Evaluating Conserved Consumptive Use in the Upper Colorado
2022 Summary Report

Photo: Reeder Creek Ranch and the Colorado River near Kremmling, CO. © Jason Houston, The Nature Conservancy

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Introduction

The "Evaluating Conserved Consumptive Use in the Upper Colorado" Project is a multi-year field research project engaging agricultural producers in the Kremmling area, researchers from multiple universities, and conservation groups in directly tackling information gaps related to voluntary water conservation measures on high altitude, irrigated grass pastures that support livestock. The Project is guided by a desire to develop, test, and evaluate water conservation tools that can support productive agriculture, associated communities, and the environment. Project results will address these key questions:

1. **How can we accurately and cost-effectively estimate water use and water conservation at scale?**
2. **What are the impacts of reduced irrigation on perennial grass fields and how do they recover under normal irrigation?**
3. **What does participation in a water conservation project mean for producers' bottom lines and for the ag-based community and economy of the region?**
4. **How do water conservation projects impact river flows and wildlife habitat?**

This information will help agricultural water users, water managers, State entities, and other stakeholders better determine how, and under what conditions, agricultural water conservation can provide drought resilience and help address local, state, and regional water supply challenges.

The Project is designed as a side-by-side comparison between reference and treatment fields. The reference fields are being irrigated and operated normally for the duration of the Project (2020-2023). The treatment fields received either no irrigation for the full 2020 season (*full irrigation withdrawal*) or no irrigation after June 15, 2020 (*partial-season withdrawal*), and then received normal irrigation in 2021 and subsequent study years. Nine landowners are participating in the Project, enrolling a total of 1,142 acres in treatment fields and another 405 acres as reference fields. Since monitoring and data collection for the Project will continue through 2023, the results discussed in this report should be considered preliminary until all the data can be incorporated.

Previous reports summarizing the overall Project objectives and research methods, along with results from the previous years, are available through the Colorado Basin Roundtable (https://www.coloradobasinroundtable.org/agriculture/upper-colorado-study).

This report summarizes initial analysis of data collected through 2022, including data on water use, forage impacts, and bird monitoring. The report also includes an Economics and Enterprise Budgeting Report that evaluates the operational and financial impacts to participants based on 2020 data, and an evaluation of modeled flow changes for 2020 and 2021. Detailed technical memos on water use estimates from remote sensing, eddy covariance, and soil moisture sensors; forage recovery; avian response surveys; river flow impacts; and the full economics analysis are provided in the Appendix.

Water Use

The majority (>80%) of agriculture on Colorado's Western Slope consists of high elevation irrigated pastures and hay meadows, and evaluation of water use on these landscapes is an important endeavor which has not been well-studied. Specifically, accurate, scalable, and cost-effective tools to estimate consumptive water use (CU) and conserved consumptive use (CCU) that are both transparent and trusted are essential if agricultural water conservation is going to be a viable and effective strategy to help address a drier future. Remote sensing models have the capability to estimate water use over large areas, and this project was undertaken to address outstanding questions about their accuracy in high elevation and low water use conditions. This project has contributed to better understanding these questions by comparing water use estimates from remote sensing models to site-specific measurements from an eddy covariance measurement system and soil moisture sensors. This report summarizes water use estimates from these three methods for the Project field sites for 2022 and includes a statistical comparison between the results from the remote-sensing models and the eddy covariance data.

Estimating Water Use with Remote Sensing Models

BACKGROUND

Using remote sensing models to estimate actual evapotranspiration (ET_a[1]) accurately and cost-effectively over large and heterogeneous landscapes is promising because it can address some of the known limitations of other methods, particularly under water conservation programs. A satellite-based energy balance approach was used to estimate ET_a for the Project's treatment and reference sites. Study site ET_a rates were modeled using the automated version of the Mapping Evapotranspiration at High Resolution with Internalized Calibration model (eeMETRIC). In addition to eeMETRIC, a combination of remote sensing-based models was used to calculate ET_a as an ensemble.

This study has demonstrated that remote sensing and modeling are accurate tools for estimating ET_a and conserved consumptive use (CCU) on high elevation pastures and hay fields in Western Colorado under both irrigation reduction and full irrigation. While fields exhibit geographic and biophysical variability due to the influence of underlying conditions, the eeMETRIC model produces valuable spatial averages that are not overly influenced by this natural heterogeneity or the special conditions of high-elevation pastures and fields under dry up conditions.

RESULTS

Study results related to remote sensing cover three main areas, (1) CCU estimates using remote sensing, (2) the issue of high variability in water use across the field sites, and (3) a comparison between the remote sensing based estimates and estimates made from a field-based eddy covariance tower.

1. Estimating CCU:

This study presents two different approaches for using remote sensing-based estimates of ET_a to estimate CCU, a "prior years approach" and a "reference approach."

[1] Because the main focus of this project was to quantify water consumed by agriculture, irrespective of underlying processes, estimation of ET and CU was undertaken as an identical pursuit without consideration of legal and technical distinctions. Therefore, the terms ET nd CU are used interchangeably, with some exceptions for describing specific processes.

Prior Years Approach Summary

- The Prior Years approach compares ET_a during the reduced irrigation/treatment year with ET_a for the same site during a selection of prior years. This approach assumes that weather conditions, management, water availability, and other factors in previous years are similar to the reduction year and subsequent recovery years.
- Using the Prior Years approach, sites that received no irrigation in 2020 averaged a 53.4% reduction in May-Sep ET_a in comparison to the 2016-2019 prior year baseline for these same sites. In 2021, the first year returning to full irrigation, ET_a on the treatment sites was still suppressed by 13.9% of the 2016-2019 baseline ET_a. During the second year, these sites were 1.7% below the prior year's baseline (Table 3.4.1.1). This shows an ongoing impact in the first year after treatment, but generally complete recovery by the second year.
- Treatment sites that implemented a partial-season approach where irrigation was restricted after June 15 in 2020 exhibited reductions in May-Sep ET_a that was 14.7% lower than the 2016-2019 baseline for these same sites. In 2021 and 2022, these treatment sites were respectively 16.1% and then 6.6% lower on average in comparison to the 2016-2019 baseline.
- Using the Prior Years approach, average 2020-2022 CCU across the study fields was 1.46 AF/acre for full season treatments and 0.76 AF/acre for split season.

Table 1. 2016-2019 Baseline ETa compared with impact (2020) and recovery year (2021, 2022) ETa

Site Name	**2016-2019 Baseline**	**2020 vs Baseline**		**2021 vs Baseline**		**2022 vs Baseline**	
	TRT ET_a	**TRT ET_a**	**Change**	**TRT ET_a**	**Change**	**TRT ET_a**	**Change**
		Full Season Irrigation Reduction					
SPR*	22.85	14.45	-36.8%	17.18	-24.8%	21.12	-7.6%
SBR	21.99	11.81	-46.3%	20.51	-6.8%	22.39	1.8%
GPR T1	23.63	6.22	-73.7%	21.12	-10.6%	23.53	-0.4%
GPR T2	25.89	11.15	-56.9%	22.37	-13.6%	25.72	-0.7%
Average	**23.59**	**10.91**	**-53.4%**	**20.30**	**-13.9%**	**23.19**	**-1.7%**
		Partial-Season Irrigation Reduction (no irrigation after June 15)					
RSR	24.57	20.45	-16.8%	21.40	-12.9%	22.25	-9.4%
RCR	21.97	19.19	-12.7%	17.73	-19.3%	21.14	-3.8%
Average	**23.27**	**19.82**	**-14.7%**	**19.57**	**-16.1%**	**21.70**	**-6.6%**

* The SPR field site experienced an irrigation water shortage in 2021 due to drought conditions, which impacted the ET_a estimates for the field. The results are still included here because they highlight the reality of implementing water conservation efforts in areas that periodically experience some degree of water supply limitations.

