Brief #1: Measuring Conservation

Estimating the Water Conservation Potential of Voluntary Irrigation Withdrawals on Working Livestock Pastures

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Overview

➢ Irrigated pasture-livestock systems dominate agriculture in Western Colorado, yet data on their water use and water conservation potential under voluntary irrigation withdrawals remains limited.

➢ We partnered with Western States Ranches to test eight irrigation scenarios on two working pastures, Orchard Ranch near Eckert and Banner Ranch near Delta, on Colorado's Western Slope.

➢ Results showed strong potential for voluntary withdrawal practices to reduce water use while maintaining some forage production. The greatest reductions came from early- and shoulder-season cutbacks—up to 47% when compared to fully irrigated reference fields.

Purpose

We evaluated the potential of voluntary irrigation withdrawal strategies, to help inform the design of practical, incentive-based water conservation programs for grazed pastures.

The findings will help stakeholders and policymakers:

- Assess the potential of voluntary irrigation withdrawals on working pastures to meaningfully contribute to regional water conservation efforts.
- Recommend measurement methods and program design features that align water savings goals with operational realities of livestock producers.

Approach

We tested 8 irrigation withdrawal strategies across ranches, using remote-sensing models to estimate actual evapo-transpiration (ETa) and conserved consumptive use (CCU).

- Treatments included full-withdrawal, spring only, fall only, shoulder month, split season (June 1, July 1, and Aug 1 shutoffs), and no-withdrawal strategies.
- Integrated livestock grazing into the study ensured that estimates reflect real-world grazing conditions.

We used NDVI remote sensing to measure ETa, CCU, and spatial variability compared to fully-irrigated reference fields.

Findings

The results provide field-based evidence that voluntary irrigation withdrawals can reduce ETa in grazed pastures.

- Seasonal ET on the fully irrigated reference fields was 33.7 and 35.3 inches at Banner and Harts Basin ranches, respectively.
- Field-scale ETa estimates, derived from NDVI, were correlated with irrigation timing.

Irrigation withdrawal implemented early in the season had the largest CCU benefit, confirming the expected outcomes.

- Full-season withdrawal and late-season only irrigation had highest CCU compared to the fully irrigated reference fields, 40-47% at Banner and 27-30% at Harts Basin.
- Standard irrigation early in growing season with mid- or late-season withdrawal (July 1 or August 1 shutoff) resulted in less CCU, 6-10% at Banner and 15-17% at Harts Basin, indicating diminished returns with delayed withdrawal.
- Irrigation only in May and September (shoulder months) showed moderate CCU, offering a balanced approach between conservation and forage growth.

Strategically implementing reductions can conserve water without fully compromising forage availability.

Insights

The findings are relevant for voluntary water-sharing programs that may compensate producers for water conservation:

- Results help fill key data gaps on ETa and CCU under irrigation curtailment in Western Colorado.
- Accurate estimation of CCU requires careful selection of reference fields, suggesting a potential benefit to using multiple reference zones.

Significant within-field variability, particularly at Orchard Ranch, influenced CCU outcomes.

- This is particularly true for heterogeneous pastures, like Orchard Ranch, where variability is more pronounced.

Combining remote sensing (SIMS and NDVI-based methods) with field data improves accuracy of water use measurements.

- Local field conditions play significant role in conservation outcomes, emphasizing the need for site-specific strategies and flexible program designs.
- ETa estimates can support the scalability and transparency of voluntary, incentive-based water-sharing programs, increasing producers view of the programs.

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Supplemental Information

Background and Motivation

Effective water resource planning depends on accurate quantification of the water balance, to ensure that policy leads to meaningful outcomes without unintended consequences or unrealistic expectations (Kuhn and Fleck, 2019). In response to this need, Conscience Bay Research launched a study in 2023 to evaluate the water conservation potential of a spectrum of irrigation withdrawal practices integrated with livestock operations, in two actively grazed pastures near Delta and Eckert, CO. These sites featured irrigated fields composed of mostly grasses with interspersed alfalfa, and integrated livestock grazing systems, reflecting real-world conditions where water availability, forage production, and animal growth performance are interconnected.

Although hay and pasture systems account for over 80% of irrigated agricultural acreage in western Colorado, CU rates for these systems have not been widely studied. This study used modeling based on remote sensing to estimate actual evapotranspiration (ETa) on irrigated pastures under simulated irrigation withdrawal. Conserved consumptive use (CCU) was estimated by comparing ETa from the affected fields to contemporaneous, fully irrigated reference sites at each location. The study provides two key contributions: (1) it offers one of the few field-scale evaluations of ETa in grass hay and pasture systems at elevations common to many irrigated areas in western Colorado; and (2) it examines how these systems respond to the timing of irrigation withdrawals. The integration of active grazing adds practical relevance by highlighting implications for forage availability and livestock carrying capacity under water conservation scenarios.

Irrigation withdrawal programs are one strategy for augmenting flows in the Colorado River during periods of natural drought or under negotiated water-sharing arrangements that compensate agricultural producers for temporarily forgoing the use of their irrigation water. These programs aim to conserve CU by reducing beneficial use on irrigated lands with legally recognized water rights--achieved by diverting less water than permitted and thereby increasing in-stream flows or storage elsewhere in the system. However, in working ranchlands where forage production directly supports grazing operations, reductions in CU can impact livestock stocking rates, grazing windows, and the viability of integrated pasture-livestock systems.

