THESIS

ALFALFA WATER USE UNDER DEFICIT IRRIGATION FOR FARM SAVINGS

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ABSTRACT

ALFALFA WATER USE UNDER DEFICIT IRRIGATION FOR FARM SAVINGS

Colorado water law allows for water rights to be leased between agriculture and municipality users. Decreasing the consumptive use (CU) of agricultural land while maintaining profits and yields will allow farmers to lease their water rights for revenue. Deficit irrigation is a water-saving approach to avoid the complete dry up of irrigated farmland while providing profitable yields and monetary gains from water transfers. To maximize water savings, efficient irrigation systems such as subsurface drip irrigation (SDI) are used to prevent water losses from soil evaporation. This study evaluated the feasibility of using SDI with deficit irrigation practices to grow alfalfa (*Medicago Sativa L.*) at production scale in northeast Colorado (2018 – 2022). Alfalfa was found to have good potential for decreasing CU due to its drought tolerance, multiple harvests per season, and improved quality of hay with less irrigation water. The Water Irrigation Scheduler for Efficient Application (WISE) model was also found to be a useful tool for estimating CU of deficit irrigated alfalfa and the regrowth phases after multiple harvests in a growing season. Mid-season corrections of the soil water deficit in WISE improved the accuracy of modeled CU. Overall the water savings from deficit irrigation at low, medium, and high irrigation levels with an SDI system can be profitable when prices for leasing water exceed hay prices per unit area of production.

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CHAPTER 1: INTRODUCTION

This research evaluated the feasibility of using modern irrigation technology with limited irrigation practices to grow commercially important crops, in this case alfalfa, at production scale. The research was conducted at the Subsurface Irrigation Efficiency Project (SIEP), a 66-hectare (165-acre) research farm, located 11 km (7 miles) east of Kersey, Colorado in central Weld County, Colorado. Alfalfa hay production in Weld County has been a vital economic resource for decades due to the cattle feed-lots in the county, but production has declined since the early 2000’s due to drought (Figure 1.1) (Scherer, 2012). The project goal is to help meet Colorado’s future water challenges by increasing the joint sustainability of irrigated agriculture and societal water uses. Agricultural sustainability involves a shift towards more water efficient crops and varieties, increasing water-use efficiency (Andales et al., 2003), and only applying the exact amount of water to achieve goals (Shawver et al., 2019). This research provides data on alternatives to the ‘buy and dry’ of agricultural land to supply water for municipalities by investigating ways to decrease the consumptive use of alfalfa to free up water for transfer to other uses.

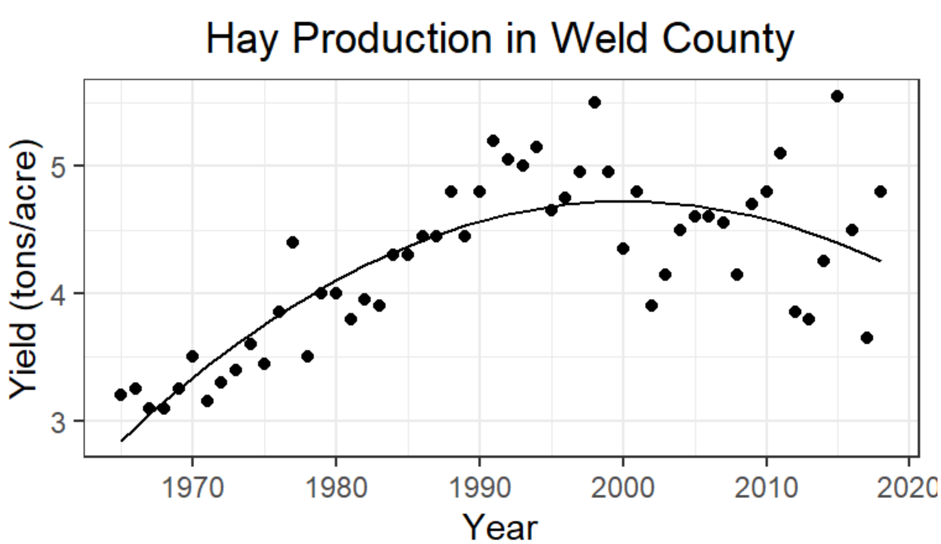

Figure 1.1. The average production of alfalfa hay per year on a per acre basis for Weld County, Colorado. Data sourced from NASS, USDA.

Typical irrigation methods for alfalfa include sprinkler, furrow, and border irrigation. These methods require more water than needed due to inefficiencies, deep percolation, runoff, and soil evaporation. Liu et al., (2022) determined that 18% of total evapotranspiration on border irrigated alfalfa fields was from soil evaporation which accounted for around 100 mm of water per season. Low flow drip irrigation methods apply an average 1233 m^3 (1 AF) per acre of cropland as compared to gravity flow irrigation methods which average 2096 m^3 (1.7AF) per acre (USDA-NASS, 2018). Crop water use of alfalfa under drip irrigation has been shown to decrease while yields increased (B. Hanson & Putnam, 2000). Alfalfa stands which are harvested multiple times per year are not suitable for aboveground drip irrigation due to low harvest machinery (Cao et al., 2021). Subsurface drip irrigation (SDI) is a more efficient way to irrigate crops by reducing soil surface evaporation and deep percolation with water application directly in the root zone. Studies have indicated a 35-55 percent savings of water delivered in a season by using SDI (Lamm & Trooien, 2003). Drip tape is buried at depths between 20-45 cm (8-18 in) and is spaced between 76 and 152 cm (30 and 60 in) apart. Subsurface irrigations can promote healthy roots to take advantage of the soil's water holding capacity (Shewmaker et al., 2013). SDI systems can be programed to deliver frequent and accurate amounts of water with efficiencies around 95%. Microirrigation, which includes drip/trickle, microspray, and similar systems, has increased from its infancy in the 1960s to 3 million acres at the turn of the century. Microirrigation accounted for 10% of the irrigated area in the U.S. in 2018 (Eisenhauer et al., 2021). Montazar et al., (2016) used an economic model which predicted 2.6 million dollars of annual net profits added to California's alfalfa industry for every percent increase in area converted from surface irrigation to SDI. SDI can increase alfalfa yield and continue to supply water during cuttings to encourage rapid regrowth (Alam et al., 2002). Economically, SDI has higher investment costs, uses less energy to pump water, and can last up to 10 years (O'Brien et al., 1998). A summary of SDI advantages and disadvantages are provided in Table 1.1. Microirrigation is popular on high-value crops in locations where water is expensive or in short supply because high value crops offset the initial costs associated with microirrigation installation and filtration systems.

Table 1.1. Advantages and disadvantages of subsurface drip irrigation.

Advantages	Disadvantages
No water loss from soil evaporation	High investment costs
Less energy to deliver water	Needs good water quality/filtration
Improves oxygen availability in root zone	Up to 10-year lifespan
Low weed invasion	Maintenance of system

Methods of deficit irrigation include delaying irrigation until a canopy is formed to reduce soil evaporation, applying water amounts below crop water demand, and maintaining the soil water level at or below the management allowed depletion (MAD) which is set at a percentage of soil available water capacity. Deficit irrigation is a strategic choice for generating income through water leasing, conservation payments, or incentive programs (Yost et al., 2021). Maximizing water use-efficiency (WUE) can help us understand potential water savings through deficit irrigation (Lindenmayer et al., 2011). A thorough understanding of crop water use efficiency, effects of water stress, and soil characteristics are needed for effective deficit irrigation management. Crops exert more energy to extract water from the soil when soil moisture decreases below MAD, thus leaving less energy for crop growth (Andales et al., 2009). Alfalfa is a deep-rooted nitrogen fixing legume that can tolerate water stress and prolonged drought by tapping into water at 5 m in depth or inducing dormancy until moisture levels rise (Hamidi & Safarnejad, 2010; Shewmaker et al., 2013). Montazar et al., (2020) found that up to 314 mm of water per season could be conserved using deficit irrigation on alfalfa while sustaining production. Deficit irrigation can increase profitability of alfalfa production in hot environments with water scarcity (Shewmaker et al., 2013), like northeastern Colorado. These hot environments require updated irrigation management strategies to provide enough water for the crops and use only the water allocated by their water right. Liu et al., (2022) found that 28% of consumptive use in alfalfa is due to soil evaporation in border irrigated plots. Another study by Lamm et al., (2012) found no significant difference in the effects of irrigation amounts on alfalfa yield with SDI in Kansas. Previous work on deficit irrigation suggests the need for a long term analysis of water conservation and resilience of alfalfa agricultural systems (Montazar et al., 2020). This multi-year project focuses on deficit irrigation scheduling using SDI systems to avoid wasteful irrigation of a crop while conserving water. Droughts, warming climate predictions, and population increase have put stress on Colorado's water supply, thus there is a need to understand agricultural water conservation while maintaining profitable crop production and quality through efficient irrigation technologies.

Project Summary

The overall goal of this research is to understand the conservation of irrigation water and to improve the ability of crops to withstand droughts, while maintaining productivity, crop quality and overall profitability in Northeastern Colorado. Efficient irrigation technologies such as subsurface drip irrigation and deficit irrigation may reduce agricultural consumptive water use while maintaining agricultural production, therefore, allowing farmers to explore the economic gain from temporary or permanent water transfer to non-agricultural sectors. To assess the conservation of irrigation water using subsurface drip irrigation, deficit irrigation schemes, and irrigation scheduling on alfalfa (*Medicago sativa L.*), SIEP began research in 2017. SIEP and the research conducted is meant to provide examples of water-saving irrigation techniques for crops vital to the economic growth and traditions of Northeastern Colorado. The objectives of this research are:

1. Estimate alfalfa evapotranspiration using the soil water balance approach with field data.
2. Evaluate the Water Irrigation Scheduler for Efficient Application (WISE) model for calculating soil water deficits and estimating consumptive water use for alfalfa production against field measurements.
3. Compare alfalfa forage quality from different deficit irrigation scheduling treatments.
4. Estimate potential water savings from deficit irrigation with a subsurface drip irrigation system and the market value of alfalfa hay based on forage quality.

Field measurements and water use data were collected during the March to September growing season from 2018 to 2022. The major steps for completing this research project are described in Chapter 2 and include weekly field measurements, measuring alfalfa yield and quality by harvest, comparing, and analyzing previous years of data, as well as computing a cost benefit analysis of using subsurface deficit drip irrigation to grow alfalfa. Chapter 3 describes the evaluation of the WISE model in its ability to model the soil water deficit and evapotranspiration of alfalfa under deficit irrigation treatments. This chapter was formatted for future submission to the *Agricultural Water Management* journal.

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CHAPTER 2: A CASE STUDY OF ALFALFA'S WATER PRODUCTION FUNCTION UNDER DEFICIT IRRIGATION FOR POTENTIAL WATER SAVINGS IN COLORADO.

Introduction

Colorado, USA, is the 6th most irrigated state with 994,765 hectares (2,458,120 acres) of irrigated land as of 2018 (USDA, 2022a). A large portion of irrigated land is used to produce alfalfa (*Medicago sativa L.*) for cattle feed. Seasonal water use of alfalfa in eastern Colorado is 942 mm which is higher than other forage crops like silage corn using 582 mm (Schneekloth & Andales, 2017). Most rivers used for irrigation water in Colorado are snowmelt fed; due to a warming trend in climate, there is less snowpack to feed these rivers. Recent droughts and a warming climate in Colorado have decreased the available water supply for irrigated crop production. Water conservation in Colorado is essential to meet demands for future population increases and crop production.

Colorado is striving for the sustainable use of limited water resources to meet the water demands of growing cities and agricultural production. It is also estimated that over the next few decades, demand for water will increase by 777,093,558 m^3 (630,000-acre feet) (Colorado Water Conservation Board, 2015). Guidelines suggest an upgrade to efficient subsurface drip irrigation, micro sprinkler, or upgraded sprinkler irrigation builds farm resiliency to water shortage (Glennon, 2022; Hawkes et al., 2018). Sustainability in this sense is the need to supply water for a growing population in cities while maintaining agricultural production to feed the growing population. Water right transfers are methods to transfer water on a temporary or intermittent basis from agricultural lands to other uses (WestWater Research, 2016). 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 the limited water resources (Colorado Water Plan Update, 2022). CWSA's provide cost savings to traditional acquisitions and can be a long-term sustainable solution by allowing 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 or the part of crop evapotranspiration (ET) that has been supplied by irrigation water in the historic past (Colorado Water Plan, 2015). Watson and Davies, (2011) predicted future water transfers to municipalities to be largely from agriculture.

Subsurface drip irrigation (SDI) is a more efficient way to irrigate 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 SDI (Lamm & Trooien, 2003). Crop water use of alfalfa under drip irrigation has been shown to decrease while yields increased (Hanson & Putnam, 2000). Deficit irrigation is a management method of irrigation that reduces water use on a field by restricting the water available for ET while optimizing crop productivity. To determine if deficit irrigation supplied by SDI is economically plausible for commercial scaled alfalfa production on the Northeastern Plains of Colorado, the water production function (WPF) of alfalfa needs to be formulated. A crop WPF is the relationship between crop yield and ET. This function is used when optimizing water allocation for irrigation. Alfalfa is a drought tolerant legume and can be managed for limited irrigation to promote higher feed quality (Brown & Tanner, 1983). Sammis, (1981) determined the relationship between alfalfa growth and ET is independent of where the alfalfa is grown but different for each cutting, with water use efficiency (WUE) being higher for the last two cuttings. Smeal et al., (1992) looked at the WPF and slope (water use efficiency) of alfalfa from 1981 to 1998 and determined that water use production functions can be transferable from year-to-year and place-to-place if factors of crop growth and maturity, season length, and climatic variables 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., (2019) 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 the South Platte Basin.

Objectives

The goal of this research is to determine if deficit irrigation of alfalfa can be used to save CU water to improve farm income by leasing through collaborative water sharing agreements. For maximum water savings we used a highly efficient SDI system to understand the effects of deficit irrigation on alfalfa production in northeast Colorado. Specific objectives were to: 1) understand how different irrigation levels affect alfalfa ET, yield, and forage quality; 2) determine if the WPF of alfalfa through deficit irrigation exhibits marginal returns conducive to water leasing; and 3) estimate the potential water savings from deficit irrigation and the market value of alfalfa hay compared to the price of a water transfer. A look into alfalfa recovery after years of deficit irrigation was also investigated.

Methods

Study Site

The Subsurface Irrigation Efficiency Project (SIEP) is located 11.2 kilometers (7 miles) east of Kersey, Colorado in central Weld County. The western section of the SIEP site (33 ha or, 82 ac) was equipped with a subsurface drip irrigation system. Driplines are buried at a depth of 25.4 cm (10 in) at 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). Components of this drip irrigation system such as a well, two ponds, a pump house, and a filtration house were installed at the southwestern edge of the western section. 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 (Figure 2.1). Each zone can be irrigated individually since each zone was equipped with its own water control valve. Applied water at each valve was measured with a flow meter housed at the head of each zone. Water used for irrigation is solely pumped, filtered groundwater. Groundwater pumping and filtration is controlled at the pump house. Alfalfa was planted in 6 zones in 2017 (Zones 19, 18, 17, 10, 9, and 8) and an additional two zones (Zones 16 and 7) of alfalfa were added the following year. These zones have been maintained with deficit irrigation scheduling in consecutive years until 2022.

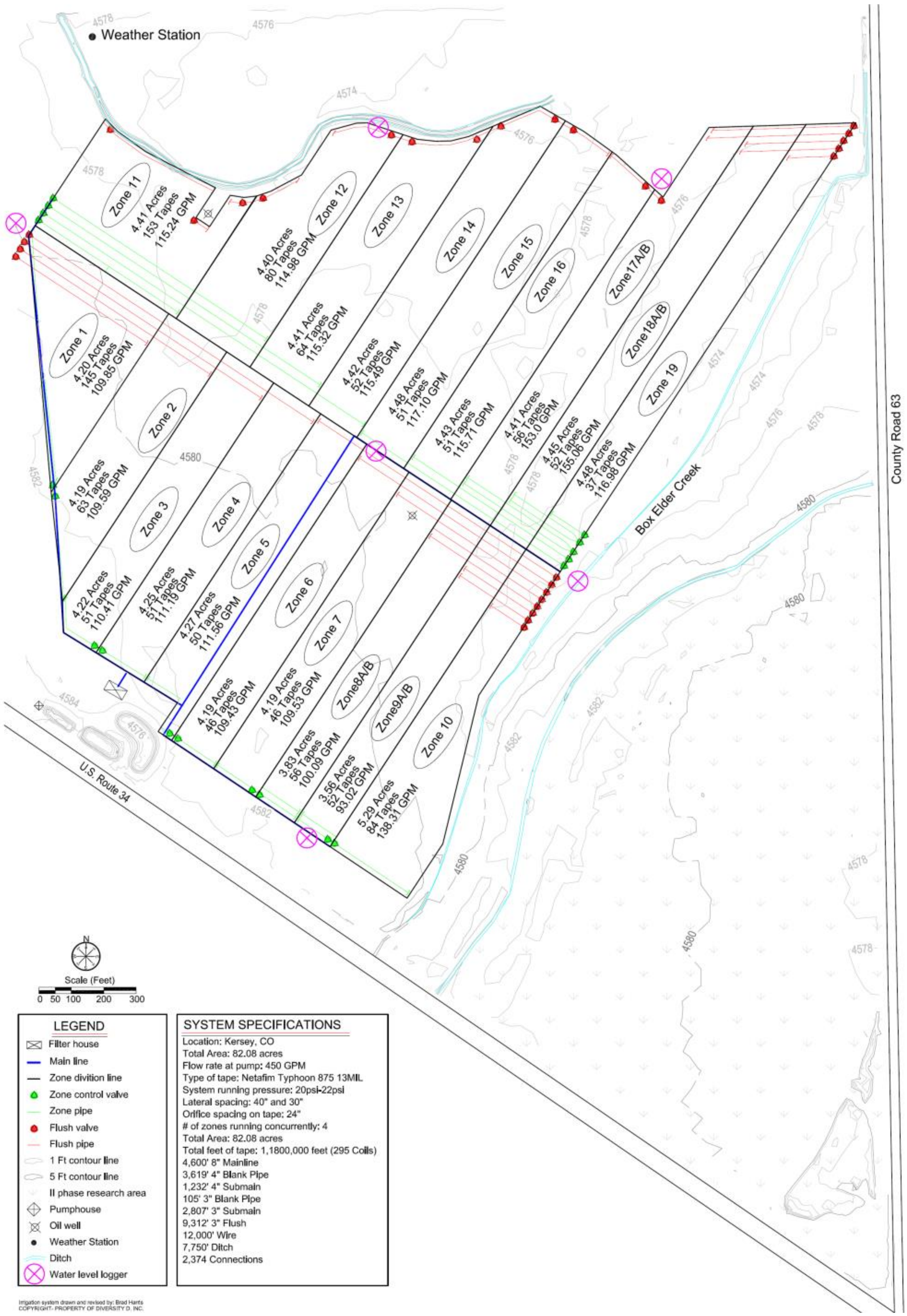

Figure 2.1. SIEP site map of the experimental field zones and irrigation system specifications.

