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Sustaining Alfalfa Forage Production with Limited Water Resources

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Sustaining Alfalfa Forage Production with Limited Water Resources

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ABSTRACT

Variability in climatic conditions and uncertainty in water supply brings challenges for sustainable irrigated forage production. Alfalfa (*Medicago sativa* L.), one of the major forage crops worldwide, is affected due to its high water demands for successful irrigated production. To address the challenge of sustaining forage yields in a changing climate, we designed three studies to understand the yield response of alfalfa under different irrigation systems and with varying water deficits. We also examined the usefulness of aerial imagery to understand the yield and quality variability in the field as affected by drought. In study 1, the potential of sub-surface drip irrigation (SDI) combined with reduced irrigation for improving forage yield, quality, and water productivity of alfalfa under water deficit conditions in California's Central Valley was explored. In study 2, we examined the two overhead irrigation systems: low elevation spray application (LESA) and mobile drip irrigation (MDI) for producing alfalfa and the impacts of deficit irrigation using these two technologies on alfalfa production, quality, and productivity. In study 3, we examined the ability of aerial imagery, specifically, multispectral and LiDAR imaging technologies to understand yield and quality variability on a field scale with differential drought treatments. Study 1 was conducted at Kearney Agricultural Research and Extension Center (Parlier, CA) from 2016-2019 using randomized complete block (RCB) design on sandy loam soil while study 2 and 3 were conducted during 2019 and 2020 at Davis, CA using split plot randomized complete block design on a clay-loam soil. In Study 1, we found that there were no significant differences between SDI and flood irrigation systems over two years of study. In small-plot studies, it is likely that flood irrigation techniques are advantageous due to smaller checks, an advantage that may disappear when larger fields are considered- thus advantages of these systems should be viewed at scale. In addition, the SDI plots had maintenance issues in the later part of the study, a common problem with SDI. But SDI had the advantage of applying water to more closely match crop evapotranspiration demands while flood seems slightly stressed during the growth cycle due to less frequent irrigation. Over the three years of study, deficit irrigation utilizing SDI resulted in yields that were 82%, 84%, and 87% of fully irrigated treatments for the 50%, 75% (sudden cutoffs), 75% (gradual deficits), respectively (percent of full ET requirement). There were slight improvements in forage quality using deficits, but differences were not great. Higher water productivities were found in deficit irrigation compared with full irrigation under SDI. Under water uncertainty, deficit irrigation using subsurface drip irrigation (SDI) could be beneficial to address the challenges of climate change, if such systems can be economically managed and maintained. In study 2, we found few differences in yield results between LESA and MDI systems in overhead irrigation of alfalfa over two years. Yields were sustained or were higher under MDI 60% cutoff compared with LESA 60% summer cutoffs, likely due to superior sub-soil moisture recharge with the dragging drip lines. Higher water productivity and irrigation water use efficiency was found in MDI-60% ET- Cutoff in 2020 (21.2 kg ha^{-1} mm^{-1}) while there were no significant differences found in 2019. In general, LESA performed better in all other treatments than MDI over the two years of study period. Both LESA and MDI systems minimized wind losses and improve deep moisture availability. MDI systems do not have the rodent or maintenance issues as does SDI but have the disadvantage of requiring some filtration. In study 3, we utilized the drought affected research field and tried to understand the spatial-temporal variability in alfalfa yield and quality using aerial imagery. Aerial flights were conducted at harvest using multispectral and LiDAR camera in separate flights. We trained the models on the field data for plant height and dry matter yields and it was found that model performed well when an unknown dataset was provided for model testing. The model was created using a step-wise regression model and was compared with random forest (RF) and support vector machine (SVM) for multispectral imagery. It was found that step-wise regression model performed somewhat better than RF and SVM with an R^2 of 0.82, 0.79 and 0.81 respectively. The model also performed well for predicting yield in a separately measured area of 11.15 m^2 with an R^2 0.83. LiDAR also performed well and predicted the yield with slightly lower R^2 (0.67) but successfully predicted yields in 11.15 m^2 area (R^2 0.91). Both multispectral and LiDAR imagery were able to predict the dry matter yield for alfalfa based on the trained models, and each system has advantages and disadvantages. LiDAR is more demanding in terms of cost and analysis requirements. Some of the predicted results exhibited bias, these may have resulted from differences in sample size or sampling protocols, but such biases can be corrected mathematically. Aerial imagery should be considered a useful tool to create yield maps, to estimate the impacts of drought on yield, and to understand sources of field variability to guide management decisions. For model applicability, further work at different scales should be conducted to predict yields on a farm or regional scale.

