

Effects of Irrigation Withdrawal on Montane Grass Hay Pastures Enrolled in a Colorado Water Conservation Program

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Abstract

This study used a paired-field approach to evaluate the recovery of grass productivity in a montane hay pasture region of the Upper Colorado River Basin following a temporary irrigation withdrawal. In 2020, two simulated water leasing scenarios were implemented: one involving full-season irrigation withdrawal, and the other involving partial withdrawal, with irrigation ending mid-season. Across eight treatment sites totaling 1,115.5 acres, these withdrawal methods were compared with five fully irrigated reference sites covering 397.6 acres. The Normalized Difference Vegetation Index (NDVI) was used to assess vegetation density and health, both to verify field pair suitability prior to the study and to monitor differences in response to water stress during and after withdrawal. A threshold of $\Delta\text{NDVI} < 0.05$ during the pre-treatment years (2018 and 2019) was associated with p values greater than 0.05, providing no statistical evidence to suggest a difference in vegetation condition between reference and treatment fields. This supported the assumption that field pairs were sufficiently similar to justify their use in the 2020 conservation simulation and irrigation withdrawal study. Following the 2020 withdrawal period, all fields returned to standard irrigation practices for the 2021–2024 growing seasons to observe recovery. Partial-season withdrawal had minimal impact on 2020 forage yields, despite irrigation ceasing after June 15. In contrast, fields under full-season withdrawal experienced an average yield reduction of 87% compared to their irrigated counterparts. Upon resumption of irrigation, yield recovery varied across treatment fields. While average yields in 2021 were not significantly different between treatment and reference fields, both sets of fields produced lower-than-expected yields overall, with considerable variability among treatment sites. This widespread reduction in productivity is likely attributed to the severe regional drought conditions that affected the Intermountain West during that year. In the following years (2022–2024), fields previously subjected to full-season withdrawal continued to show reduced productivity, averaging 25%, 35%, and 22% lower yields, respectively, despite receiving the same irrigation as their paired reference fields. A production function analysis revealed a strong relationship between evapotranspiration and biomass yield, underscoring the importance of water availability in driving forage productivity. Crude protein (CP) levels showed significant variation across sites but often remained comparable between water-stressed and fully irrigated fields, even when total yields were lower.

1. Introduction

The Colorado River Basin faces an enduring drought, shaped by the confluence of La Niña-driven precipitation declines, rapid temperature shifts, and the escalating impacts of climate change (McEvoy and Hatchett, 2023). These forces amplify the threat of prolonged and unpredictable hydrologic conditions (Udall and Overpeck, 2017; Miller et al., 2021). Shifting climate patterns diminish snowpack, deplete soil moisture, and curtail streamflow, exacerbating the already fragile equilibrium between water supply and demand in the basin (Ficklin et al., 2013; Woodhouse and Wise, 2020; Milman et al., 2021; Carroll et al., 2024). The intensifying urgency of this imbalance highlights the profound challenges confronting modern water management (Kuhn and Fleck, 2019). In response, efforts to develop adaptive strategies for sharing and conserving water are steadily advancing. In the Upper Colorado Basin, irrigated hay pastures dominate agricultural water use (MWH Americas, Inc., 2012), representing a significant reservoir of consumptive use (CU) with the potential to mitigate imbalances.

The land coverage and CU of Upper Colorado Basin hay production has garnered the attention of voluntary water-sharing programs, which compensate producers for conserved consumptive use (CCU) through temporary irrigation reductions, emphasizing the value of research on forage resilience and recovery under water stress (CWCB, 2020; Colorado Water Trust, 2024). Among forage crops, alfalfa (*Medicago sativa*) is the most extensively studied for its response to reduced irrigation, demonstrating a remarkable capacity to endure water withholding without lasting yield loss and often recovering fully within a single growing season (Guitjens et al., 1993; Hanson et al., 2007). For example, Ottman et al. (1996) documented that irrigation stoppage reduced hay yields by 0.23-0.67 T/ac in summer alfalfa cuttings while withholding irrigation during the winter had minimal effects. California studies by Orloff et al. (2003) reported that early-season irrigation cutoffs, especially in spring, may offer water conservation with limited long-term productivity losses, although cautioned that yield reductions can be more pronounced in sandy soils or low water table regions. Periods of reduced irrigation lasting 2-3 months often result in yield declines that generally rebound once irrigation resumes (Putnam, 2012), and in some cases, a 50% reduction in water application results in only a 13-20% seasonal yield decrease over two years (Putnam, 2015). Strategies such as partial season irrigation on alfalfa fields can even slightly improve forage quality while reducing yields, with full yield recovery possible when irrigation resumes the following year, depending on the severity and duration of reduction in Colorado (Cabot et al., 2017). Moreover, deficit irrigation can drive alfalfa to increase water use efficiency (WUE), with one study reporting an average 17.4% yield reduction accompanied by a 14% increase in WUE (Li et al., 2023).

Pasture grasses, on the other hand, demonstrate significant variability in their resilience to irrigation reduction, reflecting species-specific differences in their adaptability to semi-arid conditions and water stress. Orchardgrass (*Dactylis glomerata*), for instance, performs well in areas below 6,000 feet MSL where moderate temperatures and adequate water support growth, but its forage quality declines under drought conditions (Pearson et al., 2010; Xiong et al., 2022). Perennial ryegrass (*Lolium perenne*), valued for its nutritive quality, is less suited for higher elevations due to poor performance under cooler conditions (Jensen et al., 2003). Similarly, bermudagrass (*Cynodon dactylon*) demonstrates improved biomass and forage quality with saline irrigation but struggles in colder climates. These variations underscore the need for management strategies to optimize forage production especially under administratively water-limited systems (Robinson et al., 2003; Glover et al., 2004).

In the montane regions of Colorado specifically, many grasses can persist for decades without re-seeding, and possess functional traits that enable them to withstand water shortages, but different species may or may not be suited to water conservation programs. A review of the relevant literature shows grasses having varied recovery rates and overall productivity in response to water stress. Smooth brome (*Bromus*

inermis), for example, has a deep root system that allows it to access water from lower soil strata, enhancing its drought hardiness (Dong et al., 2012; Orloff et al., 2015; Mackiewicz-Walec, 2024). Timothy grass (*Phleum pratense*), on the other hand, is resilient when grown in mixed stands with legumes but growth is stunted under prolonged water stress when grown in monocultures (Marcinkevičienė et al., 2021; Silva, 2023). Regrowth studies comparing timothy and tall fescue (*Festuca arundinacea*) have identified tall fescue as having greater growth potential following periods of reduced water availability (Virkaajärvi et al., 2012). Similarly, intermediate (*Thinopyrum intermedium*) and tall wheatgrass (*Thinopyrum ponticum*) have demonstrated stable yields under deficit irrigation, occasionally outperforming fully irrigated stands when early-season watering is limited (Orloff et al., 2016). Creeping foxtail (*Alopecurus arundinaceus*), and its popular cultivar Garrison foxtail, is widely used in the higher-elevation agricultural areas of Colorado due to its adaptability to fluctuating moisture levels. Garrison foxtail was introduced for its high tolerance of waterlogged conditions and short growing seasons, making it an ideal choice for areas with poorly drained, heavy-textured soils that are common in “wild flood” irrigated areas over 6,000 ft MSL (Han et al., 2004; Darambazar et al., 2022). With proper fertilization and irrigation timing, it effectively utilizes spring and early summer moisture for robust growth, often yielding two productive cuttings per season (Volesky and Anderson, 2007).

Despite extensive research on grass species and mixtures, montane grass hay and pasture systems have not been thoroughly studied in the context of temporary irrigation withdrawals. The most comprehensive work on drought tolerance under limited irrigation in Colorado highlights certain wheatgrass species as particularly suitable (Pearson et al., 2010). However, these findings are difficult to apply broadly because such species are not always present in areas where water conservation programs are implemented. Grass composition varies widely across the Upper Colorado Basin, and while it would be ideal to focus on species with an established research base, it is equally important to investigate the resilience of pasture grasses already growing in other regions. Jones (2015) explored this issue by studying the effects of irrigation withdrawal on grass hayfield recovery across five sites located in Grand, Gunnison, Montrose, Routt, and Saguache counties. A single season without irrigation caused significant yield reductions, demonstrating that while a variety of pasture grasses (smooth brome, Kentucky bluegrass, meadow foxtail, timothy, orchardgrass) can tolerate temporarily imposed water stress, full recovery requires several years. This previous work highlighted the need for further research to better understand the time required for full yield restoration following irrigation withdrawal and resumption. The purpose of this study was to build on that foundation by monitoring recovery over a longer period and conducting an in-depth evaluation of multiple large fields within a similar montane eco-region. This approach created a controlled study area with relatively consistent grass composition across a landscape large enough to reflect the scale of actual conservation programs, offering valuable insights into forage recovery under voluntary, temporary water conservation efforts.

2 Materials and Methods

This study evaluated forage production and quality over a five-year period (2020–2024), comparing fields subjected to withdrawn or reduced irrigation with reference fields maintained under traditional irrigation rates and schedules, offering a paired analysis of treatment effects. The paired field study design is a well-established method in agricultural, environmental, and hydrological research for assessing impacts by comparing management practices with controlled reference conditions. Paired sites have been used, for example, to evaluate nutrient concentrations in tile drainage (Williamson et al., 2018), nitrate runoff in drainage water (Adeuya et al., 2012; Schilling et al., 2013), and nitrate changes after prairie restoration (Schilling and Spooner, 2006). Similar methods have been applied to examine sediment and nutrient transport under varying water conditions (Huang et al., 2003; Jokela and Casler, 2011).

The realities of working within the context shaped by the conservation program necessitated the use of a non-equivalent control group design. Conducted in a real-world setting, landowner cooperation and negotiated access dictated study conditions and precluded ideal experimental conditions such as randomization. Moreover, the parallel timeline of field selection and program initiation left no opportunity for baseline sampling prior to treatment. While empirical verification of baseline equivalence was unattainable, thoughtful pairing of treatment and reference fields, guided by producer expertise, ensured the most comparable matches possible. Despite its inherent limitations, the practical and scientific significance of the study, offering a rare, one-time opportunity to contribute to a broader understanding of water conservation, underscored the value of its implementation.

2.1 Field Designations and Irrigation Treatments in Study Area

The study took place in Grand County, Colorado, within the headwaters of the Colorado River at an elevation of approximately 7,219 feet (2,200 meters) above sea level. Agricultural operations in this region mirror much of the Rocky Mountain Western Slope, where irrigated fields are primarily devoted to hay production and livestock grazing. The soils in this area are predominantly characterized by loams and clay loams. Among these, Leavitt (Loam) is the most prominent. Binco (Clay Loam) and Harsha (Loam) also appear frequently. In addition to these soil types, Cumulic Cryaquolls are prevalent in the region, often associated with meadow environments. Average annual rainfall for the area is 12 in (305 mm), with snowfall of 55 in (1,397 mm) and 70 frost-free days. Ranches participating in the study receive irrigation water from the Colorado River through lateral diversions from Bull Run, Pass Creek, Red Dirt Creek, and Williams Fork. Water rights consist of direct flow rights that range from 0.5 - 221 ft³/s and storage rights that range from 240 - 1,870 ac-ft, through 18 separate ditches. It is not uncommon for Western Slope water conveyance networks to be administered with this degree of complexity.

Data was used from seven fields in the study area that were subjected to full irrigation withdrawal in 2020, two partially irrigated fields where water was withdrawn after June 15 in 2020, and four reference fields that were irrigated in accordance with conventional amounts and timing in 2020. Subsequently in 2021 – 2024 all fields received their full allotment of irrigation in accordance with historical diversions. Table 2.1 provides details about the study fields. Each field is labeled with an alphanumeric code that includes a three-letter ranch identifier, an “R” for reference (irrigated according to established practices) or “T” for treatment (irrigation restricted) conditions, and a numeric field designation. For example, “GPR R1” designates a reference-irrigated field at the G__ P__ Ranch, with the initials anonymized for privacy.

Reference (REF) and treatment (TRT) fields were paired as closely as possible, though practical limitations affected individual pairing in some cases. Due to the proximity of the fields, for instance, GPR R1 served as the reference for two TRT fields (GPR T1, GPR T2). These logistical adjustments were necessary due to land ownership boundaries for participating fields and the inherent challenges of precisely delineating boundaries for “wild flood” irrigated fields. The primary REF ↔ TRT pairs, therefore, were GPR R1 ↔ GPR T1, GPR R1 ↔ GPR T2, RCR R1 ↔ RCR T1, RSR R1 ↔ RSR T1, SBR R1 ↔ SBR T1, and SPR R1 ↔ SBR T1. In total, this study evaluated approximately 1,289.8 ac (521.9 ha), with 920.8 ac (372.6 ha) as TRT fields and 369.0 ac (149.3 ha) as reference fields. In a few isolated cases, unforeseen management issues, such as unexpected grazing, led to the exclusion of specific data points and these are noted for clarity. Finally, samples were taken when possible, for some smaller fields (BMR, HSR, JLM, and SBT) that were served by water rights temporarily affected by the study, due to the shared nature of the irrigation delivery infrastructure.

At fields designated as "2 Forage Sample Locations," circular exclosures were set up using cattle panels to maintain an undisturbed patch of grass for continuous sampling. Exclosures were placed in areas where

landowners identified forage production as relatively high or low. Forage samples were taken from within the exclosures, with at least three random samples collected around each exclosure to calculate average yields. This setup allowed for a controlled comparison between protected and surrounding areas, offering a more comprehensive yield assessment. For the smaller fields (BMR, HSR, JLM, and SBT), only a single forage sample area was used, with samples taken from near the middle of the field, as "high" or "low" production samples were not designated for these locations.

Table 2.1. Fields evaluated for forage recovery (Kremmling, CO)

Field Name	Irrigation Practice	Field Size	Details
BMR T1 2020	Full season, no irrigation	31.4 ac (12.7 ha)	1 Forage Sample Location
GPR T1 2020	Full season, no irrigation	202.8 ac (82.1 ha)	2 Forage Sample Locations
GPR T2 2020	Full season, no irrigation	345.2 ac (139.7 ha)	2 Forage Sample Locations
HSR T1 2020	Full season, no irrigation	85.5 ac (34.6 ha)	1 Forage Sample Location
JLM T1 2020	Full season, no irrigation	15.8 ac (6.4 ha)	1 Forage Sample Location
RCR T1 2020	Split Season, no irrigation after June 15	37.6 ac (15.2 ha)	2 Forage Sample Locations
RSR T1 2020	Split Season, no irrigation after June 15	123.2 ac (49.9 ha)	2 Forage Sample Locations
SBR T1 2020	Full season, no irrigation	70.2 ac (28.4 ha)	2 Forage Sample Locations
SBT T1 2020	Full season, no irrigation	9.1 ac (3.7 ha)	1 Forage Sample Location
Total		920.8 ac (372.6 ha)	
GPR R1 2020	Reference, historical irrigation	93.4 ac (37.8 ha)	2 Forage Sample Locations
RCR R1 2020	Reference, historical irrigation	225.9 ac (91.4 ha)	2 Forage Sample Locations
RSR R1 2020	Reference, historical irrigation	21 ac (8.5 ha)	2 Forage Sample Locations
SBR R1 2020	Reference, historical irrigation	28.7 ac (11.6 ha)	2 Forage Sample Locations
Total		369.0 ac (149.3 ha)	

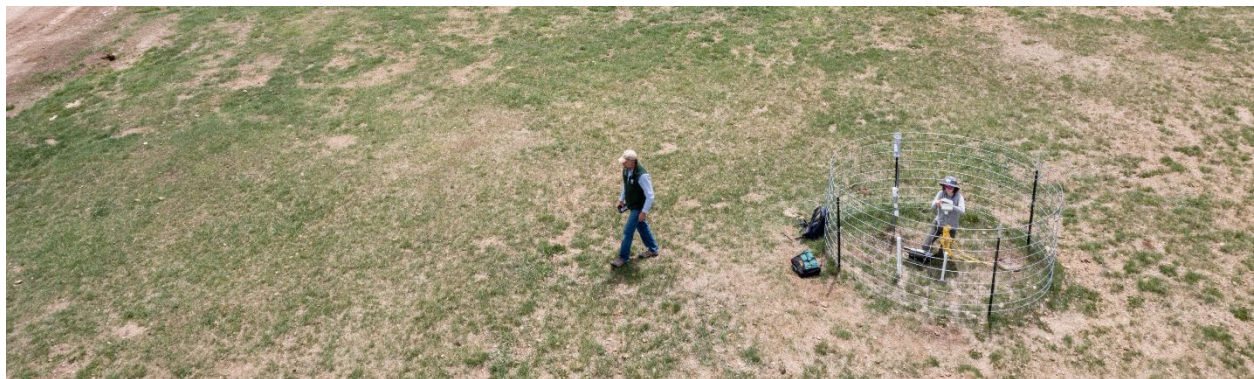


Figure 2.1. Circular exclosure to prevent animal entry, protect instrumentation, and preserve forage sampling areas.