A weather station funded by the United Water and Sanitation District and operated by the CSU Agricultural Meteorological Network (Colorado State University, 2022) is located in the northern section at 40.38°N, -104.53W°. It has been recording data since January 1, 2015. The station's name is Kersey 2 (ID name: KSY02). It is located 15 m away from the irrigated fields surrounded by natural vegetation (Figure 2.1). The 3-year average weather station data is provided in Table 2.1. The topsoil at SIEP has a clay loam texture. Deeper layers are sandy clay loam in texture. There are two major soil types in the 8 alfalfa zones, Colombo and Nunn, described below in Table 2.2 and Figure . Soil types in zones 9, 10, 18, 19 are mostly Colombo and zones 7, 8, 16, and 17 are mostly Nunn.

Table 2.1. 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)	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.

Table 2.2. Physical properties of the two major soil types at the experimental field.

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

Figure 2.2. Web Soil Survey map of the SIEP farm from the Natural Resources Conservation Service where 41 is Nunn clay loam comprising 56.9% of the area, 19 is Colombo clay loam comprising 42.8%, and 22 is Dacono clay loam in 0.3% of the area of interest.

Measurements

Weekly measurements of alfalfa canopy height and soil moisture content were recorded from 2018 to 2022. Plant height measurements in centimeters from the ground to the top of the canopy kept track of growth during each cutting cycle. Soil water content measurements were taken with a neutron soil moisture probe and capacitance sensors. The neutron probe (CPN 503, Instro Tek Inc.) uses Geiger counts by emitting neutrons into soil to measure soil moisture. Aluminum access tubes were installed at one location in each of the zones. Measurements were taken weekly at each access tube at five different depths: 30 cm, 60 cm, 90 cm, 120 cm, and 150cm. Soil volumetric water content was calculated from neutron probe count ratios using a linear calibration equation (Dane et al., 2002). 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 (see Appendix ii). The Decagon capacitance sensor, 5TE and attached datalogger, detects how the dielectric permittivity property of soil changes with water content to measure soil moisture. These sensors take automatic readings every hour and log them in the datalogger. Two sensors per plot were installed near the neutron probe access tubes at 15- and 45-cm depths. Tracking soil moisture at different depths helps 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 pump house and by weekly recordings of each zones' flow meter. Irrigations were started after the last frost of the year to prevent damage to the SDI system. In 2019 the first irrigation was on June 22, May 1st was the first irrigation in 2020, in 2021 the first irrigation was on July 21, and in 2022 the irrigations started on May 6th. Four irrigation 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 triggers irrigation when D equals or exceeds the management allowed depletion (MAD), which was set at 50% of soil available water capacity. Each irrigation treatment was implemented in two zones (Table 2.3). In 2022, irrigation levels were swapped among zones to study alfalfa recovery after continuous deficit irrigation. The standard and high treatments were switched to low and medium and vice versa.

Table 2.3. Target irrigation levels based on soil water deficits (D) and corresponding zones.

Treatment	Zones	Target Irrigation[a]
1	9 and 10	Standard
2	8 and 19	Medium
3	17 and 18	Low
4	7 and 16	High

[a]Standard = irrigate when D ≥ MAD; Medium = apply 70% of Standard; Low = apply 50% of Standard; High = apply 120% of Standard.

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 7 days at 45ºC. After drying, samples were weighed for dry matter yield and a sub-sample was ground with a Wiley Mill (Thomas Scientific Swedesboro, NJ) 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 NIR Analyzer (Unity Scientific, Westborough, MA) was used under lab conditions to obtain the neutral and acid detergent fiber (ANDF, ADF), and crude protein from each zone's harvest (see Appendix iv). The Forage Analyzer uses near infrared (NIR) analysis to provide fast, accurate, and reliable results for the livestock industry without damaging the sample (Marten et al., 1989). Relative feed value (RFV) is a calculated value used to compare hays based on how well an animal can digest the product and is often used for buying and selling hay (Ward & de Ondarza, 2008). RFV is calculated using the following standard equations where *DMI* is the dry matter intake and *DDM* is the digestible dry matter.

$$DDM = 88.9 - (0.779 * ADF) \quad [1]$$

$$DMI = \frac{120}{ANDF} \quad [2]$$

$$RFV = \frac{(DMI * DDM)}{1.29} \quad [3]$$

Estimation of alfalfa ET, water use efficiency (WUE), and market value of saved consumptive use

Actual alfalfa crop ET (ET_c) was estimated from the soil water balance equation:

$$ET_c = Irr + P + \Delta SWC \quad [4]$$

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 neutron probe 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 SDI systems. The *P* was calculated by subtracting estimated surface runoff (USDA-NRCS, 2004; curve number (CN) approach with CN = 85) from rainfall measured by the CoAgMet rain gauge.

Alfalfa dry matter yields (kg/ha) for all cuttings and zones were plotted against corresponding alfalfa ET_c (mm) to derive an alfalfa WPF. Alfalfa WUE was computed for each cutting as:

$$WUE = \frac{Dry\ Biomass\left(\frac{kg}{ha}\right)}{ETc\ (mm)} \quad [5]$$

Irrigation management affects the yield and quality of the alfalfa harvest (Orloff & Putnam, 2015). The RFVs were plotted against dry biomass (kg/ha) to deduce relationships between forage quality, yield, irrigation levels, and ET_c. Historical market value of alfalfa hay from the past five years were used to assess profitability of deficit irrigation. Higher prices per ton are given to hay that is reported as "Supreme" according to the USDA-Hay Market News Service (USDA, 2022b). Historical prices for water in the area were obtained from Northern Water's Pool Bids database (Northern Colorado Water Conservancy District, 2022).

Results

Deficit Irrigation

Length of growing season averaged 154 days from March to October with 3 or 4 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. 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 thus had the smallest ET_c per harvest. ET_c was affected by the amount of water the plant received, both irrigated and precipitation water. Reference (non-stressed) alfalfa stands require on average of 940 mm of water for ET depending on location (Shewmaker et al., 2013; Schneekloth & Andales, 2017). Since target irrigation levels (Table 2.3) were not achieved because of water shortages, deficit irrigation levels were categorized according to the average seasonal ET_c into 4 categories shown in Figure 2.3 with the same nomenclature. The more irrigation supplied to the plant the more it could transpire which is illustrated in a linear relationship in Figure 2.4. Data were excluded from the analysis on the impact of irrigation on ET when the first harvest of alfalfa was fully rainfed. Growth from first harvest occurred from March May, when the subsurface drip irrigation system was not operational because of freezing conditions.

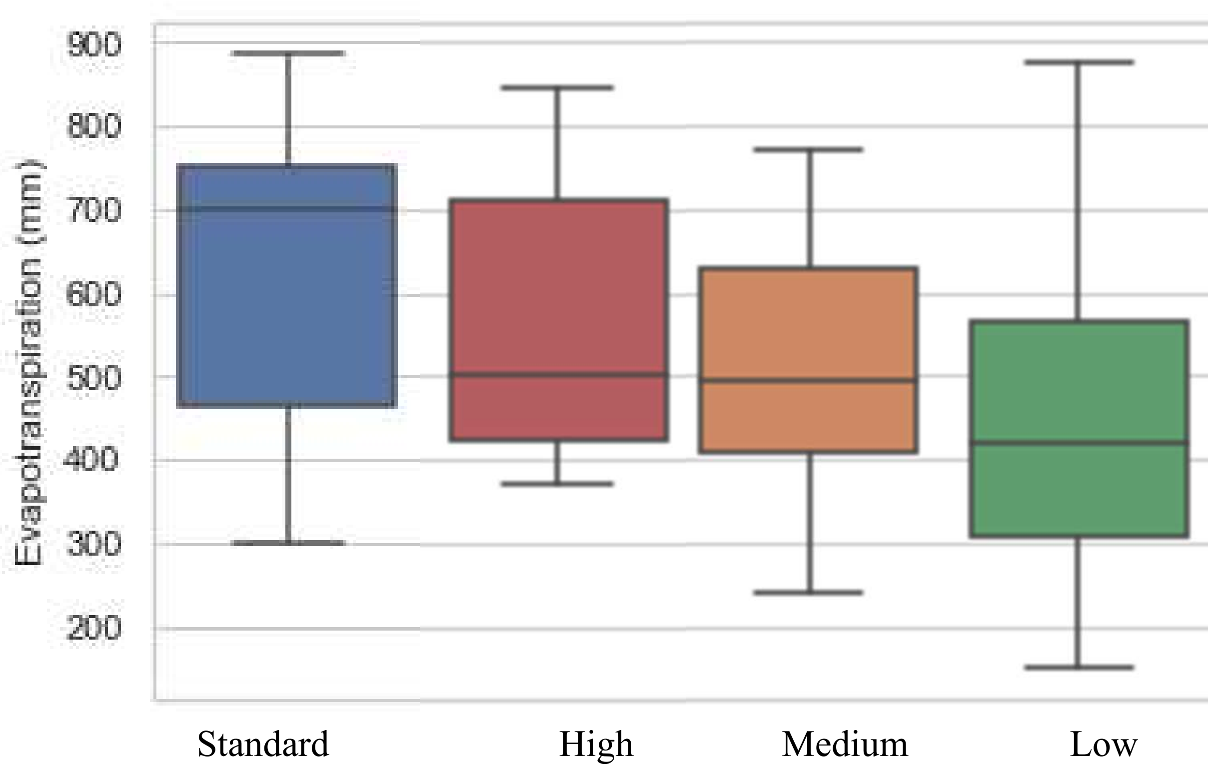

Figure 2.3. Ranges of seasonal ET for each treatment over the 5 years (2018 - 2022).

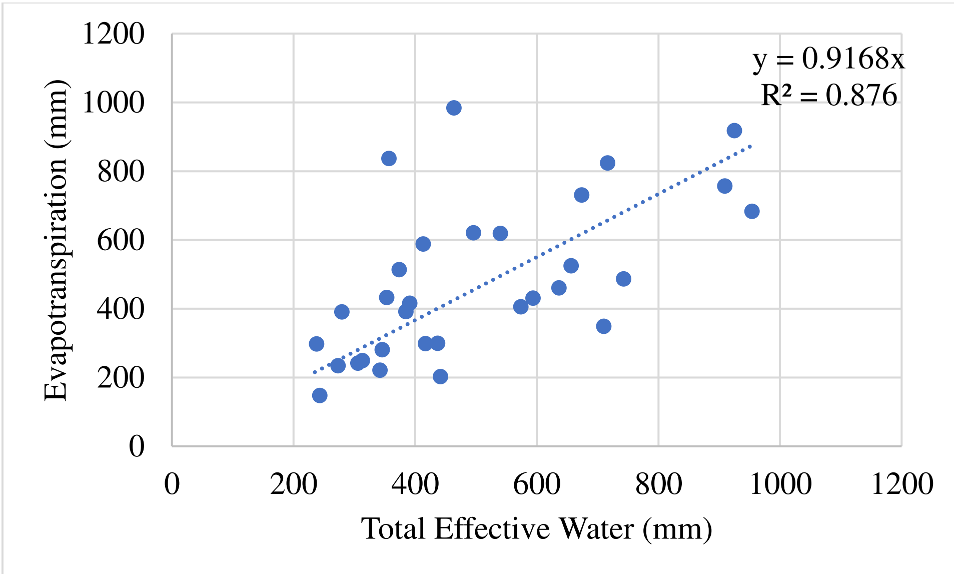

Figure 2.4. Direct relationship between total effective water (irrigation plus precipitation) and ET from all 5 years (2018 – 2022) of data collection from all 8 zones.

Alfalfa ET and Biomass

Alfalfa biomass responds positively to increasing ET and water applied. The most ET_c per harvest occurred in 2019. In the data presented in Figure 2.5, there is a separation in biomass between zones 7, 8, 9, 10 and 16, 17, 18, 19 starting in 2020. Zones 7, 8, 9, 10 are located on the south side of the field where three unlined retention ponds are located.

Irrigation treatments were switched at the beginning of 2022 resulting in increased biomass from the low irrigation turned standard irrigation. This indicates alfalfa can recover after being deficit irrigated. Alfalfa which was deficit irrigated at the low and medium irrigation 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 medium irrigation to 2022 when high irrigation was applied (Table 2.4).

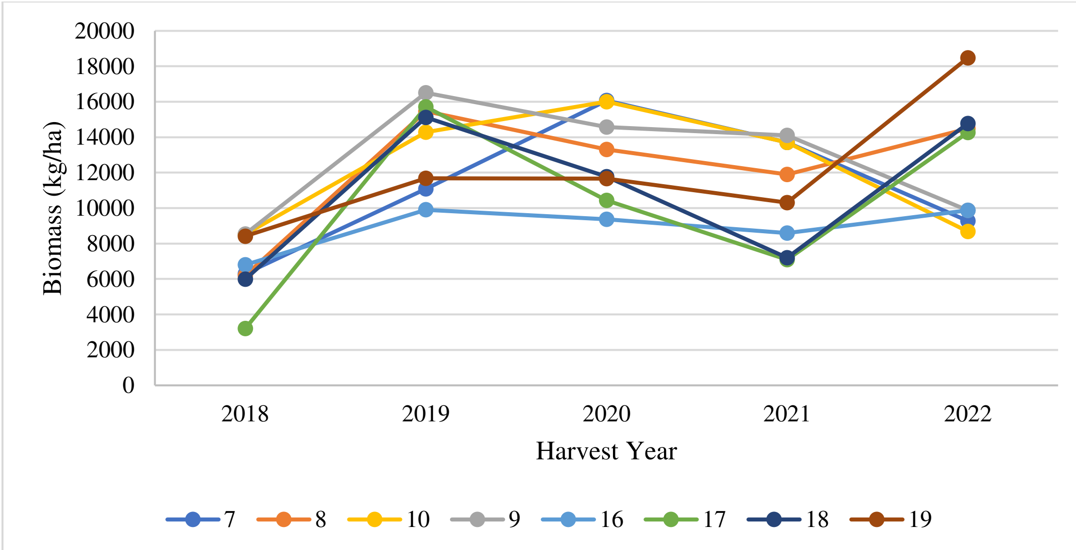

Figure 2.5. Yearly trends in total biomass yield (kg/ha) for the 8 alfalfa zones from 2018 to 2022, with 2022 having different treatment levels.

Table 2.4. Percent difference in biomass between years. Bold indicates 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%**

WPF is used for economic analysis by predicting the yield as a function of ET_c. The resulting WPF from this study is concave (Figure 2.6), agreeing with the hypothesis that a concave WPF for a given crop can be beneficial when using deficit irrigation due to decreasing marginal production per unit of water (Varzi et al., 2019). A zero x-y intercept was applied to this function to represent zero soil evaporation from SDI systems (French & Schultz, 1984).

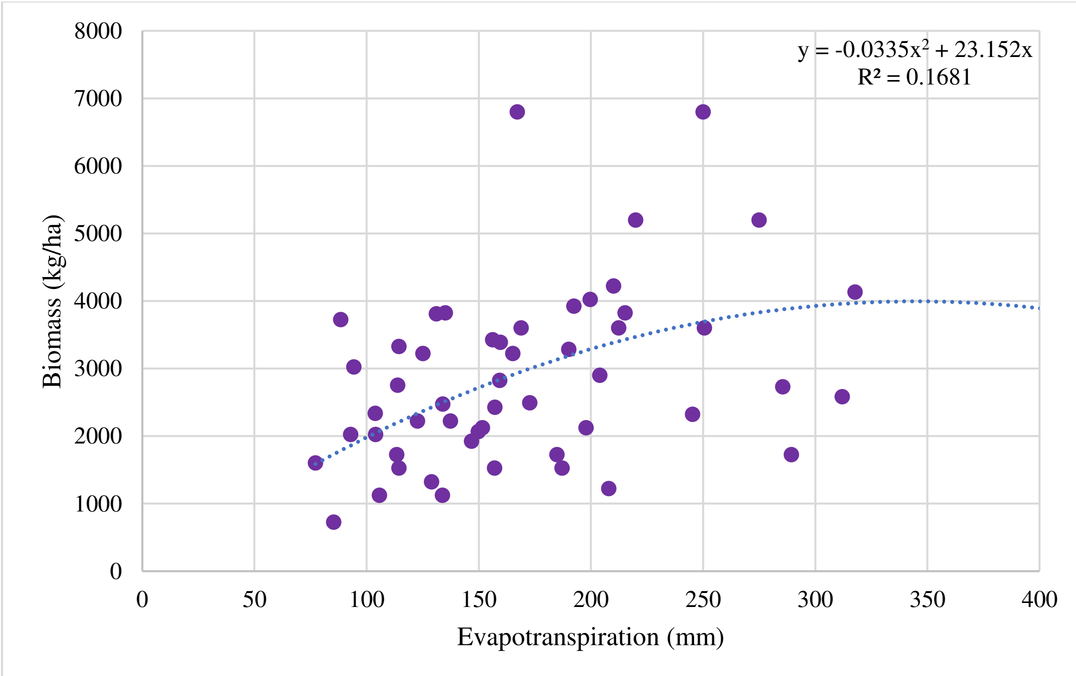

Figure 2.6. WPF of alfalfa relating ET and biomass produced under deficit irrigation treatments.