Study Sites & Irrigation Withdrawal Scenarios

The study was conducted on irrigated pastures at two sites in western Colorado: Banner Ranch (36.2 acres; 14.6 ha) and Orchard Ranch at Harts Basin (74.7 acres; 30.2 ha), located at elevations of 5,322 ft (1,622 m) and 5,552 ft (1,692 m), respectively. Banner Ranch is irrigated via furrow and gated pipe, while Orchard Ranch employs side-roll sprinkler systems. Both sites were subdivided into eight contiguous treatment zones, each approximately 5 acres in size, within a single managed field. Seven irrigation withdrawal scenarios were implemented across the zones to evaluate the impacts on forage availability and regrowth potential.

(1) Full season irrigation withdrawal [FSIW]: No irrigation after initial grazing (April 25 to May 2). A second grazing in late May/early June was possible, followed by potential fall regrowth depending on precipitation.

(2) One and done [1AD]: A single early-season irrigation was applied, then shut off soon after water became available. Grazing matched FSIW timing.

(3–5) Shutoffs on June 1, July 1, and August 1 [SO0601, SO0701, SO0801]: Irrigation continued until the specified date, then ceased. Each zone was initially grazed April 25–May 2, with possible second grazing and fall regrowth for winter grazing.

(6) Shoulder month [SM]: Irrigation was applied only in May and September. Grazing followed the standard early-season schedule, with potential for forage re-growth and winter grazing.

(7) Put it to bed wet [PITBW]: No irrigation during the growing season, with a single application in fall. Grazing followed the standard early-season schedule, with potential for late-season regrowth and winter grazing.

(8) No irrigation withdrawal (NIW): Served as fully irrigated reference (REF) zone with uninterrupted irrigation throughout the season and followed the standard season-long grazing timeline, allowing for greater forage regrowth potential.

Study Methods

The Banner Ranch study field is characterized primarily by silty clay loam soils, consistent with the dominant soil type found throughout the Public Land Survey System (PLSS) section in which it is located. The Orchard Ranch study field is divided roughly in half, with stony loam soils occupying the elevated western portion and silty clay loam soils found in the lower-lying eastern area. The soil types at this location are similar to the entire Harts Basin field portfolio that is also split rather evenly by silty clay loam and stony loam textures.

Vegetative conditions at Banner Ranch were largely uniform (Figure 1), but Orchard Ranch coverage data exhibited substantial within-field variability (Figure 2), as indicated by spatial mapping of the Normalized Difference Vegetation Index (NDVI). The heterogeneity at Orchard Ranch was primarily driven by sloping of the field in the east–west direction, such that lower-lying areas showed signs of heavy grazing and bare soil, while upper slopes maintained denser canopy cover.

In Figure 1, NDVI imagery is shown for Banner Ranch at six dates: April16, May 19, June 15, and July 19, August 19, and September 20, 2023 (arranged from earliest to latest, moving left to right and top to bottom). Each image is overlaid with zone boundaries and marked enclosures and labeled according to scenario: 1) FSIW; 2) 1AD; 3) SO0601; 4) SO0701; 5) SO0801; 6) SM; and, 7) PITBW. The contemporaneous, fully irrigated reference site is the large zone on the south side of the field.