2.2 Selection and Pairing of Reference and Treatment Fields

As noted above selection and pairing of reference and treatment fields was based landowner judgements, and expert observations. Subsequently, the Normalized Difference Vegetation Index (NDVI) was used to quantitatively assess field traits, providing a more objective measure to complement the initial field selections and address some of the limitations of the non-equivalent control group design. The NDVI is a widely used metric to assess vegetation health and density based on satellite imagery. It is calculated using reflectance values from the red (R) and near-infrared (NIR) bands of light using the simple equation $NDVI = (NIR - R) / (NIR + R)$. This index quantifies vegetative condition via the principle that healthy

foliage appears green because chlorophyll absorbs blue (450-495 nm) and red (620-750 nm) light for photosynthesis but reflects green (495-570 nm) light. Healthy plants also reflect a large amount of near-infrared (NIR) light. The index is a normalized value that ranges from -1 to +1, where higher values indicate denser, healthier vegetation, while values close to zero or negative suggest bare soil, water, or stressed vegetation. Specifically, NDVI can be categorized into three general classes: high vegetation ($NDVI > 0.5$), low vegetation ($0.2 < NDVI < 0.5$), and no vegetation ($NDVI < 0.2$) (Bala, 2023).

Previous work has shown that NDVI can effectively differentiate between various land cover types. A difference of 0.05 in NDVI values is often considered significant in ecological studies, as it can reflect substantial changes in vegetation cover or health (Reed et al., 1994). For example, NDVI has been utilized to assess changes in vegetation density over time, indicating that consistent NDVI changes can signal shifts in vegetation health (Zhang et al., 2021). Similarly, NDVI is sensitive to vegetation cover qualities, reinforcing the idea that even minor differences can be significant in ecological assessments (Mehta et al., 2021). The NDVI has been shown to be effective for assessing biomass in grazed pastures, though its accuracy can decline at lower biomass levels (Wigley et al., 2019).

2.3 Sampling Protocol for Forage Yields

Samples were designated as “H” for “high” production or “L” for “low” production, based on producer input. This stratification allowed for a more nuanced analysis of production trends, accounting for site-specific factors such as soil fertility, water availability, and historical performance. Clippings were taken monthly in June, July, and August for yield analysis, aligning with typical hay harvest and grazing schedules. Sampling was conducted in 2020, when TRT fields experienced fully curtailed or reduced irrigation, and in 2021, 2022, 2023, and 2024, when all fields were fully irrigated according to typical practices. In fields where samples within and around exclosures were similar, yield averages were calculated from all samples; however, when unexpected grazing occurred, only exclosure data could be used. Sampling followed established methods, with forage clipped from a 0.25 m² frame (Bowman et al., 2008) and dried at 130°F for 72 hours to determine dry matter in T/ac. This approach, adapted from Grev et al. (2020), ensured accurate and consistent biomass assessment across all years of the study.

2.4 Sample Processing and Analysis for Crude Protein Content

Following drying, individual samples were weighed and then ground through a Thomas Model 4 Wiley® Mill (Philadelphia, PA) with a 2 mm screen followed by a Foss™ Tecator Cyclotec Sample Mill Model 1093 (Eden Prairie, MN). Ground and centrifuged samples were used to determine dry matter (DM) and quality factors, including neutral detergent fiber (aNDF), in-vitro true digestibility (IVTD), and crude protein (CP) concentration. This publication reports solely on CP as percentage of dry matter biomass or simply crude protein content to discuss forage quality. To determine DM, samples were dried for a minimum of 72 hours at 102°C in a force air oven and weighed. Crude protein content was measured using a LECO TruSpec® CN268 Elemental Combustion Analyzer (LECO Corp., St. Joseph, MI) to determine N content. All samples from every REF and TRT location were analyzed. Crude protein content was calculated by multiplying the nitrogen percentage (N%) by the standard conversion factor of $100/16 = 6.25$, based on the assumption that proteins contain approximately 16% N.

2.5 Statistical Analysis

Welch's t-test emerged as the ideal analytical tool for comparing forage yields between the REF ↔ TRT pairs, to accommodate variability in sample sizes and unequal variances to provide reliable comparisons (Welch, 1947). This flexibility was particularly valuable given the unforeseen challenges of real-world fieldwork, including time constraints, long travel distances, conflicting grazing schedules, adverse weather, and even mosquito infestations. The most remarkable disruption occurred in 2021, when 92 bulls grazed in critical areas of the SPR site, rendering the reference field unusable for comparison with the

TRT field. This incident, along with other disruptions, led to unequal sample sizes in some cases. Despite these setbacks, data collected from undisturbed areas remained highly valuable, even though the sampling protocol was not fully implemented, and fewer samples were collected than planned.

2.6 Estimation of Actual Evapotranspiration

The automated version 0.20.33 of the Mapping Evapotranspiration at High Resolution with Internalized Calibration (METRIC) model (Allen et al., 2005; Allen et al., 2007) was used to estimate actual evapotranspiration (ET_a) at the study sites. This automated version allows the METRIC model to be accessed through the Google Earth Engine (GEE) under an automated version of METRIC (eeMETRIC). Results from the eeMETRIC model have demonstrated conformity with other methods, including weighing lysimeter, Bowen ratio, and eddy flux techniques (Tasumi et al., 2005; Allen et al., 2007; Allen et al., 2011; Irmak et al., 2011). The eeMETRIC model was used to estimate spatial averages of monthly ET_a for the study sites. The ET_a rates were then used to develop the production function relating yield to consumptive water use, by summing the water use from an assumed green-up date of April 1 each year and interpolating to the day on which forage samples were acquired.

3 Results

Yearly trends in forage yield and crude protein were evaluated over multiple years, both during and following irrigation reductions. These comprehensive analyses provide an essential examination of the multi-year effects of water conservation programs on Colorado's montane hay and pasture fields.

3.1 Equivalence Testing of NDVI Differences for Reference and Treatment Fields

For a study of this nature, the biophysical equivalence between treatment (TRT) and reference (REF) fields is critical, as it underpins the validity of comparing the impacts of imposed irrigation withdrawals. Designing for equivalence required thoughtful pairing of fields to match pre-existing vegetative compositions. However, given the limitations of a non-equivalent control group design, initial field pairing depended on the invaluable localized knowledge of ranchers, whose insights provided the best available basis for identifying comparable field conditions. To further assess the validity of these pairings, a retrospective analysis was conducted in QGIS (QGIS, 2024), utilizing annual mean NDVI values derived from field raster layers to strengthen the methodological rigor of the study (Table 3.1.1). This approach is consistent with other research that has integrated NDVI to evaluate and track pasture dynamics over time (Frongia, 2023).

Table 3.1.1. Comparison of Δ NDVI and p-values for REF and TRT field comparisons

Treatment	REF	Δ NDVI	p	Excluded Year [†]	Δ NDVI	p	Excluded Years [‡]	Δ NDVI	p
GPR T1	GPR R1	0.033	0.09	2007	0.027	0.18	[2007, 2008]	0.023	0.20
GPR T2	GPR R1	0.017	0.80	2007	0.011	0.67	[2007, 2005]	0.010	0.76
BMR	GPR R1	0.040	0.13	2007	0.034	0.26	[2007, 2009]	0.028	0.28
HSR	GPR R1	0.036	0.02	2007	0.031	0.05	[2007, 2012]	0.028	0.08
GPR T2	GPR T1	0.026	0.06	2006	0.024	0.09	[2006, 2005]	0.022	0.15
RSR T1	RSR R1	0.017	0.59	2013	0.014	0.64	[2013, 2008]	0.012	0.45
RCR T1	RCR R1	0.015	0.66	2013	0.013	0.75	[2013, 2009]	0.012	0.81
SBR T1	SBR R1	0.038	< 0.05	2007	0.033	< 0.05	[2007, 2011]	0.031	0.05
SPR T1	SPR R1	0.025	0.24	2008	0.019	0.44	[2008, 2007]	0.016	0.55

[†] Top 1 Year Exclusion. The excluded years for each pair (e.g., 2007 for many pairs) were identified.

[‡] Top 2 Years Exclusion. Both the first and second most impactful years were excluded, and p-values were recalculated.

The general guideline adopted from Reed et al. (1994) is that a mean annual NDVI difference (Δ NDVI) between the REF ↔ TRT pairs, greater than 0.05 would indicate marked variation in surface condition. Conversely, differences smaller than 0.05 suggested comparable conditions, reinforcing the conclusion of vegetative similarity between paired fields. To further substantiate this, an equivalence test was employed, interpreting non-significant p-values as evidence that Δ NDVI differences were negligible. The results of these tests largely corroborated producer assessments, affirming that the identified REF ↔ TRT pairs could be assumed appropriately paired with consistent vegetative characteristics.

To refine the analysis, additional steps were taken to identify and exclude years where the Δ NDVI between REF and TRT fields was most pronounced, operating on the hypothesis that weather might explain the observed disparities. Historical weather records from Kremmling, CO, reveal that the 2006–2007 and 2012–2013 periods were marked by drought conditions, likely stressing vegetation and contextually amplifying heterogeneity in NDVI values for these time periods. By excluding these outlier years, the analysis aimed to isolate broader similarities in NDVI while accounting for the localized impact of extreme climatic events. Even after excluding outlier years, the SPR R1 ↔ SBR T1 pair stood out as an exception to assumed equivalence. Removing the two most anomalous years brought the t-test for NDVI near non-significance and met the Δ NDVI guideline ($p < 0.05$). However, spatial mapping revealed a small lake near SBR T1 and its proximity to the Colorado River, likely influencing Δ NDVI values and complicating equivalence assessments.

3.2 Sum of Squares Analysis Across Time Periods

An additional comparison using the sum of squares (SS) statistic identified fields exhibiting greater or lesser variability in vegetative cover. Higher SS generally suggests more mixed vegetation, uneven growth, or patchy areas of stress. To account for different field sizes, a normalized metric (SS') was calculated by dividing the NDVI SS by the NDVI pixel count, thereby adjusting for variability intensity per pixel rather than total variability across all pixels. This ensured that observed differences between REF ↔ TRT pairs reflected actual pattern differences without influence of field size.

The SS' values across fields and years reveal distinct patterns over three key periods: the pre-study years (2005–2019), the irrigation withdrawal year (2020), and the subsequent recovery years (2021–2023). From 2005 to 2019, SS' values exhibited steady trends, marked by moderate variability across fields with no significant peaks or anomalies. During this period, the average SS' for TRT fields (GPR T1, GPR T2, BMR, HSR, SBR T1, and SPR T1) was 0.00191 ($\sigma = 0.00130$), while REF fields (GPR R1, SBR R1, and SPR R1) averaged 0.00151 ($\sigma = 0.00090$). A Welch's t-test found no statistically significant differences between the two groups, as all p-values exceeded the 0.05 threshold, indicating consistent patterns across the pre-study years.

However, 2020 marked a pivotal shift. With the onset of irrigation withdrawals and drought impacts, SS' values rose noticeably. The TRT fields averaged 0.00243, the highest value observed in the study, while REF fields averaged 0.00198. The increase in SS' reflects the compounded effects of reduced irrigation and environmental stress of drought. The recovery phase (2021–2023) then confirms gradual stabilization back to the pre-reduction characteristics. In 2021, SS' averages settled at 0.00228 for TRT fields with REF values notably lower at 0.00091. By 2022, SS' values declined further, averaging 0.00184 for TRT fields and 0.00162 for REF fields, signaling a narrowing gap. Finally, in 2023, convergence between the groups became apparent: SS' values reached 0.00156 for TRT fields and 0.00170 for REF fields.

3.3 NDVI Analysis of Fields After Irrigation Withdrawal

A color gradient map illustrates changes in NDVI mean values (Δ NDVI), showing differences in vegetative health between various field pairings over the years (Figure 3.3.1). Larger Δ NDVI values represent greater disparity between the well-irrigated and water-stressed fields. By focusing on the

difference between the NDVI of a well-irrigated field and a restricted irrigated field, the color gradient map effectively captures how differences in water availability affect vegetative health.

In 2018 and 2019, the Δ NDVI values remained low and within acceptable tolerance levels, indicating relatively uniform vegetative health across the field pairs during those years. However, in 2020, the NDVI values clearly diverged, reflecting a notable disparity in vegetative health likely caused by water reductions. From 2021 onward, a clear trend of recovery emerged, as the average Δ NDVI gap gradually diminished. While not yet fully aligned, the vegetative conditions between the pairs showed signs of improvement. Maps supporting the basis for Figure 3.3.1 are included in the Appendix.

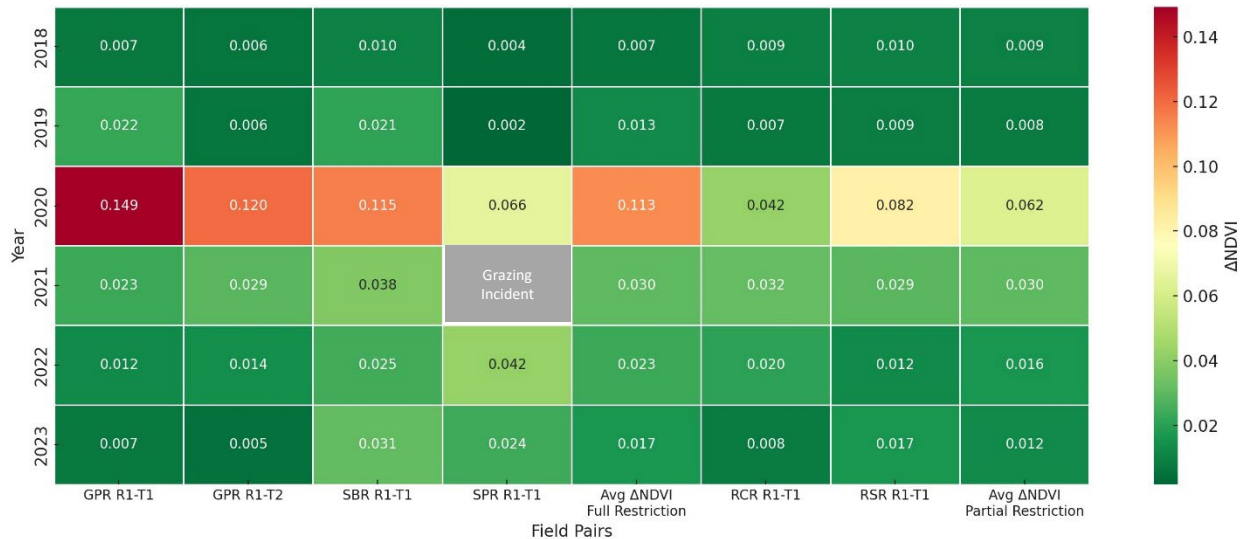


Figure 3.3.1. Temporal Changes in Δ NDVI Across Sites from 2018 to 2023, showing variations across paired fields by year, highlighting differences in vegetation health and recovery trends following irrigation management practices.