WUE

Average WUE across all zones was 0.17 Mg-ha^{-1}cm^{-1} which is consistent with other reported WUE for alfalfa (J. W. Bauder et al., 1978; Lindenmayer et al., 2011; Sammis, 1981). Although Sammis (1981) determined WUE increases as ET_c increases, our SDI approach to deficit irrigation on alfalfa has the potential to increase WUE at low irrigation levels. There was a decreasing trend between WUE and ET_c up to 524 mm (Figure7). Zone 8 in treatment 3 (Low target irrigation) had the highest WUE of all the zones but overall, the Standard target treatment had the highest average WUE (Table 2.5). A t-test for significant difference between treatments was performed and determined no significant differences in WUE between 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 low ET rates in cooler weather.

Table 2.5. Water use efficiency (WUE) of alfalfa from 2017-2022.

Target Irrigation	**WUE** (Mg ha^{-1} cm^{-1})
Standard	0.183
Medium	0.165
Low	0.171
High	0.162

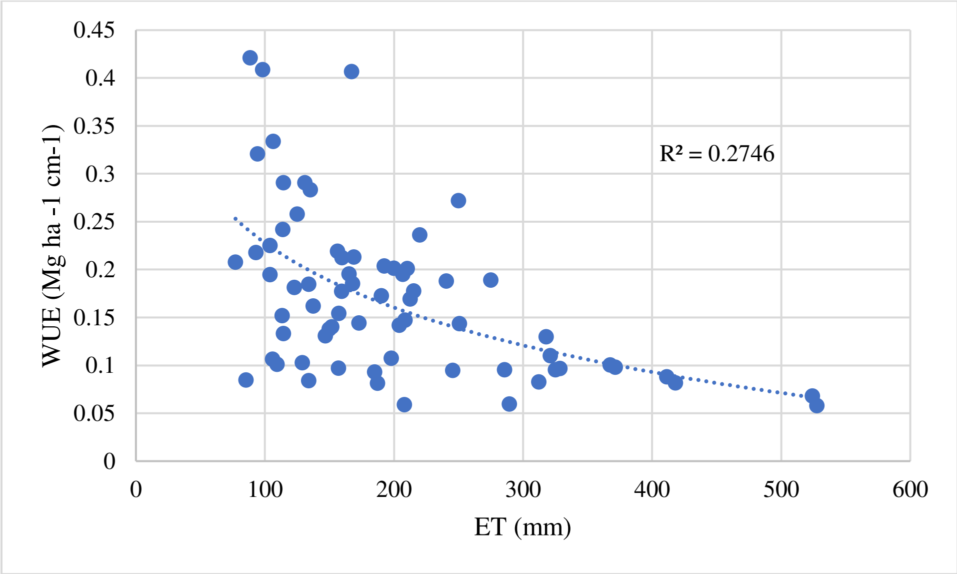

Figure 2.7. The WUE of alfalfa under deficit irrigation using subsurface drip irrigation.

Effects of Deficit Irrigation on Alfalfa Biomass and RFV

Zones that produced larger amounts of biomass tended to have lower feed quality (Figure). Of the yields reported, 75% of the samples were in the supreme quality category with 24% at premium quality (Figure). The most irrigation water per harvest occurred in 2020 that resulted 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 higher quality feed. A t-test for significance determined there was no significant difference between treatments and RFV with all p-values greater than 0.05.

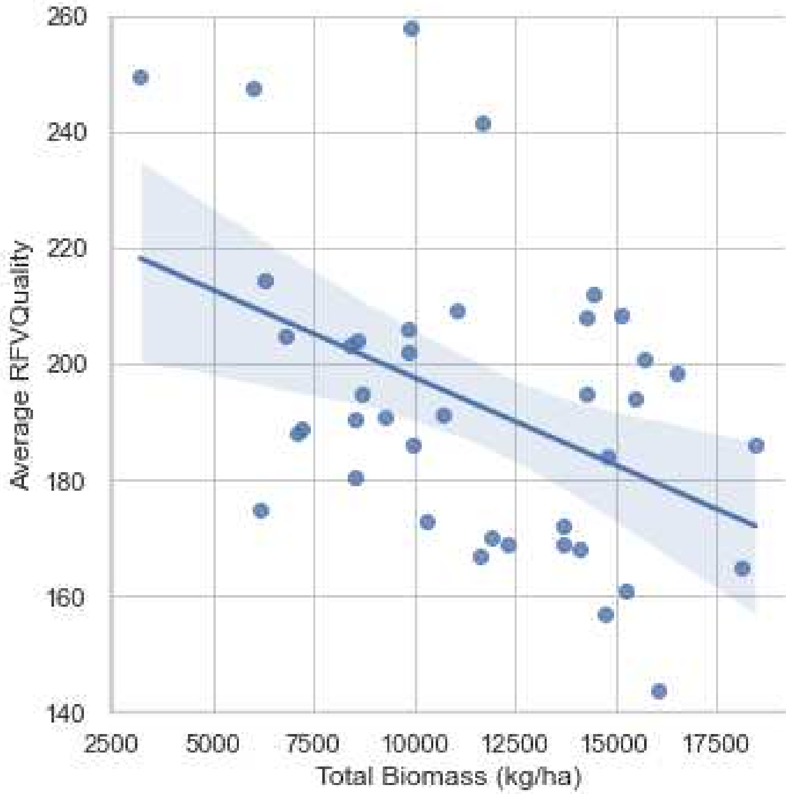

Figure 2.8. Inverse relationship between alfalfa biomass and relative feed value.

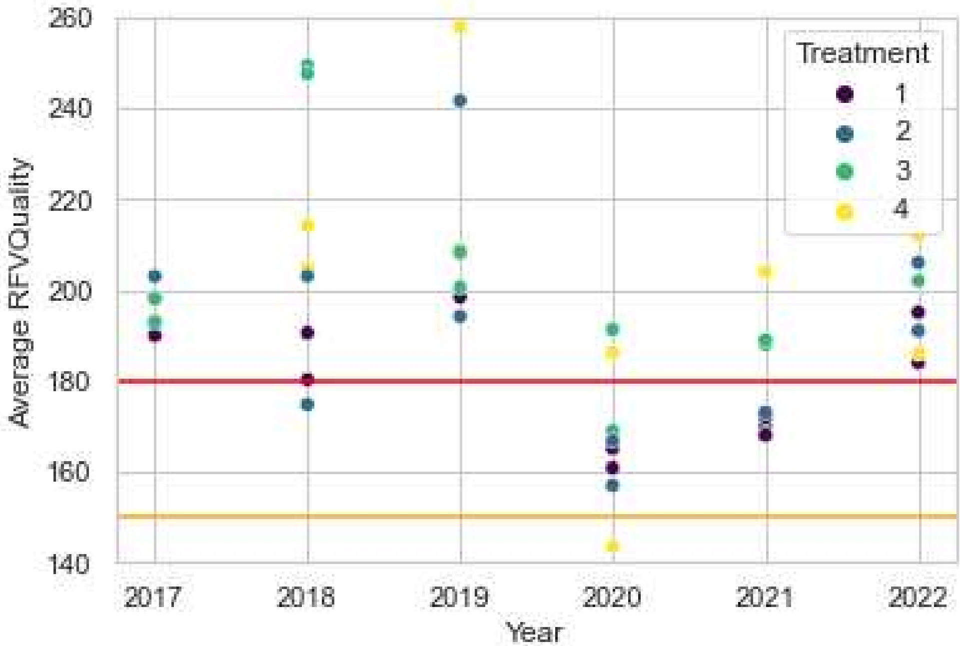

Figure 2.9. Forage quality parameter, RFV, averaged over seasonal harvests for each treatment and year. The lines show the cutoffs between supreme and premium (red line); and between premium and good (orange line) feed quality.

Estimated CU Savings and Profits

To estimate how much CU savings are possible with deficit irrigation using subsurface drip, the Water Irrigation Scheduler for Efficient Application (WISE) (Andales et al., 2014, 2020) was used to simulate daily alfalfa ET_c under no water stress by keeping the soil water deficit less than management allowed depletion (MAD) of 50% (Appendix III). 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 medium level, and 50% from the low irrigation level (Figure10). The cost to secure water for irrigation purposes was used as a lower bound in the analysis due to the many marginal costs associated with specific farm practices. The Colorado Enterprise Budget for Northeastern Colorado (https://abm.extension.colostate.edu/enterprise-budgets-crop/) details the marginal 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 (Northern Colorado Water Conservancy District, 2022). 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. The yearly mean price for a large square bale of alfalfa hay was used in the economic analysis, the large square bale weighs approximately 839 kg. The biomass samples gathered were scaled to the zone area (average 1.7 hectares, 4.3 acre) and a theoretical number of bales was calculated per zone. Biomass amounts from the no stress simulation were assumed from the max biomass produced at SIEP under subsurface drip irrigation with high irrigation water provided. An economic analysis was done to see if additional biomass made up for the lower bid price the lower quality feed received. The results showed that the additional biomass created more profit than the higher quality feed with lower biomass. The price for alfalfa hay at supreme and premium quality was compared to the price of water to determine if deficit irrigating alfalfa and leasing water rights would be profitable (). A price ratio of cost/bale to cost/AF water indicates if a profit can be made during a price period. An economic analysis from 2020 data shows that with a price ratio of 1.5 (cost/bale to cost/AF), deficit irrigation is more profitable (Table 2.6). The analysis showed that 2019 had the greatest profit return since the price of water was at its peak.

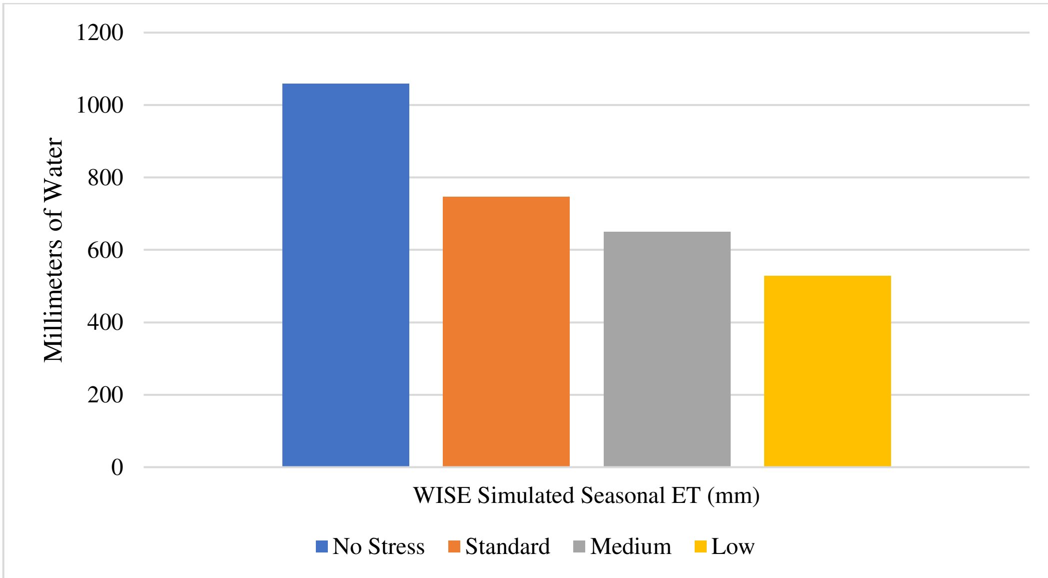

Figure 2.10. Simulated alfalfa ET_c (2020 season) from standard, medium, and low levels of target irrigation compared to a non-stressed level (No-Stress).

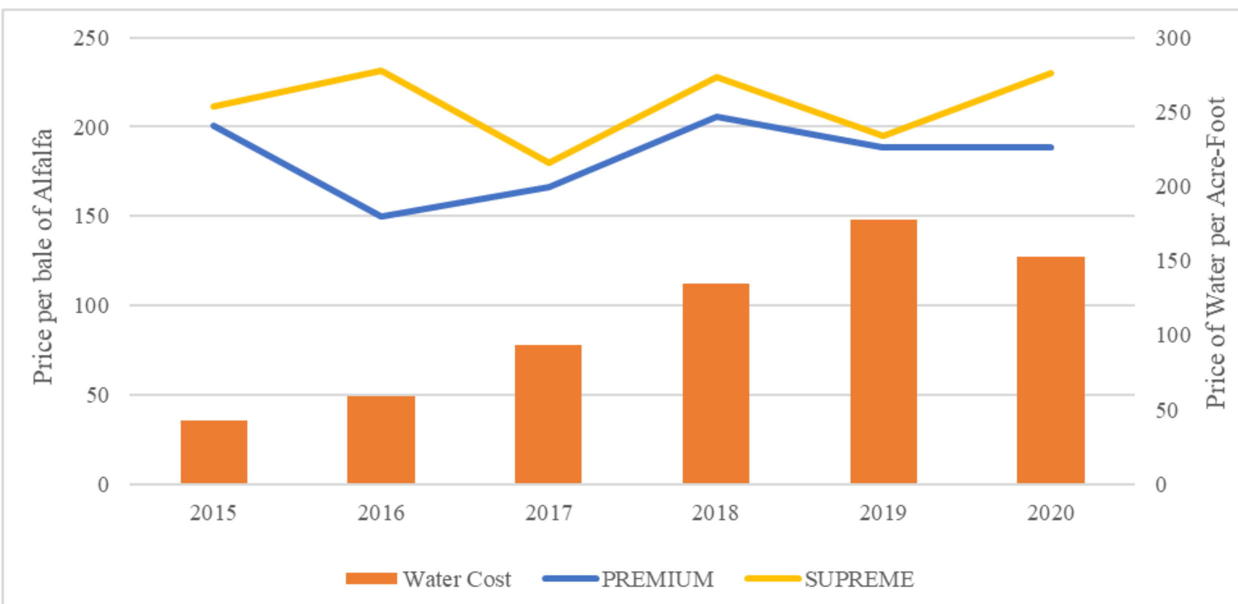

Figure 2.11. Alfalfa hay prices from 2015 to 2020 in Northeast Colorado showing supreme and premium feed quality price differences. Data from USDA Department of Ag Market and price for one acre-foot from 2015 to 2020, from Northern Water Pool Bids.

Table 2.6. Profit margins from irrigation levels compared to WISE no irrigation stress simulation of ET_c for 2020. Price for supreme quality hay in 2020 was $230.00/bale for a large square bale. Price data from Northern Water Pool Bid for 2020 is $152.40/AF.

Irrigation Level	Bales Produced/acre	Hay Profit/acre	AF of Water Saved/acre	Water Profit/acre	Total Profit/acre
No Irrigation Stress	8.95	$ 2,057.35	-	-	$ 2,057.35
Standard	6.41	$ 1,473.66	4.42	$ 673.72	$ 2,147.38
Medium	5.36	$ 1,233.61	5.78	$ 880.94	$ 2,114.55
Low	4.62	$ 1,061.72	7.49	$ 1,141.67	$ 2,203.39

Discussion

Because alfalfa is a drought tolerant legume and the WPF is concave, alfalfa can be produced under deficit irrigation to save CU. Irrigation treatments were not changed for the first 4- years of the study (2018 – 2021) to analyze impacts of continuous (long-term) deficit irrigation on alfalfa yield and CU. Simulation of a drought or limited water allocation year can be achieved during deficit irrigation treatments, switching the irrigation treatments simulates a non-drought year and how the alfalfa recovers with additional water. In 2022, the treatments were switched to investigate alfalfa recovery after deficit irrigation. Analysis shows an increase in biomass after applying deficit irrigation for 4 years then no deficit irrigation the next year indicating that alfalfa will recover after water stress and produces better quality. Some studies have shown that the dried yield of alfalfa decreases with the decrease of water supply, while the WUE increases (Ismail & Almarshadi, 2013; Lamm et al., 2012; Cao et al., 2021). Deficit irrigation treatments optimize the WUE of alfalfa by triggering alfalfa's ability to use water from the soil profile more effectively. The WUE is quite favorable for alfalfa compared with many other crops (Loomis & Wallinga, 1991; Asseng & Hsiao, 2000; Orloff & Putnam, 2015). It has been shown that optimizing WUE and irrigation management needs to be specified for each environment to capitalize on potential water savings (Hanson, 1988).

The cost for subsurface drip irrigation installation may be high but deficit irrigation can be a way to add additional profits to a farm. Subsurface drip systems provide small but frequent irrigations directly in the root zone of alfalfa providing little stimulation and growth of weeds. The results indicate that RVF of the alfalfa increases after being stress irrigated in prior years. Drought stress results in stunted plants with higher leaf counts, fine stems, less fiber, and higher digestibility (Orloff et al., 1997). This suggests that deficit irrigation can improve the quality of alfalfa and therefore price point of the harvested hay. Harvest year played a bigger role in influencing RFV values rather than treatment, 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.

Studies have shown that drip irrigation depth has a strong influence on root morphology and architecture because deficit irrigation inhibits the formation of lateral roots on alfalfa (Li et al., 2022). Deep straight roots only occur when the surface soil is subjected to water stress; the roots become longer and straighter (Li et al., 2022). 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 the WUE of roots and reduces surface water evaporation which can help increase yields while conserving water (Zhang et al., 2004; Li et al., 2022). Mooney (2022) modeled deficit irrigation with multiple irrigation methods and discovered deficit irrigation is plausible with subsurface drip and not sprinkler irrigation due to the water lost in evaporation.

