pulse to return to the sensor is directly related to the dielectric constant of the soil, which, in turn, is correlated with moisture content. By analyzing the time delays in pulse reflections, TDR sensors provide volumetric water content (VWC) at the depths where the rods are inserted into the soil profile.

The TDR-315 sensors measure VWC (0% to100%), soil permittivity (1 to 80), soil bulk electrical conductivity (EC) (0 to 5000 µS/cm), soil temperature (– 40 to +60 °C) and pore water EC (Hilhorst Model) (0 to 55000 µS/cm). Sensors were installed at depths of 6, 18, 30 and 42 cm. These depths were selected based on visual evaluations of the effective root zones. The sensors were assumed to represent the center of soil profile intervals in the root zone, such that sensor readings at 6, 18, 30 and 42 cm were assigned to 12 cm increments of 0-12, 12-24, 24-36, and 36-48 cm. The sensors were enclosed by cow panels within a small undisturbed area (~ 10 ft diameter) to protect instrumentation. Data loggers were programmed to record measurements every 15 minutes, allowing detailed measurement of the changes in soil moisture.

Groundwater levels were measured at each site using 1.0' PVC observation wells and Solinst® Level Logger Junior™ (Solinst Canada Ltd., Ontario, Canada). The transducers were installed at the bottom of PVC observation wells. Groundwater levels were corrected for barometric pressure using Solinst® Barologgers that were installed nearby. Groundwater levels were converted to depth to water table (m) based on logger measures and the depth of corresponding observation wells. Precipitation was recorded by direct read rain gages (Productive Alternatives, Fergus Falls, MN).

Figure 2.2.1. Installation of Acclima TDR-315 at GPRT1H field location for 6, 18, 30 and 42 cm.

Figure 2.2.2. Field Technician accessing Acclima Solar DataSnap SDI-12 data logger within instrument enclosure protected by cow panels.

2.3 Soil Water Balance Approach

Soil moisture timeseries were processed and analyzed using R statistical software. Time series data was quality checked through visual analysis to remove anomalous data. Time series records were smoothed using a 12-hour rolling mean and summarized to daily mean values. Data gaps in the record were treated as missing data and caused by several factors including logger malfunctions, dead batteries, and delays in logger deployments. Total soil profile VWC (%) was calculated as the average of the sensor-measured VWC (%) at the four soil depth intervals. Total soil moisture levels in the measured root zone (cm) were then derived by multiplying the total soil profile VWC by the total soil profile depth (48 cm).

A one-dimensional soil water balance (SWB) method was used to estimate ET_a (mm/d) by algebraic closure using the equation $ET_a = P_{eff} + Irr + U - SRO - DP - (D_p - D_c)$ where D_c and D_p are soil moisture deficits for current and previous day and P_{eff} is effective precipitation, Irr is irrigation, U is upflux groundwater contribution (capillary rise), SRO is surface runoff and DP is deep percolation. The soil moisture deficit (D) is calculated by subtracting the current moisture level in the root zone from the field capacity (FC) of the root zone. Limitations to the SWB approach include difficulty in capturing intra-field variability and the reliance on sensors that frequently require gravimetric calibration (Varble and Chávez, 2011). Nevertheless, because the SWB is an in-situ monitoring technique, it is a viable field method for evaluating soil water movement.

Previous studies have employed automated computing algorithms to determine FC (Fazackerley and Lawrence, 2012; Bean et al., 2018), given that field-observed FC values differ from laboratory-determined values (Evett et al., 2019). Rather than using an algorithm-derived analysis, a practical determination method (Simmone et al., 2007) was used to estimate FC for each soil depth interval in this evaluation. This method assumes that noticeable points of inflection in the VWC data can be used to estimate FC based on general patterns that emerge throughout the season. After each irrigation event, for example, a rapid spike in soil water content indicates that the soil is saturated above the field capacity and quickly drains as water percolates through the profile. After this short draining period (typically 1-3 days) the rate of change in VWC becomes more gradual, reflecting a slower rate of water extraction caused by ET. The point where the VWC exhibits a clear transition from drainage to extraction is evident by a clear inflection point, which is assumed by the practical determination method as an estimate of FC. The VWC data can be further examined for another general pattern to observe a critical moisture content reached when ET is no longer controlled by meteorological conditions. After this point, the VWC curve flattens and the permanent wilting point (PWP) can also be practically determined.