Some contextual explanations are relevant to specific sites. For the SBR R1–T1 pair, irregular Δ NDVI behavior was observed, partly due to the presence of a lake on SBR T1 field. To minimize its influence, only pixels directly overlapping the lake were removed, avoiding arbitrary exclusions. Additionally, SBR T1 field is bordered by the Colorado River, which likely provided some relief from reduced irrigation. The SPR R1–T1 comparison in 2021 was not possible due to an unplanned grazing incident where 92 bulls affected critical areas of the SPR R1 site in 2021, damaging enclosures and rendering the reference field unusable for meaningful comparison with the TRT field. This same grazing pattern was continued for the rest of the study, so data from SPR was only considered valid for 2020.

3.4 Yield Performance and Recovery During and After Irrigation-Restricted Conditions

The producers impressively pinpointed areas of high and low production. Tables 3.4.1 and 3.4.2 present dry matter forage yield comparisons for the high and low production location pairs during and after the irrigation withdrawal. In other words, Table 3.4.1 compares yields between the high production locations at the REF and TRT sites for both full-season and partial-season irrigation reduction scenarios, using Welch's t-test p-values indicating the statistical significance of yield differences.

Similarly, Table 3.4.2 compares yields between the low production locations at the REF and TRT sites for both full-season and partial-season irrigation reduction scenarios. Statistical significance is assessed for each year and field pair.

Table 3.4.1. Dry matter forage yields for **high-production** locations after irrigation reduction in 2020 and p-value for Welch's t-test comparing reference (REF) and treatment (TRT) sites

Month	Field Pair		2020 Yield (T/ac)			2021 Yield (T/ac)			2022 Yield (T/ac)			2023 Yield (T/ac)			2024 Yield (T/ac)		
	REF	TRT	REF	TRT	p	REF	TRT	p	REF	TRT	p	REF	TRT	p	REF	TRT	p
<i>Fields where irrigation was reduced for the entire 2020 season</i>																	
June	GPRR1	GPRT1	0.41	0.12	< 0.01	1.22	0.62	< 0.05	1.60	0.63	< 0.01	2.96	1.8	0.11			
July	GPRR1	GPRT1	3.28	0.23	< 0.01	2.22	2.14	0.86	3.66	3.40	0.56	5.21	5.26	0.95	3.96	2.08	0.30
June	GPRR1	GPRT2	0.41	0.16	< 0.01	1.22	0.33	< 0.01	1.60	0.92	< 0.05	2.96	1.17	< 0.05			
July	GPRR1	GPRT2	3.28	0.27	0.07	2.22	2.21	0.98	3.66	2.49	< 0.01	5.21	3.75	0.22	3.96	2.55	0.41
June	SBRR1	SBRT1	1.36	0.13	< 0.01	1.37	1.26	0.78	2.47	0.37	< 0.01	1.02	0.31	< 0.01			
July	SBRR1	SBRT1	2.85	0.27	< 0.01	1.93	2.66	0.16	3.32	1.25	< 0.01	2.09	1.29	< 0.05	1.55	0.99	0.28
June	SPRR1	SPRT1	1.71	0.52	< 0.01	0.84	0.43	---	0.52	1.50	---	nan	2.52	---			
July	SPRR1	SPRT1	2.12	0.56	< 0.01	1.79	1.62	---	1.13	2.18	---	1.04	3.82	---	1.63	2.10	---
<i>Fields under partial-season reduction (water shut off July 15, 2020)</i>																	
June	RCRR1	RCRT1	1.47	1.62	0.74	0.11	0.09	0.41	0.59	0.79	0.36	0.47	0.39	0.65			
July	RCRR1	RCRT1	1.84	2.09	0.20	nan	0.37	---	1.16	1.47	0.14	1.13	1.09	0.80			
June	RCRR2	RCRT2							2.46	1.66	< 0.05	---	---	---			
July	RCRR2	RCRT2	3.43	1.90	< 0.01	1.93	2.42	< 0.01	2.98	2.90	0.80	1.67	1.47	0.47	1.66	0.98	0.09
June	RSRR1	RSRT1	0.73	0.94	0.09	0.50	0.42	0.56	0.63	0.46	0.37	0.27	0.17	0.26			
July	RSRR1	RSRT1	2.29	2.10	0.71	2.74	2.90	0.74	2.20	2.67	0.47	1.14	1.02	0.61	1.69	1.99	0.43

* Insufficient Replicates: If either of the sites in the pair has insufficient replicates for a valid comparison, the t-test won't be performed.

† No reference site

Table 3.4.2. Dry matter forage yields for **low-production** locations after irrigation reduction in 2020 and p-value for Welch's t-test comparing reference (REF) and treatment (TRT) sites

Month	Field Pair		2020 Yield (T/ac)			2021 Yield (T/ac)			2022 Yield (T/ac)			2023 Yield (T/ac)			2024 Yield (T/ac)		
	REF	TRT	REF	TRT	p	REF	TRT	p	REF	TRT	p	REF	TRT	p	REF	TRT	p
<i>Fields where irrigation was reduced for the entire 2020 season</i>																	
June	GPRR1	GPRT1	0.45	0.08	< 0.01	0.70	0.37	0.35	1.38	0.65	< 0.05	1.80	1.32	0.25			
July	GPRR1	GPRT1	2.51	0.15	< 0.01	2.04	1.35	0.10	3.39	3.16	0.78	3.28	1.91	< 0.05	3.00	3.88	0.27
June	GPRR1	GPRT2	0.45	0.10	< 0.01	0.70	0.09	0.12	1.38	0.86	< 0.05	1.80	0.81	< 0.05			
July	GPRR1	GPRT2	2.51	0.19	< 0.01	2.04	0.81	< 0.01	3.39	2.43	0.13	3.28	2.68	0.37	3.00	2.01	< 0.05
June	SBRR1	SBRT1	1.24	0.22	< 0.01	0.71	0.71	1.00	1.33	0.84	0.28	1.56	0.53	< 0.05			
July	SBRR1	SBRT1	2.44	0.38	< 0.01	1.60	1.62	0.95	1.89	1.44	< 0.05	4.95	1.62	< 0.01	1.87	1.17	0.06
June	SPRR1	SPRT1	0.62	0.47	0.24	0.30	0.45	---	0.30	0.81	< 0.01	0.00	1.31	< 0.01			
July	SPRR1	SPRT1	0.64	0.15	< 0.01	0.26	0.68	---	0.19	2.02	< 0.01	0.13	2.67	< 0.01	0.78	1.58	< 0.05
<i>Fields under partial-season reduction (water shut off July 15, 2020)</i>																	
June	RSRR1	RSRT1	0.44	0.41	0.58	0.37	0.37	0.99	0.44	0.50	0.71	0.15	0.28	0.35			
July	RSRR1	RSRT1	1.20	1.22	0.91	2.24	1.92	0.74	2.84	2.64	0.74	0.67	0.85	0.12	1.89	0.68	0.06

* Insufficient Replicates: If either of the sites in the pair has insufficient replicates for a valid comparison, the t-test won't be performed.

† No reference site

Some statistical test results may seem counterintuitive, particularly when large observed differences in means fail to reach statistical significance. This can often be explained by factors that reduce the test's statistical power. For instance, small or unequal sample sizes can limit the ability to detect significant

differences. Additionally, higher variability within one group compared to another can further diminish the precision of the analysis, making it more challenging to draw clear conclusions. For example, with group means of 3.28 T/ac for GPRR1H and 0.23 T/ac for GPRT1H, the p-value of 0.07 is close to the conventional significance threshold ($p < 0.05$) but falls slightly short due to the underlying variability in the dataset.

Impact of Fully Restricted Irrigation Conditions

The impact of full irrigation withdrawal shows significant reductions in 2020 and then an uneven, gradual trend in recovery for the next 4 years (Table 3.4.3 and Figure 3.4.2).

In June 2020, fields that were subjected to full irrigation withdrawal produced yields that were 73% lower than those of fully irrigated REF fields (0.26 T/ac, $\sigma^2 = 0.21$ vs. 0.97 T/ac, $\sigma^2 = 0.47$; $p < 0.01$), reflecting a substantial decline in productivity under restricted conditions. This reduction coincided with an exceptionally dry growing season, with monthly precipitation in July, August, and September at 28%, 23%, and 9% of average, respectively (Colorado Climate Center). In June 2021, despite the resumption of irrigation, yields on TRT fields (un-irrigated in 2020) remained 26% lower than those of the REF fields (0.74 T/ac, $\sigma^2 = 0.35$ vs. 1.00 T/ac, $\sigma^2 = 0.06$). This yield gap suggests a lingering impact of the 2020 irrigation withdrawal and associated moisture deficits. The REF fields, although irrigated throughout, also showed reduced yields compared to typical years, likely due to carryover effects from the severe 2020 soil moisture deficit. The TRT fields, having experienced both the intentional lack of irrigation and adverse 2020 climate conditions, provided a valuable opportunity to assess recovery under harsh conditions. In June 2022, with all fields now under equal irrigation, TRT fields still produced yields 63% lower than REF fields (0.62 T/ac, $\sigma^2 = 0.02$ vs. 1.70 T/ac, $\sigma^2 = 0.29$). This sharp decline highlights the prolonged impacts of the 2020 irrigation withdrawal on soil health and field productivity. By June 2023, yields from TRT fields showed some improvement but remained 46% lower than REF fields (0.99 T/ac, $\sigma^2=0.81$ vs. 1.84 T/ac, $\sigma^2=0.77$). This moderate yield gap suggests a slow recovery trajectory, with some fields continuing to exhibit the long-term effects of the 2020 irrigation reduction.

By July, stark reductions were more evident, underscoring the severe impact of the irrigation withdrawal during a dry growing season. In July 2020, fields subjected to full irrigation withdrawal produced yields 87% lower than fully irrigated REF fields (0.29 T/ac, $\sigma^2 = 0.09$ vs. 2.31 T/ac, $\sigma^2 = 0.81$). From 2021 to 2024, both field types were irrigated equally, resulting in much closer yield values. In July 2021, average yields on the fields previously under irrigation withdrawal were nearly identical to those on the continually irrigated REF fields (1.94 T/ac, $\sigma^2 = 0.28$ vs. 1.95 T/ac, $\sigma^2 = 0.26$). However, as reflected in the large error bars in Figure 3.4.2, there was significant variability between TRT fields, with some showing July yields as much as 60% below REF fields. In 2021, the Intermountain West region of Colorado faced acute challenges due to persistent drought conditions (Western Water Assessment, 2021). Nearly the entire region entered the year in drought, with over half categorized as extreme drought. Despite some improvement from late summer monsoon rains, much of the region remained water-stressed. Contextual management decisions may have also affected the yield comparisons. Notably, nitrogen application on SBR-R1 in 2021 were eliminated due to the high cost of fertilizer, which likely contributed to lower-than-expected reference yields despite full irrigation.

In July 2022, REF fields (3.07 T/ac, $\sigma^2 = 0.65$) slightly outperformed the fields that were under irrigation withdrawal 2 years prior (2.31 T/ac, $\sigma^2 = 1.37$) by 25%, though the latter exhibited greater variability. In July 2023, REF field yields increased to 3.88 T/ac ($\sigma^2 = 0.51$), while the fields on which irrigation withdrawal had taken place 3 years prior yielded 2.52 T/ac ($\sigma^2 = 1.51$), a 35% lower yield despite equal irrigation. By July 2024, the gap narrowed further, with the fields previously under irrigation withdrawal

producing 2.03 T/ac ($\sigma^2 = 1.34$), still 22% lower than REF fields (2.60 T/ac, $\sigma^2 = 1.25$), reflecting reduced variability but continued reductions in productivity.

Table 3.4.3. Average dry matter forage yields for locations after irrigation reduction in 2020 comparing reference (REF) and treatment (TRT) sites

Month	Field Pair	2020 Yield (T/ac)			2021 Yield (T/ac)			2022 Yield (T/ac)			2023 Yield (T/ac)			2024 Yield (T/ac)		
		REF	TRT	Δ	REF	TRT	Δ	REF	TRT	Δ	REF	TRT	Δ	REF	TRT	Δ
<i>Fields where irrigation was reduced for the entire season</i>																
June	REF TRT	0.97	0.26	-73%	1.00	0.74	-26%	1.70	0.62	-63%	1.84	0.99	-46%			
July	REF TRT	2.31	0.29	-87%	1.95	1.94	-0.3%	3.07	2.31	-25%	3.88	2.52	-35%	2.60	2.03	-22%
<i>Fields under partial-season reduction (water shut off July 15)</i>																
June	REF TRT	1.10	1.28	16%	0.31	0.26	-16%	0.61	0.64	4%	0.37	0.28	-24%			
July	REF TRT	2.52	2.03	-19%	2.34	2.66	14%	2.59	2.79	8%	1.41	1.25	-11%	1.68	1.49	-11%

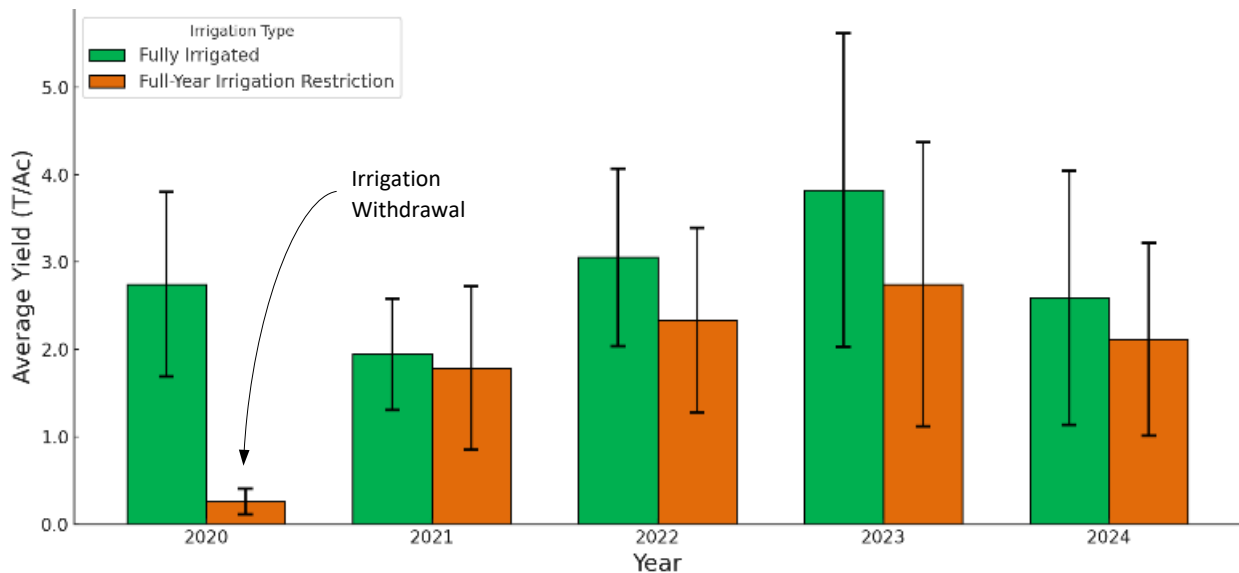


Figure 3.4.2. Impact of fully restricted irrigation condition on July forage yield over multiple years (excluding SPR data). Yields were calculated from the average of low and high production yields.

