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Developing a Crop Water Production Function for Alfalfa under Deficit Irrigation: A Case Study in Eastern Colorado

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Abstract: Recent Colorado, USA water law provisions allow a portion of irrigation water to be leased between agricultural and other users. Reducing consumptive use (CU) through deficit irrigation while maintaining some crop production could allow farmers to earn revenue from leasing water rights. This observational study aimed to determine if deficit irrigation of alfalfa (*Medicago sativa* L.) can be used to reduce CU, provide parameters for an alfalfa crop water production function (WPF), and evaluate the potential for improved farm income by leasing water. Soil water balance, evapotranspiration (ET), and dry matter yield from eight commercial fields (1.70 to 2.14 ha zones), growing subsurface drip-irrigated alfalfa, were monitored for five seasons (2018–2022) at Kersey, Colorado. Four irrigation treatments [Standard Irrigation (SI) = irrigate when soil water deficit (D) exceeds management allowed depletion (MAD); Moderate Deficit Irrigation (MDI) = 70% of SI; Severe Deficit Irrigation (SDI) = 50% of SI; and Over Irrigation (OI) = 120% of SI] were applied, with two zones per treatment. Reductions in CU ranged from 205 to 260 mm per season. The shape of the alfalfa WPF (dry biomass yield vs. ET) was concave, indicating that water use efficiency (WUE) could be optimized through deficit irrigation. The average WUE was 0.17 Mg ha^{-1} cm^{-1} and tended to increase with greater deficits. Deficit irrigation also increased the relative feed value. If conserved CU from deficit irrigation can be leased into a transfer water market, farmers could profit when the water lease revenue exceeds the forgone profit from alfalfa production. We found incremental profit from deficit irrigation and water leasing to be positive, assuming 2020 prices for hay (\$230 bale^{-1}) and water prices above \$0.50 m^{-3}.

Keywords: alfalfa; Colorado; subsurface drip irrigation; water management

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1. Introduction

Colorado, USA, is the sixth most irrigated state, with 994,765 hectares (2,458,120 acres) of irrigated land in 2018 [1]. A large portion of the irrigated land is used to produce alfalfa (*Medicago sativa* L.) for cattle feed. The average seasonal alfalfa water use in eastern Colorado, where our study is located, is 942 mm, higher than other forage crops, such as silage corn at 582 mm [2]. Surface waters used for irrigation in Colorado are snowmelt fed; however, due to recent droughts and a warming trend in the state climate, there is increasingly less snowpack to feed these rivers. This has consequently decreased the available water supply for irrigated crop production. Water conservation in Colorado is essential to meet demands for future population increases and irrigated crop production.

Colorado and other U.S. states are experiencing dwindling water resources for crop production, and other countries are also studying the feasibility of reducing irrigation to save water. Promising studies by the Chinese Institute of Water Resources indicate that subsurface drip irrigation can be used to increase the water use efficiency (WUE) and hay yield of alfalfa [3]. An experiment in Midwestern China observed lower evaporation deficit under moderate deficit irrigation of alfalfa at the budding stage than under full irrigation, concluding that deficit irrigation at the budding stage could be used to save water [4]. Deficit irrigation of other crops have also been studied. For example, researchers in Bangladesh have determined the economic return of using deficit irrigation on wheat [5]. Efforts to increase WUE around the world will become more prevalent as the need for crop production increases.

In Colorado, it is estimated that, over the next few decades, water demand will increase by 777,093,558 m^3 (630,000-acre feet) [6]. Guidelines suggest an upgrade to efficient subsurface drip irrigation, micro sprinkler, or upgraded sprinkler irrigation would build farm resiliency to water shortages [7,8]. Sustainability in this sense aims to supply water for a growing population in cities while maintaining agricultural production to feed the growing population and in-stream river flows to maintain sensitive habitats. With this aim, water rights transfers could supply water temporarily or intermittently from agriculture to other uses [9]. The Colorado Water Plan promotes collaborative water sharing agreements (CWSA), formerly known as alternative transfer methods (ATM's), so both agricultural and urban users can share limited water resources [10]. CWSAs provide cost savings to traditional acquisitions and can be a long-term sustainable solution by allowing the transfer of some water while still producing crops. Under Colorado water law, the only water that can be transferred from a farm is the historic consumptive use (CU) portion of irrigation water. This is the part of crop evapotranspiration (ET) supplied by irrigation water in the historic past [6]. Watson and Davies predicted future water transfers to municipalities to be largely from agriculture [11].

Unlike flood or sprinkler irrigation, subsurface drip irrigation (SSDI) is more efficient in irrigating crops by reducing soil surface evaporation and deep percolation with water application directly in the root zone. Studies have indicated a 35–55% savings of water delivered for seasonal use by using SSDI [12]. Crop water use of alfalfa under drip irrigation has been shown to decrease while yields increase [13]. Deficit irrigation is a management method that reduces water use on a field by restricting the water available for ET while potentially optimizing crop WUE. To determine if deficit irrigation supplied by SSDI is economically plausible for commercial-scale alfalfa production in Eastern Colorado, the water production function (WPF) of alfalfa for this region must be formulated. A crop WPF is a relationship between crop yield and ET. This function can be used to optimize water allocation for irrigation. Alfalfa is a drought-tolerant legume and can be managed for limited irrigation to promote higher feed quality [14]. Sammis [15] determined that the relationship between alfalfa growth and ET is independent of where the alfalfa is grown, but different for each cutting, with WUE being higher for the last two cuttings. Smeal et al. [16] looked at the alfalfa WPF and its slope (WUE) from 1981 to 1998 and determined that WPFs can be transferable from year-to-year and place to place if crop growth and maturity factors, season length, and climatic factors are considered. The crop WPF can determine if the marginal value of water for leasing can be more than the value of water for farming. Varzi et al. [17] found that a concave WPF financially benefits a farmer to implement deficit irrigation because leasing water to municipalities and industries are valued at a higher price than leasing water among farmers in this region.

This observational study aimed to determine if deficit irrigation of alfalfa can be used to reduce CU, provide parameters for an alfalfa crop WPF, and evaluate the potential for improved farm income by leasing water through CWSAs. For maximum water savings, we used a highly efficient SSDI system to understand the effects of deficit irrigation on alfalfa production. Specific objectives were to: (1) understand how different irrigation levels affect alfalfa ET, yield, and forage quality; (2) determine if the WPF of alfalfa exhibits diminishing marginal returns conducive to water leasing; and (3) estimate the potential water savings from deficit irrigation and the breakeven market value for lease water compared to the price of alfalfa hay that is required for this practice to become profitable. Alfalfa recovery after several years of continuous deficit irrigation was also investigated.