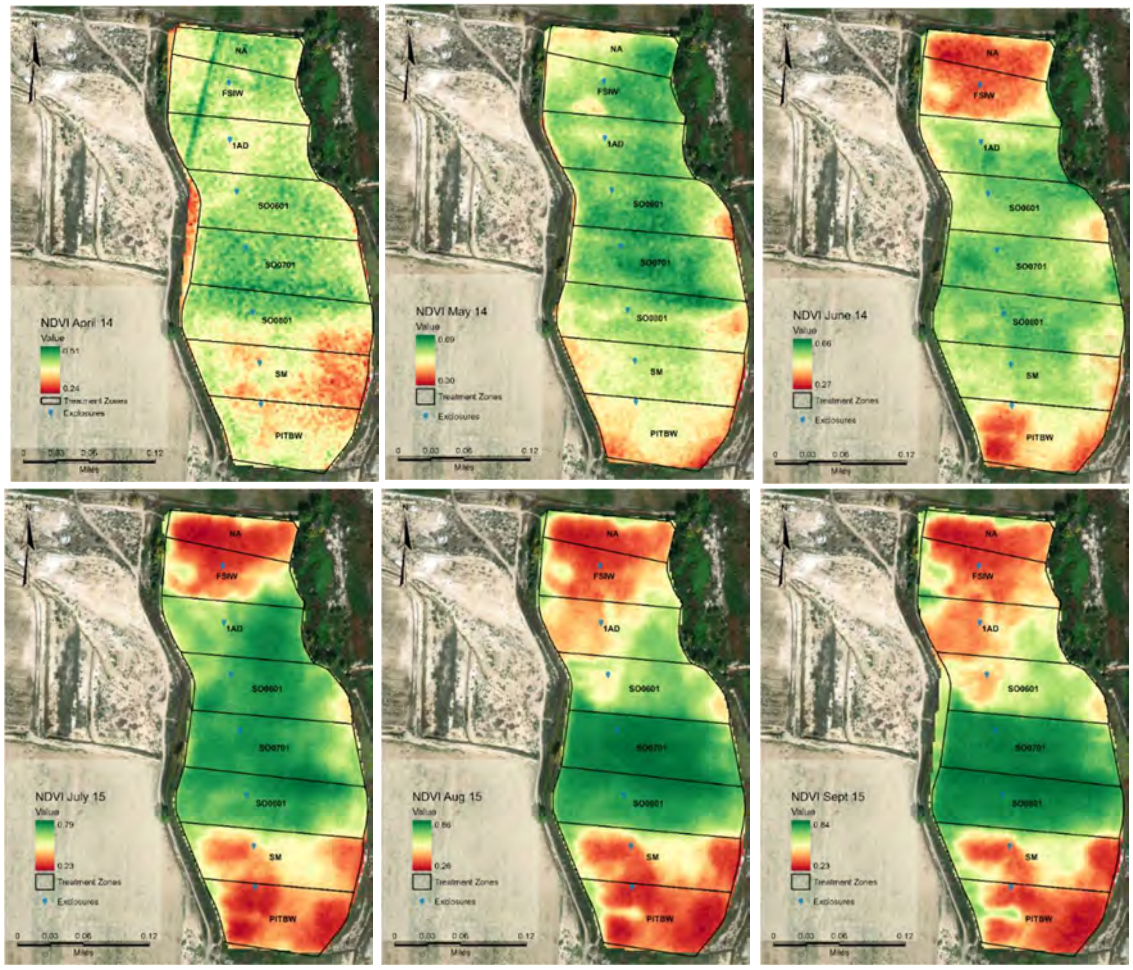

Figure 1. Time series maps of NDVI (Normalized Difference Vegetation Index) for Banner Ranch in Olathe, CO in year of irrigation withdrawal study.

One clearly noticeable attribute of this reference field is the abrupt change in vegetative health that happened during the June period. Conversations with the landowner confirmed that this impact was caused by the mechanical breakdown of the sideroll sprinkler system for a time long enough to affect consistent irrigation rates. Given this issue, only the portion of the field that maintained consistent irrigation throughout the season was isolated for analysis. This decision was made to ensure that the evaluation of vegetative health and water use reflected typical management conditions, rather than being skewed by the localized irrigation failure caused by the sideroll system breakdown.

In Figure 2, NDVI imagery is shown for Orchard Ranch at six dates: April14, May 14, June 14, July 15, August 15, and September 15, 2023 (arranged from earliest to latest, moving left to right and top to bottom). Each image is similarly overlaid with zone boundaries and marked enclosures and labeled according to treatment: 1) FSIW; 2) 1AD; 3) SO0601; 4) SO0701; 5) SO0801; 6) SM; and, 7) PITBW. The contemporaneous, fully irrigated reference site for the Banner Ranch is located nearby about 1,000 ft from the northern boundary of the study field.

Figure 2. Time series maps of NDVI for Orchard Ranch at Harts Basin in Eckert, CO in year of irrigation withdrawal study.

Stony loam soils have moderate to low water-holding capacity due to their coarse texture and high content of rock fragments, which promote rapid drainage and limit moisture availability in the root zone. These characteristics can make irrigation management more difficult, especially during extended dry periods. However, with thoughtful management practices—including timely irrigation and selection of drought-tolerant or shallow-rooted forage species—stony loam soils can still support productive pasture and hay systems. That said, yields are likely to be more variable across these soils, particularly in years with limited precipitation or under inconsistent irrigation, due to uneven moisture retention and reduced soil depth in some areas. Silty clay loam soils have moderately high to high water-holding capacity, making

them well-suited for irrigated agriculture when managed properly. Their fine texture, with a high proportion of silt and clay particles, allows them to retain substantial moisture in the root zone, supporting plant growth during dry periods. These soils are particularly favorable for growing deep-rooted perennial grasses used for grazing, hay, or pasture, if irrigation and soil structure are carefully managed to avoid issues like compaction or waterlogging.

The Satellite Irrigation Management Support (SIMS) model (Melton et al., 2012; Pereira et al. 2020) was used to estimate CU. Conserved CU was calculated by subtracting the seasonal ETa for each treatment zone from the average seasonal ETa of the fully irrigated reference condition (Zone 8). The SIMS model is included in the OpenET platform to estimate crop ETa by using a fractional cover derived from the Normalized Difference Vegetation Index (NDVI) was used to scale grass-based reference evapotranspiration (ETo) using a derived crop coefficient. The NDVI was calculated using high-resolution multispectral imagery acquired from the PlanetScope satellite constellation (www. planet.com/explorer/). The imagery provides approximately 3-m spatial resolution and includes spectral bands for NDVI computation: the red band (Band 3; 620–670 nm) and the near-infrared (NIR) band (Band 4; 820–880 nm). Scenes were selected based on cloud-free conditions and image tiles were downloaded in GeoTIFF format and clipped to the area of interest using QGIS.

Reference ET (ETr) was calculated using data from the CoAgMET stations nearest to each site, Montrose for Banner Ranch and Eckert for Orchard Ranch. Specifically, the ASCE Standardized Reference Evapotranspiration equation was applied using grass reference parameters. The choice of reference condition is critical, especially in heterogeneous fields like Orchard Ranch, where CCU estimates can differ widely across a field because of underlying variability in field conditions.