As grasses grow and extract water from the soil to satisfy water demand, the stored soil water is gradually depleted (Evett et al., 2012). In the case of full irrigation withdrawal, therefore, the estimate of ET_a by closure is calculable using only the D_p and D_c terms, which are derived from the measurements of soil moisture levels and the P_{eff} term measured by rain gages. This evaluation therefore assumes that all precipitation infiltrates. Data from groundwater level loggers and EC measurements from the TDR-315 sensors was used to verify no contribution from U. By calculating the SWB only during intervals when fields were not being irrigated or subjected to saturation, the Irr and DP terms could also be eliminated.

3. Results

3.1 Project treatment impacts to soil moisture and groundwater

Total soil profile VWC was compared across fields for the start and end of seasons for 2020-2022 to evaluate irrigation withdrawal impacts on soil moisture conditions. Start of season VWC was reported only if soil moisture sensors began logging VWC prior to the initiation of irrigation on the field for a given year. End of season VWC was reported only if the VWC timeseries extended at least 2 weeks past the end of irrigation. The timeframes for the start and end dates varied by field and year, due to installation dates and field accessibility (Table 3.1.1). As such, any comparisons between reference (conventional irrigation) and treatment (irrigation withdrawal) fields will be suspect unless the start or end dates are relatively similar. The total soil profile VWC was then derived by averaging across the four evenly spaced sensors within the top 48 cm of the soil profile, which could be weighted equally given the identical depth increments.

Start of season VWC in 2021 and 2022 was compared between reference and treatment fields to identify the potential over-winter impacts of 2020 irrigation withdrawal on spring moisture conditions in subsequent years (Figure 3.1.1 right). Values for 2021 were averaged and demonstrated a wide range of starting season VWC values in 2021 for treatment fields, but relative stability for reference fields (Figure 3.1.1 left).

Table 3.1.1. Total soil profile volumetric water content (VWC, %) at the start and end of monitoring season.

Site	2020				2021				2022			
	VWC (%)		Timeframe		VWC (%)		Timeframe		VWC (%)		Timeframe	
	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End
GPR R1	-	-	-		34	28	05/12	10/07	P	25	05/28	09/12
GPR T1	24	18	06/26	10/15	33	22	05/01	10/07	P	21	06/07	09/12
GPR T2	16	12	06/26	09/29	28	21	05/01	10/07	P	28	06/07	08/17
RCR R2	-	-	-		33	32	05/01	10/06	P	18	05/27	09/12
RSR R1	P†	34	07/16	09/29	38	25	05/01	10/07	P	-	05/26	
RSR T1	P	26	07/16	09/29	38	31	05/01	10/07	32	30	05/26	09/14
SBR R1*	-	-	-		P	35	06/04	10/06	39	33	05/25	09/07
SBR T1	15	13	06/27	08/27	29	33	05/01	09/22	26	-	05/27	09/12
SPR R1	P	16	06/29	09/30	34	19	05/01	10/06	47	16	05/24	09/10
SPR T1	17	16	06/29	09/16	37	20	05/01	10/06	41	19	05/24	09/12

*Missing 6cm sensor in all three years

†P indicates that soil moisture record began post-initiation of irrigation at the site. Missing values indicate that no data is available at start and/or end of season due to data gaps. Start (S) and End (E) dates vary by site and by year.