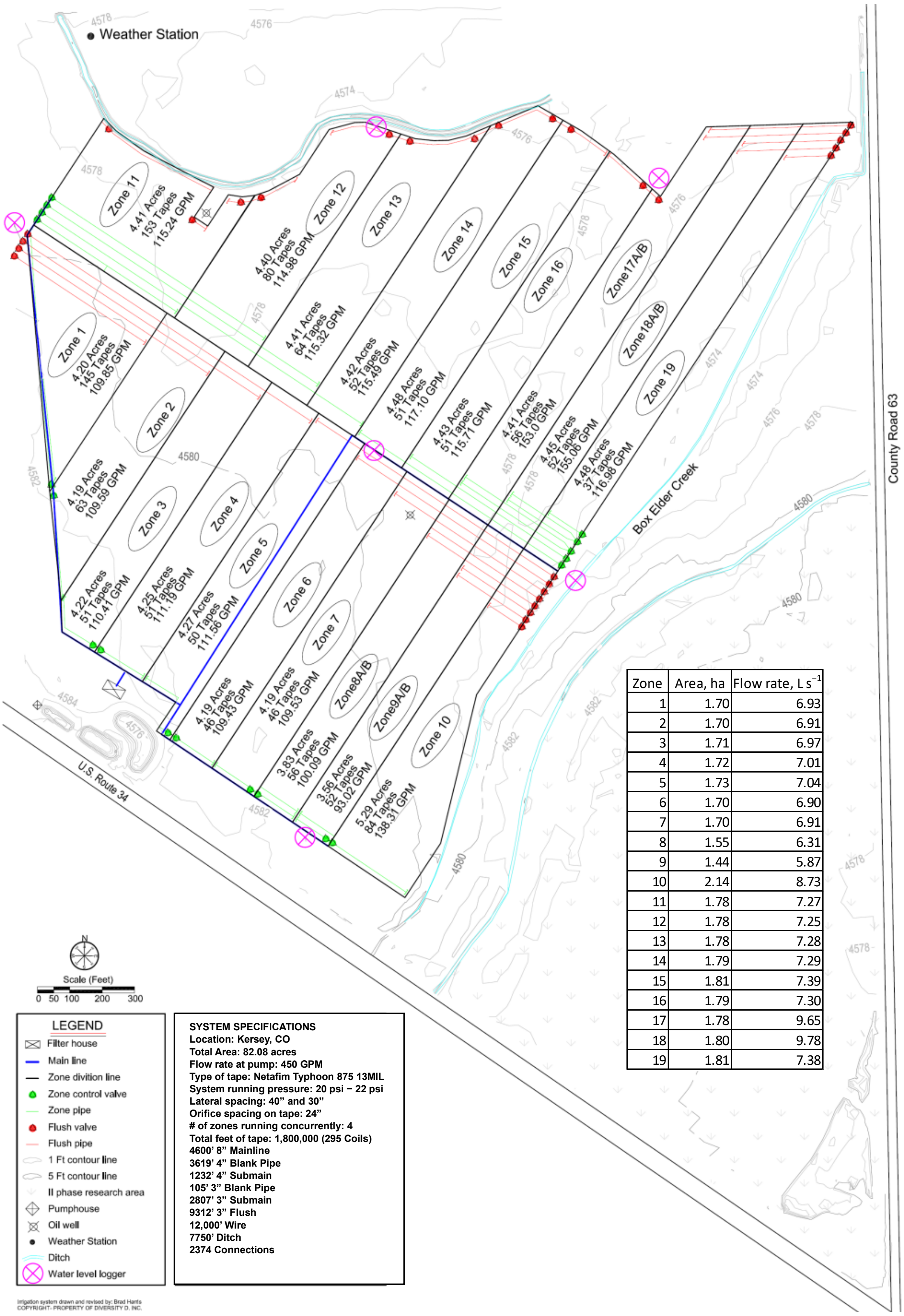
2. Materials and Methods

2.1. Observational Study Site

The Subsurface Irrigation Efficiency Project (SIEP) farm is 11.2 km (7 miles) east of Kersey, Colorado in central Weld County. It was established by the Platte River Water Development Authority, a water utility, as a demonstration site for production-scale SSDI of crops. The western section of the farm was equipped with a SSDI system on 33 ha (82 ac) in 2015 (Figure 1). Driplines are buried at a depth of 25.4 cm (10 in) in each zone. The emitters on the driplines are 61 cm (24 in) apart. The type of irrigation tape is Netafim Typhoon 875, 13 mil., 0.68 lph (0.18 gph) with a tape spacing of 76.2 or 101.6 cm (30 or 40 in). Irrigation infrastructure components for this system included a well, two ponds, a pump house, and a filtration house. The 33 ha field was divided into 19 zones, with an average area of 1.74 ha (4.3 ac) per zone, to replicate commercial-sized fields. Each zone can be irrigated individually, since each zone was equipped with a water control valve. Applied water at each valve was measured with a flow meter at the head of each zone. Water used for irrigation was pumped from groundwater and filtered. Alfalfa was planted in six zones in 2017, and two additional zones were added the following year. These zones were maintained in alfalfa with deficit irrigation scheduling in consecutive years through 2022.

This study focused on the eight zones where alfalfa was grown from 2018 to 2022. The study was observational, such that the same measurement methods were followed for each zone, but the irrigation treatments were not fully randomized and replicated because of infrastructure, equipment, and management constraints on the SIEP farm. In contrast to randomized experimental studies, observational studies have been used in hydrology when physical or location constraints limit the ability to randomize experimental units [18]. At the SIEP farm, commercial alfalfa cutting, windrowing, and baling equipment were around 4.5 m wide. Thus, measurement locations were limited to one sampling point in each zone to minimize obstructions to field operations. The maximum flow rate of the SSDI pump was 0.0284 $m^3 s^{-1}$ (450 gal min^{-1}) and could only irrigate two zones at a time. Therefore, each irrigation treatment could only be replicated twice (i.e., two zones per treatment). Four (4) irrigation treatments, with two zones per treatment, were available for observations and are described in Section 2.2. Despite the lack of a fully randomized experimental design, the data collected from the eight alfalfa zones across five growing seasons and four cuttings per season provided a broad range of alfalfa ET and yield data that made it possible to develop a WPF for this observational study. The advantage of this commercial-scale observational study is that it better represents the production conditions faced by actual farmers in the region than small-plot experimental studies.

A weather station operated by the Colorado State University Agricultural Meteorological Network (CoAgMet) [19] is located in the adjacent northern section of the SIEP farm (40.38 °N, −104.53 °W). The station began recording data on 1 January 2015. It is named Kersey 2 (ID name: KSY02) and located 15 m from the irrigated fields and surrounded by natural vegetation (Figure 1). Table 1 summarizes the three-year average weather station data. The topsoil at SIEP has a clay loam texture. Deeper layers are sandy clay loam in texture. Two major soil types, Colombo clay loam and Nunn clay loam, are described below in Table 2. Soil types in zones 9, 10, 18, and 19 are mostly Colombo, and zones 7, 8, 16, and 17 are mostly Nunn. Composite soil analyses of the topsoil (0–15 cm) in 2021 gave average macronutrient concentrations of 99.7 kg ha^{-1} NO_3-N, 55.9 ppm P, and 582 ppm K. Composite pH was 7.9, and organic matter was 2.8%.