As a matter of reference, fully irrigated fields at Meeker, CO exhibited similar forage yields averaging 2.73 T/ac for cool-season grasses under similar irrigation practices (Pearson et al., 2003), providing a useful benchmark for comparison to the fully irrigated reference sites at Kremmling, CO.

The July yield data is most relevant for evaluating field performance, as it provides clear insights and aligns with producer practices like hay cutting (Figure 3.4.2). Larger error bars reflect variability in field conditions and production rates. In ecological and agricultural research, long-term consistency in trends can be as meaningful as isolated statistical tests, particularly when practical limitations reduce study power. Here, although the error bars indicate overlap and a lack of statistical significance in individual years, a consistent pattern emerges: fully irrigated (REF) yields exceed restricted (TRT) yields year after year. This cumulative evidence suggests a real, biologically relevant difference, emphasizing the practical significance of these results even without statistical significance for single-year comparisons.

Impact of Partially Restricted Irrigation Conditions

On fields where irrigation was withdrawn after July 15, 2020, yields fared better in comparison to the fields on which irrigation was eliminated entirely. In June 2021, yields from TRT fields that underwent

partial-season irrigation in 2020 were 0.26 T/ac ($\sigma^2 = 0.23$), slightly lower than the fully irrigated REF fields at 0.31 T/ac ($\sigma^2 = 0.28$). The small difference between the two suggests that partial irrigation in 2020 helped maintain enough soil moisture to minimize long-term productivity losses. By June 2022, with all fields under full irrigation, the partially restricted fields yielded 0.64 T/ac ($\sigma^2 = 0.22$) compared to 0.61 T/ac ($\sigma^2 = 0.03$) for the REF fields. This minor increase in yields for the partially restricted fields highlights their ability to recover fully, with minimal lingering effects of the prior year's irrigation withdrawal. In June 2023, yields from the partially restricted fields were 0.28 T/ac ($\sigma^2 = 0.16$), slightly lower than the REF fields at 0.37 T/ac ($\sigma^2 = 0.14$). This modest difference reflects some variability in recovery rates but no significant or lasting impact on productivity.

In July 2021, yields from TRT fields subjected to partial irrigation withdrawal in 2020 were 2.66 T/ac ($\sigma^2 = 0.34$), slightly higher than the fully irrigated REF fields at 2.34 T/ac ($\sigma^2 = 0.57$). By July 2022, with all fields back under full irrigation, yields were fairly comparable at 2.79 T/ac ($\sigma^2 = 0.16$) for the TRT fields compared to 2.59 T/ac ($\sigma^2 = 0.55$) for the REF fields. In July 2023, yields from the partially restricted fields were 1.25 T/ac ($\sigma^2 = 0.32$), slightly lower than the REF fields at 1.41 T/ac ($\sigma^2 = 0.37$). Finally, in July 2024, yields from the partially restricted fields reached 1.49 T/ac ($\sigma^2 = 0.71$), compared to 1.68 T/ac ($\sigma^2 = 0.02$) for the REF fields, further supporting the conclusion that recovery is consistent despite temporary reductions in water availability.

3.6 Production Functions for High-Elevation Pasture Grasses

Understanding the relationship between biomass production and ET_a is crucial because it helps bridge differing perspectives: water leasing programs focus on how much water can be conserved, while producers are concerned about hay loss from reduced irrigation. A production function combines these viewpoints by quantifying how changes in water consumption impact biomass yield, creating a shared reference point. By illustrating the trade-off between water use and productivity, the production function allows ranchers and water managers to make informed decisions within a common frame of reference. This helps balance water conservation goals with maintaining agricultural output, ultimately supporting shared objectives. The analysis revealed a linear correlation between ET_a (in/ac) and yield (T/ac) across several sites, underscoring the relationship between water use and biomass production.

The crop production function scatterplot is based on an ET_a timeframe that was assumed to begin on April 1 for consistency across sites and years. While this simplifies the analysis, a more detailed approach would anchor the start of ET_a to soil temperature thresholds. For example, monitored sites in 2021 first reached 40°F (4.4°C) around May 5, marking dormancy break and the onset of ET consistent with producer observations and typical C3 species behavior. In 2022, the same threshold was not reached until May 26, reflecting a later break of dormancy due to cooler spring conditions. For the purposes of this analysis, the end of the ET_a timeframe was fixed to the grass sampling date, providing a consistent endpoint for calculating seasonal crop water use.

This scatterplot (Figure 3.6.1) illustrates a linear relationship between actual ET_a and dry matter forage yield. The best-fit linear regression line is described by the equation:

$$y = 0.203x - 01.157$$

where y is yield (T/ac) and x is ET_a (in/ac). The corresponding R² value of 0.591 indicates that approximately 59.1% of the variability in yield can be explained by consumptive water use. In contrast, the zero-intercept regression line is described by the equation:

$$y = 0.1208x$$

where y is again yield (T/ac) and x is again ET_a (in/ac), where the line is again constrained to pass through the origin. The R^2 value for this model is 0.486, meaning that about 48.6% of the variability in yield is explained by ET_a . The comparison between the two regression lines highlights that the best-fit linear regression, with a higher R^2 value, provides a better explanation of the observed variation in yield compared to the zero-intercept model.

The relationship between yield and ET_a in Figure 3.6.1 demonstrates a linear trend, where each additional inch of ET_a results in a yield increase of approximately 0.19 T/ac. While not overly remarkable, this is a useful production function, despite other environmental factors contributing to the remaining variability. Additionally, embedded in the data are distinct subgroups (GPRT1, GPRT2, GPRR1, RCRR1 and RSRT1) that show strong internal correlations. This finding can be compared to the results from Smeal et al. (2005), which suggested a yield increase of 0.14 T/ac per additional inch of irrigation for high-yielding grasses like orchardgrass and meadow brome, under an assumed sprinkler system efficiency of 85%. Adjusting for this efficiency, the yield increase per inch of actual ET would be approximately 0.165 T/ac.

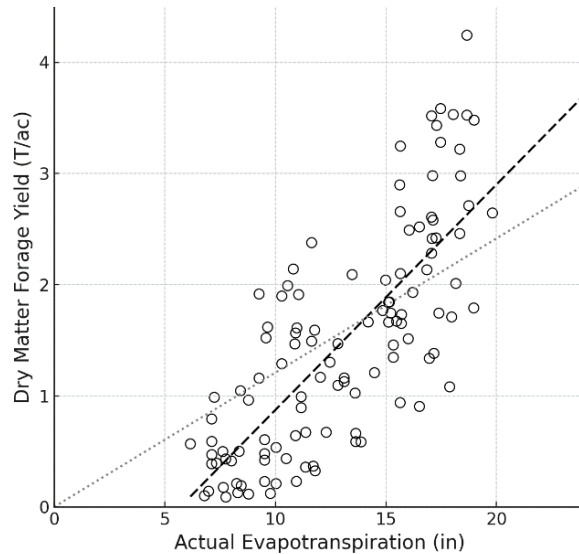


Figure 3.6.1. Yield response to consumptive use in high-elevation pastures (Grand County, CO). Grasses are dominantly Garrison Foxtail (*Alopecurus arundinaceus*), intermediate wheatgrass (*Thinopyrum intermedium*), timothy (*Phleum pratense*), and smooth brome (*Bromus inermis*)

3.7 Forage Quality During and After Irrigation-Restricted Conditions

This section examines forage quality data, focusing on how irrigation practices influence CP and fructans levels across different contexts. Specifically, the analysis compares fully irrigated sites (REF) with sites where irrigation was fully restricted (TRT).

3.7.1 Crude Protein Analysis and Trends

The goal of the CP analysis is to evaluate forage quality across multiple years during the period or recovery following irrigation withdrawal. Crude protein (CP) levels, analyzed across different sites, production types, and years (2020–2023) are provided in Table 3.7.1 for the sites where irrigation was fully restricted and Table 3.7.2 for sites where irrigation was partially restricted.

Observed CP levels in fully irrigated and restricted irrigation sites reveal several nuances when considering forage quality trends and species data. Reference sites generally showed higher CP levels in June compared to July, a pattern also observed for TRT sites, though the difference between months was

narrower for TRT. These trends align with existing research indicating an inverse relationship between yield and CP concentrations (e.g., Moyer et al., 2004; Li et al., 2022), as forage yield peaks later in the season, diluting protein content. Across 2020 to 2023, Δ CP (the change between REF and TRT) remained minimal but often slightly more favorable in July, suggesting reduced irrigation impacts during this month. Statistical tests confirm significant seasonal differences in CP levels between June and July for both REF ($p = 0.00041$) and TRT ($p = 0.00059$). However, no significant differences were observed between REF and TRT within each month, with p -values of 0.295 for June and 0.617 for July. Overall, June consistently yielded better forage quality, while July yields provided lower CP levels regardless of irrigation status. These results should be understood in the context of production operations, which must optimize the goal of higher yields against better forage quality.

Table 3.7.1. Grass crude protein impact of full irrigation reduction in 2020 over multiple years during recovery period

Site	Prod	Month	2020			2021			2022			2023		
			Crude Protein			Crude Protein			Crude Protein			Crude Protein		
			REF	TRT	Δ CP	REF	TRT	Δ CP	REF	TRT	Δ CP	REF	TRT	Δ CP
GPR	High-1	Jun	17.3	17.7	2.0%	15.5	15.3	-1.4%	15.1	14.2	-6.0%	16.2	7.3	-54.7%
GPR	High-1	Jul	10.7	12.8	20.1%	7.5	9.3	23.7%	9.9	6.6	-33.2%	6.4	3.0	-53.9%
GPR	Low-1	Jun	23.3	14.6	-37.3%	18.6	14.4	-22.5%	20.0	14.8	-26.0%	17.2	8.6	-50.3%
GPR	Low-1	Jul	16.0	14.1	-12.0%	12.5	10.5	-15.9%	11.7	8.8	-25.2%	8.1	7.0	-14.1%
GPR	High-2 ⁺	Jun	17.3	16.3	-6.2%	15.5	16.3	5.0%	15.1	16.1	6.7%	16.2	12.0	-25.8%
GPR	High-2 ⁺	Jul	10.7	15.1	41.0%	7.5	10.7	42.9%	9.9	8.3	-16.0%	6.4	5.5	-14.9%
GPR	Low-2 ⁺	Jun	23.3	14.1	-39.6%	18.6	18.9	1.6%	20.0	---	*	17.2	12.6	-26.8%
GPR	Low-2 ⁺	Jul	16.0	13.5	-15.6%	12.5	14.0	12.4%	11.7	9.7	-16.9%	8.1	6.3	-22.1%
SBR	High	Jun	14.4	21.1	46.9%	13.4	18.7	39.8%	16.8	21.0	25.4%	11.4	22.8	98.9%
SBR	High	Jul	9.3	13.5	44.2%	7.8	8.7	11.4%	9.5	13.8	45.3%	4.0	13.2	229.6%
SBR	Low	Jun	15.4	16.1	4.8%	14.6	15.7	7.3%	19.7	21.6	9.7%	13.9	18.2	31.5%
SBR	Low	Jul	10.3	14.7	43.0%	8.0	10.6	32.8%	11.3	13.3	17.7%	6.6	13.7	106.7%
SPR	High	Jun	10.1	16.1	59.5%	8.7	17.1	95.1%	11.5	11.9	3.5%	11.4	14.5	26.5%
SPR	High	Jul	9.7	13.6	39.8%	11.3	9.6	-15.0%	9.9	10.1	2.0%	7.1	8.3	16.4%
SPR	Low	Jun	14.4	18.2	26.3%	12.5	15.9	26.6%	12.3	14.5	17.9%	13.9	15.6	12.6%
SPR	Low	Jul	10.5	12.1	14.4%	11.2	10.2	-9.2%	12.0	8.9	-26.4%	10.0	8.0	-20.4%

* Sample not acquired

Table 3.7.2. Grass crude protein impact of partial irrigation reduction in 2020 over multiple years during recovery period.

Site	Prod	Month	2020			2021			2022			2023		
			Crude Protein			Crude Protein			Crude Protein			Crude Protein		
			REF	TRT	Δ CP	REF	TRT	Δ CP	REF	TRT	Δ CP	REF	TRT	Δ CP
RCR1	Only	Jun	14.4	14.0	-3.0%	10.8	9.3	-13.8%	14.4	10.4	-28.0%	9.3	8.2	-11.6%
RCR1	Only	Jul	---	*		---	7.5		10.7	7.6	-28.9%	4.4	6.4	44.5%
RCR2	Only	Jun	---	*		8.8	7.6	-13.9%	10.2	10.4	2.4%	6.2	10.0	60.9%
RCR2	Only	Jul	9.3	9.6	3.2%	6.7	5.3	-21.5%	7.1	7.9	11.5%	4.2	6.6	55.0%
RSR	High	Jun	15.3	14.3	-6.4%	14.3	14.7	2.6%	12.8	13.4	5.0%	14.1	14.2	0.3%
RSR	High	Jul	12.7	15.7	23.7%	8.4	7.1	-15.6%	8.7	7.8	-10.3%	7.6	10.5	38.3%
RSR	Low	Jun	18.3	16.7	-8.8%	15.6	16.3	4.3%	---	*	13.7	18.3	14.1	-23.2%

RSR	Low	Jul	18.2	12.7	-30.5%	9.4	6.0	-36.3%	9.2	9.5	3.7%	10.6	8.5	-19.4%
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* Sample not acquired

The narrowing CP gap between REF and TRT suggests the influence of additional factors. Species survey data, detailed in a separate technical bulletin, indicates that dominant grasses like Garrison Foxtail and Intermediate Wheatgrass play a significant role. Sites with a higher prevalence of resilient species, such as Garrison Foxtail, tend to maintain better CP levels under TRT conditions. The varying nutritional responses of these species to water stress likely drive these discrepancies, providing a species-specific explanation for why TRT sites exhibit variability but do not consistently follow the expected yield-quality tradeoffs. Overall, the gradually reducing CP gap between REF and TRT may reflect a combination of declining irrigation effectiveness in REF sites and the adaptive capacity of certain species under TRT conditions.

The year-over-year trend in crude protein (CP) levels shows a consistent decline for both REF (fully irrigated) and TRT (restricted irrigation) sites. REF sites experienced a decrease from 14.31% in 2020 to 10.90% in 2023, while TRT sites followed a similar pattern, dropping from 14.70% in 2020 to 10.09% in 2023. Both saw slight recoveries in 2022 before a sharp decline in 2023, suggesting systemic factors affecting forage quality. TRT sites exhibited greater variability year to year, highlighting the compounding impact of restricted irrigation. This decline underscores potential challenges in sustaining forage quality under changing conditions.

The comparison between fully restricted and partially restricted sites highlights key differences in crude protein (CP) levels and their implications for management practices. Fully restricted sites consistently maintained slightly higher CP levels than partially restricted sites, with the largest differences observed in 2021 (2.35%) and 2022 (1.93%). By 2023, CP levels for both groups converged, with fully restricted sites averaging 10.09% and partially restricted sites at 9.81%. However, the higher CP levels in fully restricted sites came at the cost of significantly lower yields, which diminishes their value from a producer's perspective. While fully restricted sites produced higher quality forage, the lower yields reduced overall productivity, making this approach less desirable for long-term management. Fully restricting irrigation was necessary for the water-sharing program, but the results demonstrate that it is not an optimal practice for balancing quality and yield, as partially restricted sites provided a more sustainable compromise.