Keywords: Alfalfa, SDI, Flood, LESA, MDI, deficit irrigation, forage quality, irrigation efficiency, water productivity, UAV remote sensing, yield prediction, drought, field diagnostics, Multispectral, LiDAR

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ABSTRACT

Variability in climatic conditions and uncertainty in water supply brings challenges for sustainable irrigated forage production. Alfalfa, one of the major forage crops worldwide, is affected due to its high water demands for successful irrigated production. To address the challenge of sustaining forage yields in a changing climate, this study was designed to understand the potential of sub-surface drip irrigation (SDI) combined with reduced irrigation for improving forage yield, quality and water productivity of alfalfa under water deficit conditions in California's Central Valley. An experiment was conducted at Kearney Agricultural Research and Extension Center from 2016-2019 using randomized complete block (RCB) design on sandy loam soil. SDI was implemented following the crop evapotranspiration (ET_c) requirements and soil water storage was monitored during the experiment period while surface irrigation was used as a control for comparison. Three deficit treatments using SDI were applied: terminating irrigation in July (50% of full), terminating irrigation in August (75% of full) and gradual deficit applied after July (75% of full gradual deficits). Although, the treatments were applied monitoring the full ET_c requirements, the actual applied water amounts were slightly higher than the targeted amounts accounting for system efficiency (90-95%). While there were no significant differences between surface irrigation and SDI over two years, slightly higher yields for SDI were observed in 2017, but lower in 2018, which we attributed to poor distribution uniformity and damage to the SDI system in year two. Significantly higher digestibility and crude protein values were found in SDI vs. surface irrigation in 2017, but there were no differences in 2018. Water productivity (WP) was 15.6 kg ha^{-1} mm^{-1}

for SDI and 13.9 kg ha^{-1} mm^{-1} for surface irrigation during 2017 while in 2018, SDI had WP of 14.8 kg ha^{-1} mm^{-1} while surface irrigation had a WP of 16.1 kg ha^{-1} mm^{-1}. Water productivity and irrigation water use efficiency were significantly higher for SDI compared with surface irrigation in 2017 but not 2018. Over the three years of study, deficit irrigation utilizing SDI resulted in yields that were 82%, 84%, and 87% of fully irrigated treatments for the 50%, 75% (sudden cutoffs), 75% (gradual deficits), respectively. Significant higher yields were found in SDI-100% full while lower were found in SDI-50% but higher water productivity was found in SDI-50% justifying the concept of irrigating early in the season and cutting the irrigation late in the season could be beneficial. SDI has an excellent potential of improving forage yields when maintained and protected from the rodent damages. SDI has potential of applying less amount for irrigation, it has an advantage of allowing irrigation closer to the harvest and turning on the irrigation early. Under water uncertainty, deficit irrigation using subsurface drip irrigation (SDI) could be beneficial to address the challenges of climate change.

Keywords: Alfalfa, SDI, forage quality, deficit irrigation, irrigation efficiency, water productivity

1.1 INTRODUCTION

Water scarcity is a major threat to world food production. Water limitations for agriculture may increase in the future due to the need to meet the challenge of feeding 9.7 billion people by 2050 (United Nations, 2015). With each passing year, there is likely to be a higher demand of water globally. During the next 20 years, water resources are likely to be reduced rather than increased (Pimentel et al., 2004). Worldwide, the majority of water use (2672.6 km^3 year^{-1}) is accounted for by agriculture while in North America the water use by agriculture is 177.4 km^3

year^{-1} (Frenken and Gillet 2012). Thus, strategies to improve the efficiency of irrigated agriculture are of great importance.[1]

Alfalfa (*Medicago sativa L.*) is widely considered to be the premier high yielding and high-quality forage for dairy production. Alfalfa is one of the most important and ancient crops, first domesticated in Iran (Bolton 1962; Hanson 1972; Putnam et al., 2007). Alfalfa is among the most important forages in many regions of the world, including the USA, Australia, South Africa, North Africa, Middle East, South Asia, Argentina, and China. It is the number three economic crop in the US (USDA-NASS, 2020), and, in addition to dairy, is also widely used for beef, sheep, and horses.