Zone	Area, ha	Flow rate, L s^{-1}
1	1.70	6.93
2	1.70	6.91
3	1.71	6.97
4	1.72	7.01
5	1.73	7.04
6	1.70	6.90
7	1.70	6.91
8	1.55	6.31
9	1.44	5.87
10	2.14	8.73
11	1.78	7.27
12	1.78	7.25
13	1.78	7.28
14	1.79	7.29
15	1.81	7.39
16	1.79	7.30
17	1.78	9.65
18	1.80	9.78
19	1.81	7.38

Figure 1. SIEP site map of the observational field zones and irrigation system specifications. Zone specifications were provided by the SSDI designer in USA customary units (acres and GPM), and equivalent metric units for area and flow rate are given in the table at the right of the zone map.

Table 1. Average (2020–2022) monthly weather data from the Kersey 2 CoAgMet station.

Month	Average Temperature (°C)	Average Precipitation (mm)	Average Solar Radiation (W m^{-2})	Average Wind Speed (m s^{-1})	Average Relative Humidity (%)	Average ET_r * (mm)
January	−3.45	3.07	86.78	7.76	65.26	53.80
February	−4.21	2.30	119.87	8.06	63.60	59.63
March	3.52	24.67	151.57	8.91	61.67	108.90
April	7.82	11.67	200.64	11.18	50.48	171.77
May	13.95	43.30	214.29	10.48	60.09	197.77
June	21.39	18.46	257.03	9.75	53.28	249.96
July	23.77	26.00	250.61	9.24	56.26	248.13
August	22.46	12.40	229.86	7.61	55.25	215.85
September	17.03	7.10	192.20	7.57	53.75	166.45
October	8.38	4.00	141.13	7.82	53.97	129.95
November	3.63	2.40	101.31	7.06	55.14	83.00
December	−2.15	2.15	83.89	8.12	55.66	70.40

* Reference ET for alfalfa is based on weather station parameters and the ASCE Penman Monteith standard equation [19].

Table 2. Physical properties of the two major soil types at the experimental field.

Soil Type	Field Capacity of 150 cm Rooting Zone (cm of Water)	Soil Layer Depth (cm)	Bulk Density (g cm^{-3})
Nunn clay loam	48.42	0–30	1.08
		30–60	1.46
		60–90	1.39
		90–120	1.46
		120–150	1.75
Colombo clay loam	40.37	0–30	1.06
		30–60	1.50
		60–90	1.39
		90–120	1.53
		120–150	1.46

2.2. Measurements and Water Deficit Treatments

Soil water content measurements in 2018 to 2022 were taken weekly with a neutron moisture meter, NMM (CPN 503, Instro Tek Inc., Denver, CO, USA). Aluminum access tubes were installed at one location in each of the zones. Each access tube was measured at five different depth increments: 0–30 cm, 30–60 cm, 60–90 cm, 90–120 cm, and 120–150 cm. Soil volumetric water content was calculated from NMM count ratios using a linear calibration equation [20]. Calibration equations were derived from simultaneous measurements of volumetric water content (from gravimetric soil samples) and neutron probe count ratios from dry and wet profiles in two zones (Zone 10 and 16) with different soil types, Colombo, and Nunn, respectively. Dry readings for NMM calibration were taken after the last alfalfa cutting (October), after which the soil profile was saturated, and wet readings were taken three days later. Additional wet NMM and gravimetric readings were taken the following spring (April) to increase the number of calibration points at the higher moisture contents. Tracking soil moisture at different depths helped estimate soil water deficits, indicated regions of rootzone water uptake, and aided in irrigation scheduling.

Irrigation amounts were recorded by the irrigation controller in the filter house and verified by taking weekly recordings from each zones' flow meter. Irrigations were started after the last frost of the year to prevent freeze damage to the SSDI system. During the five growing seasons, the first irrigations occurred on the following dates: 16 June 2018; 22 June 2019; 1 May 2020; 14 June 2021; and 6 May 2022. Four water deficit treatments were implemented to compare the effects of deficit irrigation on alfalfa yield and quality, as well as potential water savings. Target irrigation levels were based on soil water deficit (D) replacement, where the standard irrigation level (SI) triggers irrigation when D equals or exceeds the management allowed depletion (MAD), which was set at 50% of soil available water capacity. The additional irrigation treatments included moderate deficit irrigation (MDI) = 70% of SI, severe deficit irrigation (SDI) = 50% of SI, and over irrigation (OI) = 120% of SI. Each irrigation treatment was implemented in two zones assigned at random (Table 3).

Table 3. Levels of irrigation and corresponding zones.

Levels of Irrigation [a]	Zones
Over Irrigation (OI)	7 and 16
Standard Irrigation (SI)	9 and 10
Moderate Deficit Irrigation (MDI)	8 and 19
Severe Deficit Irrigation (SDI)	17 and 18

[a] OI = apply 120% of SI; SI = irrigate when D $\geq$ MAD; MDI = apply 70% of SI; SDI = apply 50% of SI.

In 2022, water deficit levels were swapped among zones to determine if alfalfa that experienced continuous deficit irrigation for four years could yield significantly higher when irrigations were increased in the fifth year. The standard and over-irrigation treatments were switched to severe and moderate deficits and vice versa.

Alfalfa biomass samples were hand cut from a 1 m^2 plot using a hedge trimmer to a height of 5 cm (2 in) before each field was mechanically harvested. The cut sample was bagged, weighed, and then oven-dried for seven days at 55 °C. After drying, samples were weighed for dry matter yield, and a sub-sample was ground with a Wiley Mill (Thomas Scientific, Swedesboro, NJ, USA) forage grinder equipped with a 2 mm screen and then ground to a powder with a cyclone mill with a 1 mm screen. A forage near-infrared (NIR) analyzer (Unity Scientific, Westborough, MA, USA) was used under lab conditions to obtain the neutral and acid detergent fiber (ANDF, ADF), and calculations were made to determine the relative feed value (RFV) [21]. The forage analyzer uses NIR spectroscopy to provide fast, accurate, and reliable results for the livestock industry without damaging the sample [22].