Where data gaps occurred due to missing satellite passes, continuity in the time series was restored using univariate spline interpolation. This method estimates missing values in single-variable datasets—such as time-series ET readings—by fitting a smooth curve through existing data points. Splines produce more natural and realistic transitions than straight-line (linear) methods, making them particularly well-suited to environmental data. This approach fills data gaps without introducing distortion or artificial patterns, preserving the integrity of sensor-based measurements affected by intermittent satellite coverage.

To account for the spatial variability at Orchard Ranch and exclude areas where extremely low ET was likely unrelated to irrigation deficits, the hottest 25% of pixels were excluded from analysis. It is notable that the OpenET platform also designates this field as two distinct fields. Furthermore, a 9-meter (three-pixel) border was removed along edges of the evaluation area to account for spatial non-uniformity in water application associated with the sideroll irrigation system.

Results and Discussion

NDVI Discussion. For comparison purposes, time series maps of NDVI for the same pastures in the year prior to the irrigation withdrawal study (2022) are shown in the appendix. Field-level NDVI interpretation for Banner Ranch and Orchard Ranch in 2022 provides a pre-treatment baseline, offering critical insight into natural vegetation patterns and spatial variability prior to the implementation of irrigation withdrawal scenarios in 2023 (see Appendix Figures 5 and 6).

At Banner Ranch, the NDVI time series shows that, even under uniform management, the field exhibited distinct spatial gradients in vegetative vigor, with consistently higher NDVI values observed in central and northern areas and lower values along the western and southern edges. These patterns likely reflect underlying differences in slope, soil properties, or irrigation uniformity. Although the field was largely homogeneous in early-season growth, some mid- to late-season variation emerged due to natural field conditions. The NDVI maps of the Orchard Ranch field show a clear seasonal progression in vegetative vigor, with notable contrasts between the eastern and western halves. Early in the season (April and May), the field exhibits generally healthy and uniform growth, though the western half appears slightly more vigorous. By mid-June, a sharp decline in NDVI emerges across the eastern half, indicating a substantial drop in vegetative health likely due to an irrigation disruption. This spatial disparity persists through July and August, with the western side of the field maintaining strong, uniform growth, while the eastern half shows only partial recovery. By September, the western portion continues to exhibit healthy vegetation, whereas the eastern half remains more variable and stressed, reflecting the lasting impact of the underlying field conditions irrigation issue.

Banner Ranch. The CU rates at both sites reflected clear patterns tied to irrigation timing. At the Banner Ranch, ET and CCU values generally followed expected patterns based on the timing and extent of irrigation withdrawal (Table 1). At the reference condition, April ET was lowest at 2.48 inches as grass began breaking dormancy, increasing steadily to a seasonal peak in July with 7.03 inches of ET observed in the reference field (column labeled REF). For comparison, potential evapotranspiration (column labeled PET) is included, providing context for how actual ET compared to modeled weather-based potential demand.

Table 1. Monthly and Seasonal ET (inches) and CCU (inches) by Irrigation Scenario at Banner Ranch (2023).

		REF	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7
Month	PET	NIW	FSIW	1AD	SO0601	SO0701	SO0801	SM	PITBW
April	5.02	2.48	2.16	2.12	2.1	2.15	1.91	1.56	1.59
May	6.25	4.81	4.32	4.47	4.34	4.47	4.20	3.87	3.43
June	6.75	5.51	3.95	5.90	5.86	5.97	5.69	5.01	3.93
July	8.06	7.03	3.68	5.77	6.01	6.32	6.03	3.88	2.92
August	6.29	6.26	2.98	3.96	4.76	6.05	5.76	3.24	2.43
September	5.06	4.78	2.22	2.57	3.17	4.39	4.37	2.69	2.03
October	3.11	2.9	1.20	1.38	1.67	2.2	2.34	2.01	1.57
TOTAL	40.54	33.77	20.50	26.17	27.91	31.55	30.31	22.25	17.90
CCU*			13.27	7.61	5.86	2.22	3.46	11.52	15.88

PET = Potential evapotranspiration from ASCE Standardized Equation; Montrose CoAgMET station.
*CCU = Conserved Consumptive Use based on SIMS estimated REF ET from neighboring fields.

Scenarios simulating more restrictive irrigation withdrawal showed lower total ETa and higher CCU. The full-season irrigation withdrawal [FSIW] scenario had the lowest total ET (20.50 inches) and one of the highest CCU values at 13.27 inches. Scenarios in the next two columns simulated early cutoff strategies ("one and done" [1AD] and June 1 shutoff [SO0601]) moderately conserving water, with CCU values of 7.61 and 5.86 inches per acre, respectively. The scenarios with more extended irrigation periods retained higher total ET and had lower CCU. The July 1 shutoff [SO0701] scenario and the August 1 shutoff [SO0801] scenario had CCU values of 2.22 and 3.46 inches, respectively, as more water was applied during peak demand.