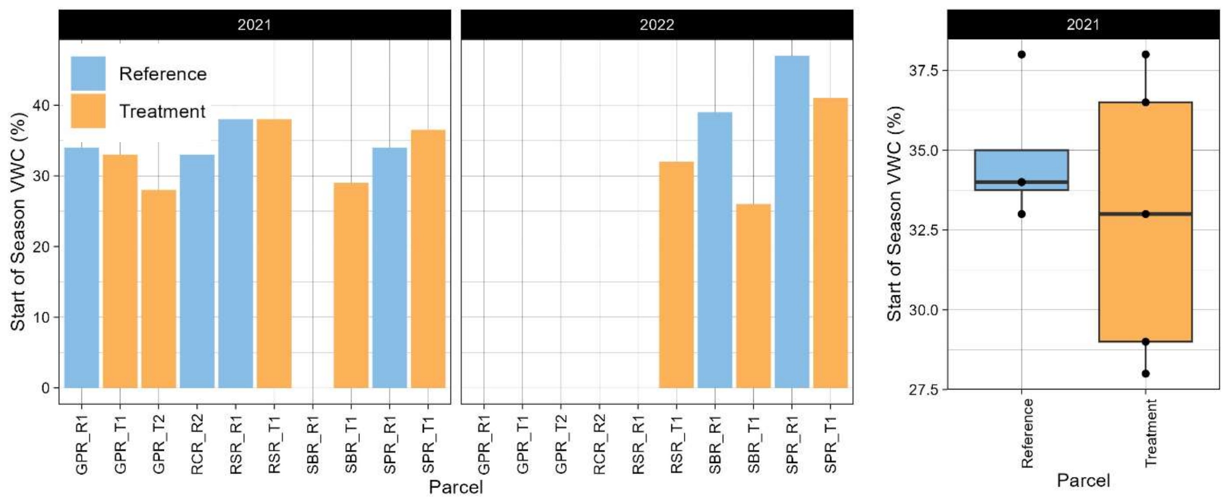

Figure 3.1.1 (right). Start of season total VWC in top 48cm of soil profile during 2021 and 2022. Data is missing if monitoring began after seasonal irrigation initiated at the field and/or due to data gaps. Figure 3.1.1 (left). Comparison of start of season total VWC between reference and treatment fields in 2021.

End of season VWC was also compared between reference and treatment fields for 2020-2022 (Figure 3.1.2 left). The depletion in VWC at the end of the 2020 irrigation withdrawal program was evident, with sensors demonstrating soil moisture levels that were approximately 50% lower than in their counterpart reference fields. The significant depletion of VWC on the treatment fields reflected the steep extraction of water from the soil profile as the vegetation continued to consume water towards the PWP level, even in the lower increments of the root zone. In subsequent years after the irrigation withdrawal program, the end of year VWC levels on the reference and treatment fields showed no obvious differences (Figure 3.1.2 right).

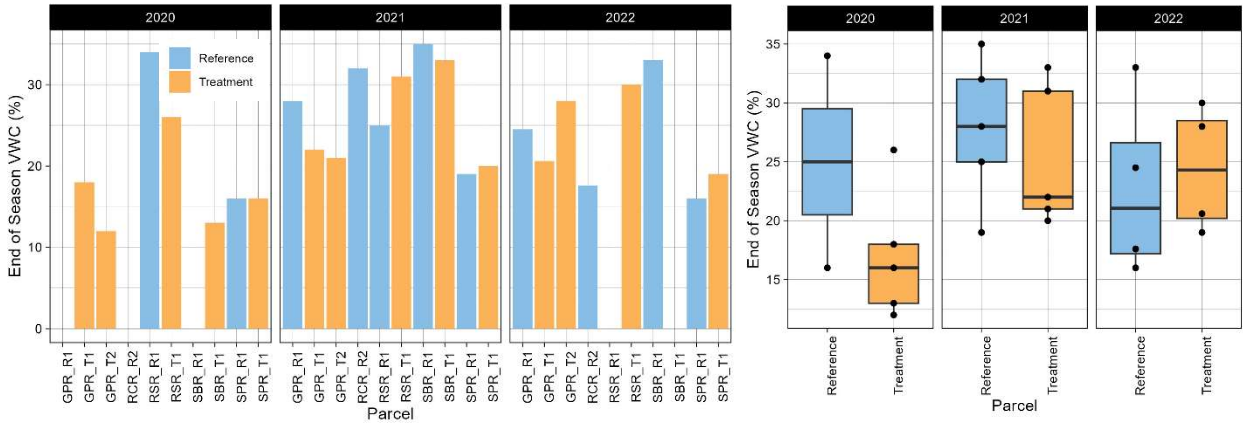

Figure 3.1.2 (left). End of season total VWC in Top 48 cm of soil profile during 2020, 2021, and 2022. Missing data is due to data gaps. Figure 3.1.2 (right). Comparison of end of season total VWC between reference and treatment fields in 2020, 2021, and 2022