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[1] **Abbreviations Used:**

SDI	Sub-Surface Drip Irrigaiton	**CP**	Crude Protein
SI	Surface/Flood Irrigation	**ADF**	Acid Detergent Fiber
ET_c	Crop Evapotranspiration	**NDF**	Neutral Detergent Fiber
WP	Water Productivity	**NDFD30**	Neutral Detergent Fiber digestibility at 30 hours
IWUE	Irrigation Water Use Efficiency	**NDFD48**	Neutral Detergent Fiber digestibility at 48 hours

Alfalfa acreage in California has been declining in recent years partly because of its high-water consumption and preference of growers to grow high value tree crops. In California, there has been a significant decrease observed in alfalfa acreage and production since its peak of 57.9% and 59.8%, respectively (Fig. 1.1). However, alfalfa remains economically viable and has added benefits to farmers including nitrogen fixation, benefits to succeeding crops, and improvement soil health (Fernandez et al. 2019). According to the National Agricultural Statistics Service (NASS, 2020), there was a 29.7% decrease in alfalfa acreage and 35.4% decrease in production since 2000 in the United Sates (Fig. 1.1).

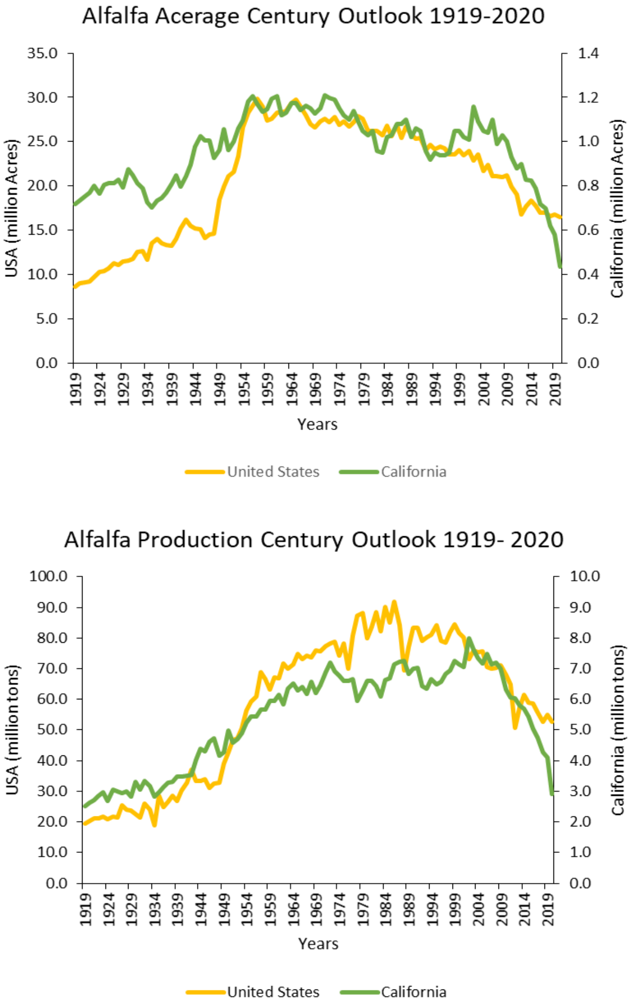


Figure 1.1. Alfalfa Century Outlook (USDA NASS 2020)

Alfalfa is well suited to irrigated cropping systems. Approximately 50% of the US alfalfa production is accomplished utilizing irrigation in western states (NASS, 2020). Declining water resources due to climate change and competition for urban, environmental and other agricultural uses require strategies to improve alfalfa productivity under such circumstances. Deficit irrigation, defined as controlled deficit irrigation, deliberately supplying less than the annual water needs of the crop) is a strategy to maximize yield output with less water use (Fereres and Soriano, 2007). It may be a useful technique to cope with water scarcity and variation in water supply from year to year. It has been reported that deficit irrigation can increase the water productivity (defined as unit of production per unit of water demand) of alfalfa (Rogers et al., 2016). Due to its perennial nature, a deficit irrigation strategy could be a viable option for increasing water use efficiency and producing high quality forage (Mushtaq and Moghaddasi, 2011). It has been shown that alfalfa can maintain or even improve the nutritive quality under severe water stressed conditions (Frate et al., 1991; Orloff 2003; Abid et al., 2016).