Table 2. Summary of CCU volumes for project area based on Prior Years Approach

			2020		2021		2022		Overall
Site	**Site Area** (ac)	**2016-2019 Baseline** (in)	**TRT ET_a** (in)	**CCU** (AF)	**TRT ET_a** (in)	**CCU** (AF)	**TRT ET_a** (in)	**CCU** (AF)	**CCU** (AF)
SPR	220.7	22.9	14.4	154.6	17.2	104.3	21.1	31.8	290.7
SBR	70.3	22.0	11.8	59.6	20.5	8.7	22.4	-2.3	66.0
GPR T1	203.1	23.6	6.2	294.5	21.1	42.4	23.5	1.6	338.6
GPR T2	345.7	25.9	11.2	424.7	22.4	101.5	25.7	5.0	531.2
RSR	123.3	24.6	20.5	42.3	21.4	32.6	22.3	23.8	98.7
RCR	37.6	22.0	19.2	8.7	17.7	13.3	21.1	2.6	24.6
Total				**984.6**		**302.7**		**62.5**	**1349.8**

Reference Approach Summary

- Another approach to estimating CCU is to compare modeled site ET_a averages between the reference and treatment sites for the same time period. Using the Reference Site Approach, the amount of CCU is equal to the ET_a for the treatment sites subtracted from the ET_a for their comparison reference site.
- The Reference Site approach is simple because it does not require estimating changes in effective precipitation, temperature, irrigation, available soil moisture, or groundwater contribution (where applicable) that could affect the baseline used in the Prior Years Approach.
- The main limitation of this method is that it assumes the selection of a comparable reference condition, and thus does not consider specific site differences that may be caused by pasture health, soil fertility, or underlying soil conditions. However, across all years of this study, the reference sites illustrated a relatively stable pattern of water use despite diverse weather conditions.
- Using the Reference Site approach, average ET_a for the treatment sites where irrigation was completely withdrawn was 57.5% lower than the reference sites. ET_a for the treatment fields under partial-season irrigation withdrawal was 20.9% lower than the reference sites (Table 3.4.2.1).
- The treatment sites under full restriction then exhibited a net reduction of 5.2% ET_a compared with their respective reference sites in 2021, indicating an overall effect of the sites returning to expected pre-reduction rates of water consumption. The treatment sites then increased their ET to 0.6% above the comparison reference conditions in 2022.
- Fields irrigated under the partial-season reduction condition exhibited net reduction of 11.8% ET_a compared with their respective reference sites in 2021, then rebounded to 0.5% above their reference sites in 2022.
- Using the Reference approach, average 2020-2022 CCU across the study fields was 1.34 AF/acre for full season treatments and 0.77 AF/acre for split season.

Table 3. Reference Field ETa compared with TRT Field ETa during impact and recovery years

	2020 Impact Year			2021 Recovery Year 1			2022 Recovery Year 2		
Site Name	**REF**	**TRT**	**Change**	**REF**	**TRT**	**Change**	**REF**	**TRT**	**Change**
				Full Season Irrigation Reduction					
SPR*	23.57	14.45	-38.7%	15.32	17.18	12.1%	19.81	21.12	6.6%
SBR	28.02	11.81	-57.8%	24.45	20.51	-16.1%	23.59	22.39	-5.1%
GPR T1	25.43	6.22	-75.5%	24.48	21.12	-13.7%	25.73	23.53	-8.6%
GPR T2	25.43	11.15	-56.1%	24.48	22.37	-8.6%	25.73	25.72	0.0%
Average	**25.67**	**10.91**	**-57.5%**	**21.42**	**20.30**	**-5.2%**	**23.04**	**23.19**	**0.6%**
				Partial-Season Irrigation Reduction (no irrigation after June 15)					
RSR	27.60	20.45	-25.9%	23.59	21.40	-9.2%	23.53	22.25	-5.4%
RCR	22.52	19.19	-14.7%	20.76	17.73	-14.6%	19.65	21.14	7.6%
Average	**25.06**	**19.82**	**-20.9%**	**22.18**	**19.57**	**-11.8%**	**21.59**	**21.70**	**0.5%**

* In addition to the water shortage condition for the SPR field site described above, the SPR reference field also experienced some unintended animal grazing in 2021, which impacted the ET_a estimates in that year.

Table 4. Summary of CCU for project evaluation area based on Reference Site Approach

		2020			2021			2022			Overall
Site	**Site Area**	**REF ET_a**	**TRT ET_a**	**CCU**	**REF ET_a**	**TRT ET_a**	**CCU**	**REF ET_a**	**TRT ET_a**	**CCU**	**CCU**
	(ac)	(in)	(in)	(AF)	(in)	(in)	(AF)	(in)	(in)	(AF)	(AF)
					Full Season Irrigation Reduction						
SPR	220.7	23.6	14.4	167.8	15.3	17.2	-34.2	19.8	21.1	-24.2	109.4
SBR	70.3	28.0	11.8	94.9	24.5	20.5	23.1	23.6	22.4	7.0	125.0
GPR T1	203.1	25.4	6.2	325.1	24.5	21.1	56.9	25.7	23.5	37.2	419.1
GPR T2	345.7	25.4	11.2	411.4	24.5	22.4	60.8	25.7	25.7	0.3	472.5
					Partial-Season Irrigation Reduction (no irrigation after June 15)						
RSR	123.3	27.6	20.5	73.5	23.6	21.4	22.5	23.5	22.3	13.2	109.1
RCR	37.6	22.5	19.2	10.4	20.8	17.7	9.5	19.7	21.1	-4.7	15.3
Total				**1083.1**			**138.5**			**28.9**	**1250.5**

