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Article

Feasibility of Moderate Deficit Irrigation as a Water Conservation Tool in California's Low Desert Alfalfa

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Abstract: Irrigation management practices that reduce water use with acceptable impacts on yield are important strategies to cope with diminished water supplies and generate new sources of water to transfer for other agricultural uses, and urban and environmental demands. This study was intended to assess the effects of moderate water deficits, with the goal of maintaining robust alfalfa (*Medicago sativa* L.) yields, while conserving on-farm water. Data collection and analysis were conducted at four commercial fields over an 18-month period in the Palo Verde Valley, California, from 2018–2020. A range of deficit irrigation strategies, applying 12.5–33% less irrigation water than farmers' normal irrigation practices was evaluated, by eliminating one to three irrigation events during selected summer periods. The cumulative actual evapotranspiration measured using the residual of energy balance method across the experimental sites, ranged between 2,031 mm and 2.202 mm, over a 517-day period. An average of 1.7 and 1.0 Mg ha^{-1} dry matter yield reduction was observed under 33% and 22% less applied water, respectively, when compared to the farmers' normal irrigation practice in silty loam soils. The mean dry matter yield decline varied from 0.4 to 0.9 Mg ha^{-1} in a clay soil and from 0.3 to 1.0 Mg ha^{-1} in a sandy loam soil, when irrigation water supply was reduced to 12.5% and 25% of normal irrigation levels, respectively. A wide range of conserved water (83 to 314 mm) was achieved following the deficit irrigation strategies. Salinity assessment indicated that salt buildup could be managed with subsequent normal irrigation practices, following deficit irrigations. Continuous soil moisture sensing verified that soil moisture was moderately depleted under deficit irrigation regimes, suggesting that farmers might confidently refill the soil profile following normal practices. Stand density was not affected by these moderate water deficits. The proposed deficit irrigation strategies could provide a reliable amount of water and sustain the economic viability of alfalfa production. However, data from multiple seasons are required to fully understand the effectiveness as a water conservation tool and the long-term impacts on the resilience of agricultural systems.

Keywords: Colorado River Basin; drought; irrigation management strategy; water deficit; water productivity

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1. Introduction

Due to recurring droughts and altered weather patterns, the Colorado River Basin is facing increasing uncertainty concerning water supplies. Hence, implementing impactful agricultural water conservation tools and strategies might have a significant value to the resiliency and profitability of agricultural systems in the low desert region of California and Arizona. It is likely that water deficits will be the reality for agriculture in the future, mostly affecting agronomic crops such as alfalfa (*Medicago sativa* L.), which accounts for about 28% of the crops grown in the area [1] and is the dominant water user in the region.

Currently, efficient use of irrigation water and improved irrigation management strategies are the most cost-effective tools to address water conservation issues. While more than 95% of California's low desert alfalfa (nearly 80,000 hectares) is currently irrigated by surface irrigation systems [2], one strategy to enhance water-use efficiency and on-farm water conservation in alfalfa fields is through improved technology of water delivery. Improved systems, such as subsurface drip irrigation, overhead linear move sprinkler irrigation, automated surface irrigation, and tailwater recovery systems might enable more precise control of irrigation water. Many of these technologies were already adopted by local farmers, although the process of adoption is continuing.

Another strategy is deficit irrigation of alfalfa, applying less water than the full crop water requirements for a season. Deficit irrigation was investigated as a valuable and sustainable crop production strategy over a wide variety of crops, including alfalfa, to maximize water productivity and to stabilize—rather than maximize—yields while conserving irrigation water [3–7].

The overall effect of deficit irrigation highly depends on the type of crop and adopted irrigation strategy. Although alfalfa is frequently criticized for its high seasonal water requirements, it has positive biological features, environmental benefits, and greater yield potential than many other crops under water stressed conditions [8], such as deep-rootedness, high yield and harvest index, contribution to wildlife habitat, and ability to survive a drought. If water allotments to alfalfa are significantly curtailed, it will result in reduced evapotranspiration (ET), CO_2 exchange, symbiotic N_2 fixation, and dry matter yield [9]. There is a positive relationship between alfalfa yield and its ET [10,11], but alfalfa yields are not always reduced in direct proportion to the reduction in applied water during droughts [12,13]. Non-stressed total season ET values are greater than most crops because of long periods of effective ground cover. Alfalfa, being a herbaceous crop, exhibits rapid growth characteristics and its yield is linearly related to ET [3,14], under optimum growing conditions. Dry matter per unit of water used in alfalfa is compared favorably with other C_3 plants.

Several studies investigated the effect of mid-summer irrigation cut-off (no irrigation after June until the following spring) on alfalfa yield. Ottman et al. [15] found that alfalfa yield under mid-summer deficit irrigation in Arizona was very low and did not recover in sandy soil, but summer irrigation termination had less effect on sandy-loam soils. At a site in the San Joaquin Valley of California, yields of a mid-summer irrigation treatment were 65% to 71% of that of a fully irrigated alfalfa, over a 2-year period [16]. Mid-summer deficit irrigation in the Imperial and Palo Verde Valleys of California reduced yields to 53–64% [17] and 46% [18], relative to a fully irrigated alfalfa. Studies in multiple environments of California showed reductions in alfalfa yield, significant conservation of water, and the consistent ability of the crop to recover after drought [3]. In long-term studies conducted on the western slope of the Rocky Mountains of Colorado, researchers determined that late-season deficits impacted yields in some cases, but not all, and that full recovery in the year following re-watering occurred in most cases [19]. In a study conducted in Nevada, significant yield reductions occurred from deficit irrigation over a three-year period, but yields were recovered under adequate irrigation during the fourth year [20]. Another study conducted in Kansas [21] showed no yield reductions in alfalfa hay yields, under 20% and 30% sustained deficit subsurface drip irrigation over the season. The researchers suggested that rainfall had a major contribution to the crop water use, with precipitation contributing to about 25% of seasonal crop water use between June and October, for the Kansas experiment.

The main purpose of this study was to identify and optimize moderate summer deficit irrigation strategies with profitable and sustainable alfalfa forage production, while conserving water under limited water conditions. The study intended to develop a dataset that could serve as a reference for further studies and an opportunity to better understand this underutilized water conservation strategy in the desert environment.

2. Materials and Methods

2.1. Field Experiments

Studies were conducted at four commercial alfalfa fields (designated "sites A1" through "A4") in the desert environment of the Palo Verde Valley, CA, USA. The study area had a true desert climate with an annual average air temperature, total annual precipitation, and ET_o of 21.4 °C, 78.2 mm, and 1782 mm, respectively (Table 1). Soil characteristics for all experimental sites pertaining to four generic horizons are provided in Table 2. Dominant soil type ranged from loams at sites A1 and A2, to clay at site A3, and sandy loam at site A4. Soil cation exchange capacity (CEC) ranged between 7.9 and 12.7 meq/100 g at site A4 to between 9.2 and 22.4 meq/100 g at site A3. The Colorado River was the source of irrigation water with an average pH of 8.1 and an average electrical conductivity (EC_w) of 1.1 dS m^{-1} for all fields.

Table 1. Monthly mean long-term (10-year, 2009–2018) climate data for Blythe, CA, USA, data from CIMIS (California Irrigation Management Information System) station NE #135.

Month	Rain (mm)	Solar Radiation (W m^{-2})	Average Air Temp. (°C)	Average Dew Point Temp. (°C)	Average Wind Speed (m s^{-1})	Total ET_o (mm)
Jan	13.4	126.4	11.1	2.8	2.1	65.2
Feb	10.2	171.9	13.5	4.2	2.2	86.2
Mar	6.4	228.8	17.5	5.4	2.4	144.0
Apr	1.3	282.3	21.0	5.8	2.8	188.7
May	2.3	322.3	24.3	8.8	2.7	227.5
Jun	0.0	331.2	29.4	13.6	2.3	232.4
Jul	8.3	295.0	32.3	19.5	2.3	221.5
Aug	9.0	275.7	32.1	20.0	2.2	202.4
Sep	5.6	232.0	28.4	17.1	2.0	157.8
Oct	6.0	186.9	22.0	11.2	1.9	122.9
Nov	3.2	140.9	14.9	5.4	1.9	76.3
Dec	12.5	111.7	10.5	2.7	2.0	58.0

Table 2. Physical and chemical properties of the soil of the four experimental sites. CEC represents the cation exchange capacity (meq/100 g). A1, A2, A3, and A4 represent alfalfa experimental sites.

Experimental Site	Generic Horizon (m)	Soil Texture			Organic Matter (%)	CEC (meq/100 g)	pH
		Sand (%)	Clay (%)	Silt (%)			
A1	0–0.3	44.2	11.1	44.7	1.7	20.6	8.0
	0.3–0.6	46.9	8.1	45.0	0.8	17.4	8.1
	0.6–0.9	41.7	7.7	50.5	0.9	18.6	8.2
	0.9–1.2	47.8	5.9	46.3	0.7	16.3	8.2
A2	0–0.3	39.7	20.6	39.7	2.3	22.4	8.1
	0.3–0.6	50.1	11.9	37.9	0.7	14.1	8.0
	0.6–0.9	75.0	5.1	19.9	0.9	8.0	8.2
	0.9–1.2	83.7	4.1	12.2	0.8	7.2	8.2
A3	0–0.3	31.5	13.2	55.3	1.3	18.1	8.0
	0.3–0.6	26.1	18.7	55.2	0.8	22.4	8.1
	0.6–0.9	88.6	2.8	8.6	0.5	10.1	8.2
	0.9–1.2	94.8	1.4	3.8	0.5	9.2	8.4
A4	0–0.3	69.3	13.1	17.6	1.7	12.7	7.9
	0.3–0.6	91.9	2.8	5.3	0.8	8.1	8.2
	0.6–0.9	82.0	8.3	9.7	1.2	8.7	8.1
	0.9–1.2	85.9	5.7	8.4	0.9	6.4	8.3

All four fields were planted in October 2018. Low desert alfalfa fields are typically harvested in a 28-day to 33-day cycle during spring and summer, while a total of 8–10 harvests per year is common in the region. Eleven harvest cycles were investigated in this study.