Reduced water consumption is likely to affect yield, but a deficit irrigation strategy can be used to improve water use efficiency and conserving water resources (Ali et al., 2007). Thereby, under limited water availability, profitable yields of alfalfa are possible by using deficit irrigation. Studies have also shown (Lindenmayer et al., 2011) that alfalfa can produce nearly normal biomass under deficit irrigation with a slight reduction in yield, in comparison to alfalfa grown with full irrigation. Some have challenged the economics of deficit irrigation strategies, however, especially when water prices are low, indicating that added incentives to implement deficit strategies may be required (Ottman and Putnam, 2017; Montazar et al., 2020)

English and Raja (1996) concluded that deficit irrigation reduces irrigation cost and improves water use efficiency. The irrigation requirement for alfalfa is high and demand of high-quality forage by the dairy industry in the U.S. is increasing. Thus, more forage must be produced while conserving water. In a study carried out by Lamm et al. (2012), deficit irrigation was practiced in alfalfa using subsurface drip irrigation (SDI) which increased crop water productivity by reduction in irrigation levels based on evapotranspiration (ET). Harmoney et al. (2013) also suggested alfalfa could be cultivated under subsurface drip irrigation without comprising yield and quality. Alfalfa can withstand severe water scarcity conditions due to its deep-rooted characteristics. Saving water in alfalfa is important since it is cultivated on 12% of irrigated land in United States (Lindenmayer et al., 2011).

Alfalfa forage quality is important economically due to the need for high quality by the dairy industry. High forage quality is defined by relatively low fiber, high protein content and high dry matter and fiber digestibility, but optimum levels depend upon the class, species, or breed of animal (Ball et al. 2001; Putnam et al., 2000). Forage quality tends to decrease with delaying the maturity of the crop and producing more yield (Lacefield, 2004). Growers must balance the desire to produce harvest maximum yield without reducing quality (Orloff and Putnam, 2004). Under water scarcity scenarios, it would be important to produce high quality as well as yield, utilizing available water. Deficit irrigation strategies must consider yield as well as quality.

Water productivity is generally defined as the amount of biomass produced per unit of crop evapotranspiration or applied water. Improving the water productivity of a crop links to the efficient management of water resources which would be beneficial in changing climate. Historically, alfalfa has the higher water use efficiency due to its high harvest index, deep-rooted characteristics, and ability to extract water from deep soil profile and remain dormant during the water scarcity periods (Fernandez et al. 2019).

Due to increasing demands on water resources, comparison of the productivity of surface irrigation and SDI is important. Additionally, examination of the impacts of deficit irrigation using the more precise SDI irrigation methods are important. The objectives of this study were:

1) To quantify the forage dry matter (DM) yield, quality and water productivity of alfalfa grown under sub-surface drip irrigation (SDI) compared with surface/flood irrigation.

2) To evaluate the impacts of deficit irrigation on yield, forage quality and water productivity using SDI.
3) To detect the differences in canopy temperatures as influenced by water stress using infrared thermometry

1.2 MATERIAL AND METHODS

The study was conducted at University of California Kearney Agricultural Research and Extension Center (KREC) Parlier, California (Fresno Co.) on Hanford sandy loam soil classified as coarse-loamy, mixed, super active, nonacid, thermic Type Xerorthents according to NRCS soil survey from 2016 through 2019. The soil physicochemical properties are provided in Table 1.1. Precipitation, temperatures, and solar radiation during the study period were typical of Mediterranean climates of California's San Joaquin Valley (Fig. 1.2). Different rainfall patterns were observed during the three years with most of rainfall occurring during the winter months.

The experiment was divided in two components. Component A (objective 1 and 3) includes two treatments, surface irrigation and SDI. In both cases, crops were grown under full irrigation to satisfy 100% $ET_{c.,}$ utilizing an ET scheduling approach. In component B (objective 2) four irrigation treatments were applied to the SDI system. These targeted: 50% of seasonal ET_c (terminating irrigation in July), 75% of seasonal ET_c (terminating irrigation in August), 75% of seasonal ET_c with continual deficits (irrigation 75% of ET_c at every irrigation), and Full irrigation to 100% ET_c. Both experiments were a randomized complete block design with four replications. Component A was implemented for two years (2017 and 2018) while component B was studied over three years (2017-2018-2019), with the exception that irrigation method shifted to flood irrigation for year 2019 after there was excessive damage to the SDI system at the end of year two.