2.3. Alfalfa ET, Water Use Efficiency (WUE), and Market Value of Reduced CU

Actual alfalfa crop ET (ET_c) was estimated from a simplification of the soil water balance equation [23]:

$$ETc = Irr + P + \Delta SWC \quad (1)$$

where ΔSWC is change in soil water content from the start of the period to the end, *Irr* is the net irrigation water amount added during the period, and *P* is effective precipitation during the period. The ΔSWC values were calculated from NMM measurements. Most periods were one week, but some periods were longer if a weekly SWC reading was missed. *Irr* was calculated as gross irrigation (mm) multiplied by 0.95 application efficiency for SSDI systems. The *P* was calculated by subtracting estimated surface runoff (curve number (CN) approach with CN = 85) [24] from rainfall measured by the CoAgMet rain gauge.

Alfalfa WUE was computed for each cutting as the ratio of dry biomass (kg ha^{-1}) to ET_c (mm). Irrigation management affects the yield and quality of the alfalfa harvest [25].

The RFVs were plotted against dry biomass (kg ha^{-1}) to deduce relationships between forage quality, yield, irrigation levels, and ET_c. The past five years' average historical market values of alfalfa hay were used to assess the comparative profitability of deficit irrigation. According to the USDA-Hay Market News Service, higher prices per ton are given to hay that is reported as "Supreme". Average historical prices for water in the area were obtained from Northern Water's Pool Bids database [26].

2.4. Statistical Analyses

Pair-wise differences between treatment means were tested using t-tests at 0.05 level of significance. Mean comparisons were made for WUE and RFV. The t-tests were performed using Python 3.1 using the function scipy.stats.ttest in the SciPy package [27]. Alfalfa dry matter yields (kg ha^{-1}) for all cuttings and zones were regressed against corresponding alfalfa ET_c (mm) to derive an alfalfa WPF. The simple linear regression specification for the yield equation included level and squared terms of the ET variable. Curvilinear regression lines were fitted for the alfalfa WPF and WUE versus ET relationship using the Polynomial Trendline function in Microsoft Excel®.

3. Results

3.1. Deficit Irrigation

The length of growing season averaged 154 days from March to October, with three or four harvests each season. Irrigation amounts applied each year varied based on the amount of precipitation and proportioned based on the irrigation schedule and water availability constrained by requirements of other crops on the SIEP farm (Table 4). All 19 zones were farmed in 2021, and water supply issues left little extra water for the alfalfa to be fully irrigated, thus 2021 was the least irrigated year and had the smallest ETc per harvest. ETc was affected by the amount of water the plant received, both irrigation and precipitation water. Reference (non-stressed) alfalfa stands require an average of 940 mm of water for ET depending on location [2]. Irrigation water available to the SIEP farm was regulated by a water district, which determined water allocations based on water levels in their reservoirs and adjoining aquifers. The water district experienced prolonged drought during this study. For example, the irrigation amounts in 2022 were significantly less than in 2020 (Table 4) because of a severe water shortage in 2022 that reduced allowable pumping from the SIEP well by 25 to 50%. Since target irrigation levels (Table 3) were not achieved because of water shortages, deficit irrigation levels were categorized according to the average seasonal ETc into four categories, shown in Figure 2 with the same nomenclature. The more irrigation supplied to the plant, the more it could transpire. However, the OI treatment exhibited lower ETc than the standard treatment because the alfalfa plants were smaller and appeared to be affected by other stresses besides water deficits. The cause of the smaller plants in the OI treatment could not be identified during the study. Data on the impact of irrigation on ETc were excluded from the analysis when the first alfalfa harvest was fully rainfed. Growth from the first harvest occurred from March to May, when the SSDI system was not operational because of freezing conditions.

Table 4. Seasonal precipitation, irrigation, and alfalfa crop ET (ETc).

Year	Precipitation (mm)	Treatment [a]	Irrigation (mm)	ETc (mm)
2022	117	OI	359	559
		SI	354	638
		MDI	265	495
		SDI	232	391
2021	138	OI	300	374
		SI	269	345
		MDI	146	240
		SDI	112	298

Table 4. *Cont.*

Year	Precipitation (mm)	Treatment [a]	Irrigation (mm)	ETc (mm)
2020	106	OI	617	502
		SI	520	558
		MDI	340	412
		SDI	240	279
2019	223	OI	545	826
		SI	470	826
		MDI	329	873
		SDI	216	700
2018	165	SI	516	743
		MDI	406	668
		SDI	335	562

[a] OI = Over Irrigation, SI = Standard Irrigation, MDI = Moderate Deficit Irrigation, SDI = Severe Deficit Irrigation.

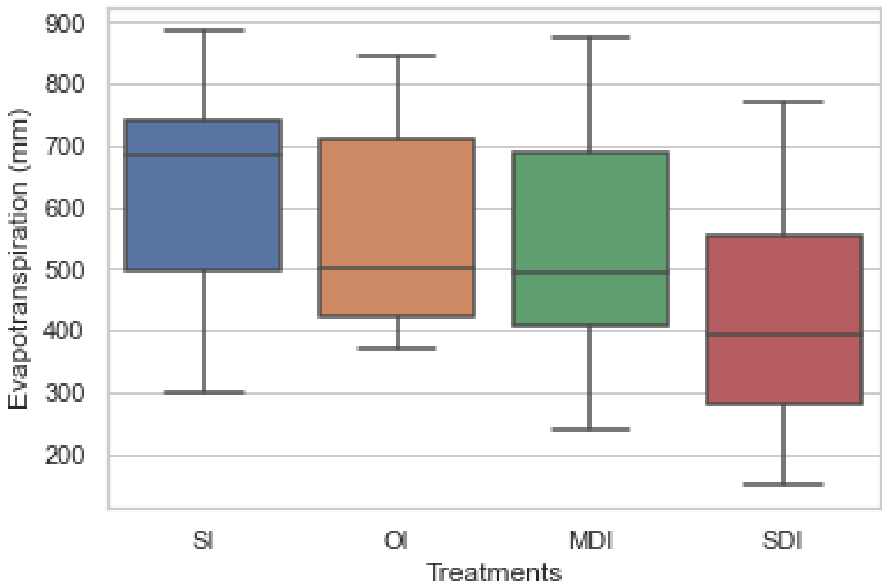


Figure 2. Ranges of seasonal alfalfa ET_c for each treatment over five years (2018–2022).

3.2. Alfalfa ET and Biomass

Alfalfa biomass responds positively to increasing ET_c and water applied. The most ET_c per harvest occurred in 2019. The data presented in Figure 3 shows a separation in biomass between zones 7, 8, 9, and 10 and 16, 17, 18, and 19, starting in 2020. Zones 7, 8, 9, and 10 are located on the south side of the field where three unlined water retention ponds are located. The alfalfa crop in those zones may have accessed some groundwater seeping from the ponds that was not detected by the 1.5-m NMM measurements. Alfalfa roots commonly grow 2 to 4 m deep or even deeper [28].