<u>*Changes in ETa Summary*</u>

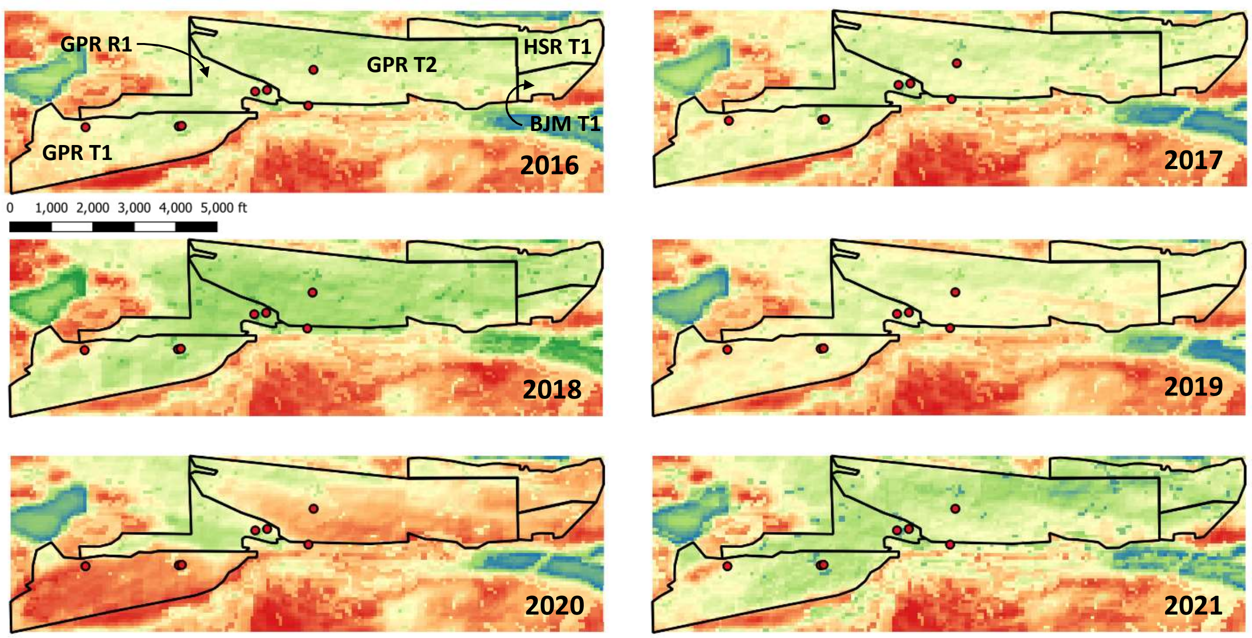
- In general, fully restricted treatment fields appeared to return more vigorously to prior year ET_a after the period of water stress, compared with the fields under partial-season reduction.
- The data show that reduced ET_a in fields that are enrolled in irrigation reduction programs persists beyond the year in which irrigation is withheld. This raises the question of whether these lag effects of diminished CU should be incorporated into a multi-year estimate for CCU.

2. Variability in water use across field sites:

- For each field site, remote sensing data from eeMETRIC is provided for each individual 30m x 30m pixel within the site. A closer look at this data shows that water use varies significantly across the sites, even with uniform management to restrict irrigation. For this study, ET_a was estimated using a spatial average for the entire field boundary. However, significant variations in water use across the site warrant consideration of other approaches that may better account for edge effect or influence from neighboring water sources for example.

- Figure 1 below shows an example of spatially mapped ET_a. Variations seen in this image can occur due to subsurface conditions, such as soil types, affected root zone depth, and availability of groundwater from either stored soil moisture or proximity to a neighboring water source, such an active irrigation supply ditch or the river itself. In the case of REF site GPR R1, for instance, there is a dramatic decrease in ET on the southern boundary of the site, adjacent to the TRT site GPR T1. Conversely, the northern boundary of GPR T2 was impacted by seepage from an irrigation water delivery ditch, which sub-irrigated the site and promoted vegetative growth. Neighboring effects such as these are real biophysical processes with actual outcomes, however, which are unavoidable but will also influence spatially aggregated ET data.

Figure 1. Spatial distribution of annual ETa during prior years (2016-2019), irrigation withholding year (2020), and return year (2021) for GPR R1, GPR T1, GPR T2, BJM T1, and HSR T1. Forage and instrumentation enclosures are designated by a red dot symbol. The red to green color ramp is a visual quantification of annual ETa from 100 mm (3.93 in) to 1,000 mm (39.4 in)



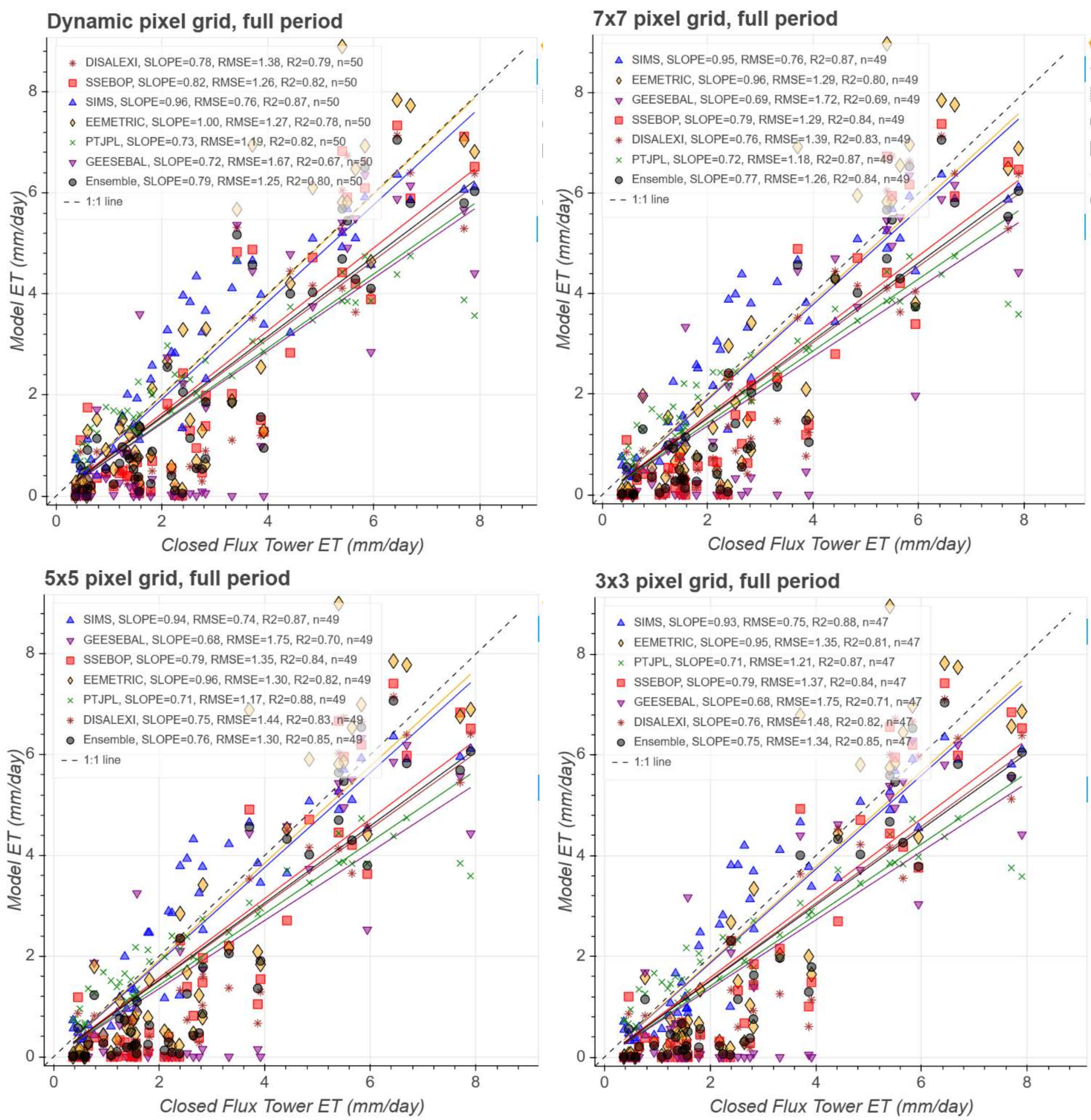
3. **Comparison of remote sensing models with eddy covariance**
   - To better understand the applicability of remote-sensing for estimating water use in the study geography (high-elevation, perennial grass pastures under reduced irrigation), ET_a estimates from remote-sensing based models were compared with the onsite measurements of ET_a made from the eddy covariance (EC) tower instrumentation. Among the modeled results, the ET_a estimates made by eeMETRIC agreed best with the ET_a derived from the EC tower, based on an average slope = 1.00, RMSE = 1.27, and R2 = 0.79 (see Figure 2).
   - The selection of eeMETRIC as the preferred model is based on a holistic assessment, considering all of the comparative statistical metrics.
     - The eeMETRIC model performs accurately under the irrigation reduction conditions, whereas temperature-based models such as SSEBop and GEESEBAL produced values of near zero during

irrigation reduction. These low values are not realistic, given residual soil moisture and the data derived from the EC tower.