The scenario with irrigation only during the shoulder months [SM] showed a seasonal ET pattern like FSIW, with total ET of 22.25 inches and CCU of 11.52 inches, reflecting limited water use during the core summer months. The last column, representing a late-season irrigation only "put it to bed wet" strategy [PITBW], displayed a total ET of 17.90 inches, and showed the highest CCU at 15.88 inches, indicating that withholding irrigation resulted in considerable water conservation, regardless of late-season irrigation.

Relative to the reference condition, both FSIW and PITBW exhibited substantially lower ET totals, highlighting the water rates possible through both early-season irrigation withdrawal. FSIW, with full-season irrigation withdrawal, had an ET total of 20.50 inches, which is 39.3% lower than the reference ET of 33.77 inches. PITBW, irrigated only late in the season, showed a slightly greater reduction, with 17.90 inches of ET, or 47.0% lower than the reference. On average, these two strategies reduced ET by 43.15%.

Orchard Ranch at Harts Basin. At Orchard Ranch at Harts Basin, ET and CCU values also followed expected patterns although conservation rates were estimated as being lower (Table 2). The early season ETa rates were also lower and peaked in July at 7.23 inches per acre of ET observed at the reference field (column labeled REF). Similar to the Banner Ranch, the full-season irrigation withdrawal FSIW scenario had the lowest total ETa (24.71 inches) and a CCU value of 10.58 inches. Scenarios that simulated early cutoff strategies ("one and done" [1AD] and June 1 shutoff [SO0601]) exhibited slightly greater CCU of 9.98 and 9.08 inches per acre, respectively. Scenarios that received greater seasonal irrigation had higher total ETa and had lower CCU. The July 1 shutoff [SO0701] and the August 1 shutoff [SO0801] scenarios had CCU values of 5.47 and 5.89 inches, respectively. The shoulder month [SM] scenario showed a seasonal ETa pattern like FSIW, but with slightly lower total ET of 23.23 inches and CCU of 12.07 inches, reflecting limited water use during the core summer months. Finally, the late-season only scenario representing a "put it to bed wet" [PITBW] strategy displayed a total seasonal ET of 25.85 inches, and a somewhat low CCU at 9.44 inches, evidently due to the irrigation that occurred in August that boosted ET.

Relative to the reference condition, both FSIW and SM exhibited the lowest seasonal ET totals, again highlighting the impact of intensive irrigation withdrawal. The FSIW scenario, which involved a full-season irrigation withdrawal, resulted in a total ET of 24.71 inches, representing a 31.0% reduction compared to the reference ET of 35.78 inches. The SM scenario, which limited irrigation to the shoulder months, produced a slightly greater reduction, with 23.23 inches of ET per acre, or 35.1% below the reference. On average, these two strategies reduced ET by 33.0%, based on data refined using a spatial filtering and masking approach to exclude non-irrigation-related variability.

Table 2. Monthly and Seasonal ET and CCU by Irrigation Scenario at Orchard Ranch/Harts Basin (2023).

		REF	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7
Month	PET	NIW	FSIW	1AD	SO0601	SO0701	SO0801	SM	PITBW
April	5.93	3.16	3.08	3.03	2.99	2.97	2.96	2.96	3.02
May	7.88	5.79	3.08	3.03	2.99	2.97	2.96	2.96	3.02
June	9.44	6.53	4.73	4.61	4.60	4.63	4.65	4.55	4.40
July	8.01	6.85	4.72	4.89	5.05	5.14	5.08	4.61	4.40
August	6.25	6.13	3.89	4.29	4.21	5.20	4.91	3.24	6.82
September	4.9	4.80	3.05	3.17	3.72	5.31	5.19	2.54	2.40
October	3.22	2.52	2.17	2.29	2.63	3.59	3.64	2.37	1.80
TOTAL	45.63	35.78	24.71	25.31	26.21	29.82	29.4	23.23	25.85
CCU*			10.58	9.98	9.08	5.47	5.89	12.07	9.44

PET = Potential evapotranspiration from ASCE Standardized Equation; Eckert CoAgMET station
*CCU = Based on Gatum (2018) average estimated REF ET from neighboring fields.

Irrigation Timing Patterns. The irrigation simulation exercise was executed very well at both sites – a credit to the ranch managers - as evidenced by the distinct and consistent ETa patterns that emerged across treatment zones throughout the growing season. The ETa rates at both sites reflected clear patterns tied to irrigation timing (See Figures 3 and 4).