The experimental fields represent soil types (a wide range from sandy loam to clay) and irrigation management practices in the low desert region of California. The surface irrigation practices consisted of straight border irrigation (sites A3 and A4) and graded furrow irrigation (sites A1 and A2). An average of 75% may be assumed as the irrigation efficiency of the irrigation systems [22]. Sites A2 and A4 were divided into three individual sections (large plots) and sites A1 and A3 were divided into six individual plots. Five irrigation strategies were studied within the experimental plots, including normal farmer irrigation practice (NI, as control strategy) and four summer deficit irrigations (DI1, DI2, DI3, DI4; Table 3). The deficit irrigation strategies were implemented by eliminating irrigation events during summer harvest cycles. For the harvest cycles of July–September, three irrigation events per cycle is common irrigation practice in the Palo Verde Valley. Three plots were accommodated for each of the deficit irrigation strategies.

Table 3. Description of irrigation management strategies imposed at the experimental sites over the study period (18-month).

Site	Number of Irrigation Events					Description of Irrigation Management Strategies
	NI	DI1	DI2	DI3	DI4	
A1	30	27	28	-	-	DI1: irrigation events were eliminated 20 July 2019, 23 August 2019, and 26 September 2019 DI2: irrigation events were eliminated 23 August 2019 and 26 September 2019
A2	31	28	29	-	-	DI1: irrigation events were eliminated 21 July 2019, 24 August 2019, and 26 September 2019 DI2: irrigation events were eliminated 23 August 2019 and 26 September 2019
A3	24	-	-	22	23	DI3: irrigation events were eliminated 31 July 2019 and 2 September 2019 DI4: irrigation event was eliminated 2 September 2019
A4	25	-	-	23	24	DI3: irrigation events were eliminated 19 July 2019 and 24 August 2019 DI4: irrigation event was eliminated 24 August 2019

NI: following normal farmer irrigation practice over the study period
DI1: 33% less applied water than corresponding NI strategy during selected summer period
DI2: 22% less applied water than corresponding NI strategy during selected summer period
DI3: 25% less applied water than corresponding NI strategy during selected summer period
DI4: 12.5% less applied water than corresponding NI strategy during selected summer period

2.2. ET Monitoring and Data Processing

The actual evapotranspiration (ET_a) was measured using the residual of energy balance (REB) method with a combination of surface renewal (SR) and eddy covariance (ECov) techniques. The SR and ECov are well-recognized methods to estimate the sensible heat flux density (H) and to calculate the latent heat flux density (LE), using the REB approach [23–28].

A full flux density tower was set up in the plots under normal farmers' irrigation practice at each of the experimental site, totaling four towers (Figure 1). In each tower, several sensors were set up. An NR LITE 2 net radiometer (Kipp & Zonen, Ltd., Delft, The Netherlands) was used to measure net radiation (Rn). Two 76.2 µm diameter, type-E, chromel-constantan thermocouples model FW3 (Campbell Scientific, Inc., Logan, UT, USA) were used to measure high frequency temperature data for computing uncalibrated sensible heat flux (H0), using the SR technique. An RM Young Model 81000RE sonic anemometer (RM Young Inc., Traverse City, MI, USA) was used to collect high frequency wind velocities in three orthogonal directions at 10 Hz, to estimate H for the latent heat flux density calculations using the ECov technique.

Each tower also consisted of three HFT3 heat flux plates (REBS Inc., Bellevue, WA, USA) inserted at a 0.05 m depth below the soil surface, to measure soil heat storage at three different locations; three 107 thermistor probes (Campbell Scientific, Inc., Logan, UT, USA) to measure soil temperature at three depths in the soil layer above the heat flux plates; three EC5 soil moisture sensors (METER Groups Inc., Pullman, WA, USA) to measure soil volumetric water content at soil depths and locations near the heat flux plate and the thermistor probes; EE181 temperature and RH sensor

(Campbell Scientific, Inc., Logan, UT, USA) to measure air temperature and relative humidity; an SP LITE 2 Pyranometer (Kipp & Zonen, Ltd., Delft, The Netherlands) to measure solar radiation; and a TE525MM tipping-bucket rain gauge with magnetic reed switch to measure precipitation.

Figure 1. A fully automated surface renewal and eddy covariance evapotranspiration (ET) tower in the plot under normal farmer irrigation practice (NI) at site A3.

Except for the soil sensors, all other sensors were set up at 1.8 m above the ground surface. The data were recorded using a combination of a Campbell Scientific CR1000X data logger and a CDM-A116 analog input module. Direct two-way communication with each monitoring flux tower was possible using a cellular phone modem model CELL210 (Campbell Scientific, Inc., Logan, UT, USA). The data of the sonic anemometer and fine wire thermocouples were collected at a 10 Hz sampling rate and the data of the other sensors were sampled once per minute. Half-hourly data were archived for later analysis.

Both the EC and SR techniques were individually employed to determine sensible heat flux density. The available energy components, R_n and G (ground heat flux density) were also measured throughout the study period. After acquiring the half-hourly H_0 data, a calibration factor (α) was established by determining the slope through the origin H values from the ECov technique versus H_0 from the SR technique, separately for the positive and negative values of H_0. The calibrated SR H value was finally estimated as $H = \alpha \cdot H_0$. The SR H and the ECov H were used to determine the LE values. The advantage from using both the ECov and SR methods was that they are independent and similar results provide a high level of confidence in the data used [26,28,29]. Latent heat flux density was calculated using the Residual of Energy Balance equation, as follows:

$$\mathrm{LE} = \mathrm{Rn} - \mathrm{G} - \mathrm{H} \quad (1)$$

where LE, G, H are positive away from the surface, and Rn is positive towards the surface. G is the ground heat flux density at the soil surface. It is assumed that Rn, G, and H are measured accurately. While use of the full eddy covariance method often does not demonstrate closure, Twine et al. [30] recommended that ECov results could be forced to have closure by holding the measured Bowen ratio (H/LE) constant, and increasing the H and LE values until Rn − G = H + LE. Twine et al. [30] also reported that using the REB method provides nearly the same accuracy as using the Bowen ratio correction. After determining LE, ET_a in mm d^{-1} was calculated by dividing the LE in MJ m^{-2} d^{-1} by 2.45 MJ kg^{-1}, to obtain the ET values in kg m^{-2} d^{-1}, which was equivalent to mm d^{-1}.

A Tule sensor (Tule technologies, Inc., Oakland, CA, USA) was used in each of the deficit irrigation plots at the experimental sites, to estimate ET_a using a surface renewal technique. The estimated daily ET_a from the Tule sensors at each site was verified by comparing with the ET_a measured from the full flux density towers.

Using the daily ET_a determined in each experimental site and the daily reference ET (ET_o) retrieved from the spatial CIMIS (California Irrigation Management Information System) data [31] for the coordinates of the monitoring station, the daily actual crop coefficient K_a (=$K_s \times K_c$) was calculated using Equation (2):

$$K_a = ET_a/ET_o \tag{2}$$

The daily stress coefficient (K_s) represents water and salt stresses, management, and environmental multipliers. To obtain the actual ET, K_s is needed to adjust crop coefficient (K_c). Spatial CIMIS combines remotely sensed satellite data with traditional CIMIS stations data, to produce site-specific ET_o on a 2-km grid, which provides a better estimate of ET_o for the individual sites.

2.3. Canopy Temperature and Soil Moisture Monitoring

Two SI-411fixed view-angle infrared thermometers (IRTs, Apogee Instruments, Logan, UT, USA) were used to measure canopy temperature in each experimental plot. The IRTs were installed on a pole with a 47.5° angle below horizon, in opposite direction, viewing north and south to match for consistency. The IRTs were installed 1.8 m from the ground surface. The average temperatures of IRTs viewing north and south were considered to be the canopy temperatures. Canopy temperature was scanned with the IRTs units every minute and readings were averaged over a 30-min interval, using ZL6 cellular data logger (METER Groups Inc., Pullman, WA, USA).

Crop Water Stress Index (*CWSI*) was estimated using the difference between measured canopy and air temperatures (dT_m), using Equation (3):

$$CWSI = \frac{(dT_m - dT_{LL})}{(dT_{UL} - dT_{LL)}} \tag{3}$$

The dT_m was compared against lower (dT_{LL}) and upper (dT_{UL}) limits of the canopy–air temperature differential, which could be reached under non-water-stressed and non-transpiring crop conditions. The Idso et al. approach [32] was used for estimating dT_{LL} and dT_{UL}.

Watermark Granular Matrix Sensor (Irrometer company, Inc., Riverside, CA, USA) was used to measure soil water tension at multiple depths of 15, 30, 45, 60, 90, and 120 cm, on a continuous basis. The data of Watermark sensors were recorded by a 900M Monitor data logger (Irrometer company, Inc., Riverside, CA, USA), on a 30-min basis.