- The PT-JPL model agreed well with EC measurements under the water-deficit conditions, but it underpredicted for well-watered conditions.
- The SIMS model is built on idealized well-managed, well-watered conditions and considered unsuitable for estimating ET for any sort of deficit irrigation scenarios.

- One explanation for why eeMETRIC performs relatively better than other models against the ET_a estimates from the EC tower is that it combines the use of NDVI, temperature, and albedo as inputs of an energy balance model. These additional parameters likely improve the performance of eeMETRIC in estimating ET_a.

Figure 2. Plots comparing ET rates from EC Tower against modeled ET rates from remote sensing data.



DISCUSSION

Given recent developments in the adoption of remote sensing tools by water administrative agencies, this research lends validation to the use of this technology for individual projects and broader programmatic and policy purposes.

This study also presents the perspective that water conservation programs must be viewed in the context of a multi-year phased process. The suppressed CU rates after the program year of irrigation indicate that some water conservation might still be occurring during the years following reduction, suggesting that multiple years of consideration could be part of the measurement and verification aspects of any water conservation program.

NEXT STEPS

Further research is recommended in order to develop the findings of this study in greater detail. This includes addressing the question of whether the spatially averaged ET_a rates assigned to the fields change measurably if the pixels used in calculating these results are selected using another heuristic beside a spatial average for the whole field. Possible approaches might include a surrounding buffer of 1 or 2 pixels to remove any edge effects, using a statistical approach to dealing with outliers near underlying water sources such as ponds, ditches or water bodies, taking only those measurements within a single standard deviation of the mean, or basing an acceptable population of measurements on a median value, rather than an average.

The ET_a data will also be utilized to produce crop production functions that help normalize the amount of CU required to produce a unit of dry matter forage. Understanding this relationship better can increase communication during negotiations for water sharing.

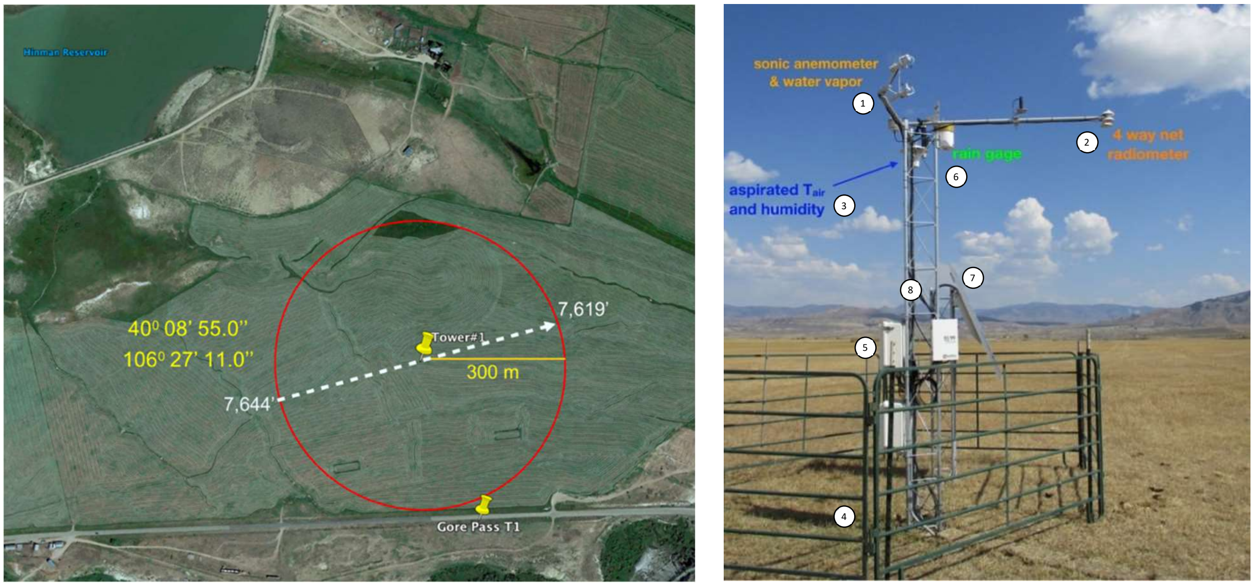
Lastly, further data will be made available for the remainder of 2022 and be included in subsequent reports, as well as data from the 2023 cropping season.

Estimating Water Use with Eddy Covariance

BACKGROUND

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 withheld for a full season in 2020 and then returned to historic irrigation practices for 2021 and 2022. Measurements from the tower taken between June 18, 2020, and October 31, 2022, were used to estimate evapotranspiration (ET_a) through the eddy covariance (EC) technique. This data was then compared to ET_a estimates from remote sensing-based models, as described in the previous section.

Figure 3. Eddy covariance tower location, surrounding fetch (red circle), and instrumentation.