Forage nutritive value and yield have direct impacts on 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 (Shewmaker et al., 2013; Yost et al., 2021). Farm management practices, including irrigation timing and amounts, influence stem to leaf and sheath ratios (Carter & Sheaffer, 1983) and plant maturity which directly affects fiber and crude protein content (Kamran et al., 2022). “Drought-stressed alfalfa matures earlier, thus forage quality will peak earlier and degrade more rapidly than under normal conditions” (Irmak et al., 2007). This research indicates that in years when there is a greater difference between the price for supreme and premium quality alfalfa hay, there will be an impact to farm income.

When water price exceeds price paid for alfalfa hay, there is a net profit to the farmer if conserved water from deficit irrigation is leased into an alternative transfer water market. Prices can change due to market fluctuations and marginal farm costs but, if the assumption is made that water will become more expensive with increased demand in CO, it will come to be more 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 $200-$300/AF (Sanden et al., 2007). Utah State University determined that precipitation stored as soil moisture will be adequate for the first spring cutting (Yost et al., 2021). Thus, when water supply is limited, irrigation water can be saved and used at its most beneficial time.

Confounding Factors

The degree of deficit irrigation applied in the treatments may have induced dormancy in the alfalfa. It is speculated that some plants located on the south side of the research farm are accessing more groundwater than the north side. Changes in deep water content are not represented in the ET_c values calculated from 150 cm neutron probe measurements. On the south end of the field, there are three unlined retention ponds which could be percolating water into the water table which is then transported toward the South Platte River on the North side of the field providing a gradient of water from the south to the north side. Further analysis on rooting depth and water table depth through telemetry is needed to determine this phenomenon.

Conclusions

Different deficit irrigation levels applied by SDI restricts the potential ET of alfalfa thus decreasing the yield, however, it improves the quality of alfalfa. The WUE of alfalfa is optimized by deficit irrigation levels and exhibits marginal returns beneficial to water leasing. A price comparison indicated that lower price ratios of cost/bale to cost/AF returns more profit received from leasing saved

CU water. 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.

Colorado is experiencing more frequent droughts combined with population increase that is stressing the natural water resources we depend on. Colorado's Water Plan encourages alternatives to traditional "buy and dry" water market transactions through the leasing of water rights, which prevents the economic loss of agricultural land (Colorado Water Plan Update, 2022). CWSA's 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 consumptive use of the agricultural land while maintaining profits and yields so farmers can lease their conserved water for a profit. Deficit irrigation is a water-saving approach to avoid the complete dry up of irrigated farmland while providing profitable yields and monetary gains from water transfers. To benefit from deficit irrigation, a farmer must 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. Alfalfa has great potential for decreasing CU due to its drought tolerance, multiple harvests per season, and improved quality of hay with less irrigation water. The increased irrigation efficiency of SDI maintains a profitable alfalfa crop for farmers and saves consumptive water with deficit irrigation for CWSA in Colorado.

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CHAPTER 3: TESTING A SIMPLE SOIL WATER BALANCE MODEL FOR SUBSURFACE DRIP IRRIGATION MANAGEMENT OF ALFALFA IN NORTHEAST COLORADO

Introduction

Colorado has 13 million hectares of agricultural land (https://ag.colorado.gov/). Due to the lack of precipitation and dry climate, around 1 million hectares are irrigated with surface water or groundwater (USDA-NASS, 2018). The overexploitation of these natural resources threatens the sustainability of irrigated agriculture in the western United States (Anapalli et al., 2019). Addressing Colorado's water challenges relies heavily on water tracking and accounting. Colorado water law mandates that historical crop consumptive water use (CU), or evapotranspiration (ET), guide water withdrawal amounts for irrigation (Allen et al., 2011; State of Colorado, 2015). The difficulty is that one standard ET rate per crop does not reflect the microclimates within the state or region. CU is affected by climatic conditions, soil types, stress conditions, and length of the growing season (A. A. Hanson, 1988).

To properly irrigate crops, a water budget must be developed (Hanson & Kehr, 1972). Key components in a water budget include ET, runoff, precipitation, irrigation, soil water, and system losses. The water budget approach consists of estimating crop water requirements and applying irrigation until the soil moisture depletion is filled (Shewmaker et al., 2013; Zinkernagel et al., 2020). Specific crops require different amounts of water based on rooting depth, leaf area, growth stage, and climatic conditions (Allen, 1998), thus field level data is needed to create a water budget. ET derivations at the local field level can require expensive equipment and labor-intensive monitoring as is the case when using lysimeters (Allen, 1998). Alfalfa (tall) reference ET calculated from the American Society of Civil Engineers (ASCE) Standardized Reference ET (ET_{rs}) Penman Monteith equation estimates potential ET under local weather conditions at full canopy under no water stress (Allen et al., 2005, 2011; Evett, et al., 2000). Reference ET is applied for consistency and reproducibility in estimating near maximum ET (Allen & Jensen, 2015). Evett, et al. (2000) showed that alfalfa is a better reference crop than grass when using the Penman Monteith equation. The ET_{rs} can then be used with appropriate crop coefficients (K_c) and water stress coefficients (K_s) to estimate actual crop ET (ET_c) (Allen et al., 1998).

Effective irrigation management avoids over irrigation, thus, reducing non-point source pollution of surface or groundwater. Unmeasured irrigation tends to waste water, nutrients, and energy and may cause soil degradation by waterlogging, erosion, and salination (Eisenhauer et al., 2021). Precise irrigation is based on the soil-plant-water relationship which determines the timing and quantity of water application needed. Recently, several studies have suggested precision irrigation increases the crop production and conserves water (Sadler et al., 2005; D. Zhang & Guo, 2016). The vital task of assuring adequate global food production must include a concerted effort to modernize irrigation systems and improve water management (Eisenhauer et al., 2021). In the future there will likely be a need for limited irrigation due to planned scenarios like water sharing or unplanned scenarios like drought. Precise irrigation scheduling requires knowledge about the soil water holding capacity, crop development, and crop water requirements that can be difficult to track in the field. An irrigation scheduling model was created at Colorado State University to simplify soil water balance calculations and determine real-time irrigation water demand at the field level (A. A. Andales et al., 2014).

WISE

The Water Irrigation Scheduling for Efficient Application (WISE) tool was developed to simplify tactical irrigation management decisions (A. A. Andales et al., 2020). WISE provides access to field-level information on the soil water deficit that can be used to estimate the irrigation requirement of several crops. Soil water deficit is the net irrigation needed to satisfy the plant's need; and if applied, avoids over- or under-irrigating (Allen & Jensen, 2015). By automating the daily calculation of ET_c from weather data, crop coefficients based on growth stage, and calculation of the soil water balance, information on the amount of water needed to refill the root zone up to field capacity (i.e., soil water deficit) can be used to recommend precise irrigation decisions (A. A. Andales et al., 2014). WISE has been tested by individual farmers, crop consultants, conservation engineers, water managers, and researchers in Colorado. To determine the specific crop water requirements, the K_c represents the effect of canopy development on ET_c. This K_c method has been accepted for many crops in different climatic conditions (Allen, 1998; Allen & Pereira, 2009). Adaptations to K_c curves have improved WISE model estimates of the soil water deficit on alfalfa and sugar beets (A. A. Andales et al., 2009, 2020). Improved water management through the use of tools such as WISE can result in water conservation, prevention of water pollution, and enhanced crop productivity.

Alfalfa

Alfalfa (*Medicago sativa L.*) is an important crop in Northeastern Colorado, providing nutritious feed for cattle but it is a water intensive plant. Seasonal consumptive water use of alfalfa, also known as ET_c, is between 800 and 1600 mm which is double that of other crops like maize (Shewmaker et al., 2013). Alfalfa is a drought and salinity tolerant crop despite its large CU. The CU varies from 1.4 to 14 mm/d (A. A. Hanson, 1988). Rooting systems of alfalfa can range from 1.5 to 4.5 m to utilize deep soil moisture (A. A. Hanson, 1988). In Northeast Colorado, flood irrigation is primarily used for alfalfa production. Improving irrigation scheduling for forage crops could conserve water quantity and quality as well as increase production (Sadler et al., 2005; Zinkernagel et al., 2020).

Objectives

The objectives of this study were to: (1) evaluate the accuracy of alfalfa crop ET_c and soil water deficit (D) simulations from WISE against observed ET_c and D calculated from soil water balance of subsurface drip-irrigated alfalfa fields in Northeast Colorado under different irrigation levels; (2) improve the WISE alfalfa ET_c estimates by making mid-season corrections in modeled soil water deficits; and (3) identify possible modifications in WISE that may improve alfalfa ET_c and D simulations.

Methods

Meteorological Data

A weather station funded by United Water and Sanitation District and operated by the CSU Agricultural Meteorological Network (Colorado State University, 2022) is located at 40.38°N, -

104.53°W. It has been recording data since January 1, 2015. The station's name is Kersey 2 (ID name: KSY02). It is located 15 m away from the irrigated alfalfa fields with natural vegetation directly surrounding it. The 3-year average weather station data is provided in Table . Missing data in the Kersey 2 CoAgMet station was filled with the Greeley 4 CoAgMet station located 24 km northwest of the study location.

Table 3.1. Monthly weather data from the Kersey 2 CoAgMet station averaged over 3 years (2020-2022).

Month	Average Temperature (°C)	Average Precipitation (mm)	Average Solar Radiation (W/m^2)	Average Wind Speed (m/s)	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 evapotranspiration for alfalfa is based on weather station parameters and the ASCE Standardized tall reference ET equation.

Site Monitoring

Eight alfalfa fields, ranging from 1.4 to 2.1 hectares, at the Subsurface Irrigation Efficiency Project (SIEP) research farm located near Kersey, CO were monitored weekly during the growing seasons between 2020 and 2022. Each field was equipped with Netafim Typhoon's Subsurface Drip Irrigation (SDI) system buried at a depth of 25.4 cm with a tape spacing of 76 cm (30 in). The irrigation capacity is 1703 liters/min (450 gpm, 0.03 m^3/s). Flow meters located at each field recorded the amount of irrigation water applied. Four irrigation treatments were implemented to compare the effects of deficit irrigation on alfalfa ET. Target irrigation levels were based on soil water deficit (D) replacement where the standard irrigation level triggers irrigation when D equals or exceeds the management allowed depletion (MAD), which was set at 50% of soil available water capacity. Each irrigation treatment was implemented in two zones (Table 3.2). In the spring of 2022, the zones and treatments were switched to investigate alfalfa recovery after deficit irrigation. Soil moisture was measured using a neutron moisture meter, NMM, (CPN 503 Hydroprobe, InstroTek, San Francisco) at 30-, 60-, 90-, 120-, and 150-cm depths from the soil surface. Soil bulk density was calculated for each measurement depth following procedures from Dickey et al. (1993). Soil volumetric water content was calculated from NMM count ratios using a linear calibration equation (Dane et al., 2002) for two soil types found in the fields, Nunn and Colombo with a clay loam texture (Appendix i). A separate calibration was performed on the topmost soil layer to reduce total error. Gravimetric soil samples from each layer were used to calculate volumetric water content for initial moisture and calibration. The resulting calibration equations were used to convert neutron count ratios to volumetric water content for the given depth of measurement (Table 3.3). The volume of water from each NMM sample depth was multiplied by the layer depth and summed together to get the current soil water content. Soil deficit observations were determined by subtracting the current soil water content from the field capacity of the root zone.

Table 3.2. Target irrigation levels based on soil water deficits (D)and corresponding zones.

Treatment	Zones	Target Irrigation[a]
1	9 and 10	Standard
2	8 and 19	Medium
3	17 and 18	Low
4	7 and 16	High

[a]Standard = irrigate when D ≥ MAD; Medium = apply 70% of Standard; Low = apply 50% of Standard; High = apply 120% of Standard.

Table 3.3. Descriptions and soil water calibration equations of each soil type found on the study site.

Soil Type	Field Capacity of 150cm Rooting Zone (cm)	Soil Layer Depth (cm)	Soil Density (g/cm^3)	Calibration Equation
Nunn	48.42	0-30	1.08	Y=0.1645x-0.012
		30-60	1.46	Y=0.1638x
		60-90	1.39	
		90-120	1.46	
		120-150	1.75	
Colombo	40.37	0-30	1.06	Y=0.1645x-0.13
		30-60	1.50	Y=0.1645x
		60-90	1.39	
		90-120	1.53	
		120-150	1.46	

With the water content measured from the NMM, a simple water balance approach was used to calculate the alfalfa ET_c (mm) that occurred between measurements (Equation 1):

$$ET_c = \Delta SWC + Irr + P \qquad [1]$$

where ΔSWC is the change in soil water content (mm), and *Irr* is the net irrigation amount (mm) and *P* is the effective precipitation (mm). Change in soil water content between measurement periods represents the difference in available water at different depths of the soil profile. *Irr* was calculated as gross irrigation (mm) multiplied by 0.95 application efficiency for SDI systems. The *P* was calculated by subtracting estimated surface runoff (USDA-NRCS, 2004; curve number (CN) approach with CN = 85) from rainfall measured by the CoAgMet rain gauge. The assumed 0.95 application efficiency accounted for evaporation losses from the soil surface via capillary movement from the SDI emitters. Deep percolation and capillary rise from a shallow water table were assumed negligible because of the stable NMM readings observed at 1500 mm depth.

WISE

The WISE model uses a crop coefficient curve (Allen & Pereira, 2009) to determine non-stressed ET_c in a specific field with unique soils and irrigation systems. Soil information including types, depths, and water holding capacity are queried from the Natural Resources Conservation Service (NRCS) Web

Soil Survey (https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm). Basic meteorological data as well as estimated reference ET_r data are acquired from Colorado Agricultural Meteorological Network (CoAgMet) stations. The user inputs gross irrigation and initial soil moisture depletion, then the model calculates daily total soil water deficit (D) and ET_c based on the crop type and management allowed depletion (MAD) level. The model keeps track of D in the root zone using equation 2 (Andales et al., 2014):

$$D_c = D_p + ET_c - P - Irr \qquad (\text{if } D_c < 0, \text{ then } D_c = 0.0) \tag{2}$$

where D_c is the soil water deficit on the current day, also known as the difference between field capacity and current soil water content in the root zone, D_p is the soil water deficit on the previous day, P is the gross precipitation for the current day, Irr is the net irrigation amount (gross amount × irrigation efficiency) infiltrated into the soil for the current day, and ET_c is the crop evapotranspiration rate for the current day. Crop evapotranspiration is calculated with equation 3:

$$ET_c = ET_r \times K_s \times K_c \tag{3}$$

where ET_r is the ASCE standardized tall reference ET from the CoAgMet station, K_s is the crop stress coefficient, and K_c is the crop coefficient. K_s is based on the soil water deficit below MAD where $K_s < 1$ for water limited conditions and $K_s = 1$ when there is no water stress. Crop coefficients are the ratios between non-stressed ET_c and ET_r derived from field studies. Alfalfa K_c curves were developed from precision weighing lysimeter data at Rocky Ford, CO (Andales et al., 2009).

Manual adjustments to the WISE model were made to better represent alfalfa, a perennial crop harvested multiple times during the growing season. Harvest dates are manually entered and the growing degree day (GDD; °C·d) calculation (see equation 3 in Andales et al., 2020) updates the crop progress toward maturity after every harvest. WISE calculated GDD for the first harvest to be 544°C·d, and the rest of the seasonal harvests was 708 °C·d. MAD was set at 50% for alfalfa. Spring green-up date and depth of root zone is needed to initiate the model. Site specific adjustments were made to represent field-level processes such as effective water calculation including the irrigation efficiency of subsurface drip irrigation systems (95%). For improved runoff estimation, the CN was set to 85 (USDA-NRCS, 2004) representing alfalfa field conditions (close-seeded legumes; straight rows in good condition; hydrologic soil group D). Capillary rise from a shallow water table was assumed to be negligible because the study site had a relatively deep groundwater table (e.g., 6.7 m to 7.6 m below ground surface measured in July 2019). Two WISE models were created, one for each soil type using the NRCS SSURGO database for Colombo and Nunn soils. Each zone was modeled using soil hydraulic properties in the1500-mm managed root zone.

Analysis

WISE model outputs of ET_c and D were compared to observed ET_c (Equation 1) and D values derived from NMM measurements of volumetric soil water content. The NMM has been established as an accurate measurement of soil water content. Error metrics of Mean Absolute Error (MAE), Root Mean Square Error (RMSE), Mean Bias Error (MBE), Relative Error (RE), Index of Agreement (IA), and Nash-Sutcliffe efficiency (NSE) were evaluated (Hodson, 2022). For each zone (field), two versions of the WISE model were tested. One included only an initial D and allowed the model to estimate the succeeding daily D throughout the season; the other included mid-season corrections of D where observed D values were manually inputted to override WISE-calculated D values on dates when NMM readings were taken. To test if WISE performed well under water-stressed (deficit) conditions, four different irrigation levels (i.e., actual irrigation amounts measured from the field study) were imposed on the modeled alfalfa crops using WISE.

Results

Observed Water Inputs and Alfalfa ET_c

The average annual precipitation is less than 274 mm of which 75-80 % falls during the growing season between April and September. Cumulative precipitation for the growing season was 106 mm, 138 mm, and 117 mm for 2020, 2021, and 2022, respectively (Table 3.4). Subsurface irrigations were applied at a depth of 25.4 cm below the surface via subsurface drip at rate of 0.03 m^3/s. Irrigations could not start until the last frost, typically May 14th in Northern Colorado, to prevent pipelines from freezing and bursting. It was assumed that the soil was at field capacity at the start of modeling efforts. Soil water content from the NMM was deducted from field capacity to obtain soil water deficit values. Field monitoring started on May 27th and ended on August 12th, in 2020 and June 16th and September 22nd in 2021. During the two-to-three-month monitoring period the ET_c of alfalfa exceeded natural precipitation.

Table 3.4. Components of the soil water balance from seasonal observational data on alfalfa.