Water deficit treatments were switched at the beginning of 2022, resulting in increased biomass from the previously severe deficit treatment that was switched to standard irrigation. This indicated that alfalfa could recover in terms of increased biomass production when irrigations are increased after being deficit irrigated for several seasons. Alfalfa that was deficit irrigated at the severe and moderate deficit levels in the early growing years can produce more biomass when standard irrigation is applied, as zone 19 did with an increase of 53% from its highest biomass year (2019) with moderate deficit irrigation to 2022 when over irrigation was applied (Table 5).

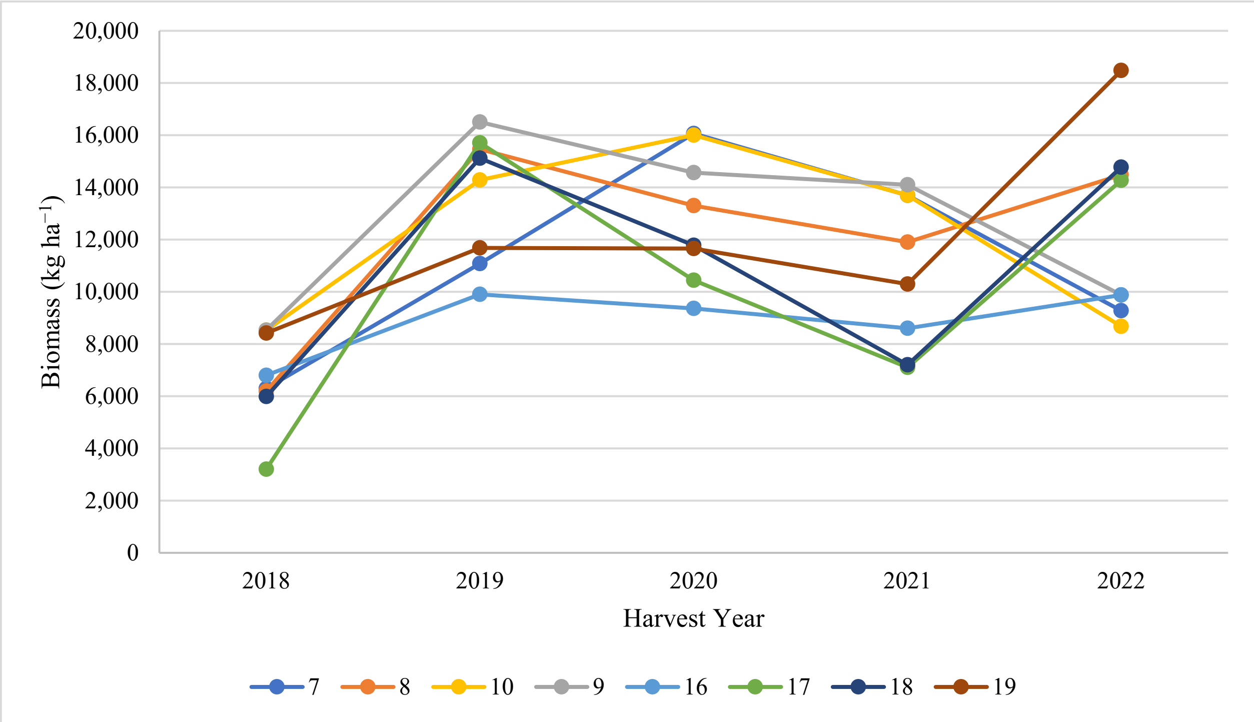


Figure 3. Yearly trends in total biomass yield (kg ha^{-1}) for the eight alfalfa zones from 2018 to 2022, with 2022 having different treatment levels.

Table 5. Percent difference in biomass between years. Positive values indicate an increase in biomass from the previous year.

Zone	2018–2019	2019–2020	2020–2021	2021–2022
7	14.74%	8.00%	−17.26%	−10.78%
8	19.87%	−16.28%	−11.76%	38.34%
9	31.06%	−13.28%	−3.33%	−7.09%
10	20.44%	10.75%	−16.82%	−18.44%
16	−37.36%	−5.74%	−8.90%	34.68%
17	59.25%	−50.48%	−47.04%	62.70%
18	47.23%	−28.41%	−63.54%	63.45%
19	3.89%	−0.17%	−13.20%	58.19%

A WPF can be used for economic analysis by predicting the yield as a function of ET_c. The resulting WPF from this study was concave (Figure 4), agreeing with the hypothesis of a diminishing marginal product per unit of ET [17]. A zero intercept was applied to this function to represent zero yield with zero ET [29,30]. The estimated parameters predict an ET_c of 346 mm at a yield of 4000 kg ha^{-1}. The concave WPF implies that WUE will increase with a decrease in ET, which is important for evaluating the economic feasibility of water transfers because it suggests that the revenue earned from CU savings can potentially offset forgone revenue from lower yields.

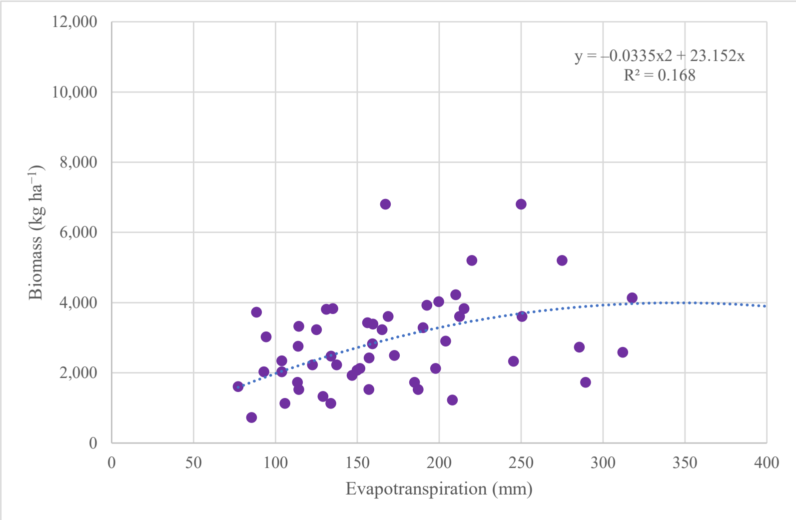


Figure 4. WPF of alfalfa relating ET_c and biomass produced under deficit irrigation treatments.

3.3. WUE

Average WUE across all zones was 0.17 Mg ha^{-1} cm^{-1}. There was a decreasing trend between WUE and ET_c up to 524 mm (Figure 5). Zone 8 in severe deficit had the highest WUE of all the zones, but overall, the standard irrigation treatment had the highest average WUE (Table 6). Pairwise t-tests showed no significant differences in WUE between treatments ($p > 0.05$), primarily because of the large variances in alfalfa biomass and ET within treatments. The first harvest had the highest WUE, which is explained by high yields, resulting from carbohydrate reserves in the plant following winter dormancy and less heat stress and lower ET rates in cooler weather.