2.4. Soil Salinity Assessment

Soil properties were surveyed and characterized within an approximate footprint area of 200 m × 200 m, around the ET monitoring stations in each plot, to assess soil salinity following deficit irrigation regimes. Surveys of apparent soil electrical conductivity (EC_a) were conducted in October 2019 (right after the alfalfa harvest), using mobile electromagnetic induction (EMI) equipment, following the guidelines developed by the U.S. Salinity Laboratory of the United States Department of Agriculture, for field-scale salinity assessment [33–36]. EC_a measurements were taken with a dual-dipole EM38 sensor (Geonics Ltd., Mississauga, ON, Canada), in horizontal (EM_h) and vertical (EM_v) dipole modes, to provide shallow (0 to 0.75 m) and deep (0 to 1.5 m) measurements of EC_a, respectively. At each of the plots, soil cores at four distinct depth ranges (0–0.3, 0.3–0.6, 0.6–0.9, and 0.9–1.2 m) were taken from 6 sampling locations, which were selected using the ESAP software to reflect the spatial variability of root zone soil salinity. A comprehensive laboratory analysis was conducted on all soil samples.

2.5. Yield Measurements and Plant Stand Evaluation

Yield sampling from the sub-plots was conducted on the same day or the day before, when the participating growers scheduled to harvest the entire experimental fields. In each irrigation plot, yield samples were taken from 12 sub-plots with a dimension of 1.5 m wide and 2.0 m long (Figure 1).

The sub-plots were harvested using a hand cutter. A portable PVC quadrate was used to accurately sample uniform sub-plot sizes. Plant cutting height was 6–8 cm. Fresh weights of plants harvested within the quadrate was recorded, after which samples were dried for three days in conventional oven at 60 °C and recorded for alfalfa dry matter (DM). The significance of deficit irrigation strategies on mean dry matter yields was evaluated using a *t*-test.

Forage quality test for each collected sample was conducted using the Near Infrared Reflectance Spectroscopy (NIRS) method [37], to determine Crude Protein (CP), Acid Detergent Fiber (ADF), and Lignin percentage.

All irrigation plots were evaluated for plant stand density in February 2020, four months after switching the deficit irrigated plots back to normal irrigation practices. A portable PVC quadrate of 0.6 m wide and 0.6 m long was used to count the number of plants from the center of the 12 sub-plots that were used for yield measurements. Mean plant numbers per hectare were compared to the plots under normal farmers' irrigation practices.

2.6. Water Productivity

Two water productivity indices were calculated to compare the efficiency of irrigation water use and actual ET, using Equations (4) and (5):

$$\text{Irrigation water productivity (IWP)} = \frac{Alfalfa\ dry\ matter}{Irrigation\ water\ applied} \tag{4}$$

$$\text{Evapotranspiration water productivity (ETWP)} = \frac{Alfalfa\ dry\ matter}{ETa} \tag{5}$$

where the unit of alfalfa dry matter is kg ha^{-1}, and the units of irrigation water applied and ET$_a$ are mm.

2.7. Statistical Analysis

The statistical significances of mean dry matter alfalfa yield and mean forage quality indices were performed using *t*-tests.

3. Results

3.1. Weather Parameters

There was higher than normal rainfall between November 2019 and March 2020 (Figure 2 and Table 1). Total precipitation was 105 mm over these five months. This precipitation amount was more than a long-term annual rainfall of the study area. The average daily air temperature, dew point temperature, solar radiation, and wind speed for the 2019 season (January 2019–December 2019) were approximately 21.0 °C, 234.8 W m^{-2}, 7.5 °C, and 2.3 m s^{-1}, respectively. However, peak daily temperatures of 30 °C to 42 °C during the late summer months when deficit treatments were imposed were common for this desert environment (Figure 2). More windy days were observed during the first half of the 2019 season, when compared with the 2020 season. The average daily wind speed was nearly 9% higher from January–June 2019 than the same season in 2020, although maximum average wind speed for the 2020 season, as recorded on 4th of February 2020 was 6.7 m s^{-1}. During the 2019 season, the month of June had the highest average daily solar radiation of 334.1 W m^{-2}, followed by May (324 W m^{-2}) and July (310 W m^{-2}).

3.2. Applied Water

The cumulative applied water (irrigation water + rainfall) for the different irrigation strategies at each site is shown in Figure 3. The total applied water was 3006, 2933, 2783, and 3125 mm in irrigation strategy NI for sites A1, A2, A3, and A4, respectively, over the 2019 season. These amounts were 788, 897, 716, and 1007 for sites A1, A2, A3, and A4, respectively, during the study period of the 2020 season. Although, most water amounts were provided by the irrigation events, the number of irrigation events were slightly different among the study sites. A total of 23 irrigation events occurred at sites A1 and A2 during the 2019 season, in irrigation strategy NI. The number of irrigation events was 22 at site A3 and 21 in at site A4.

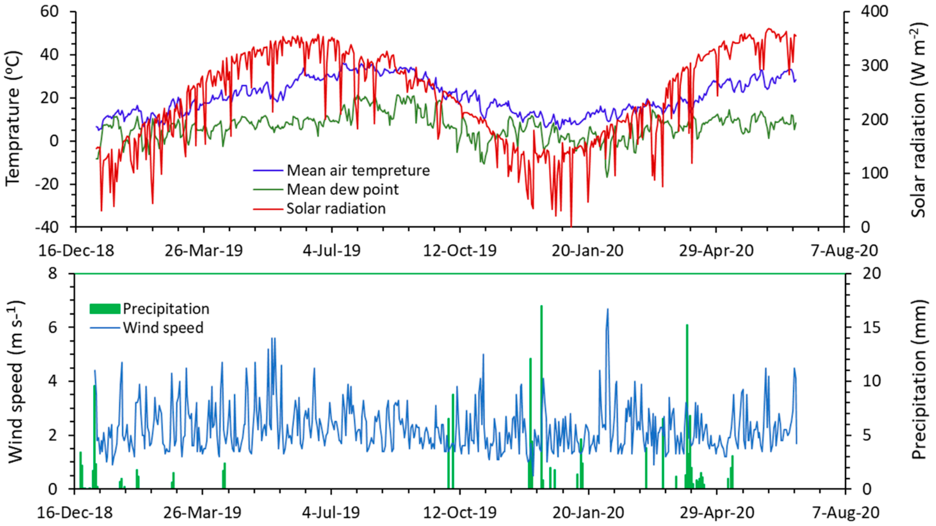

Figure 2. Daily weather data of the study area over the 18-month period of this experiment (January 2019 to June 2020).

The total reduction in the water used in the deficit irrigation strategies (DI1 to DI4) when compared with strategy NI was different at each of the experimental fields. For example, it was 314 mm in strategy DI1 and was 203 mm in strategy DI2 at site A1. The reduction in applied water was 310 mm in strategy DI1 at site A2, 185 mm in strategy DI3 at site A3, and 239 mm in strategy DI3 at site A4. The results demonstrated that the greatest amount of water conservation with the proposed deficit irrigation strategies was achieved under irrigation strategy DI1 at site A1, and the least amount was conserved in strategy DI4 at site A3.

3.3. Soil Moisture Status and Crop Water Stress

The soil moisture sensors placed within the effective root zone (15–120 cm) provided a representative condition of the soil water status. Figure 3 depicts the half-hourly soil water tension for irrigation strategy NI at sites A2 and A4, from March 2019 to June 2020. Due to the necessity of drying soils during and after alfalfa harvest, and to allow equipment to be used on alfalfa fields and for drying of hay, irrigation events typically stopped approximately 4–5 days before cuttings and resumed 4–5 days after cuttings. Therefore, changes in soil water tension could be observed before and after these dry-down periods (Figure 4). Soil water tension responded most within the top 60 cm depth, while some responses were also observed at deeper soil depths over time. For example, water tension values at site A4 sharply increased to more than 200 kPa at the topsoil (15–45 cm), before the first irrigation events, right after the alfalfa harvests. Soil water tension readings below 60 cm indicated that soil moisture was effectively maintained at a relatively uniform and desirable level during the study period, even at site A4, with a sandy loam soil where soil water tension values were less than 25 kPa.

Soil moisture data indicated that the soil at site A2, which had a silty loam soil, was generally not within the stressed range. However, alfalfa at site A4 might occasionally experience moderate water stress around cuttings. The recommended average soil water tension levels within the effective alfalfa root zone at which irrigation was triggered on loamy and sandy loam soil was at 60–90 kPa and 40–50 kPa ranges, respectively [12]. The insufficient soil moisture levels at site A4 during summer harvest cycles, from July through September (Figure 4) might have caused some mild alfalfa water stress. Soil moisture was clearly impacted by irrigation strategy DI3 at this site (Figure 5). However, additional potential mild water stress could have occurred in the middle of the harvest cycles due to halted irrigation water. For instance, soil water tension values increased to 134 and 93 kPa on 24 July 2019, at 30 and 60 cm of soil depth, as a result of eliminating the irrigation event on 19 July 2019 (Figure 5). Similarly, soil moisture readings for the same soil depths and dates at this site was less than 28 kPa for irrigation strategy NI.

Alfalfa CWSI was estimated for different irrigation strategies at each site, based on canopy temperature and air temperature measurements for three consecutive hourly periods of 1100–1200, 1200–1300, and 1300–1400 PST. The seasonal trend of midday CWSI estimated for the period of early-June 2019 through mid-October 2019 for different irrigation strategies at site A4, is shown in Figure 6. Average midday CWSI at site A4 for the period was estimated to be 0.13, 0.15, and 0.14 for irrigation strategies NI, DI3, and DI4, respectively, suggesting a similar, but relatively lower CWSI responses within the normal farmers irrigation practices. The CWSI values illustrated that moderate short-term midday water stress occurred around the alfalfa cuttings (and mid-harvest cycles) of July and August, thus, there was a good match between the findings obtained from the soil moisture data and the CWSI analysis.