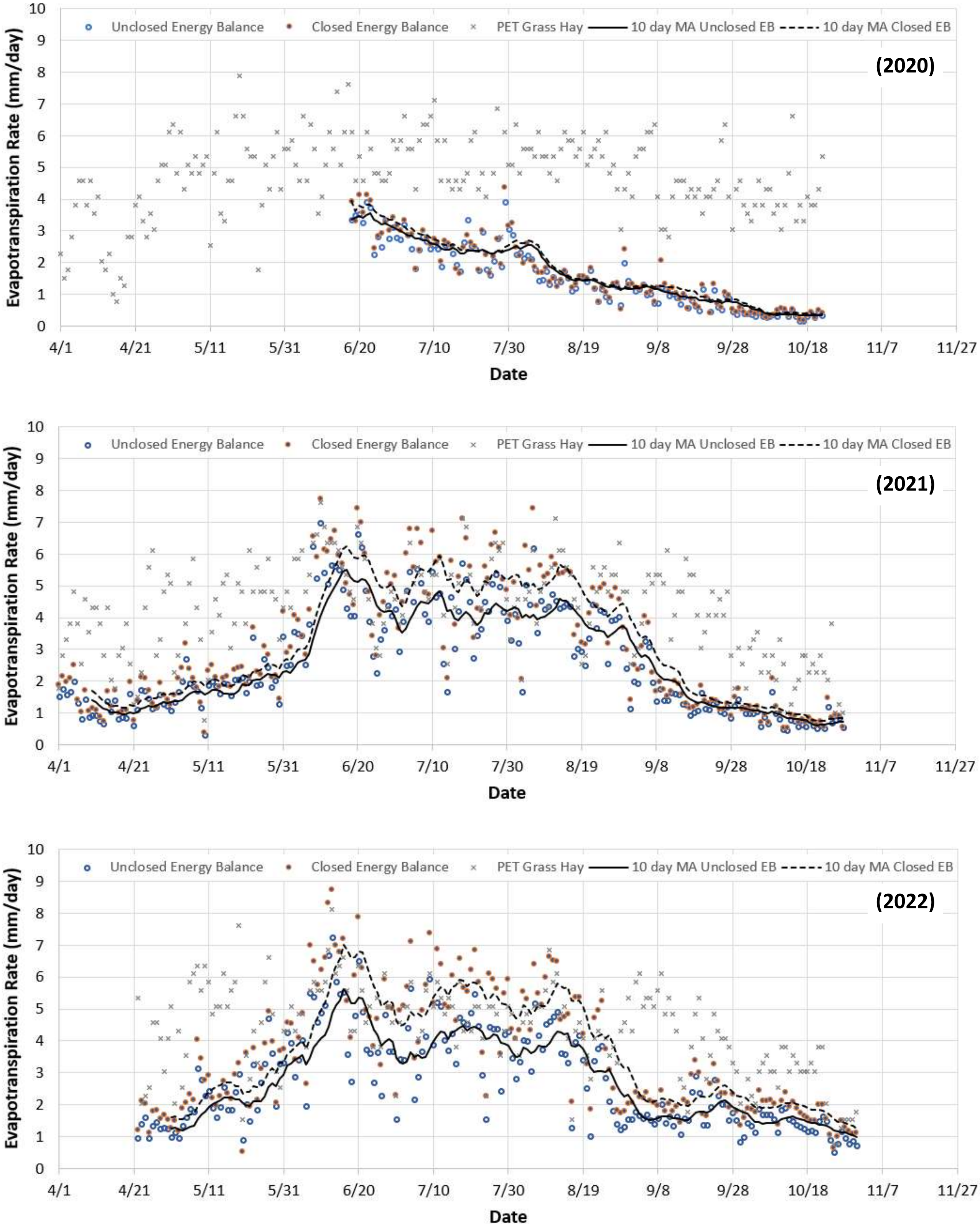


RESULTS

Eddy covariance tower instrumentation estimates water use (ET_a) through an energy balance closure approach. The accuracy of water use estimates from this approach is based on how well independently measured energy inputs balance the outputs on a scale of 0 to 1. The closer the value is to 1, the more the energy balance is said to be "closed" and the more accurate the estimate of water use. The energy balance closure analysis for 2020 reveals a strong average daily value of 0.92, indicating a high level of acceptability. In the subsequent years, 2021 and 2022, the average daily closure values were somewhat lower but remained elevated, with averages of 0.84 and 0.76, respectively. These values demonstrate a robust level of accuracy according to this methodology. The obtained results are highly dependable, with any potential alterations in fluxes due to closure adjustments being negligible.

The reduction in the actual evapotranspiration (ET_a) rate during the year of water use restriction is readily noticeable, clearly illustrating the impact of decreased irrigation on the study area (Figure 4a). In 2021, ET_a rates remained subdued until the field received its initial irrigation. One plausible explanation for this is that soil moisture levels were lower than anticipated, considering a typical fully-irrigated growing season. After the initial irrigation event in 2021, the field ET_a rates began to align more closely with potential evapotranspiration (PET or ET_p) values (Figure 4b, 4c). Towards the conclusion of the season, as temperatures declined, the ET_a rates for the grass hay experienced a significant reduction, a trend that is not reflected in the computed ET_p values.

Figure 4. ETa rate modeled from the closed and unclosed energy balance in 2020 (a), 2021 (b) and 2022 (c).



DISCUSSION

The grassland environment at high elevation pasture locations possesses a unique character, 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 due to irrigation restrictions, coupled with broader regional climate shifts, can potentially modify the evapotranspiration process. These changes are likely to have substantial implications for the water and energy balances of fields involved in water sharing agreements.

In this context, any shifts in precipitation patterns due to climate variability and alterations in ET_a because of irrigation restrictions 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-restriction year.

The study's findings demonstrate the following: (1) Imposition of irrigation restriction 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_a becomes more pronounced as the season advances into warmer months and tapers as environmental temperatures decrease. (3) Implementation of full irrigation restriction 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.

NEXT STEPS

An additional year of EC tower data for 2023 will be incorporated into future reports. Further, 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.

Estimating Water Use with Soil Moisture Sensors

BACKGROUND

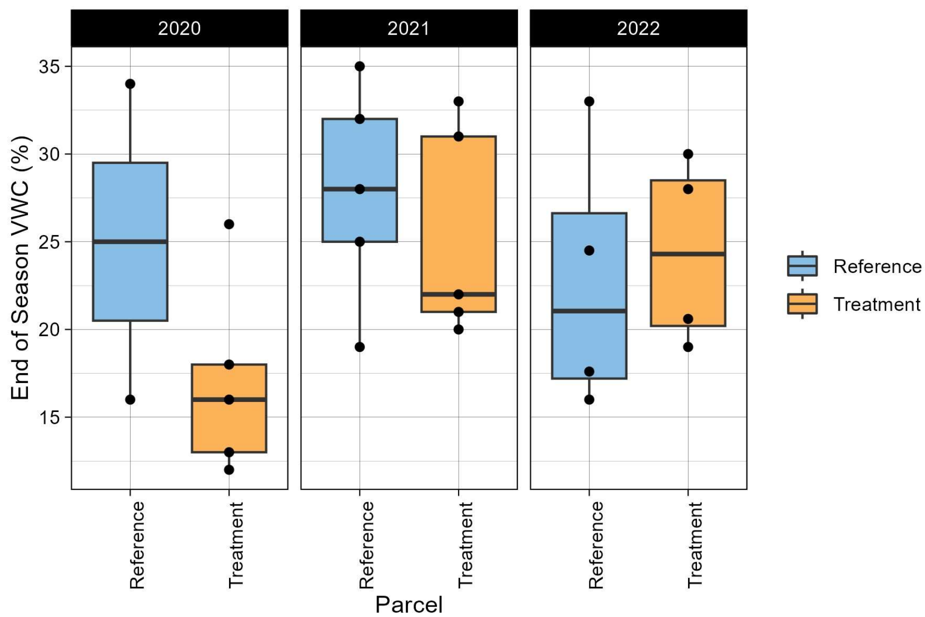
Continuous soil moisture measurements were taken in 10 project fields using in-situ Acclima TDR-315 sensors and Solar DataSnap SDI-12 data loggers (Acclima, Inc., Meridian, ID) between 2020-2022. Sensors were installed at 6, 18, 30 and 42 cm depths to represent identical 12 cm sub-zones of 0-12, 12-24, 24-36, and 36-48 cm below the soil surface within the effective root zone. The installation of these sensors was intended to serve the purpose of a low-cost method for comparing modeled evapotranspiration (ET) rates from remote sensing data against an in-field soil water balance approach based on soil moisture depletion over a specified time interval.

RESULTS

- During the evaluation period, there were 28 distinct time intervals identified during which a one-dimensional soil water balance 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.