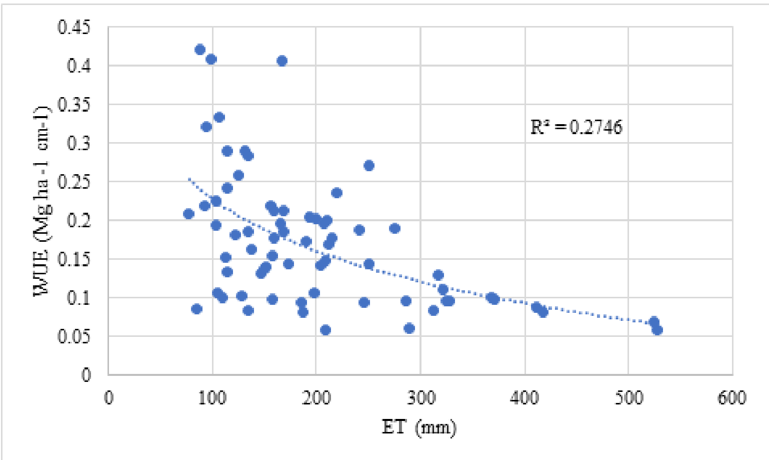


Figure 5. The WUE of alfalfa under deficit irrigation using subsurface drip irrigation. The blue dots show individual WUE per alfalfa harvest.

Table 6. Water use efficiency (WUE) of alfalfa from 2018–2022.

Irrigation Level	WUE(Mg ha^{-1} cm^{-1})
Over Irrigation (OI)	0.162
Standard Irrigation (SI)	0.183
Moderate Deficit Irrigation (MDI)	0.165
Severe Deficit Irrigation (SDI)	0.171

3.4. Effects of Deficit Irrigation on Alfalfa Biomass and RFV

Zones that produced larger amounts of biomass tended to have lower feed quality (Figure 6). Of the yields reported, 75% of the samples were in the supreme quality category with 24% at premium quality (Figure 7). The most irrigation water per harvest occurred in 2020, resulting in the lowest quality feed. Harvest year 2022 resulted in an increased feed quality with all treatments producing supreme quality hay. Lower RFV values result in lower quality grades, which are priced less than high quality feed. Pairwise t-tests showed no significant differences in RFV ($p > 0.05$) between treatments, primarily because of the large variances in RFV within treatments.

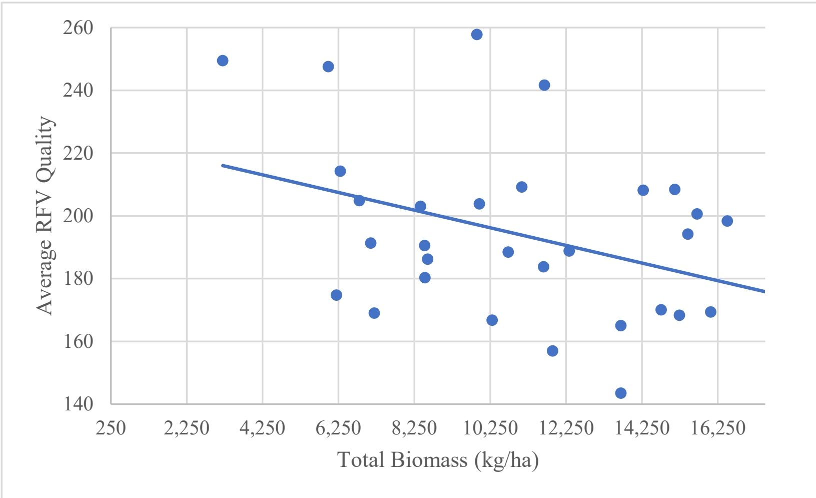


Figure 6. Inverse relationship between alfalfa dry biomass and relative feed value (RFV). Blue dots indicate RFVs for each alfalfa harvest.

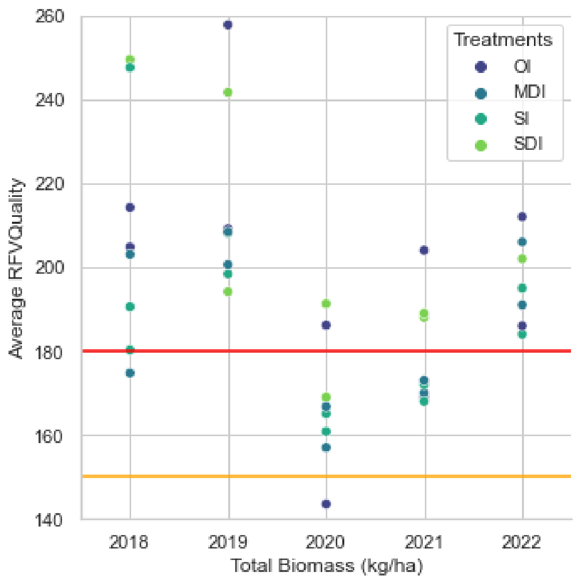


Figure 7. Forage quality, RFV, averaged over seasonal harvests for each treatment and year. The lines show the cutoffs between supreme and premium (red line) and premium and good (orange line) feed qualities.

3.5. Estimated CU Savings and Profits

To estimate how much CU savings are possible with deficit irrigation using SSDI, the Water Irrigation Scheduler for Efficient Application (WISE) [31,32] was used to simulate daily alfalfa ET_c under over irrigation by keeping the soil water deficit significantly less than management allowed depletion (MAD) of 50%. This model was then compared to deficit simulations of WISE from 2020, which resulted in CU savings of 30% from the standard irrigation level, 39% from the moderate deficit irrigation, and 50% from the severe deficit irrigation level (Figure 8). The cost to secure water for irrigation purposes was used as a lower bound in the analysis due to wide variability in costs associated with specific farm practices in the region. The Colorado Enterprise Budget for Northeastern Colorado (https://abm.extension.colostate.edu/enterprise-budgets-crop/; accessed on 17 January 2023) details the variable costs associated with alfalfa farming. The cost of energy needed to pump the water from the source to the irrigated land can be negated in the cost analysis since every owner of a water right will have this associated cost. The cost of water was pulled from the Northern Water Regional Pool program, but they did not allocate water in 2021 or 2022 [26]. A three-year average historical price was used in the analysis for those two years. Price for alfalfa fluctuates throughout the year, and timing of harvests can impact the price hay is sold at. The yearly mean price for a large square bale of alfalfa hay was used in the economic analysis, and an average large square bale weighs 839 kg. The biomass samples gathered were scaled to the zone area (average 1.7 hectares), and the expected number of bales was calculated per hectare. Alfalfa ET from the over irrigation (OI) WISE simulation was assumed to yield the maximum biomass observed at SIEP under SSDI with over irrigation. An economic analysis was done to see if additional biomass made up for the lower quality feed price received. The results showed that the additional biomass created more profit than the higher quality feed with lower biomass for deficit irrigated treatments, so the increase in quality alone was not sufficient to justify deficit irrigation from an economic perspective. In addition, the potential profitability of deficit irrigation was evaluated with respect to water leasing potential using a partial budgeting analysis. The additional revenue gained from temporarily leasing CU savings on an annual basis was compared to the forgone annual revenues from decreased alfalfa yields under deficit irrigation. Figure 9 shows recent historical prices for alfalfa ($ bale^{-1}) and agricultural water leasing ($ m^{-3}) in the study area. As a baseline value, we used a price ratio of 5.2 ($ bale^{-1} to cost m^{-3} ha^{-1}). Deficit irrigation with water leasing was not more profitable than over irrigation without water leasing at these baseline values, resulting in incremental profit losses of over $1,000 ha^{-1} for all treatments. However, because recent agricultural water leasing prices provide a lower bound estimate on the water lease prices that are likely to emerge from CWSAs that allow for temporary leasing outside of agriculture, we determined the breakeven water leasing price at which deficit irrigation would become profitable. We conducted this sensitivity analysis by holding the alfalfa price fixed and varying the water lease price. At $0.50 m^{-3}, deficit irrigation with water leasing becomes more profitable than over irrigation without water leasing for all deficit treatments. The sensitivity of deficit irrigation profitability to changes in water leasing prices is shown in Table 7.