3.7.2 Fructan Analysis and Trends

Fructans, recognized as protective agents against abiotic stresses such as drought and frost, are synthesized from sucrose by fructosyltransferases and are abundant in plants from temperate and arid regions (Van den Ende, 2013; Valluru & Van den Ende, 2008). These compounds play a critical role in plant resilience under stressful conditions by serving as storage carbohydrates and osmoprotectants. While fructans predominantly accumulate in the internodes of grasses (Gebbing, 2003), rather than the above-ground biomass sampled in this study fructan concentrations were evaluated in paired REF and TRT fields across multiple years (2020, 2021, 2022, 2023) to assess potential legacy effects of irrigation withdrawal on forage carbohydrate content (Table 3.7.2). It was hypothesized that drought stress in TRT fields would trigger fructan synthesis and storage, providing insights into how plants adapt to varying irrigation practices.

In 2020, fructan concentrations were measured across eight paired locations, all located in fields subjected to full-season irrigation withdrawal. A paired t-test comparing REF and TRT concentrations produced a mean difference of 0.199 (REF > TRT), with a t-statistic of 1.81 and a p-value of 0.113. Although reference fields had slightly higher average fructan concentrations, the difference was not statistically significant ($p > 0.05$), providing no strong evidence of an early-season treatment effect on fructan content.

These results suggest that forage quality, as indexed by fructan concentration, may be relatively resilient to short-term irrigation changes during the withdrawal year. In the GPR site, only one reference area was available, and it was used for comparison against two separate treatment areas (T1 and T2) during each sampling year.

In 2021, fructan data were collected from six full-withdrawal sites and three partial-withdrawal sites (RCR1, RCR2, and RSR). The mean difference for the full-withdrawal pairs was -0.598 (TRT > REF), with a t-statistic of -2.28 and a p-value of 0.085 . While not conventionally significant, this suggests a trend toward increased fructan accumulation in treatment fields one year following irrigation withdrawal. From 2021 onward, data from the SPR site were omitted due to untimely grazing by 92 bulls that compromised sampling integrity. In 2022, fructan concentrations again tended to be higher in treatment fields across both full- and partial-withdrawal groups. By 2023, treatment fields at full-withdrawal sites exhibited significantly higher fructan concentrations than their reference counterparts. A paired t-test revealed a mean difference of -0.823 (TRT > REF), with a t-statistic of -3.45 and a p-value of 0.018 . This statistically significant result suggests evidence of a lasting physiological response to irrigation withdrawal. Over the four-year study period, no significant differences in fructan concentration were observed during the initial withdrawal year. However, treatment fields began to show progressively higher concentrations in subsequent years, with significant differences emerging by 2023 for full-withdrawal sites. This trend suggests a delayed physiological response to irrigation withdrawal, possibly linked to altered carbohydrate storage patterns, regrowth dynamics, or species composition.

There could be multiple reasons why a pattern of increasing fructan concentration emerged in the years following irrigation withdrawal. One possibility is that species dynamics may have shifted over time, favoring more stress-tolerant or carbohydrate-storing species in the treatment fields. Alternatively, changes in plant physiological strategies related to water stress recovery could emerge. Further research is needed on this interesting topic to determine these underlying mechanisms.

Table 3.7.3. Grass fructan impact of irrigation reduction in 2020 over multiple years during recovery period.

Site	Prod	Month	2020			2021			2022			2023		
			Fructans			Fructans			Fructans			Fructans		
			REF	TRT	ΔF	REF	TRT	ΔF	REF	TRT	ΔF	REF	TRT	ΔF
<i>Full Season Irrigation Withdrawal</i>														
GPR	High-1	Jun	1.97	1.80	-8.63%	1.78	2.20	23.60%	2.27	3.10	36.56%	1.53	2.66	73.86%
GPR	Low-1	Jun	1.98	1.61	-18.69%	2.17	2.04	-5.99%	1.44	2.96	105.56%	1.17	2.71	131.62%
GPR	High-2	Jun	1.97	1.94	-1.52%	1.78	1.99	11.80%	2.27	2.60	14.54%	1.53	2.37	54.90%
GPR	Low-2	Jun	1.98	1.32	-33.33%	2.17	2.11	-2.76%	1.44	---	---	1.17	2.31	97.44%
SBR	High	Jun	1.44	1.38	-4.17%	1.93	1.98	2.59%	2.38	2.49	4.62%	2.35	2.3	-2.13%
SBR	Low	Jun	1.62	1.86	14.81%	2.21	1.98	-10.41%	2.45	2.65	8.16%	1.76	2.1	19.32%
SPR	High	Jun	2.11	1.54	-27.01%	---	---	---	---	---	---	---	---	---
SPR	Low	Jun	1.54	1.57	1.95%	---	---	---	---	---	---	---	---	---
<i>Partial-Season Irrigation Withdrawal (no irrigation after June 15)</i>														
RCR1	Only	Jun	---	1.29	---	---	1.59	---	2.51	2.25	-10.36%	2.16	2.05	-5.09%
RCR2	Only	Jun	---	---	---	1.81	1.69	-6.63%	2.00	1.97	-1.50%	3.19	2.39	-25.08%
RSR	High	Jun	1.94	2.05	5.67%	1.92	2.37	23.44%	3.13	3.13	0.00%	2.4	2.53	5.42%
RSR	Low	Jun	1.84	2.08	13.04%	1.99	2.3	15.58%	---	2.54	---	2.52	2.23	-11.51%

* Sample not acquired

† Data was omitted due to untimely grazing earlier in the season than expected by 92 bulls accessing the field.

4 Discussion

These findings provide valuable insights into the resilience and adaptive capacity of montane grass pastures under irrigation withdrawals implemented for water conservation. In 2020, the combination of imposed irrigation withdrawals and extreme drought conditions led to significant yield reductions in fields that received no water for the entire season. From 2021 to 2024, statistically significant differences between restricted and fully irrigated fields were largely absent; however, a persistent trend of lower yields in previously restricted fields remained. Although statistical tests are valuable tools for evaluating data, they are not the sole indicators of meaningful trends. The consistent pattern of higher yields in fully irrigated fields compared to treatment fields over multiple years suggests a biologically significant response, aligning with established principles of crop recovery under water-limited conditions. While yields in these treatment fields showed gradual recovery, slight differences continued to reflect the lasting impacts of earlier water stress. Throughout the recovery period, yield variability remained high, particularly in treatment fields, highlighting the influence of site-specific factors such as soil properties, water availability, and management practices.

The extreme drought conditions in 2020 likely intensified the impacts of irrigation withdrawal on treatment fields, compounding yield losses and influencing subsequent recovery. Even fully irrigated REF fields experienced water stress due to the severe precipitation deficits, which may have further exacerbated differences between treatment and REF fields. These findings suggest that effective precipitation during the withdrawal year plays a critical role in shaping immediate and long-term recovery outcomes. Investigating how water deficits in the withdrawal year affect yield resilience and recovery trajectories will be important for informing future water management and conservation strategies. Western Colorado experienced significant drought conditions in 2021. The region faced its second consecutive year of drought, with 100% of the area in drought at the beginning of the water year and over 50% classified under extreme drought. The winter snowpack was below average to near-average, leading to a much-below-average spring runoff season. Seasonal runoff volumes from regional rivers varied from 10-50% of normal, and the inflow to Lake Powell received only 28% of normal streamflow (Western Water Assessment. 2021).

This trend suggests that the impacts of the 2020 irrigation withdrawal were long-lasting, with fields requiring extended periods to fully recover productivity. While equal irrigation was applied across all fields beginning in 2021, the observed differences highlight a practically significant and consistent productivity gap that warrants consideration for long-term management strategies. These findings emphasize the importance of understanding how past stressors, like irrigation withdrawals, can have residual effects even when conditions are subsequently normalized.

The NDVI analysis illustrates a consistent recovery trajectory between water-stressed treatment fields and fully irrigated (REF) fields, whereas yield values display greater variability. While NDVI and yield are not consistently proportional, both indicators suggest a pattern of gradual, slow recovery. This divergence highlights an important distinction: vegetation health, as captured by NDVI, and productivity (yield) respond differently to stress over time, underscoring the need to interpret these metrics together for a more complete understanding of recovery dynamics. By 2022, yields in treatment fields demonstrated incomplete recovery, remaining significantly lower than those of REF fields. Despite resuming irrigation, the lingering effects of the 2020 water reductions were evident in the continued productivity gap. In 2023, while yields in treatment fields showed further improvement, they still lagged behind REF fields, reflecting the enduring impacts of earlier irrigation withdrawals. This persistent gap points to the challenges of fully restoring productivity following a severe water deficit. In 2024, recovery of pasture

grasses showed notable improvement, particularly in high-production areas. By July, yields in treatment fields approached those of REF fields, signaling near-complete recovery. However, slight yield differences persisted, suggesting that while recovery was substantial, the long-term impacts of earlier water stress have not been entirely erased. The normalized metric (SS'), calculated as NDVI SS divided by NDVI pixel count, highlights the slow recovery and emerging stabilization of field variability. These findings highlight both the resilience of pasture systems and the time required for full recovery under water-limited conditions.

Irrigation withdrawal caused a significant disparity in vegetative health, as reflected in elevated Δ NDVI values between well-irrigated and water-stressed fields in 2020. Water-stressed fields showed marked declines in performance, highlighting the immediate and severe impacts of water stress on vegetation. From 2021 onward, Δ NDVI values indicate a gradual recovery, with vegetative conditions in restricted fields beginning to converge with those of well-irrigated fields. This closing gap suggests that, while water stress initially causes substantial negative impacts, vegetation demonstrates resilience and the potential for recovery when irrigation is restored. However, the lag in recovery reflected by Δ NDVI trends underscores the importance of using only temporary reductions to minimize long-term productivity losses and ensure gradual recovery across affected sites.

In ecological and agricultural research, long-term consistency in observed trends often carries greater weight than isolated statistical tests, particularly when practical limitations reduce the power of individual studies. The fact that the REF yields consistently exceed treatment yields year after year provides compelling cumulative evidence for a real difference, even in the absence of statistical significance in individual comparisons. This enduring pattern reinforces the importance of interpreting statistical results within the broader context of biological relevance and temporal consistency, emphasizing the need to consider both statistical and practical significance when evaluating agricultural and ecological outcomes.

Variance in yields, particularly in treatment fields, remained high throughout the recovery process. The observed trends align with the region's seasonal precipitation variability. The significant reduction in yields in 2020, particularly at sites where irrigation was fully withdrawn, highlights the impact of severe irrigation limitations that persists on pasture fields. Year-over-year variance in yields underscores the difficulty of achieving consistent outcomes, as field-to-field differences become increasingly evident during recovery. What is clear is that the rate of recovery is relative to the level of water stress imposed, as the fields that had water held back for a partial season exhibited a more rapid recovery than the fields where irrigation was withheld for the entirety of the growing season. Some fields recover more slowly than others, reflecting inherent risks and variability driven by localized factors such as water availability and management. While treatment fields showed gradual recovery over time, they consistently lagged compared to REF fields. Although the yield gap narrowed in later years, persistent variance and periodic statistical differences emphasize the need for tailored interventions to address site-specific recovery challenges. Encouragingly, the trend toward recovery after four years suggests gradual progress despite these challenges.

While yield data exhibited higher year-to-year variability, NDVI showed a stronger and more consistent signal of recovery between the two fields. The Δ NDVI map reflected gradual improvement across the landscape, whereas yield measurements fluctuated more due to localized sampling around the enclosures. Taken together, the two indicators are not perfectly proportional but both point to a slow, progressive recovery, with NDVI providing whole-field coverage and yield data offering site-specific insight.

The 2022 results highlight an incomplete recovery in treatment fields, with yields still significantly lower than REF fields. In 2023, yields improved but remained consistently below REF, underscoring the lingering impacts of the 2020 water reduction even after three years of resumed irrigation. The higher

yields in 2023 compared to 2022 suggest progressive recovery, indicating that treatment fields may eventually approach full productivity with continued management and favorable conditions. Variability among sites also persisted, likely driven by soil properties, water availability, and management practices..

In 2024, the recovery of pasture grasses showed significant improvement compared to previous years, particularly in high-production areas. By July 2024, the treatment fields exhibited yields closer to those of the REF fields, indicating near-complete recovery. However, some differences persisted, with treatment fields still showing slight yield reductions compared to REF fields.

The variability in crude CP coupled with yield, observed across fully irrigated, fully restricted, and partially restricted sites underscore the complexity of managing irrigation to optimize production. Variables such as distance to groundwater, species composition, soil type, and climatic conditions likely play significant roles and warrant closer examination to develop adaptive management strategies.

The comparison of irrigation practices revealed nuanced trade-offs. Fully restricted sites consistently maintained higher CP levels than partially restricted sites. However, fully restricted sites experienced significantly lower yields, diminishing their practical value for producers. While fully restricting irrigation was necessary as part of the water-sharing program, this approach is not optimal for long-term management, as it prioritizes forage quality over productivity. Partially restricted sites, despite slightly lower CP levels, provided a better balance of yield and quality, making them a more sustainable compromise under constrained water availability. These findings highlight the importance of tailoring irrigation practices to balance ecological and production goals while adapting to water limitations.

5 Conclusions

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. While yields do not fully match those of consistently irrigated fields, the improvement over time suggests an adaptive capacity in these forage systems, particularly in high-production areas.

The Normalized Difference Vegetation Index (NDVI) was utilized to evaluate vegetative density and health on fields designated for paired studies. Before the study began, NDVI analysis ensured that fields were sufficiently similar to serve as accurate pairs. During the study, it provided a quantitative basis for comparing water-stressed fields to their well-irrigated counterparts. In subsequent years, NDVI was also used to monitor the recovery of both fields when they received equal irrigation.

Recovery is assessed by evaluating multi-year patterns in yields and quality with georeferenced data collected from areas of varying productivity. Trends in productivity and quality for both fully-irrigated REF and irrigation-deprived fields are analyzed. The findings highlight how plant responses to water stress can inform the viability of water conservation programs in the Upper Colorado Basin that identify montane (~6,000 ft MSL) hay pastures as critical to implementation of any program to reduce agricultural water use.

Looking at the trends between 2020 and 2023 in the dry matter forage yields, some general observations can be made.

- **Impact of Irrigation Reduction on Forage Yield:** Fields on which irrigation was fully withheld showed significantly reduced yields, which were still lower than fully irrigated REF fields in subsequent years, indicating lasting effects of irrigation reduction. However, some fields

demonstrated more robust over time. Despite positive, albeit slow recovery trends, water-stressed fields had not yet fully matched the yields of the REF fields by the end of 2024, underscoring the prolonged impact of prior irrigation reductions.

- **Recovery Dynamics:** The research focused on the multi-year recovery of hay and pasture grasses once irrigation was restored in 2021. While some fields showed near-complete recovery, others experienced persistent yield reductions. The speed and extent of recovery varied significantly between fields, likely influenced by species distribution, soil conditions, and local climate variations, such as the drought year in 2020, which exacerbated the impacts of irrigation curtailment.
- **Forage Quality Trends:** The study also analyzed forage quality, particularly crude protein (CP) levels, across different irrigation treatments. Fields with fully restored irrigation often had higher crude protein content compared to those with reduced irrigation, although this trend was not consistent across all sites. Interestingly, CP in water-stressed fields often approached that of REF fields, suggesting resilience in forage quality despite reduced irrigation.