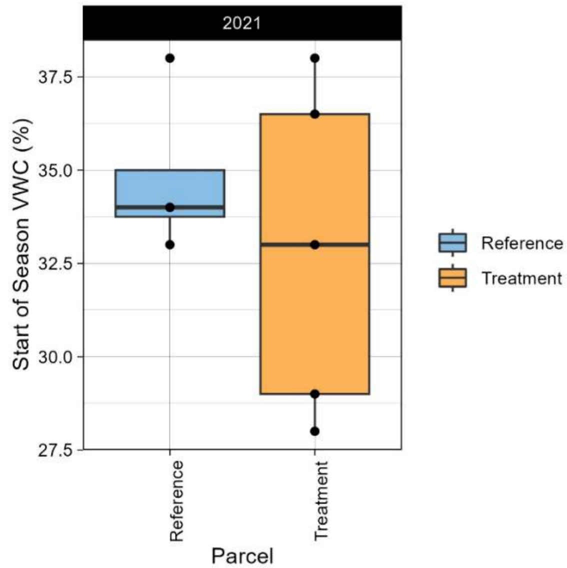
- Estimations of total ET using the soil water balance approach averaged 30% lower than the modeled estimates derived from eeMETRIC and the eddy covariance tower over the same time intervals. One possible reason for this lower estimate from the soil water balance could be that the effective root zone for these fields extends below 48 cm, which means that the sensors did not accurately account for the total soil moisture depletion.
- The sensors were also valuable for comparing before and after soil moisture levels on reference and treatment fields. This showed that after the 2020 season reference fields had an average post-season volumetric water content (VWC) of approximately 25%, while treatment fields had a 16% average VWC.

Figure 5. Comparison of end of season total VWC between reference and treatment fields in 2020-2022



- Before the 2021 irrigation season, winter precipitation (estimated at 8.2 cm based on local weather data) contributed to an increase in VWC levels on all project fields. As a result, all fields in 2021 started the season with VWC levels exceeding 30% in the estimated 48 cm root zone, although the fields affected by irrigation reductions had slightly lower levels and a much wider range of VWC values.

Figure 6. Comparison of start of season total VWC between reference and treatment fields in 2021



DISCUSSION

We observed large discrepancies between the ET_a estimates for the soil water balance method and the remote sensing method. This may be due to inherent challenges in inferring field ET_a from the specific site where the soil moisture sensors were located, root zones extending beyond the depth of the sensors, or other factors. Based on this work, it will be challenging to implement an effective soil water balance method for estimating ET_a across a large and heterogenous area. However, measuring and understanding root zone depth and VWC in the soil may be helpful in understanding how end of season and start of season conditions impact water use and recovery in fields participating in voluntary water conservation programs.

NEXT STEPS

We will incorporate one additional year of soil moisture data from 2023 into a final analysis.

Forage Recovery

BACKGROUND

As programs that pay producers to temporarily withhold irrigation gain interest as a water sharing strategy, the multi-year impact of irrigation reductions on high-elevation fields is a major concern expressed by potential participants.

An extensive dataset of forage production and quality was collected from 2020-2022 on fields where water had been withheld and reference fields that were irrigated according to customary practices. To assess the pace and degree of forage recovery, fields with fully withheld or partial-season irrigation were paired with similar reference fields that were irrigated according to historic practices throughout the study period.

In this report, recovery in 2022, two years after irrigation reduction, is assessed in terms of yields and quality. This report also reviews trends in productivity and quality in both treated and reference fields over the course of the project to date and discusses how climate conditions may have influenced those trends.

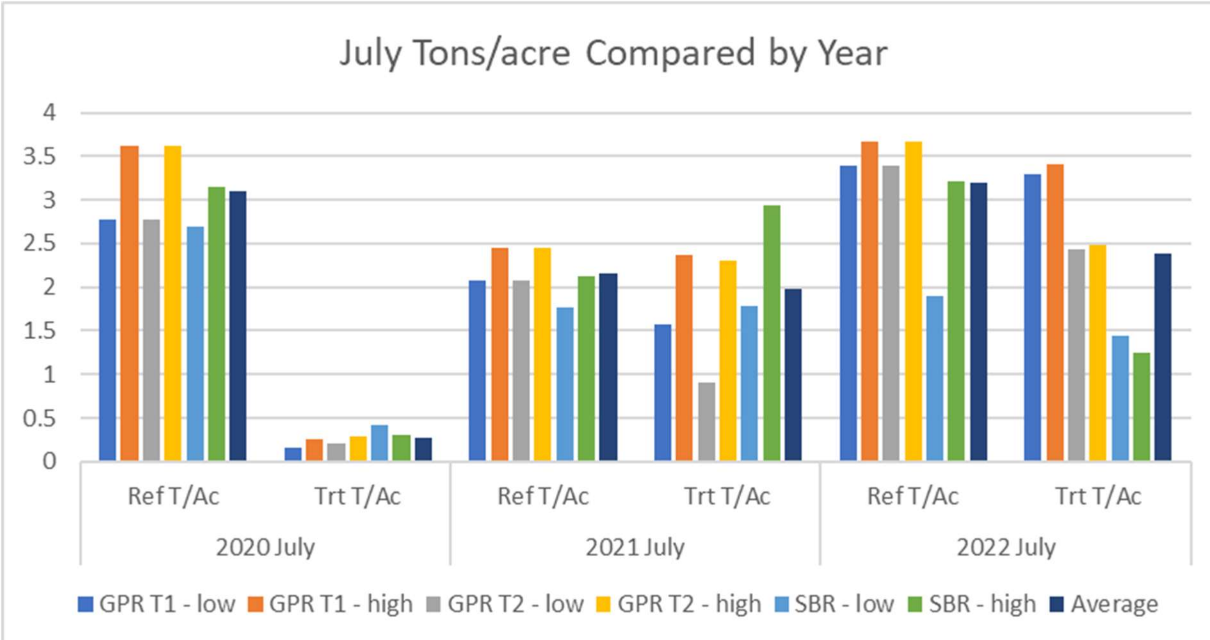
RESULTS

- As anticipated and reported in the project's 2020 report, forage productivity on the fields with full irrigation withdrawal was very low compared to the productivity on reference fields in 2020.
- In 2021, when these fields were returned to full irrigation, productivity on treated fields compared with reference fields was mixed across fields, while forage quality was typically the same or higher on treated fields compared with reference fields.
- In 2022, the second year in which treated fields were returned to full irrigation, yields on the treated fields were on average higher than they were in 2021, but still tended to be lower than yields on the reference fields. There continued to be large differences between how different treatment fields compared to their reference fields, with July yields on treated fields where irrigation had been fully withdrawn in 2020 ranging from 2.7% to 61% below yields on reference fields.
- Yields on fields with partial-season irrigation withdrawal (no water after June 15) fared better than fields where irrigation was completely withheld, with yields ranging from 7% below to 27% above yields on reference fields.
- July crude protein levels on the fields where irrigation was fully withdrawn in 2020 were also highly variable, ranging from 33.2% below to 45.3% above crude protein levels on their reference fields, with higher crude protein levels corresponding to lower yields. Results were similar for the fields where irrigation was withdrawn after July 15 in 2020.

Table 5. July Tons/Acre Compared by Year

	2020 July		2021 July		2022 July	
Site	Ref T/Ac	Trt T/Ac	Ref T/Ac	Trt T/Ac	Ref T/Ac	Trt T/Ac
GPR T1 - low	2.77	0.16	2.07	1.57	3.39	3.3
GPR T1 - high	3.62	0.26	2.45	2.37	3.66	3.4
GPR T2 - low	2.77	0.21	2.07	0.9	3.39	2.43
GPR T2 - high	3.62	0.29	2.45	2.31	3.66	2.49
SBR - low	2.69	0.42	1.76	1.79	1.89	1.44
SBR - high	3.14	0.3	2.13	2.93	3.21	1.25
Average	3.10	0.27	2.16	1.98	3.20	2.39

Figure 7. July Tons/Acre Compared by Year



DISCUSSION

This study demonstrates that significant impacts to productivity of high elevation grasses can persist for multiple years after irrigation has been withheld, although these impacts are highly variable between fields, with some showing near complete recovery. It is possible that the negative impacts on some fields may be magnified if the year in which irrigation was withheld is particularly dry, as it was in 2020, when treatment fields underwent full or partial season irrigation withdrawal.