Groundwater water levels were also analyzed to identify if project conservation treatments impacted groundwater levels. Shallow groundwater (defined as when levels were above the bottom of the observation well) was only observed during periods that fields were undergoing irrigation and for a short duration after irrigation cessation. At all treatment and reference fields, groundwater water levels were below the bottom of observation wells (at least 1.5 - 2.5m deep) at the start and end of all three irrigation seasons. These observations demonstrate the well-drained conditions of the soils and may provide evidence of deeper rooting than previously hypothesized.

Winter cumulative precipitation (October through April) from 2016-2022 was obtained from two nearby CoAgMet climate stations to evaluate the degree that winter precipitation can recharge soil moisture volumes (Table 3.1.2). Winter precipitation was summarized for each water year. Winter precipitation in the 2021 winter (following the 2020 treatment year) ranged between the two stations from 7.8 to 8.6 cm, which corresponds to roughly 16-18% of the depth of the 48cm soil profile. This value provides a likely maximum estimate of winter soil moisture recharge since some unknown amount of winter precipitation will be lost to evapotranspiration and sublimation. The amount of winter precipitation can also vary substantially by year with winter precipitation between 2016-2022 ranging between 6.3 to 13.6 cm. In some cases, but not all, treatment fields appeared to have had soil moisture restored by winter moisture (Figure 3.1.2 right). It is also notable that winter precipitation levels have continued to decline every year for the past 5 years in this region, raising concerns for participants in irrigation withdrawal programs who may be hesitant about grass recovery or needing more irrigation water in subsequent years.

Table 3.1.2. Winter Precipitation (cm) by Water Year at nearby CoAgMet Stations from 2016-2022.

Water Year	Kremmling (krm01)	Wolford Reservoir (wfd01)
2016	-	6.25
2017	-	13.64
2018	-	12.83
2019	9.68	9.86
2020	7.57	9.12
2021	7.87	8.64
2022	7.16	7.59
2016-2022 Average	**-**	**9.70**

3.2 Comparison of ET_a rates derived from soil water balance and remote sensing

The SWB method was assessed only for periods when irrigation was not occurring and when soil VWC was below the estimated FC. It was assumed that all precipitation infiltrates and that groundwater contributions including capillary rise and lateral flow are negligible during non-irrigated periods. During time periods that met these criteria, the SWB was simplified such that cumulative ET_a derived from the SWB (SWB-ET_a) is calculated as the sum of the change in soil moisture in upper 48 cm soil profile between the start and end date (Δ-soil) and the cumulative rainfall based on rain gage data. Data from each project field met the evaluation criteria for 1-3 periods each year (Table 3.2.1).

Table 3.2.1. Comparison of ET_a estimates from soil water balance (SWB-ET_a) and remote-sensing based eeMetric. Positive percent differences indicate that WB-ET_a estimates are higher than eeMetric-ET_a.