The experiment had a field area of 1.16 ha and each plot was 7.6 m wide and 76.2 m long (Fig. 1.3). Alfalfa seed (cv. AmeriStand RR835NT RR-fall dormancy 8) was planted October 18 2016 at 25 kg ha^{-1} in 20 cm rows at 1.5 cm depth after land preparation. Drip tape was installed September 2016 in all the experimental units. Each plot has 10 drip lines installed at 30 cm deep and lateral spacing 76 cm apart before planting the crop. The drip tape was Netafim Typhoon-type with internal diameter of 22.25 mm, wall thickness 0.33 mm, flowrate 189.27 $mm^3 sec^{-1}$ and emitter spacing 355.6 mm. A subsoil delivery system was installed that delivered the 4 SDI treatments according to the water management of each treatment (Fig. 1.4 & 1.5).

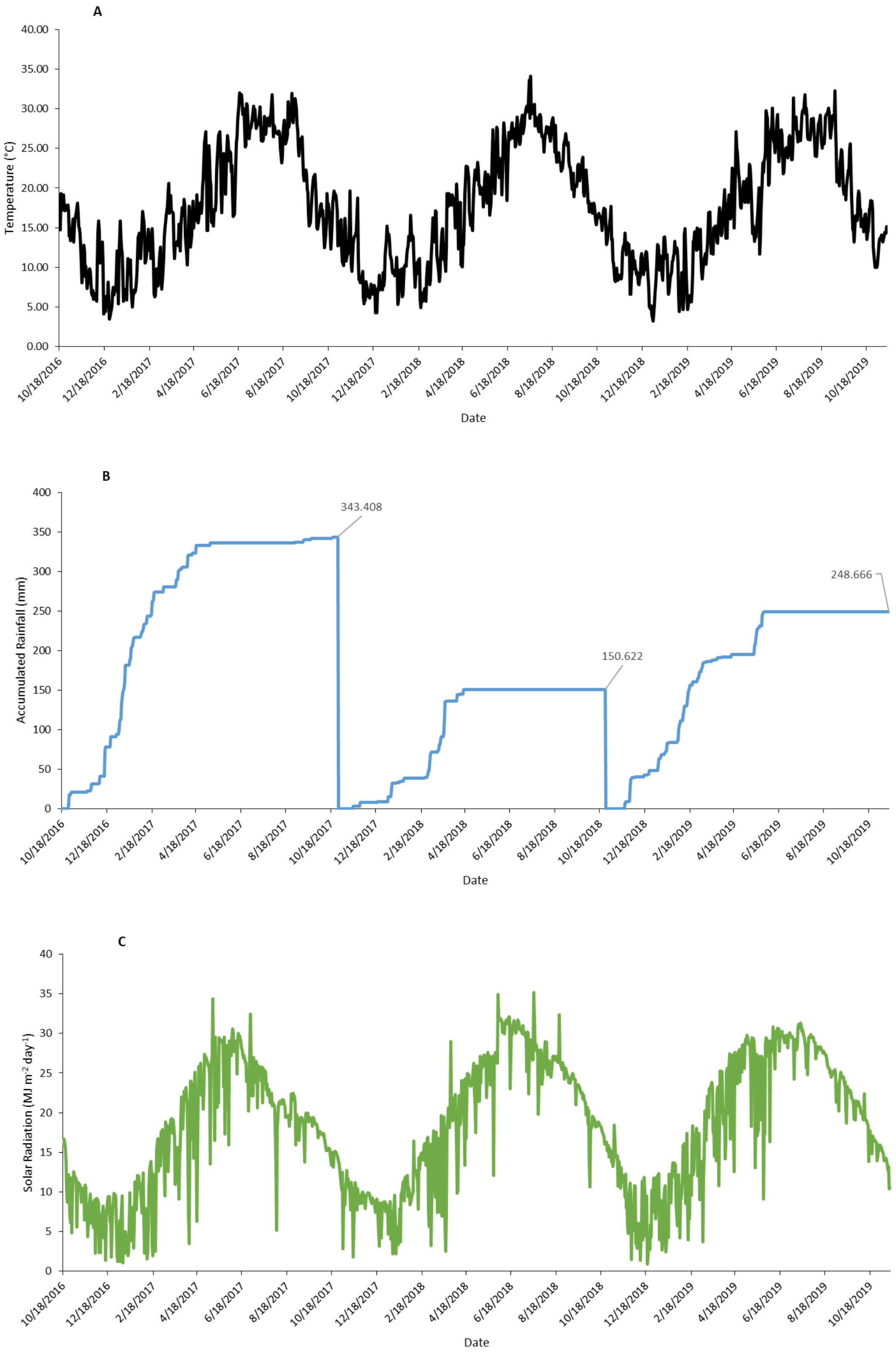


Figure 1.2. (A) Average temperature (°C), (B) accumulated rainfall (mm) and (C) Solar Radiation (MJ m^{-2} day^{-1}) for the study period 2017-2018-2019, data observed from CIMIS station 39-Parlier