NEXT STEPS

One final year of forage data will be collected and analyzed for 2023. This data will be incorporated into a final summary report for the project.

Economics & Enterprise Budgeting

BACKGROUND

As Colorado River Basin water supplies shrink due to drying conditions and overallocation, the potential to balance supply and demand by paying farmers and ranchers to use less water is one of the policy options that has been put on the table. Whether this is a viable option for particular producers in particular circumstances depends both on how the programs are structured and other external factors.

To address this, we investigated the economic impacts to Grand County, Colorado hay producers from withholding irrigation water in exchange for set payment rates in 2020. Producers either entered into an agreement for either a full irrigation withdrawal or a partial-season withdrawal. For the full withdrawal, they agreed to turn off water for their fields for the entire irrigation season. Under the partial-season withdrawal, they agreed to turn off irrigation water on June 15th. Partial season payments were set at $281 per acre and full irrigation withdrawal were $621 per acre for the one year of reduced irrigation.

Interviews with a small set of agricultural producers participating in the study were conducted to determine costs and revenues associated with their hay production on both reference (control) and treatment (variable) fields. Data related to operations were collected from producers and used to build enterprise budgets for each of their study fields to determine their overall profit/loss on a per acre and per field basis. The results of this small study are influenced by factors specific to the climate conditions of the project year (very dry) and geography (high elevation, short growing season), so the "break even" number is not generalizable to other circumstances. However, this report does identify important, broadly applicable factors that increase risks for those producers participating in programs that pay them to temporarily withhold irrigation, and the magnitude of compensation that may be required to keep certain producers economically whole in dry years.

RESULTS

Table 6. Results from reference field enterprise analysis for the six operators participating in the study. Results reported are gross receipts, total operating and fixed costs, net receipts before factor payments, and return to management and risk.

REFERENCE FIELDS	**Average**	**Max**	**Min**
Gross Receipts	$ 319.61	$ 455.28	$ 66.00
Total Operating + Fixed Costs	$ 313.14	$ 426.74	$ 211.21
Net Receipts Before Factor Payments	$ 7.47	$ 192.82	$ (282.88)
Factor Payments	$203.50	$203.50	$203.50
Return To Management and Risk	$ (196.03)	$ (4.68)	$ (486.38)

Table 7. Results from treatment field enterprise analysis for the four operators participating in full season withdrawal. Results reported are total operating costs, net receipts before factor payments, and return to management and risk.

TREATMENT FIELDS – Full Season	**Average**	**Max**	**Min**
Gross Receipts	$ 621.00	$ 621.00	$ 621.00
Total Operating + Fixed Costs	$ 220.30	$ 266.18	$ 152.74
Net Receipts Before Factor Payments	$ 400.69	$ 468.26	$ 354.77
Factor Payments	$203.50	$203.50	$203.50
Return To Management And Risk	$ 197.19	$ 264.76	$ 151.27

Table 8. Results from treatment field enterprise analysis for the two operators participating in partial season withdrawal. Results reported are gross receipts, total operating and fixed costs, net receipts before factor payments, and return to management and risk.

TREATMENT FIELDS – Partial Season	**Average**	**Max**	**Min**
Gross Receipts	$ 467.50	$ 566.00	$ 369.00
Total Operating + Fixed Costs	$ 310.00	$ 325.40	$ 294.59
Net Receipts Before Factor Payments	$ 157.51	$ 240.60	$ 74.41
Factor Payments	$203.50	$203.50	$203.50
Return To Management And Risk	$ (46.00)	$ 37.10	$ (129.09)

The report concludes that payments of $621/acre of land subjected to a full season of irrigation withdrawal were sufficient to bring net economic gains of $393.22/acre to producers that grew hay strictly for sale (i.e. no livestock also relied on grazing the hay fields). Producers who accepted partial season payments of $281 per acre experienced a net increase of $150.03 per acre. In both instances, these gains are compared directly to net profits from reference fields that were irrigated normally during the same period.

However, producers that relied on their hay fields to feed cattle experience a net loss of profit, despite the payments. The study found that producers with livestock would have needed an average payment of at least $970.66/ acre to fully compensate them for the additional costs they incurred by withholding irrigation on the study fields. This was due to the high cost of hay to replace the harvested hay and pasture grass that they would have grown to feed their herds had they irrigated normally. The dry conditions in 2020 led to low hay yields across the region, decreasing the availability of hay and also driving up the prices.

It is worth noting that in the extremely dry conditions in 2020, study participants operated at a loss on the reference (control) fields they irrigated normally. In the highly variable climate conditions faced by high elevation ranches, it is not unusual to have bad years, where profits are negative. In this environment, the potential impacts of producers incurring additional risk by accepting payments for irrigation withdrawal that may not fully compensate for the associated costs are enhanced for livestock producers. However, for hay producers the payments provided a significant benefit over reference conditions.

DISCUSSION

Beyond the implications for high elevation hay producers, this study demonstrates the importance of considering all elements of a farm or ranch operation and how they interact, as well as how climate and market factors could affect them, in order to accurately capture the payment that may be required to fully compensate producers for the costs of withholding irrigation. Given the variability of the climate and market factors that can affect these costs, an important question is who bears the risk of the price ultimately not being "right," when weather and market conditions may be uncertain at the time an agreement is struck. If the price is set too low, the producer may be operating at a loss and bearing much more risk and stress of procuring additional feed for the late fall and winter months. If the price is set too high, the producer may get a windfall, while the paying entity overpays. This question should be considered by both program designers and producers considering participation in similar programs. Additionally, given the variability in water use described previously in the report, there may be advantages to structuring payments on a per acre basis for a defined management practice, rather than per acre-foot of conserved consumptive use.

NEXT STEPS

Additional work will be completed to incorporate economic info from subsequent years (2021-2023) when full irrigation was returned to the treatment fields.

River Flow Monitoring

BACKGROUND

Water conservation projects on irrigated agricultural lands can impact rivers and streams that are either sources of irrigation water or recipients of surface or groundwater return flows. Under the Project, full or partial- season irrigation withdrawal in 2020 reduced both surface water diversions and consumptive water use. These reductions are also expected to impact groundwater, reducing, or eliminating lagged return flows to streams. Evaluating these potential hydrological changes requires understanding the quantity and timing of stream flows under 'normal' operations and changes along the reach due to water conservation.

This study uses two approaches to evaluate stream flow impacts:

1. Field-based channel water balance studies, which include stream flow measurements along reaches impacted by the project during a typical irrigation year and a water conservation year.
2. Development and use of simulation tools for modeling impacts of the project on surface stream flows and groundwater return flows.

RESULTS

- Field-based channel water balance measurements were unable to detect the impact of water conservation activities. We expect this is due, in some cases, to the expectation for relatively small groundwater return flows relative to streamflows in the receiving stream/river and, in other cases, due to high uncertainty in the location of groundwater return flow accrual.