Field Name	Year	Period	Δ-soil (cm)	Precip (cm)	WB-AET (cm)	EEMetric-AET (cm)	Difference (cm)	% Diff
GPR_R1	2021	5/12/2021 - 5/28/2021	2.62	0.00	2.62	1.27	1.35	105.2
		7/31/2021 - 10/7/2021	5.05	5.89	10.95	25.65	-14.71	-57.4
	2022	7/26/2022 - 9/12/2022	5.79	6.40	12.19	17.07	-4.88	-28.6
GPR_T1	2020	6/26/2020 - 10/21/2020	2.79	3.25	6.05	8.33	-2.29	-27.5
	2021	8/1/2021 - 10/7/2021	7.21	5.89	13.11	21.18	-8.08	-38.1
	2022	7/11/2022 - 9/12/2022	11.28	9.30	20.57	25.02	-4.45	-17.8
GPR_T2	2020	6/26/2020 - 9/29/2020	1.78	3.25	5.03	18.31	-13.28	-72.5
	2021	8/1/2021 - 10/7/2021	6.83	5.89	12.73	24.74	-12.01	-48.5
	2022	7/28/2022 - 8/17/2022	3.28	4.55	7.82	10.87	-3.05	-28.1
RSR_R1	2020	8/3/2020 - 8/17/2020	4.88	0.00	4.88	5.87	-0.99	-17.2
		8/27/2020 - 9/28/2020	4.60	1.04	5.64	11.38	-5.74	-50.5
	2021	5/1/2021 - 5/24/2021	1.30	0.00	1.30	1.63	-0.33	-20.2
		7/27/2021 - 10/4/2021	9.53	4.75	14.27	22.58	-8.31	-36.8
	2022	6/10/2022 - 6/15/2022	1.78	0.00	1.78	3.71	-1.93	-52.1
RSR_T1	2020	7/16/2020 - 9/28/2020	3.25	2.13	5.38	17.73	-12.34	-69.6
	2021	5/1/2021 - 6/2/2021	3.28	0.00	3.28	3.07	0.20	6.4
		8/1/2021 - 10/6/2021	5.18	3.56	8.74	18.47	-9.73	-52.7
	2022	7/30/2022 - 8/12/2022	3.10	0.99	4.09	7.04	-2.95	-41.8
SBR_T1	2020	6/27/2020 - 8/27/2020	1.22	1.04	2.26	16.94	-14.68	-86.7
	2021	5/1/2021 - 5/31/2021	4.57	0.00	4.57	3.86	0.71	18.6
		7/26/2021 - 8/16/2021	4.17	3.02	7.19	9.17	-1.98	-21.7
		9/2/2021 - 9/21/2021	3.68	1.47	5.16	6.60	-1.45	-21.9
SPR_R1	2020	6/29/2020 - 9/29/2020	13.13	3.71	16.84	33.07	-16.23	-49.1
	2021	6/5/2021 - 10/4/2021	10.52	9.73	20.24	30.81	-10.57	-34.3
	2022	6/12/2022 - 9/12/2022	12.83	11.23	24.05	32.69	-8.64	-26.4
SPR_T1	2020	7/16/2020 - 9/16/2020	0.00	2.54	2.54	11.46	-8.92	-77.9
	2021	5/27/2021 - 10/5/2021	7.49	10.36	17.86	38.96	-21.11	-54.2
	2022	6/21/2022 - 9/10/2022	9.22	11.23	20.45	29.59	-9.14	-30.9

Cumulative SWB-ET_a estimates were compared to estimated cumulative ET_a calculated over the same timeframe from the remotely sensed eeMetric daily model ET_a estimates (sourced from OpenET). Differences in ET_a estimates between the two methods were evaluated by calculating both absolute and percent differences, individually for each period identified (Table 3.2.1). Estimations of total ET using the soil water balance approach averaged 33.3% lower than the modeled estimates derived from eeMETRIC over the same time intervals. One possible reason for this variation could be that the effective root zone for these fields extends below 48 cm in depth, which means that the sensors did not accurately account for the total soil moisture depletion.

The positive percent differences indicate that SWB-ET_a is notably lower than the estimates derived from eeMETRIC. A boxplot includes all comparison periods described in Table 3.2.1 and includes different fields, years, and timeframes.

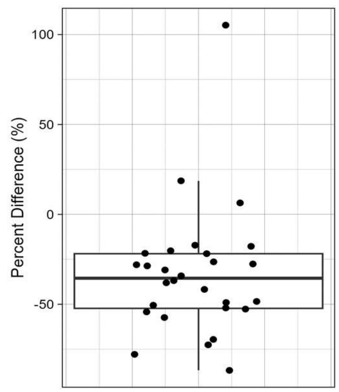

Figure 3.2: Percent difference between cumulative ET_a estimates from Soil Water Balance (SWB-ET_a) and remote-sensing based estimates (eeMETRIC) for 2020-2022 data.