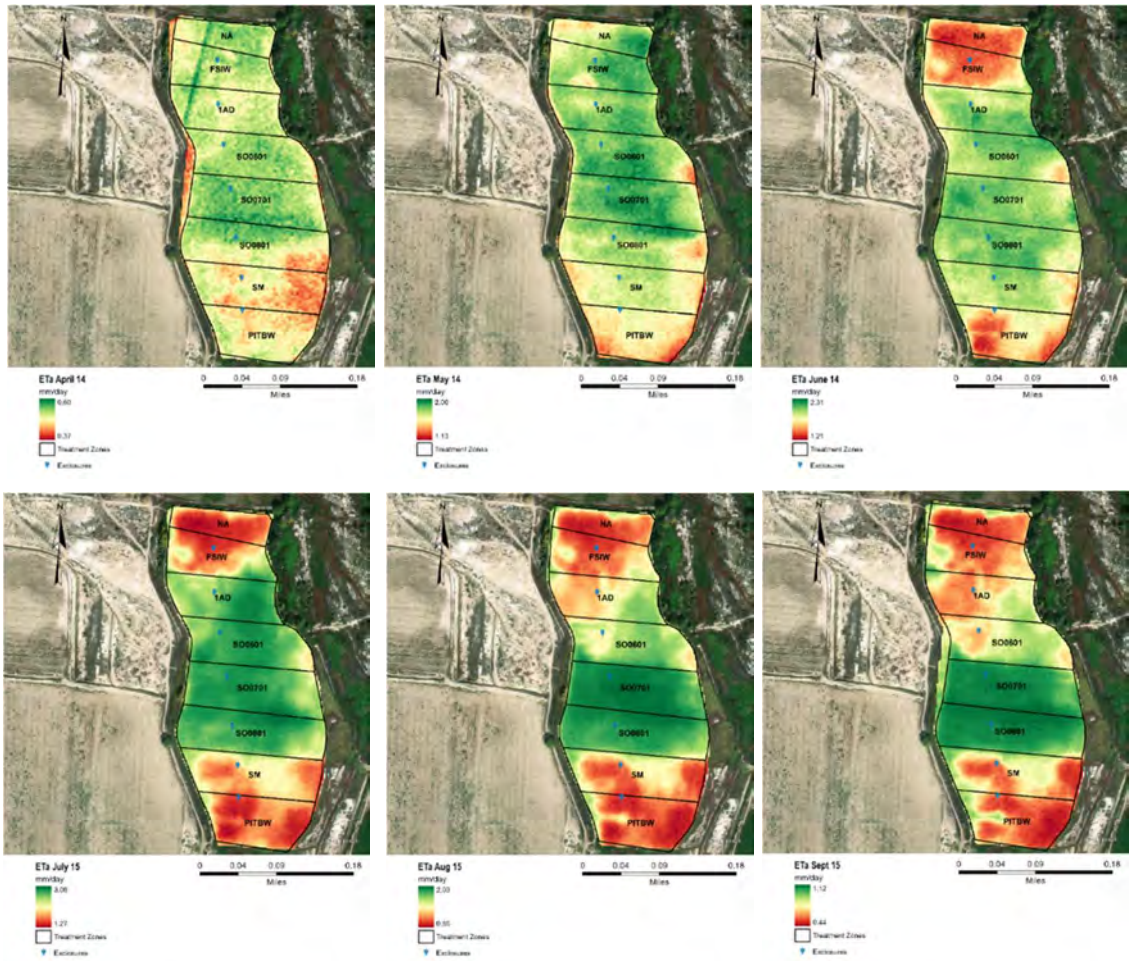

Figure 3. Time series maps of ET (mm/day) for Banner Ranch in Olathe, CO in year of irrigation withdrawal study.

In Figure 3, for Banner Ranch, imagery is shown at six dates: April 14, May 14, June 14, July 15, August 15, and September 15, 2023. Each image is overlaid with zone boundaries and marked enclosures. The image is labeled using scenario codes: 1) FSIW; 2) 1AD; 3) SO0601; 4) SO0701; 5) SO0801; 6) SM; and, 7) PITBW. In April and May, ETa values are relatively uniform across the field, with slightly reduced water use in the FSIW and PTIBW zones, indicating the early impacts of limited irrigation. By June, clear differences emerge, with the FSIW zone in the north and the PTIBW zone in the south showing substantial reductions in ETa, reflecting the intended irrigation withdrawal strategies. These patterns persist through July, August, and September, with the FSIW and PTIBW zones consistently displaying lower ETa relative to the reference and shoulder-month-only (SM) irrigation zones. The uniformity of treatment effects within each zone and across time highlights the success of the simulation and provides confidence in the integrity of the water management treatments applied. The only modest exception is the difference between the 1AD and SM scenarios, which should have received irrigation at roughly the same time. The 1AD treatment appears to have received irrigation in May, however, while the SM ETa spike did not occur until June, suggesting a later irrigation timing. Notably, September ET levels were also strong.

In Figure 4, for Orchard Ranch at Harts Basin, imagery is shown at six dates: April 16, May 19, June 15, July 19, August 19, and September 20, 2023. Each image is overlaid with zone boundaries and marked enclosures.