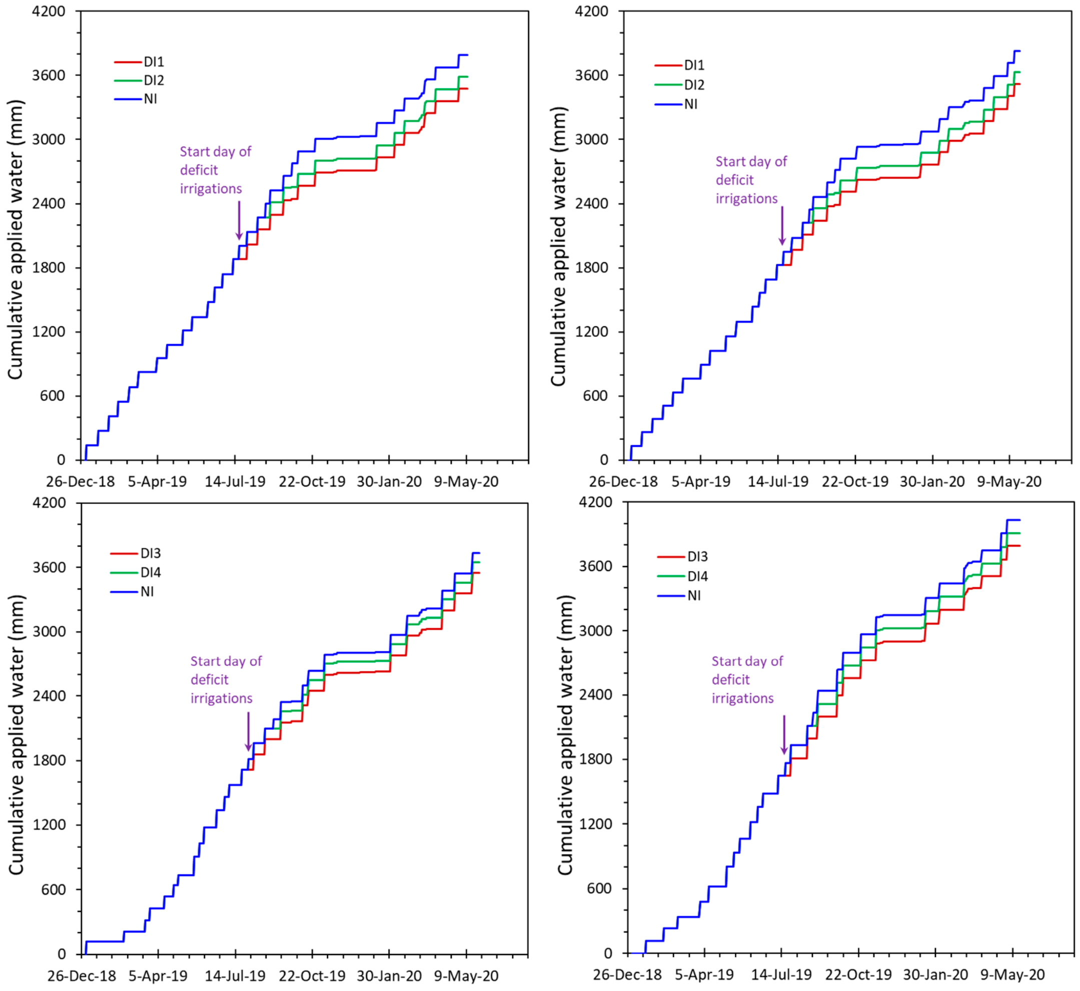

Figure 3. Cumulative applied water in each of the experimental irrigation strategies (NI, DI1–DI4) and sites (A1–A4) over the study period.

3.4. Actual Evapotranspiration and Crop Coefficients

ET_a was determined by calculating half-hourly latent heat flux density, using the REB approach with the SR and EC techniques. The daily ET_o, ET_a from the SR calculations, and K_a values for the irrigation strategy NI, at sites A1 and A4 are shown in Figure 7. The ET_a varied widely for each crop harvest cycle and throughout the experimentation seasons at both sites. For example, the ET_a at site A4 ranged between 3.4 mm d^{-1} after alfalfa cutting and 9.3 mm d^{-1} at midseason full crop canopy, from June through August. The maximum and minimum ET_a at site A1 were 2.6 mm d^{-1} and 0.3 mm d^{-1} during three-months of the study period, November 2019 to January 2020.

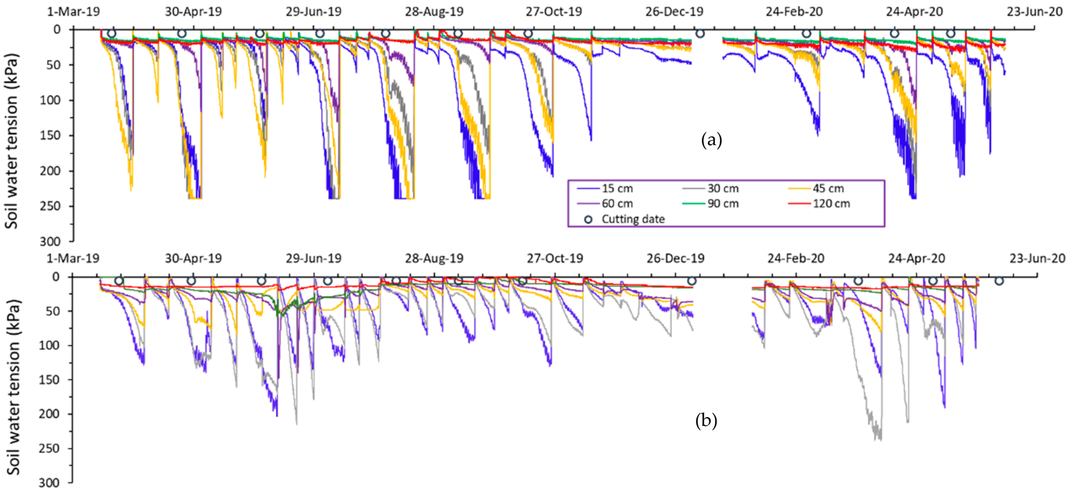

Figure 4. Half-hourly soil water tension (kPa) measured at multiple depths of 15 cm, 30 cm, 45 cm, 60 cm, 90 cm, and 120 cm in plots under normal farmer irrigation practice (NI) at—(**a**) site A4 and (**b**) site A2, from March 2019 to June 2020. Cutting dates are demonstrated with circles on the x-axes.

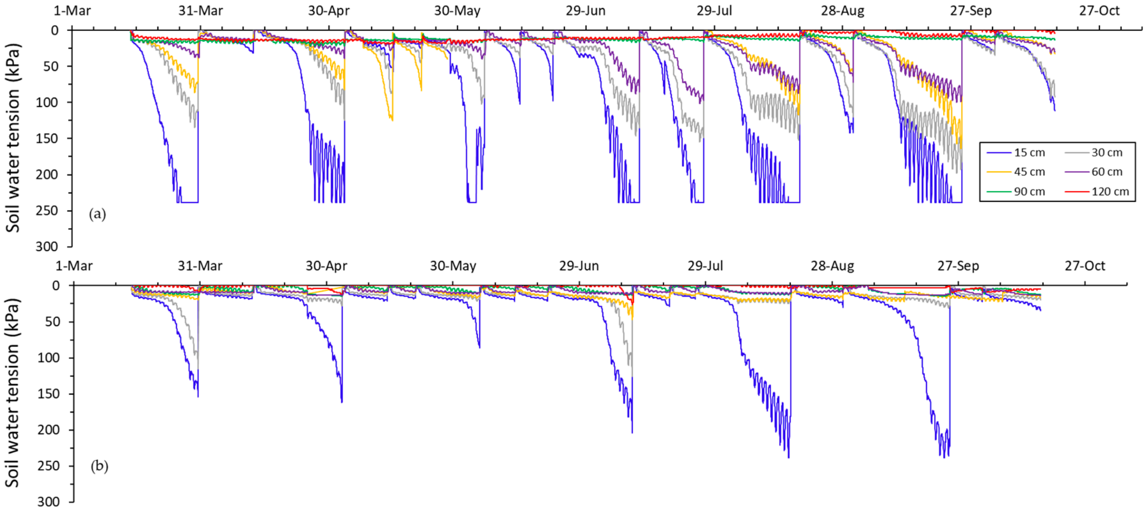

Figure 5. Half-hourly soil water tension (kPa) measured at multiple depths of 15 cm, 30 cm, 45 cm, 60 cm, 90 cm, 120 cm in plots under (**a**) irrigation strategy DI3 at site A4 and (**b**) irrigation strategy DI4 at site A4, from March 2019 to mid-October 2019.

The cumulative ET_a (CET_a) in irrigation strategy NI at sites A1–A4, for a 517-day period (1 January 2019 to 31 May 2020) was 2202, 2187, 2031, and 2175 mm, respectively (Figure 8). For a one-season 12-month irrigation period (2019) for the same irrigation strategy, the cumulative ETa was 1596 mm at site A1, 1582 mm at site A2, 1423 mm at site A3, and 1558 mm at site A4. Comparing the total applied water and the cumulative ET_a under normal farmer irrigation strategies indicated that the plots under NI irrigation strategy remained over-irrigated during the whole study period. However, moderate water stress was occasionally observed for the NI irrigation strategy, particularly at sites A3 and A4, because of the dry-down around alfalfa harvests or the unprecedented delays in irrigation schedules.