These points provide insight into the effects of reduced irrigation on forage yield, the complexity of recovery dynamics, the interplay between forage quality and irrigation, and the role of species-specific resilience in high-elevation pastures.

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Appendix Table 1. Annual NDVI Metrics for Reference and Treatment Fields (2005–2023)

Year	Field	Count	Max	Mean	Min	Range	Std dev	Sum	SS	SS'
<i>Fields where irrigation was reduced for the entire season</i>										
2005	BMR	178	0.50	0.44	0.34	0.16	0.03	77.65	0.11	0.0006
2006	BMR	178	0.47	0.43	0.31	0.16	0.02	77.25	0.11	0.0006
2007	BMR	178	0.43	0.36	0.26	0.17	0.03	64.22	0.11	0.0006
2008	BMR	178	0.40	0.36	0.25	0.15	0.03	64.19	0.12	0.0007
2009	BMR	178	0.37	0.34	0.27	0.09	0.01	59.67	0.03	0.0002
2010	BMR	178	0.41	0.37	0.28	0.13	0.02	65.03	0.09	0.0005
2011	BMR	178	0.49	0.44	0.32	0.17	0.03	77.83	0.14	0.0008
2012	BMR	178	0.44	0.38	0.28	0.17	0.03	66.93	0.17	0.0010
2013	BMR	178	0.53	0.46	0.39	0.14	0.03	82.77	0.12	0.0007
2014	BMR	178	0.59	0.53	0.34	0.25	0.05	94.23	0.36	0.0020
2015	BMR	178	0.54	0.47	0.33	0.20	0.04	83.93	0.23	0.0013
2016	BMR	178	0.55	0.44	0.33	0.21	0.04	77.79	0.25	0.0014
2017	BMR	178	0.46	0.41	0.33	0.13	0.02	72.43	0.07	0.0004
2018	BMR	178	0.44	0.39	0.19	0.25	0.04	68.56	0.30	0.0017
2019	BMR	178	0.55	0.43	0.13	0.42	0.06	76.04	0.63	0.0035
2020	BMR	178	0.35	0.30	0.14	0.21	0.03	52.70	0.17	0.0010
2021	BMR	178	0.44	0.37	0.14	0.30	0.05	65.56	0.45	0.0026
2022	BMR	178	0.50	0.44	0.15	0.36	0.06	78.35	0.57	0.0032
2023	BMR	178	0.53	0.47	0.17	0.36	0.06	83.47	0.61	0.0034
2005	GPR_T1	1201	0.53	0.42	0.20	0.33	0.05	498.57	3.22	0.0027
2006	GPR_T1	1201	0.45	0.39	0.22	0.23	0.03	472.17	1.40	0.0012
2007	GPR_T1	1201	0.55	0.39	0.20	0.34	0.05	473.61	2.53	0.0021
2008	GPR_T1	1201	0.40	0.34	0.19	0.21	0.03	405.19	1.17	0.0010
2009	GPR_T1	1201	0.40	0.35	0.21	0.19	0.03	420.48	1.02	0.0008
2010	GPR_T1	1201	0.46	0.37	0.23	0.23	0.03	446.24	1.28	0.0011
2011	GPR_T1	1201	0.52	0.44	0.28	0.24	0.05	523.89	2.71	0.0023
2012	GPR_T1	1201	0.45	0.38	0.21	0.24	0.04	453.66	1.92	0.0016
2013	GPR_T1	1201	0.56	0.46	0.26	0.30	0.05	552.19	3.33	0.0028
2014	GPR_T1	1201	0.60	0.51	0.27	0.34	0.07	614.99	5.12	0.0043
2015	GPR_T1	1201	0.57	0.47	0.27	0.30	0.05	566.53	2.98	0.0025
2016	GPR_T1	1201	0.55	0.43	0.25	0.29	0.05	511.77	3.47	0.0029
2017	GPR_T1	1201	0.54	0.42	0.24	0.31	0.05	501.11	2.54	0.0021
2018	GPR_T1	1201	0.60	0.42	0.22	0.38	0.05	499.78	3.12	0.0026
2019	GPR_T1	1201	0.55	0.44	0.27	0.28	0.04	526.40	1.47	0.0012
2020	GPR_T1	1201	0.51	0.31	0.18	0.32	0.05	372.69	2.55	0.0021
2021	GPR_T1	1201	0.52	0.40	0.20	0.31	0.05	481.86	3.42	0.0028
2022	GPR_T1	1201	0.59	0.47	0.24	0.35	0.05	561.94	2.71	0.0023
2023	GPR_T1	1201	0.56	0.50	0.28	0.28	0.04	598.70	2.28	0.0019
2005	GPR_T2	2022	0.60	0.47	0.25	0.35	0.04	959.50	3.24	0.0016

2006	GPR_T2	2022	0.52	0.45	0.23	0.29	0.03	918.04	1.58	0.0008
2007	GPR_T2	2022	0.60	0.45	0.23	0.37	0.04	901.30	2.57	0.0013
2008	GPR_T2	2022	0.47	0.39	0.24	0.23	0.03	785.05	1.52	0.0007
2009	GPR_T2	2022	0.46	0.39	0.23	0.23	0.02	783.63	1.14	0.0006
2010	GPR_T2	2022	0.46	0.40	0.23	0.22	0.02	814.00	1.15	0.0006
2011	GPR_T2	2022	0.54	0.45	0.27	0.27	0.03	919.70	2.24	0.0011
2012	GPR_T2	2022	0.47	0.41	0.22	0.25	0.03	832.55	1.27	0.0006
2013	GPR_T2	2022	0.59	0.46	0.29	0.31	0.04	935.28	2.71	0.0013
2014	GPR_T2	2022	0.59	0.51	0.29	0.31	0.04	1031.85	2.82	0.0014
2015	GPR_T2	2022	0.56	0.50	0.31	0.24	0.03	1012.03	1.59	0.0008
2016	GPR_T2	2022	0.58	0.47	0.28	0.30	0.03	943.45	2.42	0.0012
2017	GPR_T2	2022	0.50	0.43	0.26	0.24	0.02	875.34	1.05	0.0005
2018	GPR_T2	2022	0.56	0.43	0.24	0.32	0.03	868.14	2.10	0.0010
2019	GPR_T2	2022	0.56	0.45	0.29	0.27	0.03	919.03	2.29	0.0011
2020	GPR_T2	2022	0.49	0.34	0.23	0.26	0.05	686.20	5.24	0.0026
2021	GPR_T2	2022	0.55	0.40	0.22	0.32	0.04	798.93	3.08	0.0015
2022	GPR_T2	2022	0.52	0.47	0.29	0.23	0.02	942.96	0.79	0.0004
2023	GPR_T2	2022	0.54	0.50	0.33	0.20	0.02	1012.69	0.49	0.0002
2005	HSR	496	0.46	0.39	0.21	0.25	0.04	193.72	0.94	0.0019
2006	HSR	496	0.47	0.41	0.23	0.25	0.05	201.99	1.02	0.0020
2007	HSR	496	0.56	0.40	0.20	0.36	0.06	197.24	1.67	0.0034
2008	HSR	496	0.43	0.37	0.22	0.22	0.03	181.29	0.57	0.0012
2009	HSR	496	0.39	0.32	0.20	0.19	0.04	157.52	0.73	0.0015
HSR	HSR	496	0.43	0.36	0.20	0.23	0.05	178.45	1.06	0.0021
2011	HSR	496	0.51	0.42	0.28	0.23	0.05	209.53	1.32	0.0027
2012	HSR	496	0.44	0.35	0.19	0.25	0.04	173.95	0.97	0.0019
2013	HSR	496	0.54	0.45	0.23	0.31	0.04	220.77	0.77	0.0016
2015	HSR	496	0.58	0.48	0.36	0.22	0.03	239.53	0.58	0.0012
2016	HSR	496	0.55	0.45	0.33	0.22	0.03	223.06	0.55	0.0011
2017	HSR	496	0.48	0.42	0.30	0.18	0.03	208.77	0.32	0.0006
2018	HSR	496	0.51	0.41	0.29	0.23	0.03	203.19	0.49	0.0010
2019	HSR	496	0.51	0.44	0.31	0.20	0.03	218.15	0.36	0.0007
2020	HSR	496	0.50	0.34	0.24	0.26	0.05	170.51	1.41	0.0028
2021	HSR	496	0.50	0.39	0.26	0.24	0.04	193.74	0.68	0.0014
2022	HSR	496	0.50	0.45	0.31	0.19	0.03	224.06	0.40	0.0008
2023	HSR	496	0.56	0.51	0.36	0.20	0.03	255.29	0.38	0.0008
2005	SBR_T1	413	0.52	0.40	0.14	0.38	0.06	164.48	1.72	0.0042
2006	SBR_T1	413	0.49	0.38	0.06	0.42	0.07	157.27	1.77	0.0043
2007	SBR_T1	413	0.52	0.39	0.17	0.35	0.06	159.66	1.71	0.0041
2008	SBR_T1	413	0.47	0.36	0.07	0.40	0.07	150.16	1.74	0.0042
2009	SBR_T1	413	0.46	0.37	0.17	0.29	0.05	151.98	0.99	0.0024
2010	SBR_T1	413	0.49	0.39	0.08	0.41	0.06	162.22	1.71	0.0041

2011	SBR_T1	413	0.51	0.36	0.06	0.45	0.08	149.78	2.64	0.0064
2012	SBR_T1	413	0.44	0.37	0.17	0.27	0.05	151.20	0.93	0.0023
2013	SBR_T1	413	0.60	0.50	0.23	0.36	0.06	205.57	1.44	0.0035
2014	SBR_T1	413	0.56	0.42	0.05	0.51	0.07	175.52	2.17	0.0053
2015	SBR_T1	413	0.53	0.42	0.17	0.37	0.06	174.13	1.52	0.0037
2016	SBR_T1	413	0.51	0.39	0.18	0.33	0.05	162.40	0.92	0.0022
2017	SBR_T1	413	0.48	0.38	0.17	0.31	0.04	155.09	0.80	0.0019
2018	SBR_T1	413	0.48	0.36	0.21	0.27	0.04	150.36	0.78	0.0009
2019	SBR_T1	413	0.55	0.43	0.13	0.42	0.06	176.49	1.66	0.0015
2020	SBR_T1	413	0.50	0.36	0.11	0.39	0.07	150.24	1.80	0.0028
2021	SBR_T1	413	0.52	0.41	0.09	0.43	0.06	170.92	1.71	0.0019
2022	SBR_T1	413	0.59	0.47	-0.01	0.60	0.08	194.68	2.76	0.0018
2023	SBR_T1	413	0.58	0.49	0.15	0.44	0.07	200.39	1.83	0.0015
2005	SPR_T1	1289	0.55	0.46	0.33	0.21	0.03	586.81	1.45	0.0011
2006	SPR_T1	1289	0.55	0.43	0.31	0.25	0.04	554.75	2.51	0.0020
2007	SPR_T1	1289	0.61	0.48	0.33	0.28	0.05	619.97	2.93	0.0023
2008	SPR_T1	1289	0.73	0.57	0.39	0.34	0.05	740.01	3.85	0.0030
2009	SPR_T1	1289	0.52	0.43	0.30	0.21	0.03	549.44	1.49	0.0012
2010	SPR_T1	1289	0.55	0.40	0.27	0.29	0.05	520.13	2.69	0.0021
2011	SPR_T1	1289	0.62	0.52	0.38	0.24	0.04	667.91	2.31	0.0018
2012	SPR_T1	1289	0.52	0.36	0.23	0.29	0.05	463.60	3.55	0.0028
2013	SPR_T1	1289	0.60	0.49	0.34	0.26	0.05	632.67	3.64	0.0028
2014	SPR_T1	1289	0.69	0.50	0.31	0.38	0.05	638.66	3.12	0.0024
2015	SPR_T1	1289	0.58	0.45	0.35	0.22	0.04	584.03	2.01	0.0016
2016	SPR_T1	1289	0.60	0.51	0.39	0.22	0.04	660.14	1.92	0.0015
2017	SPR_T1	1289	0.57	0.47	0.35	0.21	0.04	605.16	1.88	0.0015
2018	SPR_T1	1289	0.71	0.49	0.30	0.41	0.08	626.76	8.67	0.0067
2019	SPR_T1	1289	0.60	0.50	0.33	0.28	0.04	640.82	2.34	0.0018
2020	SPR_T1	1289	0.55	0.40	0.30	0.25	0.06	510.07	4.15	0.0032
2021	SPR_T1	1289	0.62	0.42	0.30	0.32	0.06	541.69	4.57	0.0035
2022	SPR_T1	1289	0.73	0.58	0.41	0.32	0.05	749.02	3.33	0.0026

REFERENCES for fields where irrigation was reduced for the entire season

2005	GPR_R1	527	0.54	0.45	0.23	0.32	0.04	236.81	0.80	0.0015
2006	GPR_R1	527	0.53	0.44	0.21	0.32	0.04	231.01	0.89	0.0017
2007	GPR_R1	527	0.62	0.48	0.19	0.43	0.06	253.02	2.07	0.0039
2008	GPR_R1	527	0.46	0.38	0.21	0.25	0.03	202.63	0.60	0.0011
2009	GPR_R1	527	0.44	0.38	0.20	0.24	0.03	198.37	0.47	0.0009
2010	GPR_R1	527	0.47	0.39	0.23	0.24	0.03	206.90	0.54	0.0010
2011	GPR_R1	527	0.56	0.46	0.27	0.30	0.04	243.92	0.79	0.0015
2012	GPR_R1	527	0.49	0.41	0.24	0.25	0.03	216.85	0.43	0.0008
2013	GPR_R1	527	0.60	0.45	0.29	0.31	0.05	239.35	1.36	0.0026
2014	GPR_R1	527	0.61	0.50	0.28	0.33	0.04	264.88	0.69	0.0013