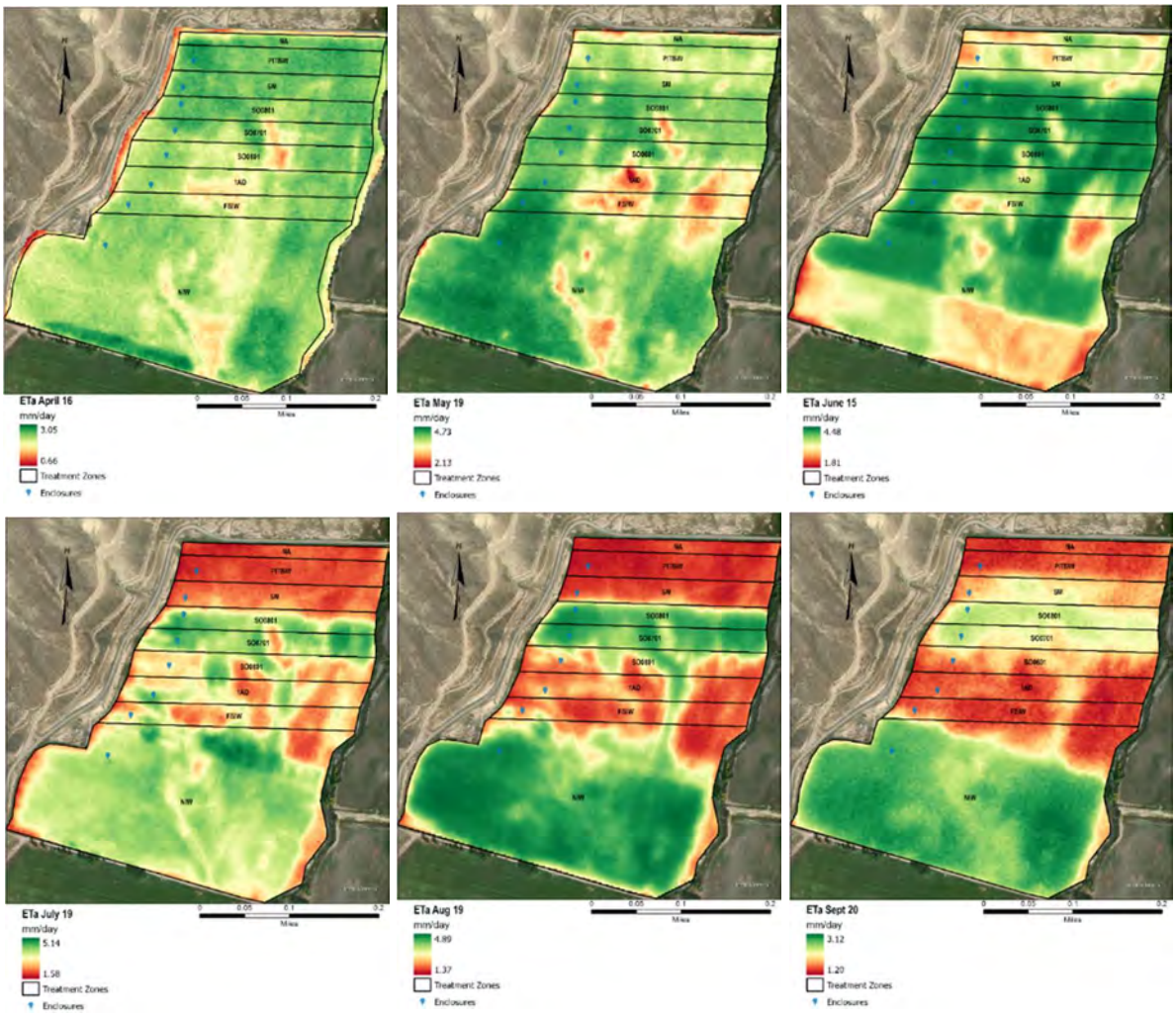

Figure 4. Time series maps of ET (mm/day) for Orchard Ranch in Eckert, CO in year of irrigation withdrawal study.

The image is labeled using scenario codes: (1) FSIW; 2) 1AD; 3) SO0601; 4) SO0701; 5) SO0801; 6) SM; and, 7) PITBW. Two distinct spatial patterns are evident in the field: a north-to-south gradient resulting from the deliberate irrigation treatments applied using the side roll system, and an east-to-west gradient driven by underlying field conditions and infrastructure limitations. Th ETa maps illustrate these seasonal patterns of water use, showing how CU varied spatially and temporally under different irrigation management strategies. In the early season (April 16 and May 19), ETa values are relatively uniform across the field, with only minor spatial variation. However, by June 15, a pronounced divergence appears, with ETa dropping sharply in the eastern half of the field, indicating significantly lower water use compared to the west. This east–west contrast persists through July, August, and September, suggesting sustained vegetation stress or limited water availability in the eastern zones. The mechanical failure in the side roll system disrupted water delivery to the eastern half of the field for an extended period, unrelated to the experimental design. To ensure a valid evaluation of treatment effects, only the northwestern portion of the field, where irrigation remained consistent throughout the season, was used in the core analysis. This approach ensured that ETa estimates more accurately reflected management-driven outcomes rather than confounding factors such as irrigation system failure or spatial variability in soil and topography.

Closing Takeaways

On working ranchlands where forage production directly supports grazing operations, reductions in CU can impact livestock stocking rates, grazing windows, and the viability of integrated pasture-livestock systems. The 2023 evaluation of CCU across Banner and Orchard Ranch demonstrates that irrigation withdrawal strategies can produce measurable reductions in crop evapotranspiration (ET) on these pastures, especially when implemented early in the season. Overall, these results align with anticipated outcomes: earlier or more limited irrigation produced greater conserved consumptive use, while sustained mid- and late-season irrigation reduced the conservation. Treatment scenarios that experienced full-season irrigation withdrawal or received only limited early- or late-season irrigation consistently exhibited the highest CCU values. These outcomes validate the foundational assumption that reduced water application, when properly timed, translates into reduced consumptive use.

While this general pattern held true across both sites, the results also underscore the importance of local field conditions in shaping water conservation outcomes. For instance, at Orchard Ranch, where the field was more heterogeneous in terms of soil characteristics and crop vigor, the choice of reference conditions had a notable effect on CCU estimates. This highlights the need for careful reference field selection and potentially the use of multiple reference zones in operational programs.