- Results generated for the Colorado River, Wolford Reservoir and Williams Fork suggest that a coupled simulation modeling approach has the capacity to provide general insights into the impacts of irrigation withdrawal on the hydrology of down-gradient streams and reservoirs.
- The simulated effects of water conservation activities in the Kremmling area help quantify increases to Wolford Reservoir and Williams Fork Reservoir inflows early in the runoff season and modest decreases in those inflows later in the summer. Increased inflows in the runoff period likely resulted in a larger reservoir spill in the early summer. Decreased inflows later in the summer may have limited opportunities for additional water storage, particularly in Wolford Reservoir.
- The simulation of water conservation activities on streamflows in the Colorado River indicate modest and variable effects across the irrigation season. Simulated flow differences resulting from conservation ($\pm$ 10 cfs) relative to late summer streamflows (200-400 cfs) confirm the challenges posed for direct measurement of water conservation treatment impacts where streamflow measurement error on the order of 5-8% is typical.
- Refining estimates of specific treatment impacts on timing and magnitude of streamflow alteration due to water conservation activities in the Kremmling area would require data collection to further constrain irrigation rates and application patterns, physical soil parameters and aquifer properties.
- Uncertainty in model outputs is primarily driven by a lack of local data describing soil infiltration rates, hydraulic conductivity, porosity, and aquifer transmissivity. Soil characteristics can be better constrained via field data collection, but adequate characterization of aquifer characteristics will likely remain a prohibitively costly and complex undertaking at most locations.
- Monte Carlo style simulation modeling approach will likely remain the best approach for estimating the range of potential consequences associated with a planned or implemented water conservation activities similar to those conducted in the Kremmling area. This modeling approach helps analyze complex systems with high levels of uncertainty by repeatedly generating random samples of inputs and using them to estimate outcomes.

DISCUSSION

The 2021 Report provided an update on the field-based estimates of impact, which compared field measurements in the two study reaches (Colorado River and Pass Creek) taken monthly from August to November in both 2020 and 2021. As described in the 2021 Report, the initial project results suggest that the channel water balance approach for these sites may have limited utility for identifying the impacts of irrigation withdrawal on late-season, local streamflow patterns. This is due to several factors, including climatic variations such as temperature and precipitation, changes in irrigation water management on adjacent, non-participating fields, uncertainties in field-based measurements, groundwater return flows that may be lagged for more than several months, and/or incorrect assumptions in the selection of measurement locations to accurately capture groundwater return flows from participating parcels. The report further concludes that “overcoming challenges associated with interannual variability and a lack of experimental control likely requires study designs where the effects of the treatment and the reference condition can be characterized across multiple years. Such study designs may also require additional measurements to address confounding factors such as irrigation patterns of non-participating parcels and streamflow in tributaries. These studies must also overcome uncertainties in streamflow measurements which may mask treatment effects that are below detectable thresholds. This is probably not feasible in most settings and illustrates the need for alternative approaches for quantifying impacts of water conservation on streamflow.”

The “Water Conservation Project Impacts on Streamflow in the Kremmling Area” technical report attached to this 2022 Report confirms the 2021 findings regarding the challenges and limitations of direct measurement of conservation impacts on stream flows and describes a modeling approach to measure such impacts and major findings resulting from the modeling effort.

NEXT STEPS

This portion of the project has been completed.

Avian Response to Irrigation Changes

BACKGROUND

Irrigated agricultural lands throughout Colorado provide important wildlife habitat for a number of avian species, and given the potential need for agricultural water conservation, there is a critical need to understand how and to what degree reduced irrigation may influence bird use of these habitats. To address this, five agricultural properties with varying levels of irrigation withdrawal were monitored in 2020 (during irrigation withdrawal) and 2 subsequent years (2021 and 2022, when irrigation levels throughout all properties were returned to normal) using the Bird Conservancy of the Rockies' Integrated Monitoring in Bird Conservation Regions (IMBCR) Field Protocols for Spatially Balanced Sampling of Landbird Populations.

RESULTS

- During the 3 years (2020 through 2022) of avian surveys for the project, biologists documented a total of 4,580 avian detections across 64 different species. The three avian species with the most recorded detections throughout all monitoring years combined and within each individual year were the cliff swallow (*Petrochelidon pyrrhonota*), savannah sparrow (*Passerculus sandwichensis*), and red-winged blackbird (*Agelaius phoeniceus*).
- Sixty-four (64) different species were recorded during the 3-year study period. Thirty (30) of the 64 total species recorded from 2020 through 2022 were labeled as 'water-associated' species; the remaining 34 species were labeled as 'upland' species. Water-associated species had a combined total of 3,301 detections across all 3 years.
- Despite consisting of only 47% of the total species richness recorded, water-associated species represented 72% of all detections documented over the 3 combined years of surveys.
- Approximately 25% more species were recorded in 2021 (when irrigation was first returned to normal levels) than in 2020. However, between 2021 and 2022, a decrease of 36% in recorded water-associated species occurred, although irrigation levels remained unchanged between those years.
- Temperatures at the time of the surveys appeared to be consistent with the trends in avian detections of all species across the 3 survey years. The third year of surveys (2022) was the coldest with nearly 60% of the point counts being completed in temperatures under 10 degrees Celsius or 50 degrees Fahrenheit. In that year, three of the four temperature ranges (roughly 10-degree intervals ranging from 28-70 degrees Fahrenheit) had less than 11 detections per point count.
- Conversely, 2021 was the warmest year for surveys with only 17% of the point counts completed below 10 degrees Celsius or 50 degrees Fahrenheit. In that year, one temperature interval (40-49 degrees Fahrenheit or 4 to 9 degrees Celsius) had approximately 13 detections per point count but all other intervals ranged from 19 to more than 25 detections per point count.

DISCUSSION

Avian monitoring provided inconclusive results as to the short-term effects of irrigation water conservation practices on the occurrence of avian detections and species richness. Our expectation was that the number of avian detections and species richness would increase in response to a return of normal irrigation levels. Surveys results in the first year after irrigation withdrawal (2021) clearly demonstrated an increase in water-associated avian detections and species richness among treatment field point count locations. However, similar findings were expected in 2022 (the second year of normal irrigation levels after withdrawal) and this was not demonstrated in the survey results that year. In some regard, the results from 2022 were diminished from those in 2020 (treatment year), which further opposed our expectations. Although water-associated species detections were slightly higher in 2022 than in 2020 (approximately 6% more), species richness was 20% lower in 2022.

Birds are highly diverse, mobile creatures that use a wide array of habitats for many different seasonal purposes, often making it challenging to interpret the outcomes of avian monitoring efforts. Avian abundance and diversity can be influenced by a combination of many factors. Sorting through the plausible combinations of influential factors can be difficult or infeasible, especially when baseline data were not collected prior to the implementation of this project.

Finally, the results of the surveys for this project are likely impacted by the relatively small number of agricultural properties and the small extent within each individual property where the project was implemented. Due to this limitation, as well as others stated above, inference of these results should be done with caution.

NEXT STEPS

This project offered a unique opportunity to look at the effects of water conservation practices on avian communities. The results suggest that water-associated species detections and species richness may be influenced by both water availability (primarily represented as supplied irrigation) and temperature conditions at the time the surveys were completed. However, due to the design of the project, no avian data were collected prior to the implementation of the water conservation practices in 2020 (i.e., baseline data) to be able to compare the effects of the water conservation treatments both before and after the treatments were implemented. Further research is needed to assess more specific impacts to avian species (both in overall diversity as well as particular water-associated species) from irrigation withdrawal. Additional studies across multiple seasons may also provide meaningful information regarding the impacts of water conservation practices on avian communities, as some avian species may also use high-elevation perennial grass pastures outside the nesting season at other critical life-stage periods (e.g., as migration stopover habitat).