2015	GPR_R1	527	0.57	0.50	0.30	0.27	0.03	263.71	0.49	0.0009
2016	GPR_R1	527	0.54	0.45	0.27	0.27	0.04	238.18	0.70	0.0013
2017	GPR_R1	527	0.54	0.43	0.24	0.30	0.04	229.22	0.67	0.0013
2018	GPR_R1	527	0.50	0.42	0.22	0.28	0.04	222.95	0.73	0.0014
2019	GPR_R1	527	0.53	0.46	0.27	0.26	0.03	242.66	0.64	0.0012
2020	GPR_R1	527	0.55	0.46	0.25	0.29	0.06	242.21	1.67	0.0032
2021	GPR_R1	527	0.52	0.42	0.25	0.28	0.03	223.64	0.41	0.0008
2022	GPR_R1	527	0.53	0.48	0.20	0.33	0.02	253.15	0.29	0.0006
2023	GPR_R1	527	0.56	0.51	0.28	0.28	0.02	266.43	0.22	0.0004
2005	SBR_R1	160	0.53	0.44	0.31	0.22	0.03	70.64	0.18	0.0011
2006	SBR_R1	160	0.53	0.40	0.32	0.21	0.04	64.73	0.27	0.0017
2007	SBR_R1	160	0.53	0.46	0.35	0.18	0.04	72.93	0.22	0.0014
2008	SBR_R1	160	0.49	0.41	0.33	0.16	0.03	65.21	0.16	0.0010
2009	SBR_R1	160	0.44	0.39	0.30	0.13	0.02	62.07	0.07	0.0005
2010	SBR_R1	160	0.46	0.41	0.31	0.15	0.03	66.11	0.13	0.0008
2011	SBR_R1	160	0.50	0.42	0.28	0.23	0.04	66.76	0.26	0.0016
2012	SBR_R1	160	0.44	0.39	0.31	0.13	0.03	62.87	0.10	0.0006
2013	SBR_R1	160	0.60	0.50	0.41	0.19	0.03	80.11	0.18	0.0011
2014	SBR_R1	160	0.56	0.45	0.27	0.29	0.06	71.73	0.62	0.0039
2015	SBR_R1	160	0.51	0.45	0.37	0.14	0.03	72.18	0.18	0.0011
2016	SBR_R1	160	0.50	0.43	0.36	0.14	0.03	69.02	0.10	0.0006
2017	SBR_R1	160	0.47	0.43	0.35	0.13	0.02	68.30	0.07	0.0004
2018	SBR_R1	160	0.44	0.38	0.29	0.16	0.02	61.21	0.08	0.0005
2019	SBR_R1	160	0.54	0.46	0.36	0.18	0.03	73.42	0.13	0.0008
2020	SBR_R1	160	0.56	0.49	0.37	0.19	0.03	77.84	0.14	0.0009
2021	SBR_R1	160	0.53	0.46	0.34	0.19	0.03	73.90	0.12	0.0007
2022	SBR_R1	160	0.60	0.51	0.36	0.24	0.03	81.61	0.17	0.0011
2023	SBR_R1	160	0.62	0.56	0.43	0.19	0.03	88.94	0.18	0.0011
2005	SPR_R1	168	0.53	0.44	0.35	0.19	0.03	74.15	0.17	0.0010
2006	SPR_R1	168	0.54	0.41	0.18	0.36	0.04	68.37	0.28	0.0017
2007	SPR_R1	168	0.53	0.44	0.36	0.18	0.04	74.10	0.26	0.0016
2008	SPR_R1	168	0.53	0.44	0.34	0.20	0.04	74.35	0.29	0.0017
2009	SPR_R1	168	0.47	0.42	0.35	0.12	0.03	69.88	0.15	0.0009
2010	SPR_R1	168	0.46	0.39	0.31	0.15	0.03	65.58	0.17	0.0010
2011	SPR_R1	168	0.61	0.52	0.38	0.23	0.05	88.01	0.37	0.0022
2012	SPR_R1	168	0.46	0.37	0.27	0.18	0.05	61.37	0.38	0.0023
2013	SPR_R1	168	0.55	0.47	0.35	0.20	0.04	79.01	0.24	0.0014
2014	SPR_R1	168	0.60	0.48	0.30	0.30	0.05	81.02	0.42	0.0025
2015	SPR_R1	168	0.53	0.44	0.33	0.20	0.05	73.74	0.38	0.0022
2016	SPR_R1	168	0.58	0.49	0.36	0.22	0.04	82.02	0.32	0.0019
2017	SPR_R1	168	0.53	0.45	0.37	0.16	0.04	76.00	0.23	0.0013
2018	SPR_R1	168	0.64	0.48	0.31	0.33	0.07	81.07	0.82	0.0049

2019	SPR_R1	168	0.56	0.50	0.31	0.26	0.04	83.23	0.23	0.0014
2020	SPR_R1	168	0.56	0.46	0.37	0.19	0.04	77.60	0.32	0.0019
2021	SPR_R1	168	0.50	0.42	0.32	0.19	0.04	70.45	0.20	0.0012
2022	SPR_R1	168	0.71	0.62	0.50	0.21	0.06	104.73	0.55	0.0033

Fields under partial-season reduction (water shut off July 15)

2005	RCR_T1	219	0.53	0.44	0.33	0.20	0.03	95.75	0.20	0.0009
2006	RCR_T1	219	0.49	0.45	0.31	0.18	0.02	98.99	0.13	0.0006
2007	RCR_T1	219	0.53	0.47	0.33	0.20	0.02	103.21	0.12	0.0005
2008	RCR_T1	219	0.55	0.48	0.30	0.25	0.04	104.97	0.37	0.0017
2009	RCR_T1	219	0.41	0.36	0.26	0.14	0.03	78.53	0.14	0.0006
2010	RCR_T1	219	0.43	0.40	0.27	0.16	0.02	86.98	0.08	0.0004
2011	RCR_T1	219	0.51	0.46	0.35	0.16	0.03	101.78	0.15	0.0007
2012	RCR_T1	219	0.43	0.38	0.28	0.15	0.03	82.77	0.16	0.0007
2013	RCR_T1	219	0.52	0.42	0.33	0.18	0.03	92.47	0.23	0.0010
2014	RCR_T1	219	0.57	0.50	0.38	0.19	0.03	110.00	0.19	0.0009
2015	RCR_T1	219	0.47	0.42	0.32	0.14	0.02	92.98	0.09	0.0004
2016	RCR_T1	219	0.58	0.51	0.33	0.25	0.04	112.43	0.39	0.0018
2017	RCR_T1	219	0.54	0.48	0.31	0.23	0.03	104.25	0.17	0.0008
2018	RCR_T1	219	0.58	0.50	0.26	0.32	0.05	109.50	0.55	0.0025
2019	RCR_T1	219	0.55	0.49	0.33	0.22	0.04	107.33	0.44	0.0020
2020	RCR_T1	219	0.49	0.42	0.28	0.21	0.03	92.70	0.20	0.0009
2021	RCR_T1	219	0.51	0.44	0.31	0.19	0.03	97.30	0.23	0.0010
2022	RCR_T1	219	0.64	0.53	0.36	0.29	0.05	115.96	0.56	0.0025
2023	RCR_T1	219	0.56	0.51	0.34	0.21	0.03	112.54	0.23	0.0010
2005	RSR_T1	724	0.52	0.44	0.30	0.22	0.04	315.27	1.04	0.0009
2006	RSR_T1	724	0.52	0.43	0.29	0.23	0.04	309.30	1.31	0.0011
2007	RSR_T1	724	0.53	0.44	0.30	0.23	0.04	317.64	1.07	0.0006
2008	RSR_T1	724	0.50	0.40	0.26	0.24	0.04	286.47	1.21	0.0010
2009	RSR_T1	724	0.44	0.39	0.27	0.17	0.03	281.28	0.62	0.0008
2010	RSR_T1	724	0.46	0.39	0.29	0.17	0.03	282.42	0.55	0.0008
2011	RSR_T1	724	0.55	0.42	0.27	0.28	0.05	304.48	1.76	0.0022
2012	RSR_T1	724	0.45	0.37	0.26	0.19	0.03	265.45	0.74	0.0009
2013	RSR_T1	724	0.59	0.49	0.35	0.24	0.04	354.81	1.44	0.0013
2014	RSR_T1	724	0.54	0.44	0.31	0.23	0.04	321.47	0.94	0.0007
2015	RSR_T1	724	0.50	0.42	0.30	0.20	0.03	306.81	0.74	0.0006
2016	RSR_T1	724	0.54	0.43	0.32	0.22	0.03	308.53	0.76	0.0007
2017	RSR_T1	724	0.49	0.42	0.32	0.17	0.03	305.15	0.70	0.0008
2018	RSR_T1	724	0.50	0.39	0.30	0.20	0.03	283.58	0.64	0.0006
2019	RSR_T1	724	0.54	0.42	0.29	0.25	0.04	307.50	1.45	0.0022
2020	RSR_T1	724	0.49	0.39	0.28	0.21	0.04	281.71	1.07	0.0023
2021	RSR_T1	724	0.48	0.40	0.29	0.19	0.03	291.92	0.70	0.0008
2022	RSR_T1	724	0.53	0.46	0.32	0.21	0.04	330.92	1.04	0.0011

2023	RSR_T1	724	0.55	0.49	0.31	0.24	0.03	353.95	0.78	0.0008
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REFERENCES for fields under partial-season reduction (water shut off July 15)

2005	RCR_R1	1323	0.56	0.45	0.24	0.32	0.04	600.67	2.11	0.0016
2006	RCR_R1	1323	0.62	0.45	0.23	0.39	0.04	597.65	2.51	0.0019
2007	RCR_R1	1323	0.54	0.48	0.27	0.27	0.04	631.83	1.70	0.0013
2008	RCR_R1	1323	0.58	0.48	0.25	0.34	0.05	636.94	3.36	0.0025
2009	RCR_R1	1323	0.46	0.39	0.21	0.25	0.04	510.71	1.65	0.0012
2010	RCR_R1	1323	0.49	0.38	0.22	0.27	0.04	504.22	2.03	0.0015
2011	RCR_R1	1323	0.57	0.47	0.27	0.31	0.05	616.98	2.70	0.0020
2012	RCR_R1	1323	0.47	0.39	0.23	0.25	0.04	514.93	1.95	0.0015
2013	RCR_R1	1323	0.55	0.45	0.28	0.27	0.04	600.82	2.13	0.0016
2014	RCR_R1	1323	0.59	0.51	0.30	0.29	0.04	672.57	2.38	0.0018
2015	RCR_R1	1323	0.58	0.44	0.26	0.32	0.04	583.55	1.91	0.0014
2016	RCR_R1	1323	0.62	0.50	0.23	0.39	0.05	655.83	3.61	0.0027
2017	RCR_R1	1323	0.63	0.48	0.26	0.36	0.05	640.52	3.14	0.0024
2018	RCR_R1	1323	0.61	0.51	0.23	0.38	0.05	673.49	3.47	0.0026
2019	RCR_R1	1323	0.61	0.50	0.28	0.33	0.05	657.78	2.84	0.0021
2020	RCR_R1	1323	0.56	0.47	0.22	0.34	0.05	616.15	3.63	0.0027
2021	RCR_R1	1323	0.56	0.48	0.23	0.33	0.05	629.57	2.71	0.0021
2022	RCR_R1	1323	0.64	0.55	0.24	0.40	0.05	727.24	3.53	0.0027
2023	RCR_R1	1323	0.60	0.52	0.26	0.34	0.04	690.12	2.46	0.0019
2005	RSR_R1	122	0.54	0.46	0.38	0.16	0.03	56.14	0.10	0.0009
2006	RSR_R1	122	0.52	0.43	0.33	0.19	0.03	53.06	0.13	0.0011
2007	RSR_R1	122	0.49	0.43	0.35	0.13	0.02	53.01	0.08	0.0006
2008	RSR_R1	122	0.42	0.37	0.28	0.14	0.03	44.57	0.12	0.0010
2009	RSR_R1	122	0.45	0.39	0.32	0.14	0.03	47.29	0.09	0.0008
2010	RSR_R1	122	0.45	0.39	0.32	0.13	0.03	47.20	0.10	0.0008
2011	RSR_R1	122	0.49	0.42	0.32	0.17	0.05	51.81	0.26	0.0022
2012	RSR_R1	122	0.44	0.39	0.29	0.15	0.03	47.28	0.10	0.0009
2013	RSR_R1	122	0.59	0.53	0.43	0.15	0.04	64.48	0.15	0.0013
2014	RSR_R1	122	0.54	0.46	0.39	0.15	0.03	55.81	0.08	0.0007
2015	RSR_R1	122	0.49	0.42	0.36	0.13	0.03	51.40	0.08	0.0006
2016	RSR_R1	122	0.49	0.43	0.36	0.13	0.03	52.34	0.08	0.0007
2017	RSR_R1	122	0.49	0.44	0.35	0.14	0.03	53.09	0.10	0.0008
2018	RSR_R1	122	0.46	0.40	0.33	0.12	0.02	48.98	0.07	0.0006
2019	RSR_R1	122	0.55	0.43	0.33	0.22	0.05	52.87	0.26	0.0022
2020	RSR_R1	122	0.56	0.47	0.31	0.25	0.05	57.52	0.28	0.0023
2021	RSR_R1	122	0.49	0.43	0.34	0.14	0.03	52.75	0.10	0.0008
2022	RSR_R1	122	0.54	0.47	0.38	0.16	0.03	57.27	0.13	0.0011
2023	RSR_R1	122	0.57	0.51	0.43	0.14	0.03	61.66	0.09	0.0008

Site-Based Yield Analysis: Low and High Production Areas

Site	Month	Low Production Location Yields (T/ac)					High Production Location Yields (T/ac)				
		2020	2021	2022	2023	2024	2020	2021	2022	2023	2024
GPRR1	June	0.45	0.70	1.38	1.80	---	0.41	1.22	1.60	2.96	---
GPRR1	July	2.51	2.04	3.39	3.28	3.00	3.28	2.22	3.66	5.21	3.96
GPRT1	June	0.08	0.37	0.65	1.32	---	0.12	0.62	0.63	1.80	---
GPRT1	July	0.15	1.35	3.16	1.91	3.88	0.23	2.14	3.40	5.26	2.08
GPRT2	June	0.10	0.09	0.86	0.81	---	0.16	0.33	0.92	1.17	---
GPRT2	July	0.19	0.81	2.43	2.68	2.01	0.27	2.21	2.49	3.75	2.55
RCRR1	June	---	---	---	---	---	1.47	0.11	0.59	0.47	---
RCRR1	July	---	---	---	---	---	1.84	---	1.16	1.13	---
RCRR2	June	---	---	---	---	---	---	---	---	---	---
RCRR2	July	---	---	---	---	---	3.43	1.93	2.98	1.67	1.66
RCRT1	June	---	---	---	---	---	1.62	0.09	0.79	0.39	---
RCRT1	July	---	---	---	---	---	2.09	0.37	1.47	1.09	---
RCRR2	June	---	---	---	---	---	---	---	---	---	---
RCRT2	July	---	---	---	---	---	1.90	2.42	2.90	1.47	0.98
RSRR1	June	0.44	0.37	0.44	0.15	---	0.73	0.50	0.63	0.27	---
RSRR1	July	1.20	2.24	2.84	0.67	1.89	2.29	2.74	2.20	1.14	1.69
RSRT1	June	0.41	0.37	0.50	0.28	---	0.94	0.42	0.46	0.17	---
RSRT1	July	1.22	1.92	2.64	0.85	0.68	2.10	2.90	2.67	1.02	1.99
SBRR1	June	1.24	0.71	1.33	1.56	---	1.36	1.37	2.47	1.02	---
SBRR1	July	2.44	1.60	1.89	4.95	1.87	2.85	1.93	3.32	2.09	1.55
SBRT1	June	0.22	0.71	0.84	0.53	---	0.13	1.26	0.37	0.31	---
SBRT1	July	0.38	1.62	1.44	1.62	1.17	0.27	2.66	1.25	1.29	0.99
SPRR1	June	0.62	0.30	0.30	0.00	---	1.71	0.84	0.52	0.00	---
SPRR1	July	0.64	0.26	0.19	0.13	0.78	2.12	1.79	1.13	1.04	1.63
SPRT1	June	0.47	0.45	0.81	1.31	---	0.52	0.43	1.50	2.52	---
SPRT1	July	0.15	0.68	2.02	2.67	1.58	0.56	1.62	2.18	3.82	2.10

Table 3.4.1. Dry matter forage yield comparison for high-production locations after irrigation reduction in 2020 and p-value for Welch's t-test comparing reference (REF) and treatment (TRT) sites