The daily K_a values for the sites A1 and A4 (irrigation strategy NI) over the study period are shown in Figure 7. The K_a value depended on alfalfa growth stages, ranging from smallest during initial growth stage, just after each harvest, and reaching the maximum when the crop height was at mid and full canopy development stages, attained prior to each harvest cycle. Large K_a values were attained at both sites during March and April (ranging from 0.47 after harvest to 1.24 at full canopy). Growth of alfalfa in early season (January) and late season (November to December) was slower due to cooler weather and lower solar radiation, in which lower K_a values were observed. The average K_a values of alfalfa sites over the study period varied from 0.8 at site A3 to 0.87 at site A1 (Figure 8 and Table 4).

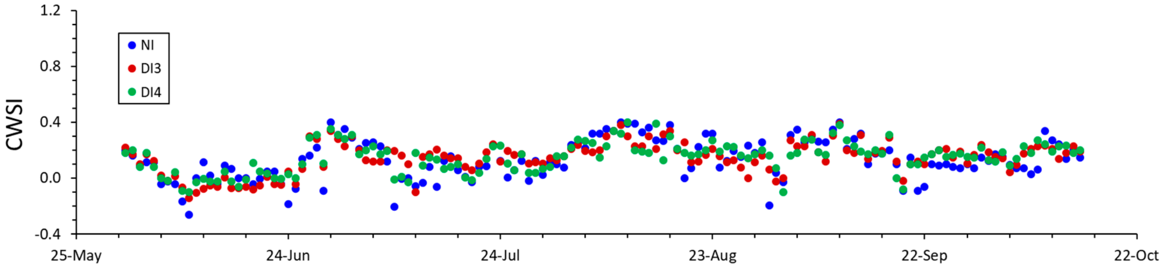

Figure 6. Daily crop water stress index (CWSI) values for the plots under different irrigation strategies (NI, DI3, and DI4) at site A4. NI, DI3, and DI4 represent normal farmer irrigation practice, applying 25% less water than NI, and applying 12.5% less water than NI, respectively.

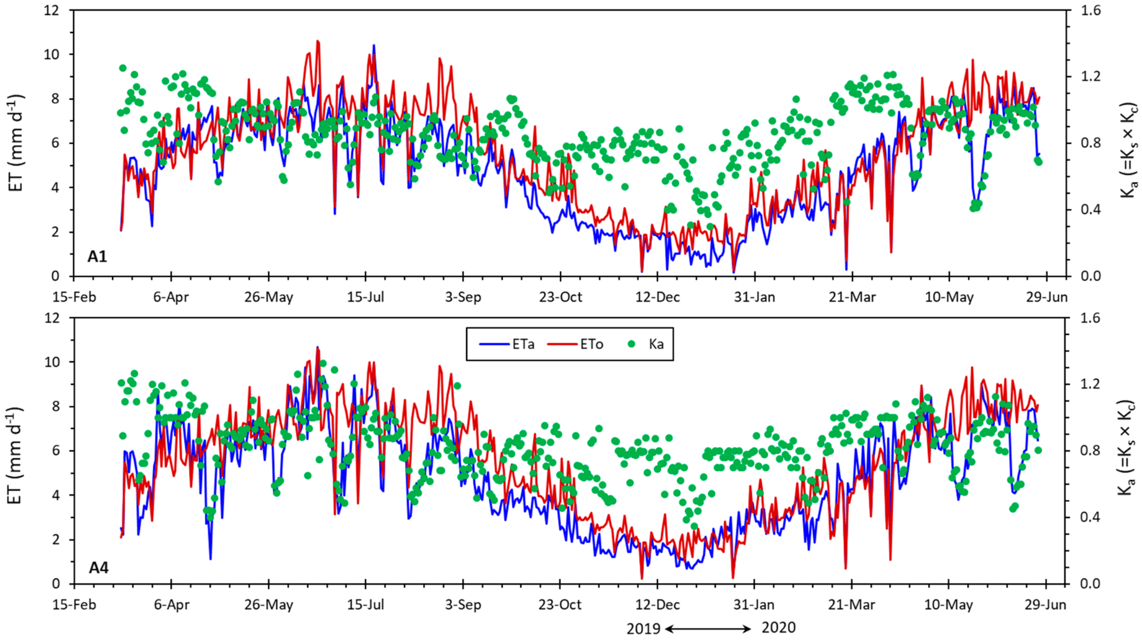

Figure 7. Daily reference evapotranspiration (ET_o), daily actual evapotranspiration (ET_a), and daily actual crop coefficient (K_a) at sites (**A1**) and (**A4**), from March 2019 to June 2020.

Average K_a values at harvest cycles (eight cuttings in 2019 and three cuttings in 2020) for each experimental site are provided in Table 4. The results demonstrated seasonal variabilities in the harvest cycle K_a values. With an average seasonal K_a value of 0.87 for the 2019 season at the site A1, the average cutting cycle K_a values varied from 0.72 (cutting cycle 8) to 1.0 (cutting cycle 2). Average seasonal K_a values for the 2019 season at sites A2, A3, and A4 were 0.86, 0.79, and 0.84, respectively. There was a considerable increase in average K_a value (12.5%) at site A3 from the 2020 cropping season compared to 2019. Lower K_a values in the first three harvest cycles of the 2019 season might have been due to poor irrigation management. Site A3 received 424 mm water during the first three months of 2019, which was the lowest amount of water applied amongst the experimental sites (Figure 3). While trivial differences (an average of 5%) were found in the average K_a values at sites A1 and A2 during harvest cycles of June–August (cutting cycles 4 to 6) at site A1 and A2, substantial differences (average of 20%) were obtained in the mean K_a values of cutting cycles at sites A3 and A4.

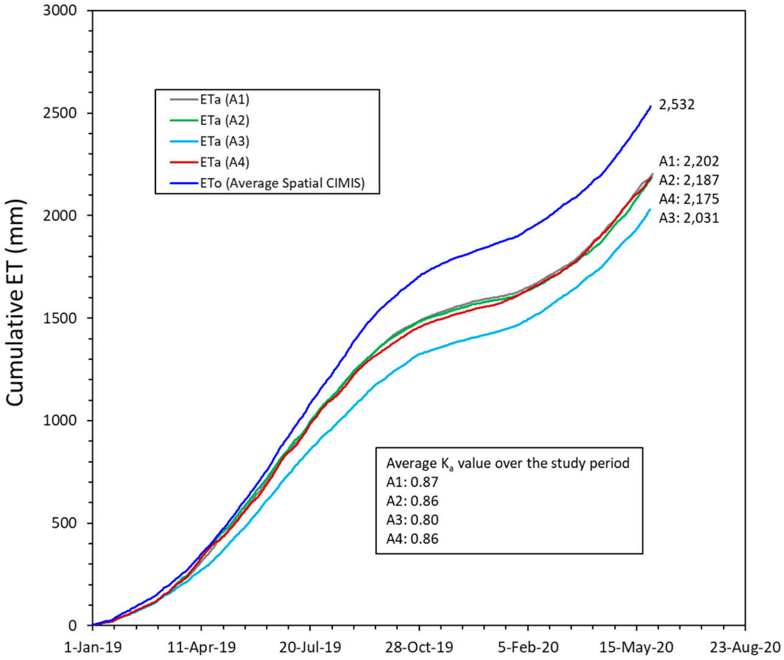

Figure 8. Cumulative reference evapotranspiration (Spatial CIMIS ET_o) and cumulative actual evapotranspiration (ET_a) at each of the experimental sites (A1–A4). The cumulative ET_a are provided for the plots under normal farmer irrigation practices at each site. The average spatial CIMIS ET_o of the four sites is provided as ET_o.

Table 4. Mean (±standard deviation) K_a values of harvest cycles for each experimental site (A1–A4) determined from surface renewal measurements. The values are reported for the normal farmer irrigation practices over eight cuts in the season 2019 (Year 1) and three cuts in the season 2020 (Year 2).

Cut—Year Number	Harvest Time	K_a			
		A1	A2	A3	A4
Cut 1—Year 1	23 Mar–4 Apr	0.81 (±0.13)	0.81 (±0.14)	0.79± (0.16)	0.80 (±0.14)
Cut 2—Year 1	24 Apr–8 May	1.00 (±0.14)	1.03 (±0.15)	0.83 (±0.16)	1.01 (±0.11)
Cut 3—Year 1	1 Jun–12 Jun	0.94 (±0.13)	0.92 (±0.13)	0.78 (±0.14)	0.83 (±0.14)
Cut 4—Year 1	3 Jul–12 Jul	0.89 (±0.12)	0.87 (±0.13)	0.85 (±0.13)	0.98 (±0.12)
Cut 5—Year 1	5 Aug–16 Aug	0.88 (±0.14)	0.86 (±0.11)	0.83 (±0.10)	0.86 (±0.15)
Cut 6—Year 1	5 Sep–19 Sep	0.85 (±0.10)	0.82 (±0.11)	0.75 (±0.12)	0.77 (±0.11)
Cut 7—Year 1	9 Oct–29 Oct	0.78 (±0.12)	0.74 (±0.13)	0.74 (±0.11)	0.73 (±0.12)
Cut 8—Year 1	31 Dec–15 Jan	0.72 (±0.14)	0.73 (±0.14)	0.71 (±0.13)	0.70 (±0.15)
Cut 1—Year 2	4 Mar–30 Mar	0.78 (±0.16)	0.79 (±0.15)	0.83 (±0.17)	0.87 (±0.14)
Cut 2—Year 2	20 Apr–5 May	1.02 (±0.13)	0.93 (±0.15)	0.97 (±0.15)	0.94 (±0.15)
Cut 3—Year 2	22 May–14 Jun	0.90 (±0.14)	0.89 (±0.13)	0.90 (±0.12)	0.90 (±0.12)
Average	-	0.87 (±0.10)	0.86 (±0.09)	0.82 (±0.07)	0.86 (±0.10)

The observed average K_a value from this study was lower than the value (0.95) suggested by Doorenbos and Kassam [38] for dry climate and 0.99 reported by Hanson et al. [3] for the Sacramento Valley. However, the average K_a value was about the same as what was found by Kuslu et al. [39].