Year	Precipitation (mm)	Treatment	Irrigation (mm)	ET_c (mm)
2022	117	Standard	353.9	559.2
		Medium	264.5	391.4
		Low	231.5	627.2
		High	358.9	638.0
2021	138	Standard	269.2	345.1
		Medium	145.6	240.1
		Low	111.5	297.8
		High	299.7	259.2
2020	106	Standard	708.9	557.7
		Medium	339.5	412.3
		Low	240.2	278.8
		High	617.4	411.7

The ASCE Standardized ET_r equation represents ET from a hypothetical uniform surface and dense alfalfa crop with a canopy height of 50 cm with no water stress. WISE was found to adequately simulate cumulative ET_c for the standard level of irrigation (i.e., irrigations applied when D exceeds MAD). For example, WISE cumulative ET_c in 2021 for zone 10, standard irrigation, agreed well with observed cumulative ET_c (Figure 2.1).

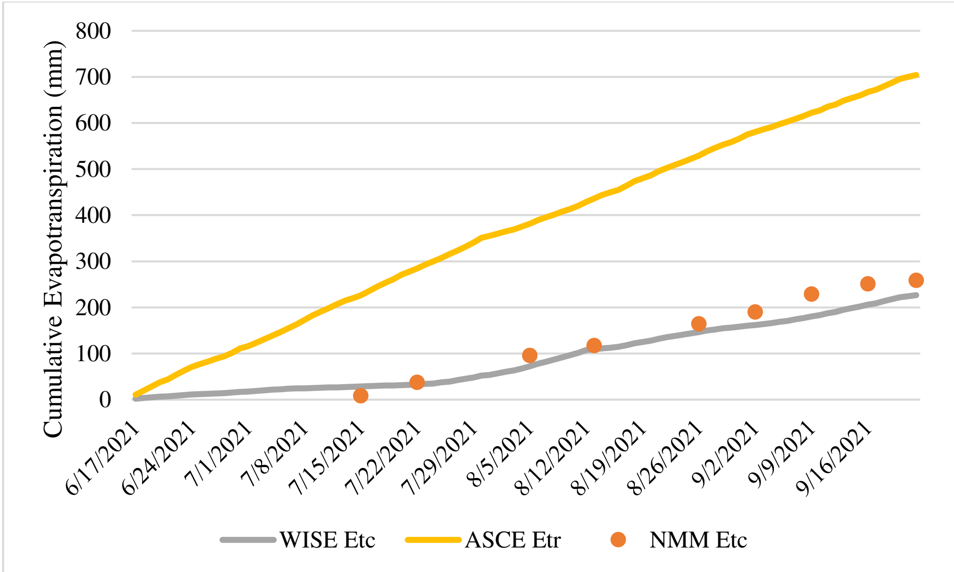

Figure 3.1. Cumulative alfalfa ET_c simulated by WISE (WISE ET_c) compared to observed ET_c Calculated from Equation 1 (NNM ET_c) in 2021 for Zone 10, standard irrigation. Cumulative reference ET (ASCE ETr) shows the high evaporative demand caused by semiarid conditions.

Model Output and Improvement

Output from the WISE model provides components of the water balance equation. Figure 3.2 shows an example of the applied irrigations, precipitation events, and modeled ET_c compared to ET_r for the 2020 growing season. The greatest difference between ET_r and WISE ET_c occurs during the peak of summer when daytime temperatures exceed 30°C, creating a more stressful and water demanding environment for the crop, an example of this discrepancy. Figure 3.2 shows the difference in ET_r and ET_c for Zone 10 in 2020. WISE modeled ET_c was in good agreement with observed data as a representative of the output, Zone 10, standard irrigation level in 2020 is shown having a RMSE of 15.91 mm and R^2 of 0.9 (Figure 3.3A). The soil deficit calculation had an even better correlation with observed NMM measurements with an R^2 of 0.99 and a relative error of 0.33% (Figure 3.3B). WISE captured observed fluctuations in soil moisture deficit throughout the growing season.

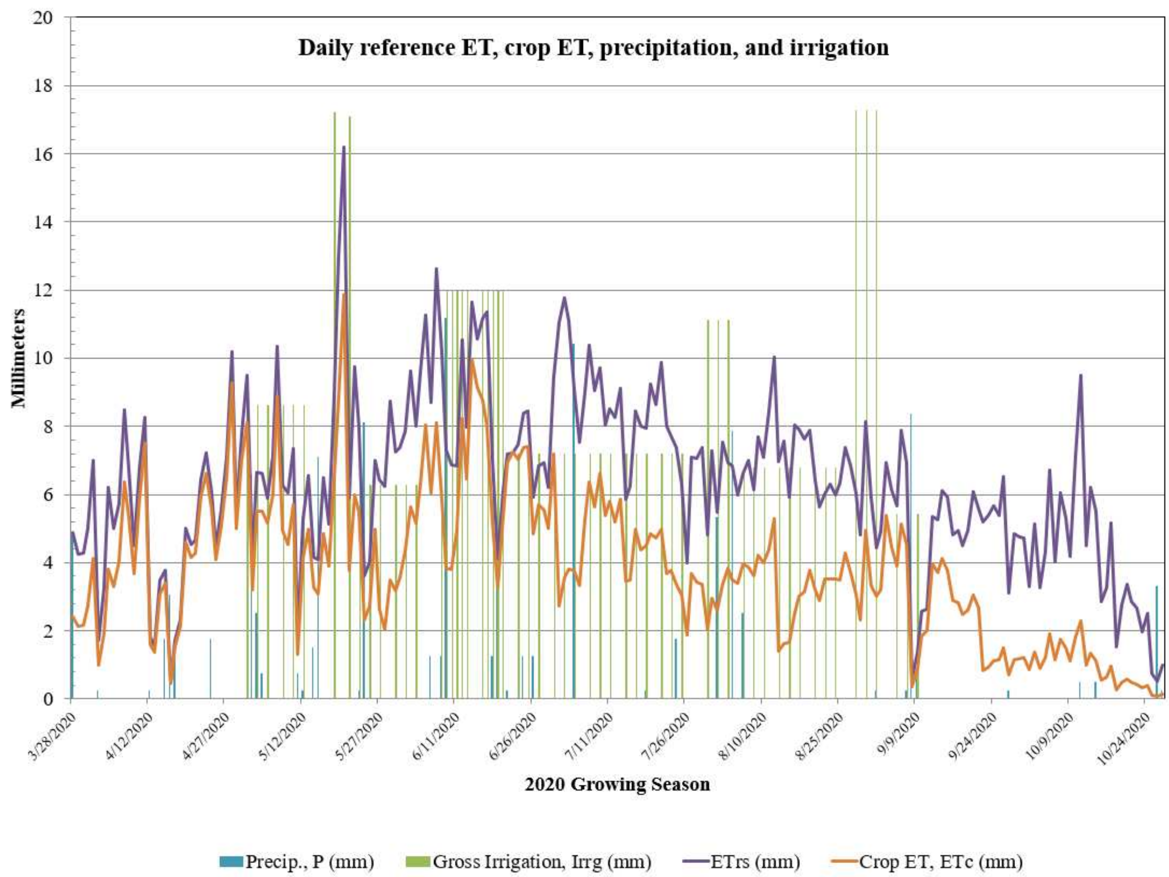

Figure 3.2. WISE water balance model output from Zone 10, 2020.

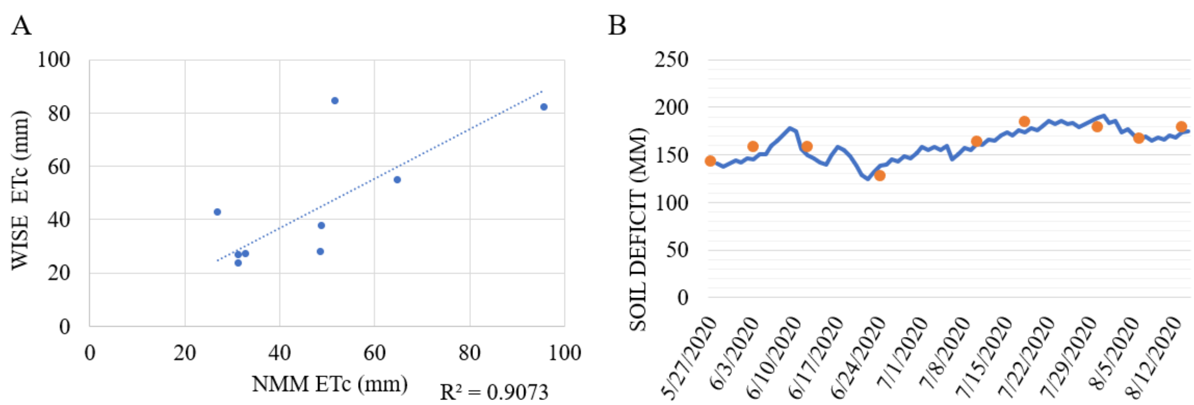

Figure 3.3. A) Observed ET_c calculated from the NMM (NMM ET_c) compared to WISE modeled Et_c for Zone 10, standard irrigation in 2020. B) Soil water deficit modeled by WISE compared to the observed NMM soil water deficit (dots) for Zone 10, standard irrigation in 2020.

Timing and amount of irrigation water is crucial for maintaining soil moisture levels that are optimum for plant growth. As an example of WISE performance under low irrigation (50% of standard irrigation), the WISE output for Zone 18, is shown in 2021 (Figure 3.4). Soil water deficit, D_c, exceeded the MAD level on June 29th, 2021, but was able to come back up to MAD level (horizontal line in Figure 3.4Figure) through applications of irrigation in conjunction with a large rainfall event. Similar patterns occurred throughout the season with high deficit levels.

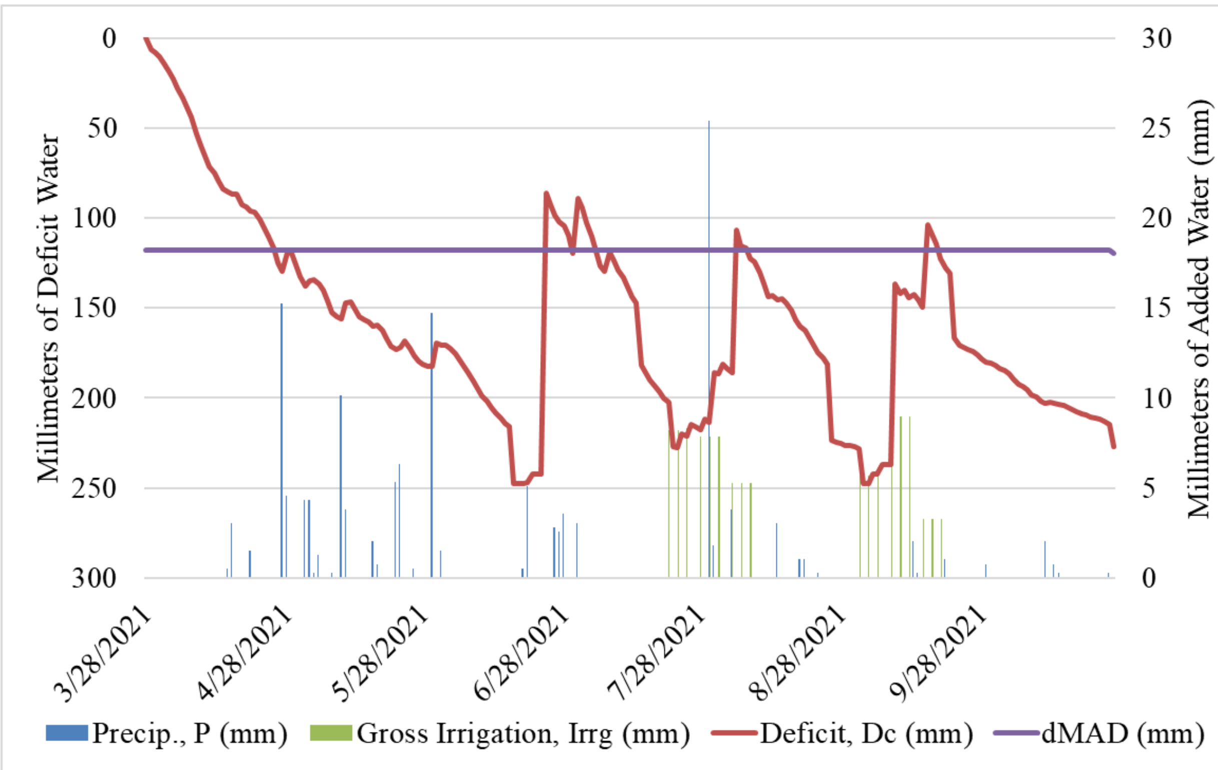

Figure 3.4 Soil deficit estimations for Zone 18, low irrigation in 2021 from WISE plus precipitation and irrigation events with management allowed depletion level in purple.

For improved simulations of ET_c and D, mid-season corrections in D were made when observed D values were available from NMM readings. The corrections of D in the model resulted in reduced ET_c errors for both the standard (Treatment 1) and low irrigation (Treatment 3) levels (Table 3.5). Note that irrigation levels in zones were switched in 2022. In Zone 10, under standard irrigations in 2020, the mean absolute error dropped from 13.5 to 10.8 mm when corrections to D were made. WISE generally performed better in estimating ET_c under standard irrigation compared to low and medium irrigation levels. The more stressed treatments produced larger relative errors and percent bias in 2020 and 2021 (Table 3.5). Figure 3.5 A and B show model simulations with and without the soil deficit corrections (Figure 3.5A) and corresponding ET_c (Figure 3.5B). For low irrigation levels (i.e., greater D), WISE tended to overestimate D and underestimate ET_c because of more severe simulated water stress.

Table 3.5. WISE ET_c error metrics for 2020 -2022 with bold values showing model improvement after mid-season corrections of D.

Year		**2020**		
	Treatment 1		Treatment 3	
Statistic[a]	Z10	Z10 Corrected	Z18	Z18 Corrected
MAE (mm)	13.501	**10.785**	13.459	**12.071**
MBE (mm)	-2.626	**-2.340**	-4.189	8.024
RMSE (mm)	15.907	**12.992**	16.767	**15.501**
RE (%)	-5.475	**-4.879**	-13.155	25.199
IA	0.843	**0.912**	0.559	0.387
NSE	0.399	**0.662**	-0.477	-5.191
Year		**2021**		
	Treatment 1		Treatment 3	
Statistic[a]	Z10	Z10 Corrected	Z18	Z18 Corrected
MAE (mm)	13.555	**10.735**	37.338	**25.789**
MBE (mm)	-7.383	**6.958**	-37.338	**-13.033**
RMSE (mm)	16.150	**13.493**	42.779	**27.937**
RE (%)	-26.228	**24.721**	-76.056	**-25.547**
IA	0.647	**0.859**	0.456	0.404
NSE	-0.056	**0.437**	-2.586	**-0.529**
Year		**2022**		
	Treatment 1		Treatment 3	
Statistic[a]	Z18	Z18 Corrected	Z10	Z10 Corrected
MAE (mm)	24.380	**23.185**	12.815	**9.694**
MBE (mm)	-16.863	**-5.712**	0.247	-4.611
RMSE (mm)	31.811	**28.853**	15.434	**12.131**
RE (%)	-39.966	**-13.537**	0.988	-18.413
IA	0.506	**0.583**	0.899	**0.902**
NSE	-0.171	**0.035**	0.657	**0.670**

[a]Statistics: MAE = mean absolute error, MBE = mean bias error, RMSE = root mean squared error, RE = relative error, IA = index of agreement, NSE = Nash-Sutcliffe efficiency, Z10 = Zone 10, Z18, Zone 18.

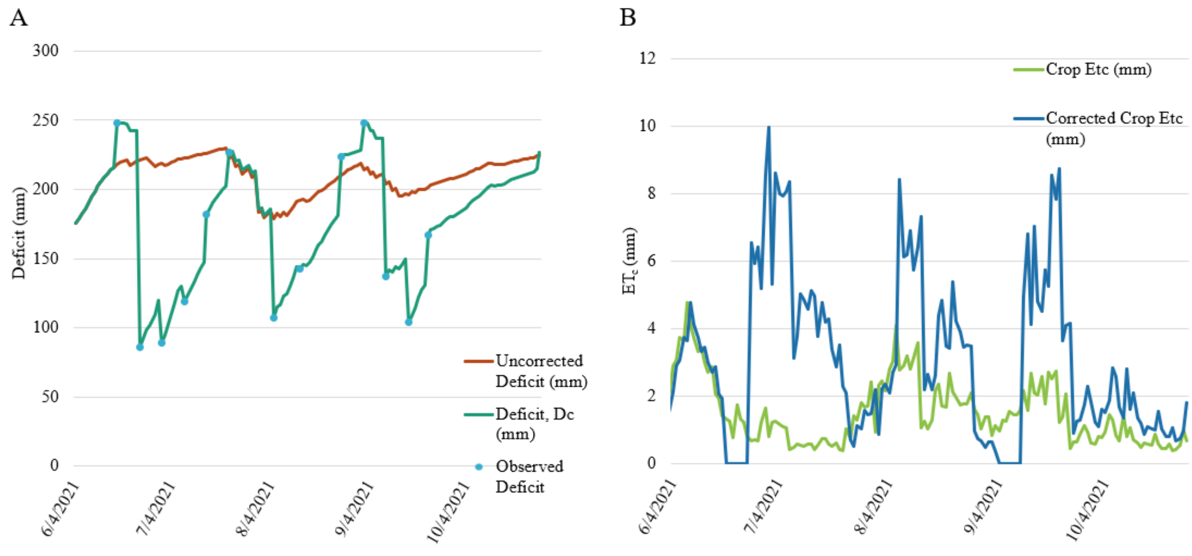

Figure 3.5. A) WISE model corrected with observed D in Zone 18, 2021. The green line is not corrected with observational deficit data while the blue line is corrected with NMM observed deficit. B) Simulated Crop ET (ET_c) with and without corrections based on observed deficit values, Zone 18, low irrigation level, 2021.