4. Discussion

The comparative analysis of ET_a derived from two distinct methodologies, one based on in-situ TDR sensors and the other relying on remote sensing-based modeling, revealed a substantial discordance in the obtained results. This discordance, while not entirely unexpected, aligns with existing knowledge concerning the predictive accuracy of soil water balance methods for ET_a, typically falling within a range of 10-30%. Furthermore, the potential for additional errors, stemming from physical or equipment malfunction, extends to approximately 10-40% (Allen et al., 2011). By juxtaposing these error margins with the heightened precision anticipated from the utilization of remote sensing energy balance techniques, a reasonable inference arises: the SWB-ET_a estimates were likely computed accurately, yet their reliability was potentially compromised by equipment malfunction or an incomplete characterization of the root zone profile.

The absence of alignment between the two methods rendered the original intent of the TDR sensors ineffective. Considering the established precision of the Acclima TDR-315 sensors and their meticulous installation by experienced experts, however, the most plausible interpretation for this incongruity is that the grasses in this area tend to develop deeper root systems than previously assumed. A deeper rooting pattern would enable them to effectively access water resources from deeper within the soil profile. Therefore, despite the inaccuracy of the SWB-ET_a estimates, a useful result was derived from this work pertaining to the underlying field conditions. Specifically, the knowledge of deeper rooting grasses provides an insight against which to compare the patterns of recovery in forage across the different field sites.

Additionally, the sensor installation yielded valuable results by providing precise measurements of VWC at both the beginning and end of the irrigation season in high-elevation hayfields and grass pastures managed by ranchers. These findings indicate that irrigation withdrawal initiatives are likely to lead to soil moisture depletion levels comparable to PWP. The restoration of these diminished levels relies entirely on the quantity of winter moisture that accumulates in the region of program participation, and the rates of precipitation in this regard can be erratic and unreliable.

5. Conclusion

This evaluation focused on the utilization of TDR sensor-derived soil moisture and water table data at specific locations within hayfields and grass pastures subjected to irrigation withdrawal. These measurements were collected to provide in-situ data for validating modeled actual evapotranspiration (ET_a) estimates from remote sensing data. The evaluation reports significant differences between ET_a estimates derived from a soil water balance approach and remote sensing-based estimates, with the former being consistently lower. These differences are likely to be attributable to the depth limitations of the sensors in accurately accounting for total soil moisture depletion. The examination of total soil profile volumetric water content at the initiation and conclusion of the irrigation seasons spanning 2020 to 2022 showed a substantial depletion in soil moisture within the treatment fields subsequent to the 2020 irrigation withdrawal. Nevertheless, in the subsequent years, the initial and terminal VWC levels in both reference and treatment fields exhibited no discernible distinctions. The consistent presence of groundwater levels beneath the depths of observation wells implied well-drained soil characteristics, hinting at the possibility of deeper root systems.

The comparison of in-situ sensors and remote sensing-based modeling revealed substantial disparities, primarily attributable to the reported accuracy limitations of soil water balance methods (10-30%) in contrast to the anticipated precision of remote sensing energy balance techniques. Equipment malfunction or incomplete root zone profiling, with the latter being the more plausible scenario, likely influenced the SWB-ET_a estimates. These findings provided valuable insights into the potential existence of deeper grass root systems, enabling water extraction from greater soil depths, a crucial factor in assessing forage recovery across diverse field sites.

The study underscored the consequences of irrigation withdrawal, leading to soil moisture depletion reaching levels akin to the permanent wilting point. The restoration of these levels will hinge on the fluctuating rates of winter moisture accumulation, a variable yet unpredictable phenomenon within the study region. These findings bear significance for producers and ranchers contemplating participation in water-sharing programs targeting perennial grass pastures and hay fields.

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