3.5. Soil Salinity and Water Availability Features

It is well-known that salinity associated problems are a major challenge for global food production, with particularly critical impact in the low desert region. Applications of excess water to control soil root zone salinity is an important agricultural practice for these regions and considered a ‘beneficial use’ of water, since soils and crop production can only be sustained by controlling salinity. Buildup of salinity might be considered a serious concern and likely a key limitation for any reduced water demand strategies in the region. Therefore, it is important to understand the impact of deficit irrigation on potential soil salinity buildup and soil water balances, vis-à-vis evapotranspiration and devising optimal irrigation management.

Spatially interpolated map of EM_v at sites A1, A2, and A4 in late October of 2019, just before all deficit irrigated plots were switched to normal farmer irrigation practice after the 1.5-year study, is shown in Figure 9. The entire surveyed areas that were affected by the different irrigation strategies at these sites exhibited small EM_v measurements (11.13–174.57 mS m^{-1} or 0.11–1.17 dS m^{-1}). These measurements approximate the differences in EM values (which is affected by salinity, texture, and moisture) in approximately the top 1.2 m of soil. Inconsequential differences were observed among EM_v values of the plots treated with different irrigation strategies. However, we should point out that these were moderate deficit treatments, and more severe deficits might cause greater excess salinity buildup.

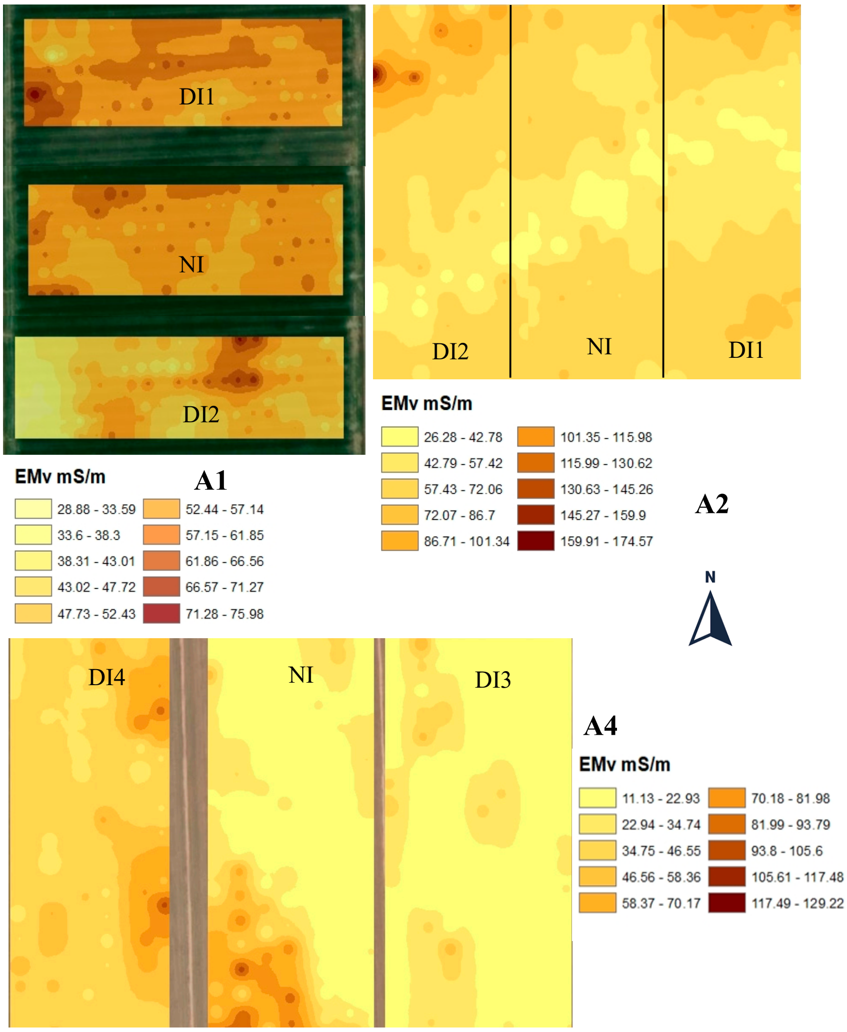

Figure 9. Spatial distribution of ancillary variable EM_v (electromagnetic induction measurement in the vertical coil orientation) at sites (**A1**), (**A2**), and (**A4**). 100 m S m^{-1} is equal 1 dS m^{-1}.

In this study, the mean EC_e at the effective crop root zone (30–120 cm), across the experimental sites in late October 2019, demonstrated that deficit irrigation strategies had some impacts on the soil salinity (Figure 10), however, these values were always in the ‘acceptable’ range for alfalfa. A higher level of ECe values were observed in plots under irrigation strategy DI1, in comparison to plots under irrigation strategies NI and DI2, at sites A1 and A2 (furrow irrigated alfalfa fields). For instance, the mean ECe at site A2 was 2.2 dS m^{-1} and 4.2 dS m^{-1} at 60 and 90 cm soil depths, respectively, in irrigation strategy DI1. However, the values were 1.47 and 1.76 dS m^{-1} in irrigation strategy NI, and were 1.45 and 2.2 dS m^{-1} in irrigation strategy DI2, at the corresponding depths, respectively.

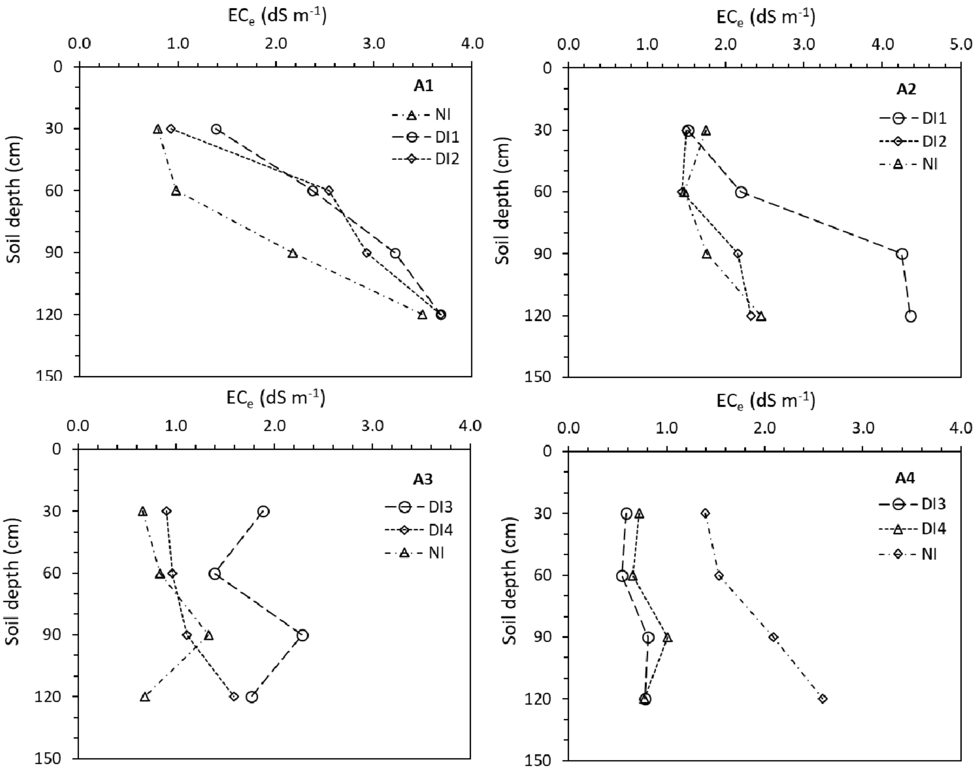

Figure 10. Whole-soil profile representations of mean EC_e (electrical conductivity of the saturation extract) distribution of observed values in different irrigation strategies at four experimental sites. The complete data (collected in late October 2019) from the six soil core sampling locations in plots under different irrigation strategies at each site were used to plot EC_e.

3.6. Alfalfa Yield Responses

Alfalfa dry matter values for eight seasonal cuttings 2019 (Y1) and the first three cuttings for 2020 (Y2) under each irrigation strategies of all experimental sites are illustrated in Figure 11. The results indicated that the first four cuttings were the most productive for all sites in 2019. For instance, mean DM yield at site A2 from irrigation strategy NI were 4.7, 4.0, 4.7, and 3.9 Mg ha^{-1} for first, second, third, and fourth cuttings, respectively. For sites A1, A2, and A4, mean DM values for the first three cuttings in 2020 were lower than the corresponding DM values in 2019. At site A3, alfalfa DM yields were relatively lower than the other sites over the first three cuttings of the 2019 season.

Alfalfa mean DM yields from the 5th to 7th cuttings in 2019 were much lower than the first four cuttings even under full irrigation practices. Yields in late summer were moderately affected by deficit irrigation strategies. For example, yield reduction at site A1 from cuttings 5, 6, and 7 in irrigation strategy DI1, compared to irrigation strategy NI were 0.3, 0.8, and 0.6 Mg ha^{-1}, respectively (Figure 11). The reduction in DM yield was 0.5 Mg ha^{-1} for cutting 6 and was 0.4 Mg ha^{-1} for cutting 7 in irrigation strategy DI2. Yields summed over the 11 cuttings, over 1.5 years, were reduced from 0.7% to 4.6% (0.3 to 1.7 Mg ha^{-1}) by the deficit irrigation practices at the four sites.