Sources of Errors and Possible Model Modifications

All estimates of ET_c contain some error whether it be systematic or random (Allen et al., 2011). Some dramatic decreases in soil water content can be attributed to harvest times where irrigations were stopped to allow harvested hay to dry in windrows. The evaporation of plant water during the drying period after harvest was not modeled in WISE. The daily time step of the model can introduce sources of error. When irrigations happen after the workday, they should not be counted in that days' water balance because NMM readings were taken in the morning. Alfalfa is sensitive to water stress when in the regrowth period after harvest which can create a difference in actual crop coefficient values and the ones used in WISE that were determined from Rocky Ford, CO lysimeter studies (Andales et al., 2009). The K_s values are dependent on soil water holding capacities calculated from SSURGO data, which may not represent field conditions. This simple equation for K_s did not seem to work well for high water stress situations in the low and medium irrigation treatments and with alfalfa's ability to root deeper to find sources of moisture. Zone 17 in 2021 with low irrigation levels is an example of this problem in WISE.

The NMM returned water amounts that were below the wilting point for the entire 1.5-meter sampling depth, although the plant showed growth during this period.

Measuring the change in soil water over a period of time has been used to determine ET_c for nearly a century but major sources of uncertainty come from soil drainage and upward water movement (Allen et al., 2011). There are possible sources of error in the calculation of initial and final soil water content, and the calculation of effective water used in this analysis. Field-calculated soil bulk densities differ from reported SSURGO densities creating error between the measured soil deficits and calculated deficits in WISE. Effective water assumes 95% of the irrigation reaches the plant root zone, which can be an overestimate in dry, water demanding climates. Irrigation application efficiencies, which was assumed constant in WISE, could change according to SDI system performance (e.g., leaks or emitter plugging could reduce efficiency). In the water balance calculation, some potential sources of error could be:

- Residual moisture in neutron access tube can create a false moisture level and errors in subsequent conversion to volumetric water content.
- Alfalfa roots tapping into moisture sources below measured depth.
- Ignoring surface runoff (during rainfall events), deep percolation, or capillary up flux when they could be happening in the actual field water balance.
- There could be errors in the flow meter readings used to estimate irrigation amounts, especially if leaks occurred past the flow meter.
- Gravimetric soil sample errors due to evaporation occurring from field site to electronic scale.
- Crop coefficients from the lysimeter data were from southeast Colorado with furrow-irrigated alfalfa, so they may be too high especially for the regrowth periods after harvests.

Discussion

Relative error and root mean square error of WISE ET_c decreased when observed soil deficits were input in the model. The addition of observed soil deficit measurements corrects the model to field-level, resulting in an improved water balance model for tracking and accounting CU. Similarly,. Liu et al., 2022) determined that the soil water balance method was in good agreement with measured values. WISE provides quick access to the information needed for efficient irrigation scheduling for producers, managers, and researchers (Bartlett et al., 2015).

Correcting the WISE model with observed soil deficits improved model output. However, the corrected model generally tends to underestimate ET_c with a negative mean bias. Wise simulated Zone 10 better than Zone 18 in all years. Zone 10 was the zone where soil samples were taken from to perform the NMM calibration. Thus, soil water content measurements from NMM and corresponding observed deficits were probably most accurate in Zone 10. This highlights the importance of using field-specific soil parameters and sensor calibrations in modeling the soil water balance for irrigation scheduling.

It is concluded that the WISE simple water balance method can adequately estimate actual crop water needs when augmented with observational soil water content data. WISE was able to predict the ET_c values well for the less water stressed irrigation treatment. Water stress conditions from deficit irrigation treatments were problematic for WISE when trying to predict soil deficit and evapotranspiration. The K_s value hit the minimum multiple times in the medium and low irrigation levels, returning zero ET_c on some days even when site observations showed active plant growth. This may also be evidence that alfalfa roots were tapping into deeper moisture than observed from the 1.5 m NMM access tubes. The effective rooting depth of alfalfa is 1.8 m (6 ft) with mean root length of 2.3 m (7.5 ft) (Adhikari & Missaoui, 2017) although individual taproots may exceed 6 m (20 ft) (Bauder, 2020).

It is increasingly important to understand the value of water monitoring and modeling for future crop production in a water scarce environment. Decision tools such as WISE can be used for efficient irrigation scheduling and avoiding crop stress by tracking the soil water deficit and irrigating when it approaches the MAD level. The model follows the measured data well but tends to underestimate ET_c. Studies suggest alfalfa can do well at a MAD level of 55-60% (Bauder et al., 1978; Hanson et al., 2000) and, if implemented into WISE, would reduce the simulated stress (i.e., increase K_s) and increase simulated ET_c. Some suggested improvements to the WISE model are to fine tune K_s calculations with more detailed alfalfa ET_c measurements (e.g., daily instead of weekly water balance measurements). A 24-hour time step in water balance measurements would avoid timing issues with irrigation and precipitation events that are lumped when using weekly or longer time steps. Furthermore, hourly time steps would capture the diurnal curve of ET_c.

Conclusions

WISE has the ability to model ET_c of subsurface drip-irrigated alfalfa fields under different irrigation levels. However, treatments with more water stress were poorly modeled in WISE due to the possibility of alfalfa roots accessing soil moisture at greater depths than measured. When soil water content is monitored and implemented in WISE with mid-season corrections, better estimates of actual ET_c and D are produced. Updating WISE soil water balance equation with observed data more frequently may improve simulations. Potential research on modeling an array of deficit irrigation management practices would improve the relevancy of WISE in a water stressed future.

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CHAPTER 4: CONCLUSIONS AND RECOMMENDATIONS

The goal of this research was to assess the feasibility of reducing alfalfa consumptive water use (CU) through deficit irrigation using subsurface drip irrigation (SDI) in northeastern Colorado. Information on alfalfa yield, forage quality, and CU under various levels of SDI can help make water conscious decisions for the future of alfalfa production in water short circumstances. The results helped identify possible solutions to future water challenges by exploring the feasibility of alfalfa deficit irrigation and SDI practices that could enable water sharing as envisioned in the Colorado Water Plan (Colorado Water Plan Update, 2022).

Alfalfa is a good crop to use for deficit irrigation because of its increased water use efficiency (WUE) at low water applications and its ability to recover after deficit treatments. It is an option for alfalfa farmers interested in leasing water rights through the Collaborative Water Sharing Agreements (CWSA) to implement the most efficient irrigation system to prevent excess water losses. The increased irrigation efficiency of subsurface drip irrigation can maintain a profitable alfalfa crop while saving consumptive water. This study provides some evidence that deficit irrigation of alfalfa could provide CU savings that may be used in alternative water transfer methods.

The Water Irrigation Scheduler for Efficient Application (WISE) tool can model CU of deficit irrigated alfalfa for improved irrigation management. However, crop water stress affects the ability for plants to transpire (Allen, 1998), thus making it difficult for WISE to accurately model reduced alfalfa CU using the conventional water stress coefficient (K_s). Further adjustments to the alfalfa crop coefficient (K_c) and improvements to the water stress function in WISE are recommended. It was found that mid-season corrections of the soil water deficit can improve the accuracy of WISE estimated CU.

Farm profit through leasing of saved CU can be made if the cost of water exceeds the alfalfa hay price after expenses. It is understood that there is a big investment to establish an alfalfa stand which can provide profit for many years. Thus, it is not our goal to persuade farmers to switch to alfalfa but rather for current alfalfa farmers to consider deficit irrigation as a possible mechanism to gain additional income through CWSA. Pre-season considerations for farmers are to determine if water is available season-long and what the price for 1-AF of water is for leasing.

We discovered a management gap between the results of proposed SDI methods and practical application of the methodology. Most previous research on alfalfa water consumption and deficit irrigation performance has been conducted in small-scale experimental plot settings and using conventional irrigation technology. On a production scale farm, it is hard to be accurate and precise in scheduling irrigations, in timing of harvest, and in bailing biomass per zone suitable for precise scientific analysis (e.g., statistical analysis). The technical and economic viability of modern irrigation technologies and practices must also be demonstrated at scales if they are to find wider acceptance among producers. Therefore, production scale scientific research like our study is needed to close the management gap between small plot-scale studies and large-scale agricultural production. We found limitations of the SDI controller produced timing issues to allow enough time for each zone to be irrigated fully. The designed 450 GPM flow rate of the SIEP SDI system was not achieved in many instances when leaks, valve issues, and required repairs/maintenance affected system operations. SDI is also susceptible to freezing conditions early in the season, making it difficult to fill the soil water up to field capacity in early spring, resulting in plant stress when there is low precipitation before first irrigation.

Standard harvest management practices were implemented, with alfalfa windrows left on the field to dry down to marketable moisture content. During these times, the SDI system could not be operated because of traction or soil compaction concerns with heavy harvesting equipment. Relative Feed Value (RFV) drops the longer it stays in the windrows if harvest is delayed, so baling was completed as soon as weather conditions permitted. It is recommended to shut off irrigations right before harvests so farm equipment will not get stuck in wet soil. Our experience indicated this does not happen with SDI, but field observations of soil moisture is essential. Greater yields could have resulted with longer SDI run times, creating an additional economic gain. Stand density and root health inspections would have aided this research and is recommended for future research. As with any irrigation system, SDI comes with regular maintenance and management challenges. Overall, this study found that SDI was able to produce production scale alfalfa hay at supreme qualities and saved consumptive water for possible CWSA.

Results from this 5-year study were made available to the public through educational pamphlets and conference presentations in 2022 at the American Water Resources Association (Colorado Chapter) Conference and the Colorado Water Congress. Chapters 2 and 3 of this thesis will be submitted to peer reviewed journals for possible publication. In addition, fact sheets will be developed for distribution to producers and irrigators though Colorado State University Extension.

APPENDIX i: NEUTRON MOISTURE METER CALIBRATION PROCEDURE

Calibration of the neutron moisture meter probe determines a relationship between neutron probe count ratios and volumetric water content (Dane et al., 2002). The resulting volumetric water content is used in a soil water balance equation to solve for evapotranspiration. Site specific field calibrations are needed for accurate measurements of soil moisture content. The following procedure was used at the Subsurface Irrigation Efficiency Project (SIEP) research farm located in Kersey, CO.

Required Materials

- 5.08 cm (2") diameter soil auger and extensions
- Neutron tube (e.g., 1.5" pipe) of desired length
- Madera probe, extender, putty knives, and large bolt
- Soil Tins/Ziploc bags
- Sharpie
- Neutron moisture meter (NMM) CPN 503, Instro Tek Inc.
- Tube puller (i.e. muffler puller)
- Handyman jack or Giddings Probe
- Drying Oven
- Weighing scale

Field Procedures

1. Use soil auger to drill a hole to the depth where the desired NMM reading will be taken (e.g. 15cm). These depths will be determined by the stopper placement on the NMM cable.
2. Use Madera probe and extender to take a soils sample at that depth, careful to not disturb the soil, ensuring an accurate representation of the soil structure at that depth
3. Use putty knives and large bolt to clip soil sample and push it out of the Madera probe into a soil tin or Ziploc bag, ensuring no moisture is lost and label location and depth with sharpie

4. Repeat steps 1 – 3 for each desired depth of NMM measurement (e.g., 15 cm, 30 cm, …, 150 cm)
5. Place neutron tube into auger hole, and use nearby loose soil to fill around pipe, ensuring good soil-pipe contact. You may want to wiggle the pipe around as you backfill to help the soil reach the bottom of the auger hole.
6. Place NMM on newly installed neutron pipe, take a standard count, and then take neutron count measurements at each soil depth. Record values for calibration.
7. (If the neutron tube will not be permanently installed, else skip to step 8) Use tube puller and handyman jack to remove neutron tube, then backfill hole
8. Repeat steps 1 – 7 as many times as necessary at a single location to obtain sufficient soil samples to perform a linear calibration (minimum of 3 samples).
    a. Note: The number of samples needed depends on changes in soil texture and bulk density across locations and depths. A separate linear calibration must be made for each significant change in texture and bulk density.

Lab Procedures

1. Remove soil tin lid and use weighing scale to record the weight of wet soil plus the soil tin.
2. Place lidless tin with wet soil into baking oven to dry for at least 24 hours at 105°C
3. Record weight of dry soil

Calibration Analysis

1. Calculate gravimetric water content (GWC), bulk density (BD), and then volumetric water content (VWC) from the following equations:

GWC = [(Weight of wet soil and tin−weight of tin) − (Weight of dry soil and tin−weight of tin)] ÷ (Weight of dry soil and tin−weight of tin)

$$\mathbf{BD} = (\text{Weight of dry soil and tin} - \text{weight of tin}) \div \text{Volume of Madera probe sample}$$

$$\mathbf{VWC} = \text{GWC} \times \text{BD}$$

2. Normalize NMM data by standard count
   a. To determine the normalized neutron count for calibration (*f*), each NMM measurement (*m*) at depth (*i*), must be normalized by the standard count (*c*) for each location (*j*) using the following ratio:

$$f_{i,j} = m_{i,j} \div c_j$$

3. Clean data prior to calibration
   a. Check for outliers due to measurement, calculation, and other errors. Remove outliers as appropriate
4. Create linear model to calibrate *f* to VWC
   a. Using ordinary least squares regression, create a linear model relating *f* to observed VWC:

$$\text{VWC} = \text{m}(f) + \text{b}$$

Where *m* and *b* are empirically fit slope and intercept parameters, respectively.

5. Check model fit
   a. Use the coefficient of determination (R^2) and root mean squared error (RMSE) to determine the goodness of fit of the linear model.
   b. Some guidelines
      i. R^2 should be greater than 0.85
      ii. RMSE should be less than 0.01 $cm^3\ cm^{-3}$

Results

At the SIEP experimental research field, Zones 10 and 16 were chosen as calibration plots to represent the two different soil types, Colombo and Nunn respectively. Soil samples were gathered on

10/4/2021 and 4/7/2022 to capture the range of soil moisture levels. October represents the dry field after irrigations have been shut off and April represents naturally saturated soils after the winter's snow has melted and is stored in the soil. It is common for neutron probe readings in the shallow depths to be inaccurate due to the loss of neutrons to the surface. The shallow depth (0-30 cm) reading has a separate calibration equation to adjust for the loss of neutrons.

Table i.1. Bulk density results from soil samples in two soil types.

Depth (cm)	Colombo Bulk Density (g/cm^3)	Nunn Bulk Density (g/cm^3)
0-30	1.06	1.08
30-60	1.50	1.46
60-90	1.39	1.39
90-120	1.53	1.46
120-150	1.46	1.75

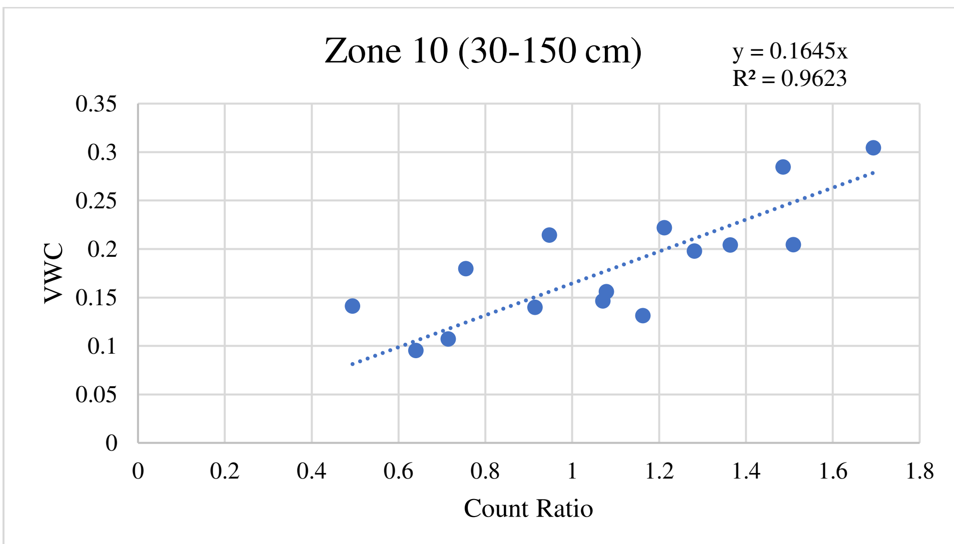

Figure i.1. Zone 10 Colombo soil type calibration for depths from 30-150 cm.

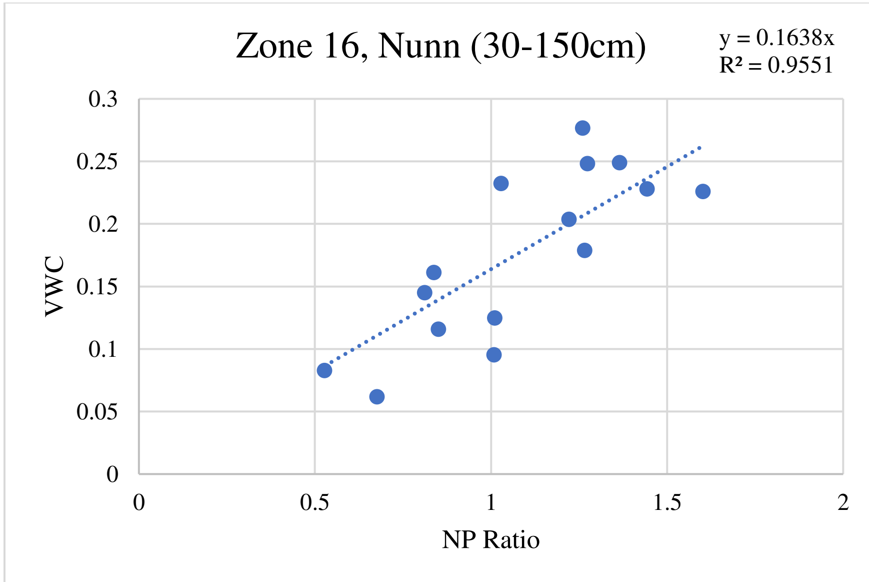

Figure i.2. Zone 16 Nunn soil type calibration for depths 30-150 cm.