Table 7. Net profit ($ ha^{-1}) from leasing saved CU at different water prices.

Irrigation Level	Yield Bales ha^{-1}	CU Saved m^3 ha^{-1}	Water Price, $ m^{-3}				
			0.12	0.24	0.36	0.48	0.60
OI	22.10	-	-	-	-	-	-
SI	15.83	3133.6	−$1066	−$690	−$314	$62	$438
MDI	13.25	4097.4	−$1544	−$1052	−$560	−$69	$423
SDI	11.41	5310.1	−$1821	−$1184	−$547	$90	$727

Note: Net profit is the difference between water revenue and lost revenue from forgone yields. Yield revenue was based on a fixed price of $230 for a large square bale of supreme quality alfalfa hay in 2020. The baseline water price of $ 0.12 m^{-3} ($152.40 AF^{-1}) was from Northern Water Pool Bids for 2020.

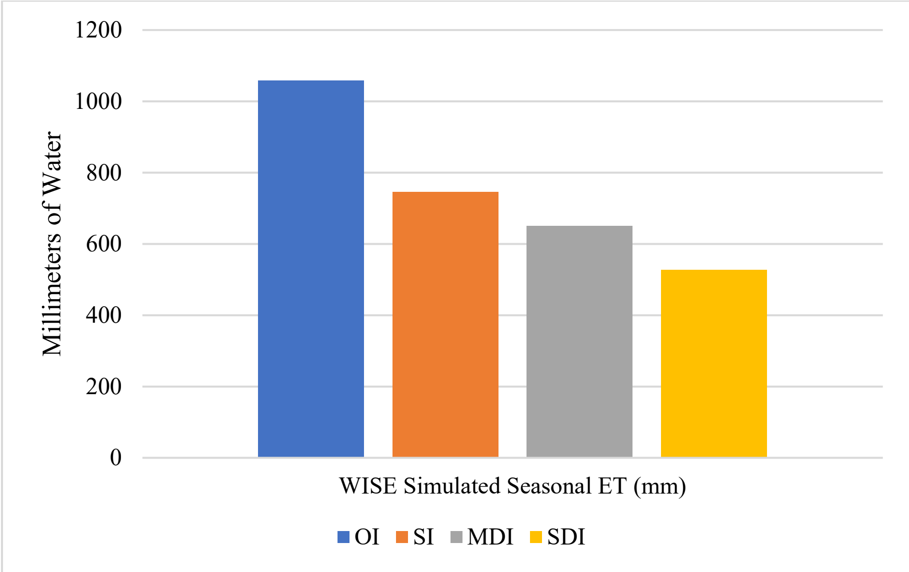


Figure 8. WISE simulated alfalfa ET_c (2020 season) from over, standard, moderate deficit, and severe deficit irrigation levels.

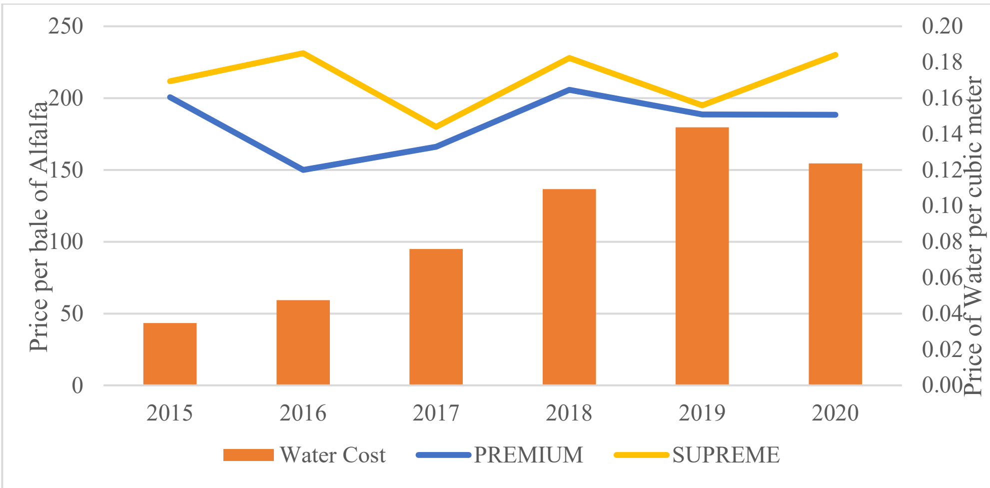


Figure 9. Alfalfa hay prices from 2015 to 2020 in Northeast Colorado showing supreme and premium feed quality price differences. Data from USDA Department of Ag Market and price for one cubic meter from 2015 to 2020, from Northern Water Pool Bids.

4. Discussion

The average WUE across all zones was consistent with other reported WUEs for alfalfa [15,29,30]. Although Sammis [15] determined WUE increases as ET_c increases, our SSDI approach to deficit irrigation on alfalfa has the potential to increase WUE at severe deficit irrigation levels [15]. Some studies have shown that the dry matter yield of alfalfa decreases with the decrease of water supply, while the WUE increases [3,33,34]. With the concave shape of the alfalfa WPF, deficit irrigation can optimize the WUE of alfalfa by triggering alfalfa's ability to use water from the soil profile more effectively. The WUE under deficit irrigation is quite favorable for alfalfa compared with other crops [35–37]. It has been shown that optimizing WUE and irrigation management needs to be specified for each environment to capitalize on potential water saving, which motivates our study in Eastern Colorado, USA [38].