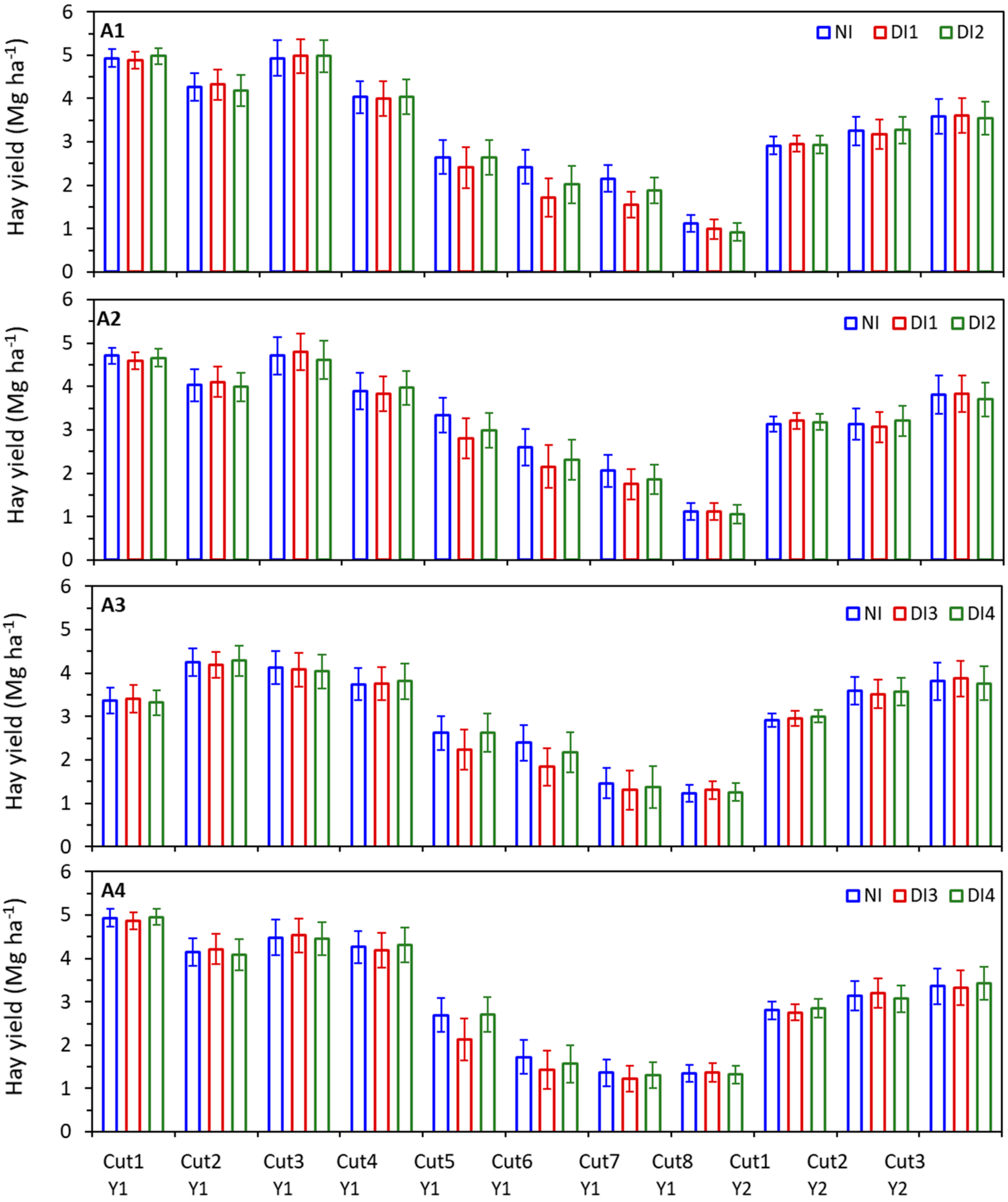

Figure 11. Mean dry matter (DM) yields of each irrigation strategy (NI, DI1–DI4) at the experimental sites (**A1**–**A4**) for eight cuttings in the season 2019 (Cu1-Y1 to Cut8-Y1) and three cuttings in the season 2020 (Cut1-Y2 to Cut3-Y2). The bars demonstrate the standard deviation of DM values.

3.7. Forage Quality

There was a trend for a small improvement in forage quality due to the deficit irrigation strategies, but not at all sites (Table 5). A significant reduction in acid detergent fiber was observed in deficit irrigation strategies DI1 at site A2 and DI2 at site A1, compared to normal irrigation practice (p values of 0.001 for DI1 at site A2, 0.02 for DI2 at site A1). Significant crude protein increase was also found from implementing deficit irrigation regimes DI1 at site A2 (p value of 0.04) and DI3 at site A4 (p value of 0.01), but not at other sites. No significant impact was observed on lignin percentage. The improved forage quality might be attributed to a reduction in stem growth (increase % leaf) under such irrigation practices. Small improvements in alfalfa forage quality under deficit irrigation regimes was also reported by other researchers [5,40,41].

Table 5. Mean forage quality indices (Acid Detergent Fiber (ADF), Crude Protein (CP), and Lignin) of normal farmer irrigation practices against deficit irrigation strategies. The forage quality data of June through September 2019 was used for this analysis (*t*-test).

Site	**ADF (%)**					**CP (%)**					**Lignin (%)**				
	NI	**DI1**	**DI2**	**DI3**	**DI4**	**NI**	**DI1**	**DI2**	**DI3**	**DI4**	**NI**	**DI1**	**DI2**	**DI3**	**DI4**
A1	29.1	28.9 ^{ns}	27.8 *	-	-	21.0	20.7 ^{ns}	20.8 ^{ns}	-	-	5.2	5.1 ^{ns}	5.2 ^{ns}	-	-
A2	31.2	26.4 *	28.2 ^{ns}	-	-	19.6	22.5 *	21.2 ^{ns}	-	-	5.2	5.1 ^{ns}	5.1 ^{ns}	-	-
A3	27.6	-	-	25.7 ^{ns}	27.5 ^{ns}	18.3	-	-	19.4 ^{ns}	18.4 ^{ns}	4.5	-	-	4.6 ^{ns}	4.7 ^{ns}
A4	31.2	-	-	26.5 ^{ns}	30.0 ^{ns}	17.6	-	-	20.6 *	18.3 ^{ns}	5.1	-	-	4.9 ^{ns}	5.0 ^{ns}

^{ns} Non-significant. * Significant at the 5% level of probability.

3.8. Water Conservation Versus Yield Reduction

Deficit strategies with alfalfa are primarily feasible due to the seasonal yield patterns of the crop, with heavy yields during early season, and very light yields in late summer. Approximately 73–74% of total alfalfa seasonal yield productivity at the experimental sites occurred by mid-July (20 July 2019), right before starting summer deficit irrigation strategies (Figure 12). This finding is similar to results from research reported for the Sacramento Valley of California [5,39]. The deficit irrigation strategies could affect the 5th through 7th cuttings, while only 21–22% of the annual DM yield was produced during this period.

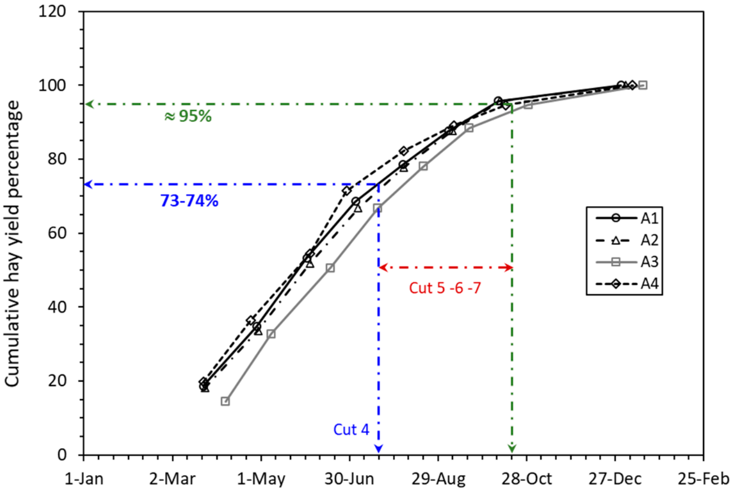

Figure 12. Cumulative alfalfa yield percentage over the growing season 2019 at the experimental sites (A1–A4). Results are provided for the normal irrigation practices at each site.

A significant DM reduction was observed in deficit irrigation strategies DI1 and DI2, compared to normal irrigation practice at site A2 (p value of 0.0004 for DI1 and 0.002 for DI2). There was also a significant yield reduction in deficit irrigation DI1 at site A1 (p value of 0.0005) (Table 6). No significant DM reduction was affected by deficit irrigation regimes DI3 and DI4 at sites A3 and A4; and deficit irrigation DI2 at site A2. The findings suggest an average of 1.7 Mg ha^{-1} and 1.0 Mg ha^{-1} dry matter yield reduction in deficit irrigation strategies DI1 and DI2 at sites A1 and A2, respectively (Table 6). The average DM yield reduction at sites A3 and A4 was nearly 1.0 Mg ha^{-1} in deficit irrigation strategy DI3 and 0.4 Mg ha^{-1} in deficit irrigation strategy DI4.