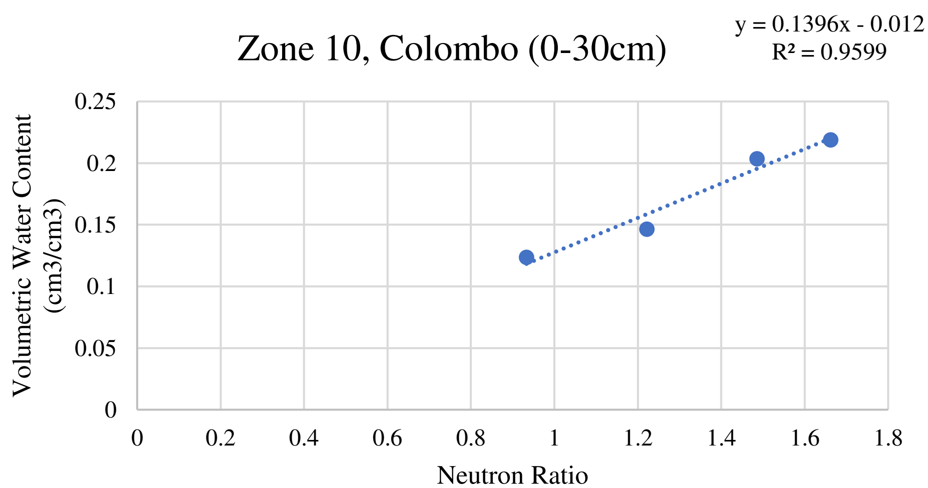

Figure i.3. Colombo soil type calibration for the shallow soil layer.

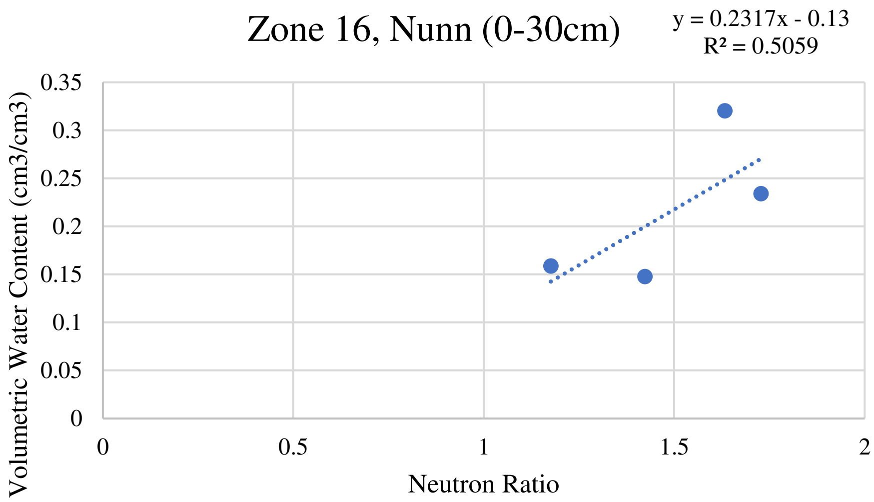

Figure i.4. Nunn soil type calibration for the shallow soil layer.

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APPENDIX ii: WISE STATISTICAL RESULTS

Error metrics between observation data and simulations using WISE determine the model's ability to predict evapotranspiration at the field level. Observations were calculated from the neutron moisture meter soil water content measurements. Four error metrics were calculated for the uncorrected and mid-season corrected WISE model.

Root Mean Square Error (RMSE) = $\sqrt{\frac{1}{N} * \sum_{i=1}^{N}(O-P)^2}$

Mean Absolute Error (MAE) = $\frac{1}{N} * \sum_{i=1}^{N}|O-P|$

Relative Error (RE) = $\frac{|O-P|}{O}$

Mean Bias Error (MBE): = $\frac{1}{N} * \sum_{i=1}^{N}(O-P)$

Table ii.1. WISE ET_c error metrics for 2020 -2022 with bold values showing model improvement after mid-season corrections of D.

Year								**2020**								
	Treatment 1				**Treatment 2**				**Treatment 3**				**Treatment 4**			
Stats[a]	Z9	Z9 Corrected	Z10	Z10 Corrected	Z8	Z8 Corrected	Z19	Z19 Corrected	Z17	Z17 Corrected	Z18	Z18 Corrected	Z7	Z7 Corrected	Z16	Z16 Corrected
MAE	23.04	**22.99**	13.50	**10.79**	20.88	29.69	37.23	**26.04**	3.41	28.67	13.46	**12.07**	26.81	**22.74**	14.15	**10.86**
MBE	-7.76	-18.63	-2.626	**-2.34**	-1.20	24.43	-36.62	**-22.16**	3.41	-28.67	-4.19	8.02	-11.56	**-1.49**	-4.49	**-1.06**
RMSE	20.08	25.71	15.91	**12.99**	24.16	34.50	51.96	**37.79**	6.526	37.04	16.77	**15.50**	39.21	**36.55**	16.61	**14.11**
RE	-10.21	-24.53	-5.48	**-4.88**	-2.65	54.25	-68.68	**-32.70**	-12.56	-74.47	-13.16	25.20	-17.80	**-2.29**	-8.75	**2.06**
Year								**2021**								
	Treatment 1				**Treatment 2**				**Treatment 3**				**Treatment 4**			
Stats[a]	Z9	Z9 Corrected	Z10	Z10 Corrected	Z8	Z8 Corrected	Z19	Z19 Corrected	Z17	Z17 Corrected	Z18	Z18 Corrected	Z7	Z7 Corrected	Z16	Z16 Corrected
MAE	18.69	24.08	13.56	**10.74**	9.08	14.93	12.23	27.72	17.33	23.73	37.34	**25.79**	18.95	21.52	27.37	37.28
MBE	-9.02	-20.68	-7.38	**6.96**	-3.53	13.45	-10.31	-27.72	-14.13	**-14.10**	-37.34	**-13.03**	-9.32	21.52	-1.74	-37.28
RMSE	24.01	28.17	16.15	**13.49**	11.28	17.10	18.58	30.57	20.17	28.17	42.78	**27.94**	24.07	25.29	33.42	46.14
RE	-24.02	-55.07	-26.23	**24.72**	-17.47	66.62	-48.54	-82.2	-53.36	-91.49	-76.06	**-25.55**	-26.29	60.73	-7.07	-85.81
Year								**2022**								
	Treatment 1				**Treatment 2**				**Treatment 3**				**Treatment 4**			
Stats[a]	Z17	Z17 Corrected	Z18	Z18 Corrected	Z7	Z7 Corrected	Z16	Z16 Corrected	Z9	Z9 Corrected	Z10	Z10 Corrected	Z8	Z8 Corrected	Z19	Z19 Corrected
MAE	26.70	40.62	24.38	**23.19**	16.15	23.17	11.35	23.95	8.06	**6.15**	9.79	**9.59**	11.85	**11.34**	22.07	37.27
MBE	-24.41	-40.62	-16.86	**-5.71**	-11.96	12.33	-6.96	-23.85	-1.13	2.52	-3.04	**-1.02**	-4.32	6.46	-14.84	-35.47
RMSE	30.35	43.64	31.81	**28.85**	21.76	27.65	14.06	26.68	10.18	**7.36**	11.49	**11.28**	16.16	**13.74**	30.93	40.91
RE	-43.38	-74.60	-39.97	**-13.54**	-37.08	38.21	-25.48	-82.98	-4.60	10.27	-13.21	**-4.44**	-15.25	22.84	-33.45	-76.18

APPENDIX iii: ECONOMIC ANALYSIS

To test how much deficit irrigation treatments using subsurface drip irrigation can save in consumptive water (CU), a model was created using the Water Irrigation Scheduler for Efficient Application (WISE) to simulate alfalfa under no stress by keeping the soil moisture level below 50%, the standard management allowed depletion (MAD) for alfalfa (Figure iii.1). This model output was then compared to simulations of WISE from the 2020 growing season. Irrigation requirements and total evapotranspiration were compared. There is a 30% CU savings from the standard irrigation treatment level, 39%, and 50% CU savings from the medium and low irrigation treatments, respectively (Figure iii.2). No stress biomass production was assumed from the max amount of biomass produced in all years of our research with subsurface drip irrigation.

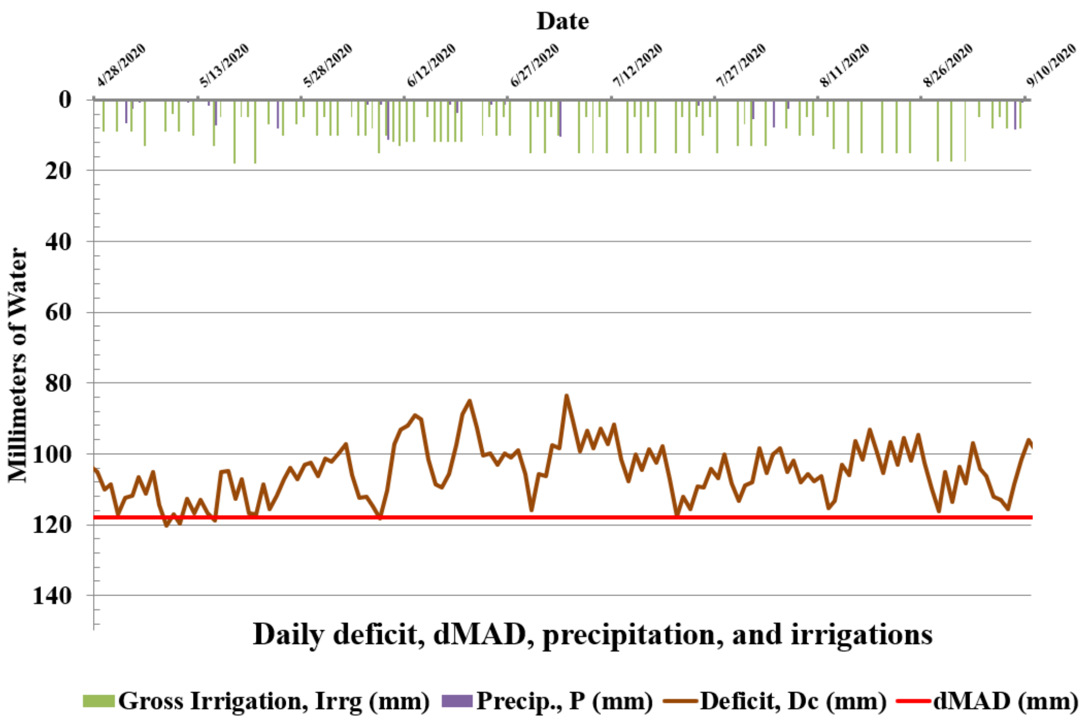

Figure iii.1. WISE 2020 model simulated for no water stress.

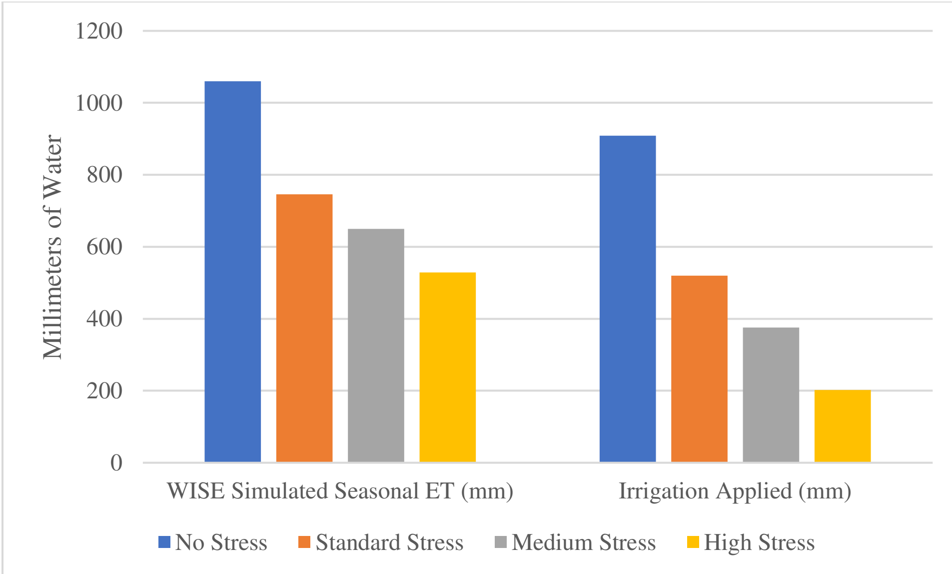

Figure iii.2. Water savings from high, medium, and standard stress deficit irrigation treatments subtracted from the non-stressed treatment water use.

Table iii.1. Simulated bales produced from stress treatments and consumptive water saved.

Treatment	**Bales Produced/Acre**	**AF Water Saved/Acre**
No stress	8.95	-
Standard	6.41	4.42
Medium	5.36	5.78
High	4.62	7.49

With 75% of the alfalfa produced from 2017 to 2022 in the supreme feed quality category, prices per bale reflect this majority. A large square baler was used to bale the alfalfa into squares weighing approximately 839 kg. Biomass samples taken were scaled to represent the entire zone with an average of 1.7 hectare (4.3 acres) and then divided to get number of bales produced per treatment zone. Price for water acquisition was acquired from the Northern Water Regional Pool Bid program where extra water is allocated for a price per acre-foot. Northern Water did not allocate water in 2021 or 2022 therefore a three-year average was used for this analysis (Table iii.2) (Northern Colorado Water Conservancy District, 2022). A price ratio indicates a profit made from deficit irrigating alfalfa and leasing water through the Colorado Collaborative Water Sharing Agreement (CWSA) (Colorado Water Plan, 2015; 2022). The higher the price ratio the less savings received from leasing saved CU water (Table iii.3).

Table iii.2. Price Ratios of alfalfa sold per bale to water sold per acre-foot for 2018-2022.

	2017	**2018**	**2019**	**2020**	**2021**	**2022**
$/Bale Supreme Quality	180	228	195	230	220	240
$/Acre-Foot of water	93.75	134.88	177.36	152.40	154.88	
Price Ratio (bale/AF)	1.92	1.69	1.10	1.51	1.42	1.55

Table iii.3. Profit margins per acre from alfalfa produced in stress and no stress treatments and water profits made from stress treatments ($/acre). Bold indicates a greater profit than no stress production of alfalfa.

	Stress Level	Hay Profit	Water Profit	Total Profit		Stress Level	Hay Profit	Water Profit	Total Profit
2017	No Stress	1,610.10	-	1,610.10	2020	No Stress	2,057.35	-	2,057.35
	Standard	1,153.30	414.45	1,567.75		Standard	1,473.66	673.72	**2,147.38**
	Medium	965.44	541.92	1,507.35		Medium	1,233.61	880.94	**2,114.55**
	High	830.91	702.31	1,533.22		High	1,061.72	1,141.67	**2,203.39**
2018	No Stress	2,039.18	-	2,039.18	2021	No Stress	1,967.90	-	1,967.90
	Standard	1,460.65	596.27	**2,056.92**		Standard	1,409.59	684.69	**2,094.28**
	Medium	1,222.72	779.67	2,002.38		Medium	1,179.98	895.28	**2,075.25**
	High	1,052.34	1,010.42	**2,062.77**		High	1,015.56	1,160.25	**2,175.81**
2019	No Stress	1,744.28	-	1,744.28	2022	No Stress	2,146.80	-	2,146.80
	Standard	1,249.41	784.07	**2,033.47**		Standard	1,537.73	684.69	**2,222.42**
	Medium	1,045.89	1,025.22	**2,071.11**		Medium	1,287.25	895.28	**2,182.52**
	High	900.16	1,328.65	**2,228.81**		High	1,107.88	1,160.25	**2,268.13**

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APPENDIX iv: FORAGE QUALITY ANALYIS RESULTS

A NIR Forage Quality Analyzer was used to determine quality parameters of the biomass samples from the field plot. Crude Protein (CP), Acid detergent fiber (ADF), lignin, acid neutral detergent fiber (ANDF), in vitro digestible matter (IVTDMD48), digestible NDF (DNDF48) were reported, and digestible dry matter (DDM), dry matter intake (DMI), and relative feed value (RFV) were calculated values (Equations 1, 2, 3 respectively). Tables from 2018 to 2022 show these values in the following pages. A t-test of significance was preformed to determine if treatment influenced RFV (Tables 1 – 6). It was determined that there was no significant difference between treatment and RFV. Results of this test are in the following tables.

$$DDM = 88.9 - (0.779 * ADF) \quad [1]$$

$$DMI = \frac{120}{ANDF} \quad [2]$$

$$RFV = \frac{(DMI * DDM)}{1.29} \quad [3]$$

Table iv.1. Two-Sample Assuming Equal Variances between Treatment 1 and 4.

Treatment	T1	T4
	Treatment 1	*Treatment 4*
Mean	180.906	196.5892
Variance	1623.603	2426.979
Observations	30	27
Pooled Variance	2003.381	
Hypothesized Mean Difference	0	
df	55	
t Stat	-1.32086	
P(T<=t) one-tail	0.096008	
t Critical one-tail	1.673034	
P(T<=t) two-tail	0.192017	
t Critical two-tail	2.004045	

Table iv.2. Two-Sample Assuming Equal Variances between Treatment 1 and 2.

Treatment	T1	T2
	Treatment 1	*Treatment 2*
Mean	180.906	185.9602
Variance	1623.603	2039.415
Observations	30	30
Pooled Variance	1831.509	
Hypothesized Mean Difference	0	
df	58	
t Stat	-0.4574	
P(T<=t) one-tail	0.324547	
t Critical one-tail	1.671553	
P(T<=t) two-tail	0.649094	
t Critical two-tail	2.001717	

Table iv.3. Two-Sample Assuming Equal Variances between Treatment 2 and 3.