Observed reductions in ET_c between standard and deficit irrigated alfalfa (205 to 260 mm) were similar in magnitude to those reported by Hanson et al. [39] in the Sacramento Valley of California (224 to 239 mm). This study demonstrated that alfalfa can be grown under deficit irrigation with SSDI to save water (i.e., reduce ET_c) at a commercial scale. The ability of alfalfa to increase its yield when irrigations were increased, even after four years of deficit irrigation, showed that it is a resilient crop and holds potential for CWSAs. For example, water sharing arrangements could include deficit irrigation of alfalfa during drought years when CU savings could be leased to municipalities. After drought conditions are alleviated, then irrigations can be increased for more alfalfa hay production.

Our results also offer important practical insight on implementing deficit irrigation on commercial-scale SSDI systems. In this study, deficit irrigation treatments were applied uniformly throughout the entire season. This deficit irrigation strategy is easier to apply at a commercial scale because of simplicity of programming the SSDI controller and there is no need to change the deficit levels based on alfalfa growth stage. However, Liu et al. [4] found that deficit irrigation of alfalfa at the budding stage had less negative effect on yield compared to uniform deficits through all growth stages. They found that greater yield reductions occurred when alfalfa was deficit-irrigated at the regrowth or branching stages. At a commercial scale, deficit irrigation based on alfalfa growth stages would require frequent phenological observations and more complex SSDI controller programming.

The cost for SSDI installation is high, but deficit irrigation could be a way to add additional profits to a farm. Subsurface drip systems provide small, but frequent, irrigations directly in the alfalfa's root zone, providing little stimulation and growth of weeds. The results indicate that RVF of the alfalfa increases after being deficit irrigated in prior years. Drought stress results in stunted plants with higher leaf counts, fine stems, less fiber, and higher digestibility [40]. This suggests that deficit irrigation can improve the quality of alfalfa and therefore the price point of the harvested hay. Harvest year played a bigger role in influencing RFV values rather than treatment, and it could be speculated that RFV changes are a result of alfalfa age, weather effects that year, or not dependent on irrigation management but other farm management decisions. Future research could evaluate the profitability of SSDI investments compared to the annual benefits of water leasing over time. Additional management costs with SSDI, such as leaching requirements to prevent buildup of soil salinity, could also be included in estimating profitability.

Studies have shown that drip irrigation depth strongly influences root morphology and architecture because deficit irrigation inhibits the formation of lateral roots on alfalfa [41]. Deep straight roots only occur when the surface soil is subjected to water stress; the roots become longer and straighter [42]. The deeper the roots, the more energy used to transport water upward. When water is applied directly in the root zone, energy is conserved. Subsurface drip irrigation systems improve root WUE and reduce surface water evaporation, which can help increase yields while conserving water [38,39]. Mooney [43] modeled deficit irrigation with multiple irrigation methods, including SSDI, and discovered deficit irrigation is plausible with SSDI and not sprinkler irrigation in our study area due to the water lost in evaporation.

Forage nutritive value and yield have direct impacts on the profitability of alfalfa production. The first cutting of the season for alfalfa is the highest yielding due to the higher spring WUE compared to later cuttings with larger stems [41]. Farm management practices, including irrigation timing and amounts, influence stem to leaf and sheath ratios [44,45] and plant maturity, which directly affect fiber and crude protein content [46]. Drought-stressed alfalfa matures earlier, thus forage quality will peak earlier and degrade more rapidly than under normal conditions [47]. This research indicates that, in years when there is a greater difference between the price for supreme and premium quality alfalfa hay, there could be an impact on farm income.

Prices can change due to market fluctuations and farm costs. When water price exceeds the price paid for alfalfa hay, the farmer can profit if conserved water from deficit irrigation is leased into an alternative transfer water market. However, if the assumption is made that water will become more scarce with increased demand in Colorado, it could become profitable to use deficit irrigation. California is a good example of this high demand for irrigation water and price increase; in 2007, irrigation water was sold for \$0.16-0.24 m^{-3} (\$200–\$300 AF^{-1}) [48]. Utah State University determined that precipitation stored as soil moisture will be adequate for the first spring cutting [44]. Thus, when water supply is limited, irrigation water can be saved and used at its most beneficial time.

Some confounding factors may have influenced the alfalfa yield and ET_c measurements at the SIEP farm. The degree of deficit irrigation applied in the treatments may have induced dormancy in the alfalfa. Alfalfa roots may have accessed deep groundwater, but changes in deep soil water content were not represented in the ET_c values calculated from NMM measurements that were only 150 cm deep. On the field's south end, three unlined water retention ponds could have percolated into shallow groundwater that may have flowed toward the South Platte River on the North side of the field. This may have provided a groundwater gradient from the south to the north side that could have contributed to additional alfalfa root water uptake. Further analysis on rooting depth and water table depth through telemetry at the SIEP farm is needed to determine this phenomenon.

5. Conclusions

The study resulted in three main takeaways. First, deficit irrigation with SSDI technology successfully reduced actual ET of alfalfa below potential ET, thus decreasing yield. However, deficit irrigation also improved alfalfa quality in relative feed value, although the difference does not influence market value classification significantly. Second, deficit irrigation with SSDI technology resulted in increased WUE for alfalfa. This suggests that water leasing may become feasible if the water price is sufficiently high to offset the forgone revenue from decreased yield. A price comparison indicated the ratio of cost/bale to cost/water to return a profit from leasing saved CU water. Finally, our study also showed that an alfalfa stand will recover after prolonged deficit irrigation and can produce more and better-quality hay after switching to higher irrigations.

The results hold important implications for the joint sustainability of irrigated agriculture and other societal water uses in Colorado. The state is experiencing more frequent droughts combined with population increases, stressing natural water resources. Colorado's Water Plan encourages alternatives to traditional "buy and dry" water market transactions by leasing water rights, preventing agricultural land loss [10]. CWSAs provide a way for farmers to add value to their farm and not dry up the agricultural land. Effective use of this method requires a decrease in CU from the agricultural land while maintaining some level of profit and yield. Deficit irrigation is a water-saving approach to avoid the complete dry up of irrigated farmland while sustaining profitable yields and monetary gains from water transfers. To benefit from deficit irrigation, a farmer could choose an efficient irrigation system that prevents water losses that are not beneficial to the crop. The crop of choice is a factor in how much savings a farmer can expect. This study confirms that deficit-irrigated alfalfa has potential for decreasing CU due to its drought tolerance, multiple harvests per season, and improved hay quality with less irrigation water. The increased WUE with SSDI suggests that it could be a profitable management practice for alfalfa farmers and serve as a water supply method for CWSAs in Colorado. However, more research into the technical feasibility is needed, including monitoring for deep root water extraction and an economic evaluation of SSDI investment costs relative to the annual benefits of water leasing.

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