The total amount of conserved water across the experimental sites varied from 83 mm (3.0%) at site A3 to 314 mm (10.5%) at site A1, relative to what was used under seasonal water applied in normal irrigation practice. Summer deficit irrigation strategies enhanced the IWP values, but not the ETWP values (Table 7). For instance, irrigation strategies DI1 and DI2 at site A2 improved the IWP value by 0.5 and 0.4 kg ha^{-1} mm^{-1}, respectively, compared to the irrigation strategy NI (with an IWP of 8.9 kg ha^{-1} mm^{-1}).

Table 6. The total mean dry matter yield (Mg ha^{-1}) for different irrigation management strategies and total mean dry matter yield in normal irrigation practice at the experimental sites (18-month period). The significance of independent *t*-tests is provided.

Site	Normal Irrigation Practice (NI)	Deficit Irrigation Strategy			
		DI1	DI2	DI3	DI4
A1	36.2	34.6 *	35.4 ^{ns}	-	-
A2	36.6	35.0 *	35.5 *	-	-
A3	33.5	-	-	32.6 ^{ns}	33.1 ^{ns}
A4	34.3	-	-	33.2 ^{ns}	34.0 ^{ns}

^{ns} Non-significant. * Significant at the 5% level of probability.

Table 7. The irrigation water productivity (IWP) and actual evapotranspiration (ET) water productivity (ETWP) values in different irrigation strategies (NI, DI1–DI4) at each of the experimental sites (A1–A4).

Site	Irrigation Strategy	*IWP* (kg ha^{-1} mm^{-1})	*ETWP* (kg ha^{-1} mm^{-1})
A1	NI	8.9	16.6
	DI1	9.3	16.1
	DI2	9.3	16.4
A2	NI	8.9	16.4
	DI1	9.4	16.1
	DI2	9.3	16.3
A3	NI	8.4	16.1
	DI3	8.6	15.8
	DI4	8.6	16.1
A4	NI	8.0	15.9
	DI3	8.3	15.6
	DI4	8.2	15.9

4. Discussion

Alfalfa was historically reported to be a moderately sensitive crop to salinity, with estimated yield declines above a saturated soil extract (EC$_e$) of 2.0 dS m^{-1} [42]. However, more recent reports and experiments in California confirmed that alfalfa has a much higher tolerance of salinity. Field and greenhouse experiments estimated tolerance of alfalfa varieties up to approximately 6.0 EC$_e$ or higher [43]. The findings from this study suggest that the proposed deficit irrigation strategies might cause salt accumulation at the crop root zone (particularly for furrow irrigated alfalfa fields) and this practice might elevate soil salinity class from a non-saline soil (0–2 dS m^{-1}) to slightly saline (2–4 dS m^{-1}) condition. Soil salinity can be managed by switching to farmer irrigation practices in early fall (mid- to late-October), with no need for the excessive water to leach salts.

The deliberate re-filling of the soil profile with irrigation water after implementing summer deficits should be considered, both in terms of water availability, salinity management, and water-use policy. The continuous soil moisture readings in this study verified that there was insignificant soil moisture depletion from deficit irrigations to require some recharge (Figures 4 and 5). As can be seen from the soil water tension data plots, the average soil water tension was kept constant at about 88 kPa, at the top 30 cm, and maintained at about 15 kPa, for the 45–120 cm soil depth. Consequently, farmers might confidently refill the soil profile after implementing summer deficit irrigation strategies and switching to their normal irrigation practices with little excessive water needs in the fall.

At sites A1–A4, the total mean annual DM yield in irrigation strategy NI for 2019 was 26.2, 26.5, 23.2, and 25.0 Mg ha^{-1}, respectively (Figure 11). These alfalfa yield values from the long-seasoned low desert sites are generally higher than the average alfalfa yield in California, which ranges from 14.6 to 16.1 Mg ha^{-1}, and a thirty-year (1984–2013) statewide average yield of 15.3 Mg ha^{-1} [44]. Dry matter yields of 11.2 Mg ha^{-1} was reported in an earlier deficit study that imposed severe water deficits, restricting applications to 1,249 mm seasonal water use in the Imperial Valley [3].

Alfalfa plant stand evaluation conducted on 18 February 2020 showed no significant differences in the plant population between the deficit irrigation strategies and normal irrigation practices, suggesting that there is no evidence of losing the alfalfa plant density from the implemented deficit irrigation strategies. For instance, plant population per hectare at site A1 was estimated to be 103×10^6, 105×10^6, and 102×10^6 in the plots under irrigation strategies NI, DI1, and DI2, respectively. Additionally, no yield reduction was observed from the summer deficit irrigation strategies within the first three harvest cuttings of the 2020 season (Figure 10), indicating a full recovery of the crop upon re-watering.

None of the deficit irrigation strategies produced severe water or salinity stress at the experimental sites. Soil water availability in non-sandy soils (sites A1–A3) was retained at a desired level during and after summer irrigation strategies. At site A4 (sandy loam soil), the residual soil moisture below the depth of 45 cm was consistent at a non-stressed level, and supplied enough water for alfalfa, suggesting that this might be a primary reason why there was only a small reduction in total ET_a of deficit irrigated plots. The maximum ET_a reduction (54 mm) was observed in irrigation strategy DI1 at site A2, when compared with strategy NI. The findings revealed that ET_a was not directly reduced in relation to the level of reduction in applied water. This might be part of the reason why no improvement was gained in the ETWP values from moderate deficit irrigation strategies. Further measurement is necessary to provide a more solid conclusion on the impact of the deficit irrigation strategies on ET_a. Overall, the ETWP values computed for the normal farmer irrigation practices and deficit irrigation trials at the experimental sites (an average of 16.1 kg ha^{-1} mm^{-1}) were as high as the values predicted by Montazar et al. [45] for alfalfa fields, under subsurface drip irrigation in the low desert of California.

Imposition of summer water deficits is likely to result in yield reductions, a finding that was similar to other researches [3–7,17]. The findings suggest that conserving 0.083–0.314 (ha.m) ha^{-1} water through summer deficit irrigation strategies might result in 0.3–1.7 Mg ha^{-1} yield loss in California's low desert alfalfa production system. Therefore, while insignificant yield reduction is unpreventable, the proposed management strategies could serve as an effective water conservation tool. The hay yield reduction might be a consequence of reduced water distribution uniformity caused by the deficit irrigation regimes. Large-scale farming systems in the low desert, along with the use of surface irrigation methods, resulted in lower water distribution uniformity values (over time and space) with deficit irrigation strategies. Results expected from these deficit irrigation strategies would likely be more favorable in more efficient irrigation systems such as subsurface drip irrigation systems or advanced overhead sprinkler systems.

The practice of filling the soil profile so that it holds as much water as possible would be an effective early-season alfalfa irrigation strategy. Such practice might allow alfalfa to take full advantage of the available water and promote its rapid, early season growth, when the yield potential was highest, and when soil and water temperatures were not likely to be high enough to stress the crop and limit crop productivity. Consequently, combining full irrigation in winter-spring with moderate deficit irrigation during summer could be an efficient approach in conserving water than continuously irrigating (or over irrigating) for the entire season.

5. Conclusions

This study aimed at assessing the effectiveness of moderate deficit irrigation strategies during summer harvest cycles (less applied water than normal farmers' irrigation practices) on conserving water and maintaining a robust hay production.

The proposed deficit irrigation strategies conducted showed a promising and decent amount of water conservation and simultaneously generated desirable hay yields and quality. However, yield penalties of this practice must be considered. These moderate deficit irrigation practices resulted in an average of 1.47 Mg ha^{-1} and 0.31 Mg ha^{-1} hay yield reduction, but used

33% (≈0.31 (ha.m) ha^{-1}) and 12.5% less applied-water than normal farmer practice over the summer (≈0.10 (ha.m) ha^{-1}), respectively.

Several cautionary notes need to be considered with the data reported and the analysis provided in this study:

- The ET and crop coefficient values reported herein are referred to as observed or actual values, which are limited by water deficits and salinity, and the 'dry down' required for frequent harvests. The maximum crop ET (ET_c) is limited only by energy availability to vaporize water and not soil hydrology or salinity, or droughts imposed by harvest scheduling. Imposed stress, such as this, is common to almost all alfalfa growing regions.
- Although stand density under desert conditions decays more rapidly than other locations, there were negligible differences between different deficit irrigation strategies and normal farmers' irrigation practices in this study after one year of water deficits. However, it is uncertain whether multiple years of summer irrigation strategies might threaten the long-term viability of the crop stand and yields.
- Although, it might be unlikely to prevent salinity buildup due to summer water deficits, salinity issues are likely to be managed through irrigation practices that flush salts in the months after implementing deficit irrigations. Continuous monitoring of soil salinity is recommended to ensure flushing/leaching salts out of root zone over multiple deficit irrigation seasons.
- The importance of re-filling of the soil profile with water, in the year after implementing summer irrigation strategies, need to be considered both in terms of water availability, crop production, and policy. Such practices might enable shifting water demand to water-rich time periods in early spring. This practice would benefit both early season growth and salinity management in subsequent years. In this study, continuous soil moisture readings verified that soil moisture was insignificantly depleted in the deficit irrigation fields. However, data from multiple irrigation seasons are required to fully certify this conclusion.
- Implementation of the proposed summer deficit irrigation strategies on alfalfa could provide a reliable source of seasonally available water as well as sustain the economic viability of agriculture in the region. These strategies might be sustainable as an effective water conservation tool if such measures provide adequate economic incentives to the participating farmers. Incentive programs to farmers must offset the risk of implementing the proposed practices (even trivial production loss), as a tool for adopting water conservation practices.

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Conflicts of Interest: The authors declare no conflict of interest.

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