Month	Field Pair		2020 Yield (T/ac)			2021 Yield (T/ac)			2022 Yield (T/ac)			2023 Yield (T/ac)			2024 Yield (T/ac)		
	REF	TRT	REF	TRT	p	REF	TRT	p	REF	TRT	p	REF	TRT	p	REF	TRT	p
<i>Fields where irrigation was reduced for the entire season</i>																	
June	GPRR1	GPRT1	0.41	0.12	< 0.01	1.22	0.62	< 0.05	1.60	0.63	< 0.01	2.96	1.8	0.11			
July	GPRR1	GPRT1	3.28	0.23	< 0.01	2.22	2.14	0.86	3.66	3.40	0.56	5.21	5.26	0.95	3.96	2.08	0.30
June	GPRR1	GPRT2	0.41	0.16	< 0.01	1.22	0.33	< 0.01	1.60	0.92	< 0.05	2.96	1.17	< 0.05			
July	GPRR1	GPRT2	3.28	0.27	0.07	2.22	2.21	0.98	3.66	2.49	< 0.01	5.21	3.75	0.22	3.96	2.55	0.41
June		BMR					1.99	---†		1.61	---†		2.48	---†			
July		BMR		0.12	---†		2.01	---†		2.58	---†		4.59	---†			
June		HSR					1.59	---†		3.36	---†		3.86	---†			
July		HSR		0.67	---†		2.71	---†		3.53	---†		4.38	---†			
June		JLM					1.91	---†		3.11	---†		4.25	---†			
July		JLM					1.65	---†		4.64	---†		4.19	---†			
June		SBT					2.50	---†		1.52	---†		3.40	---†			
July		SBT		0.14	---†		2.04	---†		1.73	---†		3.64	---†			
June	SBRR1	SBRT1	1.36	0.13	< 0.01	1.37	1.26	0.78	2.47	0.37	< 0.01	1.02	0.31	< 0.01			
July	SBRR1	SBRT1	2.85	0.27	< 0.01	1.93	2.66	0.16	3.32	1.25	< 0.01	2.09	1.29	< 0.05	1.55	0.99	0.28
June	SPRR1	SPRT1	1.71	0.52	< 0.01	0.84	0.43	---*	0.52	1.50	< 0.05	nan	2.52	---*			
July	SPRR1	SPRT1	2.12	0.56	< 0.01	1.79	1.62	---*	1.13	2.18	< 0.05	1.04	3.82	< 0.01	1.63	2.10	0.35
<i>Fields under partial-season reduction (water shut off July 15)</i>																	
June	RCRR1	RCRT1	1.47	1.62	0.74	0.11	0.09	0.41	0.59	0.79	0.36	0.47	0.39	0.65			
July	RCRR1	RCRT1	1.84	2.09	0.20	nan	0.37	---*	1.16	1.47	0.14	1.13	1.09	0.80			
June	RCRR2	RCRT2							2.46	1.66	< 0.05	---	---	---*			
July	RCRR2	RCRT2	3.43	1.90	< 0.01	1.93	2.42	< 0.01	2.98	2.90	0.80	1.67	1.47	0.47	1.66	0.98	0.09
June	RSRR1	RSRT1	0.73	0.94	0.09	0.5	0.42	0.56	0.63	0.46	0.37	0.27	0.17	0.26			
July	RSRR1	RSRT1	2.29	2.1	0.71	2.74	2.90	0.74	2.20	2.67	0.47	1.14	1.02	0.61	1.69	1.99	0.43

* Insufficient Replicates: If either of the sites in the pair has insufficient replicates for a valid comparison, the t-test won't be performed.

† No reference site

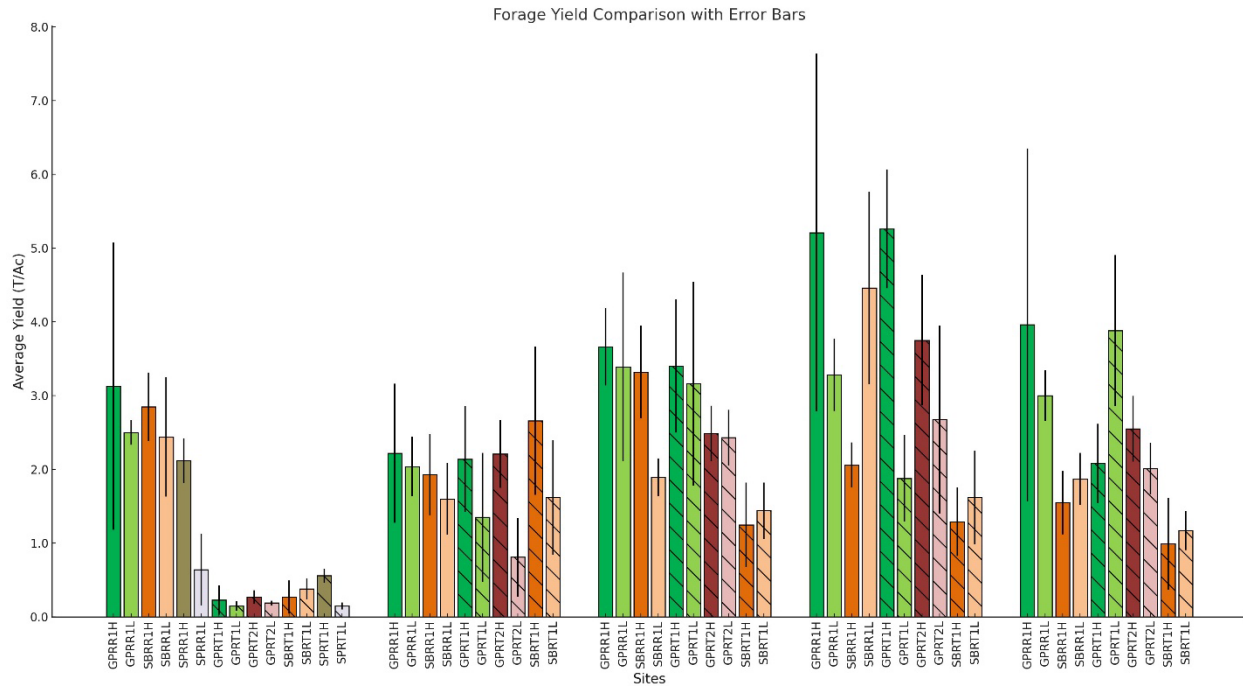


Table 3.7.1. Grass crude protein impact of full irrigation reduction in 2020 over multiple years during recovery period

Site	Prod	Month	2020			2021			2022			2023		
			Crude Protein			Crude Protein			Crude Protein			Crude Protein		
			REF	TRT	ΔCP	REF	TRT	ΔCP	REF	TRT	ΔCP	REF	TRT	ΔCP
BMR	Only‡	Jun	n/a	---	*	n/a	10.2		n/a	11.8		n/a	10.8	
BMR	Only‡	Jul	n/a	6.3		n/a	4.2		n/a	10.5		n/a	6.5	
GPR	High-1	Jun	17.3	17.7	2.0%	15.5	15.3	-1.4%	15.1	14.2	-6.0%	16.2	7.3	-54.7%
GPR	High-1	Jul	10.7	12.8	20.1%	7.5	9.3	23.7%	9.9	6.6	-33.2%	6.4	3.0	-53.9%
GPR	Low-1	Jun	23.3	14.6	-37.3%	18.6	14.4	-22.5%	20.0	14.8	-26.0%	17.2	8.6	-50.3%
GPR	Low-1	Jul	16.0	14.1	-12.0%	12.5	10.5	-15.9%	11.7	8.8	-25.2%	8.1	7.0	-14.1%
GPR	High-2†	Jun	17.3	16.3	-6.2%	15.5	16.3	5.0%	15.1	16.1	6.7%	16.2	12.0	-25.8%
GPR	High-2†	Jul	10.7	15.1	41.0%	7.5	10.7	42.9%	9.9	8.3	-16.0%	6.4	5.5	-14.9%
GPR	Low-2†	Jun	23.3	14.1	-39.6%	18.6	18.9	1.6%	20.0	---	*	17.2	12.6	-26.8%
GPR	Low-2†	Jul	16.0	13.5	-15.6%	12.5	14.0	12.4%	11.7	9.7	-16.9%	8.1	6.3	-22.1%
HSR	Only	Jun	n/a	---	*	n/a	9.4		n/a	10.2		n/a	10.0	
HSR	Only	Jul	n/a	---	*	n/a	7.6		n/a	7.7		n/a	4.9	
JLM	Only	Jun	n/a	---	*	n/a	6.6		n/a	12.2		n/a	---	*
JLM	Only	Jul	n/a	---	*	n/a	6.5		n/a	8.3		n/a	5.2	
SBR	High	Jun	14.4	21.1	46.9%	13.4	18.7	39.8%	16.8	21.0	25.4%	11.4	22.8	98.9%
SBR	High	Jul	9.3	13.5	44.2%	7.8	8.7	11.4%	9.5	13.8	45.3%	4.0	13.2	229.6%
SBR	Low	Jun	15.4	16.1	4.8%	14.6	15.7	7.3%	19.7	21.6	9.7%	13.9	18.2	31.5%
SBR	Low	Jul	10.3	14.7	43.0%	8.0	10.6	32.8%	11.3	13.3	17.7%	6.6	13.7	106.7%
SBT	Only	Jun	n/a	---	*	n/a	10.6		n/a	12.6		n/a	10.9	
SBT	Only	Jul	n/a	---	*	n/a	6.8		n/a	9.3		n/a	7.3	

SPR	High	Jun	10.1	16.1	59.5%	8.7	17.1	95.1%	11.5	11.9	3.5%	11.4	14.5	26.5%
SPR	High	Jul	9.7	13.6	39.8%	11.3	9.6	-15.0%	9.9	10.1	2.0%	7.1	8.3	16.4%
SPR	Low	Jun	14.4	18.2	26.3%	12.5	15.9	26.6%	12.3	14.5	17.9%	13.9	15.6	12.6%
SPR	Low	Jul	10.5	12.1	14.4%	11.2	10.2	-9.2%	12.0	8.9	-26.4%	10.0	8.0	-20.4%

* Sample not acquired

† Reference for GPRR1 H and L used for both GPRT1 and GPRT2 pairs

‡ Only one sample taken per field. No production gradient

Table 3.7.3. Grass fructan impact of irrigation reduction in 2020 over multiple years during recovery period.

Site	Prod	Month	2020			2021			2022			2023		
			Fructans			Fructans			Fructans			Fructans		
			REF	TRT	ΔF	REF	TRT	ΔF	REF	TRT	ΔF	REF	TRT	ΔF
BMR	Only‡	Jun	n/a	---	*	n/a	1.63		n/a	2.85		n/a	2.07	
BMR	Only‡	Jul	n/a	---	*	n/a	2.40		n/a	2.28		n/a	2.08	
GPR	High-1	Jun	1.97	1.80	-8.4%	1.78	2.20	23.8%	2.27	3.10	36.6%	1.53	2.66	74.2%
GPR	Low-1	Jun	1.98	1.61	-18.8%	2.17	2.04	-6.1%	1.44	2.96		1.17	2.71	
GPR	High-2†	Jun	n/a	1.94		n/a	1.99		n/a	2.60		n/a	2.37	
GPR	Low-2†	Jun	n/a	1.32		n/a	2.11		n/a			n/a	2.31	
GPR	High-1	Jul	1.73	1.66	-3.7%	1.91	1.63	-14.5%	2.40	2.45	2.2%	2.16	2.85	31.8%
GPR	Low-1	Jul	1.69	1.56	-7.5%	1.37	1.85	35.5%	1.43	1.94	35.4%	1.64	2.40	46.8%
GPR	High-2†	Jul	n/a	1.19		n/a	1.61		n/a	2.63		n/a	2.46	
GPR	Low-2†	Jul	n/a	1.38		n/a	1.95		n/a	2.00		n/a	2.67	
GPR	High-1	Aug	1.40	---	*	1.98	1.97	-0.5%	2.35	2.60	10.5%	1.93	2.86	48.0%
GPR	Low-1	Aug	1.59	---	*	1.83	2.04	11.9%	1.67	2.45	47.1%	1.49	2.78	86.3%
GPR	High-2†	Aug	n/a	---	*	n/a	2.00		n/a	2.48		n/a	2.96	
GPR	Low-2†	Aug	n/a	---	*	n/a	1.90		n/a	2.84		n/a	2.75	
HSR	Only	Jun	n/a	---	*	n/a	2.14		n/a	2.09		n/a	1.82	
HSR	Only	Jul	n/a	---	*	n/a	1.80		n/a	2.15		n/a	1.98	
JLM	Only	Jun	n/a	---	*	n/a	2.01		n/a	2.20		n/a	---	*
JLM	Only	Jul	n/a	---	*	n/a	1.66		n/a	1.99		n/a	1.80	
SBR	High	Jun	1.44	1.38	-4.6%	1.93	1.98	2.3%	2.38	2.49	4.8%	2.35	2.30	-2.0%
SBR	Low	Jun	1.62	1.86	14.8%	2.21	1.98	-10.4%	2.45	2.65	7.9%	1.76	2.10	19.7%
SBR	High	Jul	1.26	1.39	10.2%	1.68	1.86	10.2%	2.59	2.47	-4.8%	3.19	1.58	-50.6%
SBR	Low	Jul	1.58	1.80	14.1%	2.27	1.88	-17.2%	2.32	2.22	-4.6%	1.70	1.71	0.4%
SBR	High	Aug	1.38	---	*	1.99	2.03	2.2%	2.66	2.79	4.8%	2.67	1.99	-25.5%
SBR	Low	Aug	1.29	---	*	2.27	2.31	1.8%	2.76	2.81	1.9%	2.10	1.99	-5.4%
SBT	Only	Jun	n/a	---	*	n/a	1.59		n/a	2.35		n/a	1.99	
SBT	Only	Jul	n/a	---	*	n/a	1.83		n/a	2.24		n/a	2.24	
SPR	High	Jun	2.11	1.54	-27.1%	2.46	2.14	-13.2%	2.61	2.24	-14.3%	---	*	1.61
SPR	Low	Jun	1.54	1.57	2.1%	2.04	1.79	-12.3%	2.69	2.00	-25.9%	---	*	1.73
SPR	High	Jul	1.82	1.21	-33.2%	2.02	1.52	-24.6%	2.76	2.05	-25.5%	2.59	1.39	-46.3%
SPR	Low	Jul	1.41	1.09	-22.7%	1.70	1.62	-4.7%	2.45	1.97	-19.4%	2.39	1.50	-37.3%

SPR	High	Aug	1.23	0.99	-19.2%	1.81	1.58	-12.7%	---	3.06		---	---	
SPR	Low	Aug	1.09	1.16	6.5%	1.78	1.66	-6.8%	2.56	2.28	-11.0%	---	---	
RCR1	Only	Jul	1.71	---		1.64	1.89	15.6%	2.55	2.62	2.7%	3.00	2.77	-7.6%
RCR1	Only	Jun		1.29			1.59		2.51	2.25	-10.4%	2.16	2.05	-4.8%
RCR1	Only	Aug	2.38	1.28	-46.4%	---	---		3.10	2.80	-9.5%	---	---	
RCR2	Only	Jul	1.36	1.14	-16.1%	1.44	1.70	18.1%	2.37	2.13	-10.3%	2.82	2.04	-27.7%
RCR2	Only	Jun	---	---		1.81	1.69	-6.5%	2.00	1.97	-1.3%	3.19	2.39	-25.2%
RSR	High	Jul	1.52	1.73	13.8%	1.59	2.12	32.7%	2.78	3.14	12.7%	2.40	2.32	-3.5%
RSR	High	Jun	1.94	2.05	5.9%	1.92	2.37	23.1%	3.13	3.13	0.2%	2.40	2.53	5.4%
RSR	High	Aug	1.48	---		1.91	1.94	1.7%	2.70	2.94	9.0%	2.13	2.28	7.4%
RSR	Low	Jul	1.80	1.66	-8.0%	1.60	2.16	35.2%	2.56	2.66	3.7%	1.74	2.28	31.1%
RSR	Low	Jun	1.84	2.08	13.0%	1.99	2.30	15.7%	---	2.54		2.52	2.23	-11.2%
RSR	Low	Aug	1.23	---		1.79	2.20	23.0%	2.40	2.95	22.7%	1.95	2.08	6.2%

* Sample not acquired