Treatment	T2	T3
	Treatment 2	*Treatment 3*
Mean	185.9602	196.5892
Variance	2039.415	2426.979
Observations	30	27
Pooled Variance	2222.627	
Hypothesized Mean Difference	0	
df	55	
t Stat	-0.84989	
P(T<=t) one-tail	0.199535	
t Critical one-tail	1.673034	
P(T<=t) two-tail	0.399069	
t Critical two-tail	2.004045	

Table iv.4. Two-Sample Assuming Equal Variances between Treatment 2 and 4.

Treatment	T2	T4
	Treatment 2	*Treatment 4*
Mean	185.9602	200.9517
Variance	2039.415	2539.732
Observations	30	29
Pooled Variance	2285.185	
Hypothesized Mean Difference	0	
df	57	
t Stat	-1.20425	
P(T<=t) one-tail	0.116735	
t Critical one-tail	1.672029	
P(T<=t) two-tail	0.233469	
t Critical two-tail	2.002465	

Table iv.5. Two-Sample Assuming Equal Variances between Treatment 1 and 3.

Treatment	T1	T3
	Treatment 1	*Treatment 3*
Mean	180.906	200.9517
Variance	1623.603	2539.732
Observations	30	29
Pooled Variance	2073.632	
Hypothesized Mean Difference	0	
df	57	
t Stat	-1.6904	
P(T<=t) one-tail	0.048207	
t Critical one-tail	1.672029	
P(T<=t) two-tail	0.096414	
t Critical two-tail	2.002465	

Table iv.6. Two-Sample Assuming Equal Variances between Treatment 4 and 3.

Treatment	T4	T3
	Treatment 4	*Treatment 3*
Mean	196.5892	200.9517
Variance	2426.979	2539.732
Observations	27	29
Pooled Variance	2485.444	
Hypothesized Mean Difference	0	
df	54	
t Stat	-0.3272	
P(T<=t) one-tail	0.372389	
t Critical one-tail	1.673565	
P(T<=t) two-tail	0.744779	
t Critical two-tail	2.004879	

Table iv.7. Forage Quality Results from each harvest in 2018.

2018	Zone	Treatment	Kg/ha	CP	ADF	IVTDMD48	LIGNIN	ANDF	DNDF48	RFV	TDN (%)
1st cut	7	4	3488	20.013	25.43	84.008	6.97	29.5	11.639	217.8637	63.26936
	8	2	3688	17.914	28.363	81.537	7.248	34.725	14.111	178.9615	61.06521
	9	1	2388	19.946	24.407	84.537	7.235	30.267	12.599	214.7921	64.03814
	10	1	2488	21.732	23.575	86.066	6.859	28.59	13.072	229.4999	64.66339
	16	4	3888	19.362	26.836	82.141	7.244	31.211	11.852	202.6559	62.21275
	17	3	1278	23.151	19.388	87.605	6.742	24.578	11.069	279.3073	67.80992
	18	3	1588	21.893	18.819	88.123	6.46	24.455	10.953	282.3981	68.23752
	19	2	2688	22.545	21.439	86.56	6.551	26.7	12.068	251.5426	66.26859
2nd cut	8	2		19.137	33.537	79.994	8.515	41.958	20.161	139.175	57.17694
	9	1	2773	21.458	31.463	80.916	8.444	39.363	19.477	152.1682	58.73556
	10	1	2573	19.355	31.688	79.024	8.779	41.081	18.933	145.4077	58.56647
	17	3	1923	20.251	24.778	84.123	7.197	29.474	12.473	219.6589	63.75933
	18	3	1988	21.767	23.877	84.693	7.309	28.397	12.718	230.289	64.43643
	19	2	2718	20.024	31.322	80.479	8.432	37.843	16.906	158.5502	58.84152
3rd cut	7	4	2813	21.087	27.005	82.942	8.021	29.977	12.78	210.5897	62.08574
	8	2	2508	18.235	26.747	81.558	8.027	30.713	11.916	206.1519	62.27963
	9	1	3373	20.145	30.971	81.635	8.686	34.673	15.245	173.7793	59.10529
	10	1	3463	20.362	28.227	82.529	8.365	31.639	13.268	196.7286	61.16741
	16	4	2913	22.159	27.501	85.096	7.45	30.329	13.737	206.9605	61.713
	18	3	2408	20.262	24.027	85.16	7.126	28.382	12.473	230.0278	64.32371
	19	2	3013	21.462	27.771	84.379	7.934	31.431	14.615	199.0818	61.51009

Table iv.8. Forage Quality Results from each harvest in 2019.

2019	Zone	Treatment	CP	ADF	IVTDMD 48	Lignin	ANDF	DNDF48	RFV	TDN (%)
1st Cut										
	8	2	19.313	35.919	80.859	7.58	39.127	21.357	144.8333	55.38687
	9	1	20.885	32.325	81.426	7.399	36.028	19.949	164.5202	58.08776
	10	1	19.733	32.655	81.442	7.272	37.026	19.969	159.4398	57.83977
	16	4	20.668	28.43633	83.53733	6.650667	32.09167	17.01233	193.6425	61.0101
	17	3	21.058	32.0415	82.4425	7.3535	33.5815	18.31	177.1436	58.30081
	18	3	20.038	33.199	82.067	7.448	35.883	19.857	163.4199	57.43095
	19	2	21.8235	31.087	82.0885	7.2115	33.3265	18.0645	180.6137	59.01812
2nd cut	7	4	21.841	28.459	84.732	6.54	31.743	18.156	195.5544	60.99306
	8	2	22.997	25.403	87.163	5.585	28.475	17.599	225.7748	63.28965
	9	1	22.105	29.393	86.602	6.263	32.44	19.208	189.2663	60.29116
	10	1	23.845	26.149	89.197	5.54	28.591	18.444	222.968	62.72903
	16	4	25.157	22.806	90.861	4.81	25.982	18.06	254.6812	65.24129
	17	3	21.245	28.896	85.638	5.872	31.567	18.092	195.6415	60.66466
	18	3	23.531	25.984	88.818	5.926	27.803	17.696	229.7174	62.85302
	19	2	23.879	27.084	88.841	5.531	29.899	19.228	210.9476	62.02637
3rd Cut	7	4	21.235	34.056	79.525	7.813	39.252	21.427	147.8115	56.78692
	8	2	19.193	35.089	78.138	7.953	40.661	21.576	140.8485	56.01062
	9	1	21.836	32.415	81.955	7.288	35.64	19.723	166.1282	58.02013
	10	1	19.978	34.955	79.037	8.023	39.758	21.454	144.2917	56.11132
	16	4	23.416	25.836	84.249	6.624	28.44	16.303	224.9493	62.96425
	17	3	18.897	36.575	74.598	8.64	44.018	22.461	127.6604	54.89389
	18	3	19.532	34.001	79.24	7.238	41.036	23.146	141.4826	56.82825
	19	2	21.315	23.51	82.624	6.435	26.985	15.234	243.3245	64.71224
4th Cut	7	4	21.574	22.394	88.583	5.747	23.389	13.912	284.1927	65.55091
	8	2	20.626	24.241	86.076	6.206	24.569	13.464	265.0959	64.16289
	9	1	21.346	23.046	88.098	5.727	24.126	14.787	273.5529	65.06093
	10	1	21.744	21.8	89.383	5.293	21.878	13.638	305.7879	65.9973
	16	4	24.905	19.245	91.791	5.261	19.215	13.245	357.8026	67.91738
	17	3	21.63	21.715	88.367	5.651	22.176	13.506	301.9565	66.06118
	18	3	21.642	22.235	89.661	5.303	22.264	13.721	299.0705	65.6704
	19	2	22.512	20.261	90.32	5.362	20.502	13.916	331.7506	67.15386

Table iv.9. Forage Quality Results from each harvest in 2020.

2020	Zone	Treatment	CP1	ADF2	IVTDMD483	Lignin	ANDF4	DNDF485	RFV6	TDN (%)7	DDM
1st Cut	7	4	22.808	37.371	79.902	7.59	44.894	21.115	123.8846	54.29569	59.78799
	8	2	22.638	39.252	77.043	7.721	50.202	22.387	108.0707	52.88212	58.32269
	9	1	23.832	36.559	82.471	7.492	43.96	20.863	127.8552	54.90591	60.42054
	10	1	24.47	34.957	83.312	7.263	41.45	20.427	138.3982	56.10981	61.6685
	16	4	23.916	31.467	82.244	6.642	37.789	16.961	158.4987	58.73255	64.38721
	17	3	22.523	37.195	79.374	7.451	44.967	21.069	123.9671	54.42796	59.9251
	18	3	24.715	35.516	81.686	7.517	43.319	20.066	131.4919	55.68973	61.23304
	19	2	25.046	33.381	84.008	6.995	38.891	17.954	150.4412	57.29418	62.8962
2nd Cut	7	4	21.153	37.022	79.351	7.516	41.546	18.38	134.4766	54.55797	60.05986
	8	2	25.147	34.636	83.664	6.205	38.876	20.01	148.1599	56.35105	61.91856
	9	1	25.037	35.693	82.878	6.156	40.363	20.615	140.804	55.55671	61.09515
	10	1	25.007	34.336	82.015	6.406	36.297	16.874	159.286	56.5765	62.15226
	16	4	26.713	30.866	86.452	5.321	34.893	18.886	172.9017	59.1842	64.85539
	17	3	26.259	31.414	85.794	5.739	35.388	19.232	169.361	58.77238	64.42849
	18	3	26.27	31.645	84.903	5.935	36.158	18.79	165.2915	58.59878	64.24855
	19	2	27.241	31.257	86.333	5.134	35.112	19.412	171.0163	58.89036	64.5508
3rd Cut	7	4	24.033	35.907	80.379	7.316	38.159	17.175	148.5302	55.39589	60.92845
	8	2	25.198	31.357	83.376	6.307	35.041	16.369	171.156	58.81521	64.4729
	9	1	26.479	29.376	84.1	6.33	31.797	14.964	193.1324	60.30394	66.0161
	10	1	26.711	30.008	82.787	6.383	31.799	13.823	191.6801	59.82899	65.52377
	16	4	27.444	28.453	83.881	5.833	30.054	13.639	206.5588	60.99757	66.73511
	17	3	28.998	24.37	86.82	5.407	26.843	13.58	242.2901	64.06595	69.91577
	18	3	27.57	28.765	83.864	6.178	29.889	14.009	206.9426	60.7631	66.49207
	19	2	26.134	32.613	81.347	7.257	35.284	16.08	167.3978	57.87133	63.49447
4th Cut	7	4	24.14	33.368	80.848	6.914	35.011	13.866	167.1404	57.30395	62.90633
	8	2	25.913	29.459	82.055	6.649	30.596	11.426	200.517	60.24156	65.95144
	9	1	25.321	31.14	82.33	6.991	33.133	13.956	181.4868	58.97829	64.64194
	10	1	24.927	32.855	82.33	6.494	34.476	14.581	170.8123	57.68947	63.30596
	16	4	26.587	28.205	82.286	6.489	30.126	12.049	206.6616	61.18394	66.92831
	17	3	27.993	25.763	81.508	7.111	27.901	10.362	229.4846	63.01911	68.83062
	18	3	24.873	32.61	79.775	7.109	34.305	13.236	172.1813	57.87359	63.49681
	19	2	26.917	30.936	78.361	8.052	33.834	12.787	178.1636	59.1316	64.80086

Table iv.10. Forage Quality Results from each harvest in 2021.

2021	Zone	CP	ADF	IVTDMD48	LIGNIN	ANDF	DNDF48	DDM	DMI	RFV6	TDN (%)
4th Cut	19	29.627	27.191	83.092	5.967	30.133	15.771	67.71821	3.982345	209.0522	67.71821
	18	26.117	30.35	78.118	7.349	35.806	17.207	65.25735	3.351394	169.5373	65.25735
	17	26.435	29.286	78.278	7.335	33.339	14.78	66.08621	3.599388	184.3953	66.08621
	16	29.139	24.731	86.686	5.864	26.556	15.822	69.63455	4.518753	243.9235	69.63455
	10	29.321	27.08	85.852	6.161	30.446	18.833	67.80468	3.941404	207.1672	67.80468
	9	27.815	30.616	82.719	6.77	34.972	20.052	65.05014	3.431316	173.0292	65.05014
	8	25.808	30.513	81.907	7.251	33.291	17.33	65.13037	3.604578	181.9903	65.13037
	7	27.539	29.774	85.068	6.427	33.387	19.891	65.70605	3.594213	183.071	65.70605
3rd Cut	18	27.066	26.396	85.306	5.493	29.07	16.664	68.33752	4.127967	218.6783	68.33752
	16	25.611	27.783	84.039	5.962	31.089	17.46	67.25704	3.859886	201.2438	67.25704
	9	23.902	31.937	81.297	6.54	34.56	18.01	64.02108	3.472222	172.322	64.02108
	8	24.734	29.676	83.061	6.034	32.234	17.496	65.7824	3.722777	189.8397	65.7824
	10	24.702	30.598	83.55	6.326	33.246	18.127	65.06416	3.609457	182.0514	65.06416
	17	27.454	23.789	86.852	4.92	27.057	16.35	70.36837	4.435081	241.9298	70.36837
	19	24.901	30.033	83.026	6.043	32.43	17.715	65.50429	3.700278	187.8946	65.50429
	7	21.188	36.948	78.2	7.507	39.758	19.336	60.11751	3.01826	140.6591	60.11751
2nd Cut	7	26.71	27.7	85.758	6.168	32.051	19.824	67.3217	3.744033	195.3912	67.3217
	9	27.546	28.37	86.912	5.819	32.283	19.291	66.79977	3.717127	192.4831	66.79977
	19	26.277	29.926	85.015	6.131	34.782	19.864	65.58765	3.45006	175.4119	65.58765
	10	24.52	34.073	81.914	6.96	39.657	21.65	62.35713	3.025947	146.2709	62.35713
	18	27.285	26.207	86.262	5.406	30.211	17.98	68.48475	3.972063	210.8727	68.48475
	8	26.644	29.488	85.059	6.089	33.894	19.933	65.92885	3.54045	180.944	65.92885
	16	26.232	30.123	85.579	6.104	34.907	20.537	65.43418	3.437706	174.3748	65.43418
	17	24.914	30.475	82.123	6.701	35.117	18.405	65.15998	3.417148	172.6057	65.15998
1st Cut	17	25.116	31.426	82.846	6.072	38.71	22.155	64.41915	3.099974	154.8044	64.41915
	8	22.491	37.85	80.081	7.552	43.388	22.655	59.41485	2.765742	127.3846	59.41485
	9	24.543	35.076	79.868	6.667	42.359	21.516	61.5758	2.832928	135.2247	61.5758
	10	25.397	32.047	83.459	6.497	39.381	22.509	63.93539	3.047155	151.024	63.93539
	7	24.938	32.012	84.148	6.567	37.611	21.738	63.96265	3.190556	158.1988	63.96265
	19	24.664	30.807	83.274	6.608	37.138	20.609	64.90135	3.231192	162.5649	64.90135
	18	23.703	30.929	83.342	6.513	38.646	21.734	64.80631	3.105108	155.9927	64.80631
	16	26.643	26.455	85.289	5.734	32.463	19.195	68.29156	3.696516	195.6906	68.29156

Table iv.11. Forage Quality Results from each harvest in 2022.

2022	Zone	CP	ADF	IVTDMD48	LIGNIN	ANDF	DNDF48	DMI	DDM	RFV
1st Cut	19	26.632	27.397	81.793	6.232	31.107	15.414	3.857653	67.55774	202.0266
	18	25.689	31.978	80.444	6.462	35.378	18.058	3.391938	63.98914	168.2537
	17	26.609	30.841	81.571	6.071	33.597	17.897	3.571747	64.87486	179.6253
	16	28.605	26.982	81.566	5.988	30.463	15.929	3.939205	67.88102	207.2847
	10	29.618	26.005	84.106	5.828	30.227	16.862	3.969961	68.64211	211.2453
	9	29.572	25.639	84.698	5.38	30.114	17.652	3.984858	68.92722	212.9187
	8	25.923	27.362	81.392	6.325	30.548	14.559	3.928244	67.585	205.8065
	7	26.095	33.63	76.984	7.864	39.672	20.204	3.024803	62.70223	147.0247
2nd Cut	19	25.01	30.811	82.662	6.073	36.527	19.375	3.285241	64.89823	165.2762
	18	24.423	31.316	82.36	6.417	35.439	17.804	3.3861	64.50484	169.3177
	17	25.928	27.036	85.653	5.307	31.58	17.735	3.799873	67.83896	199.829
	16	27.365	25.195	84.448	5.449	29.127	15.504	4.119889	69.2731	221.2383
	10	25.156	29.409	81.767	6.352	34.192	17.109	3.509593	65.99039	179.5344
	9	27.53	26.354	84.223	5.386	31.124	17.01	3.855546	68.37023	204.3446
	8	26.937	26.235	85.271	5.438	30.38	16.499	3.949967	68.46294	209.6328
	7	27.474	26.302	85.126	5.565	30.458	17.307	3.939852	68.41074	208.9366
3rd Cut	19	22.236	27.753	79.987	6.694	32.742	13.813	3.665017	67.28041	191.1503
	18	22.756	25.808	81.299	6.302	29.973	13.588	4.003603	68.79557	213.5118
	17	24.592	27.121	81.385	6.224	30.717	14.114	3.906632	67.77274	205.2427
	16	21.061	27.712	79.269	7.106	32.889	13.632	3.648636	67.31235	190.3863
	10	21.218	26.847	79.636	6.762	32.504	13.53	3.691853	67.98619	194.5698
	9	20.853	27.511	80.643	6.703	33.345	15.076	3.59874	67.46893	188.2195
	8	24.584	24.819	81.783	6.272	29.247	13.021	4.102985	69.566	221.2622
	7	23.114	24.848	82.364	6.411	29.915	13.393	4.011366	69.54341	216.2512