Overall, the findings provide clear evidence that strategically timed irrigation reductions, especially in early- and shoulder-season periods, can conserve water without entirely forfeiting forage production. These results are especially relevant for voluntary water-sharing programs, where producers may be compensated for foregone irrigation. The study also reinforces the value of combining remote sensing with site-specific ground data to inform water policy decisions rooted in the realities of working agricultural landscapes.

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Appendix

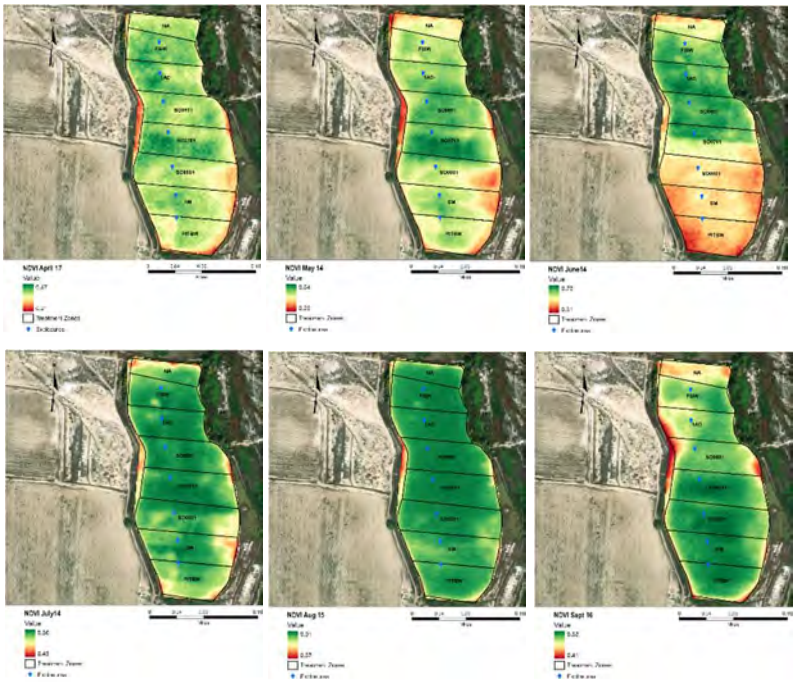

Figure 5. Time series maps of NDVI for Banner Ranch in Olathe, CO in year prior to irrigation withdrawal study. Imagery is shown at six dates: April 19, May 18, June 15, July 19, August 21, and September 19, 2022. Each image is overlaid with zone boundaries and marked enclosures. The image is labeled using scenario codes: 1) FSIW; 2) 1AD; 3) SO0601; 4) SO0701; 5) SO0801; 6) SM; and, 7) PITBW.

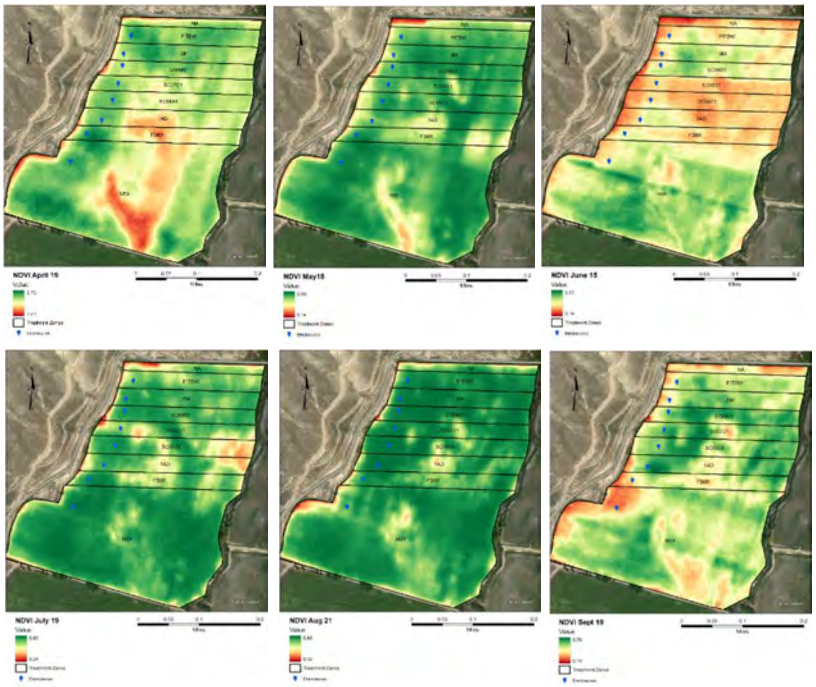

Figure 6. Time series maps of NDVI maps for Orchard Ranch in Eckert, CO in year prior to irrigation withdrawal study. Imagery is shown at six dates: April 19, May 18, June 15, July 19, August 21, and September 19, 2022. Each image is overlaid with zone boundaries and marked enclosures. The image is labeled using scenario codes: 1) FSIW; 2) 1AD; 3) SO0601; 4) SO0701; 5) SO0801; 6) SM; and, 7) PITBW. The contemporaneous, fully irrigated reference site is the large field on the south side of the field.