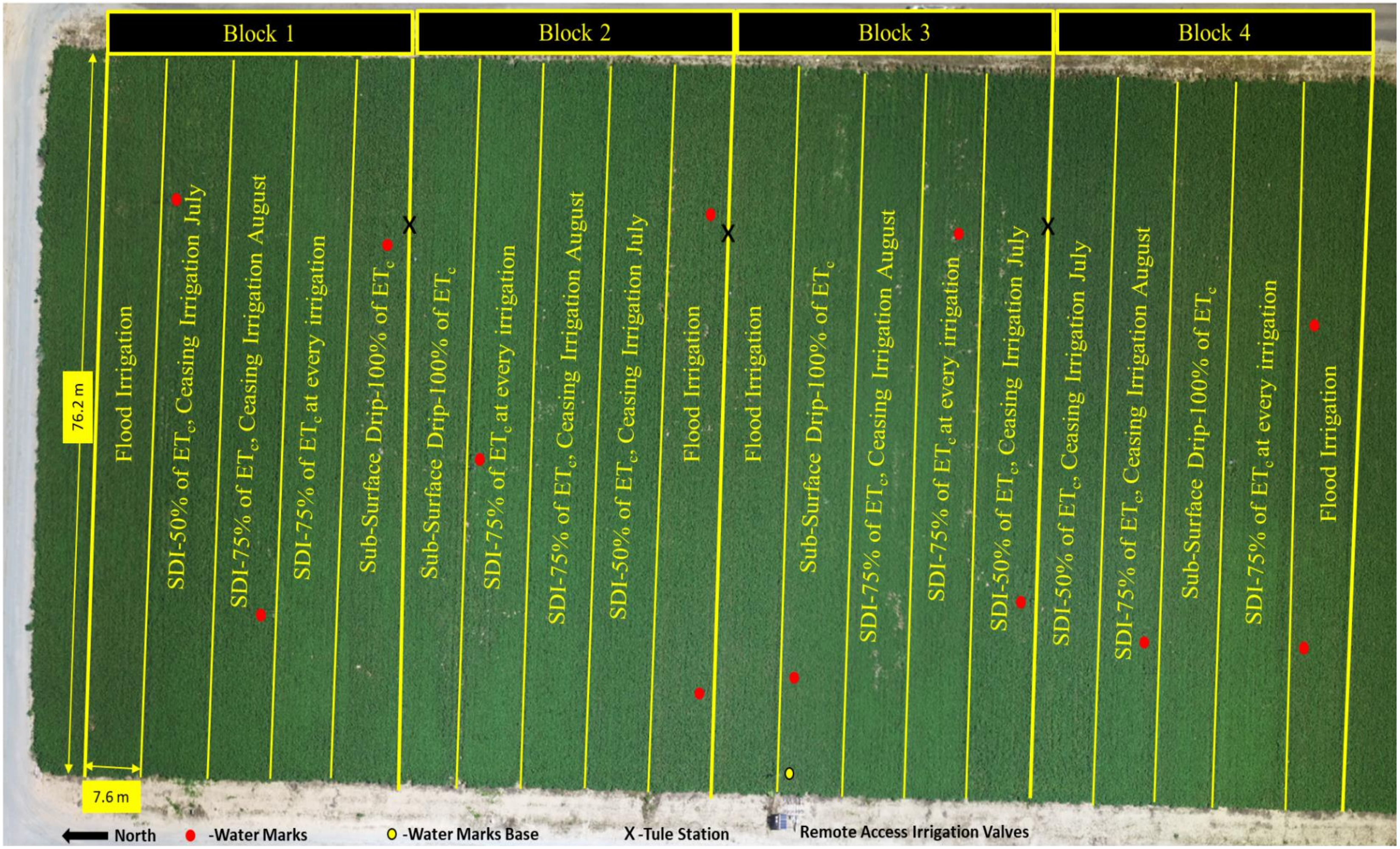


Figure 1.3. Experimental layout as randomized complete block design with locations of soil moisture sensors and Tule stations

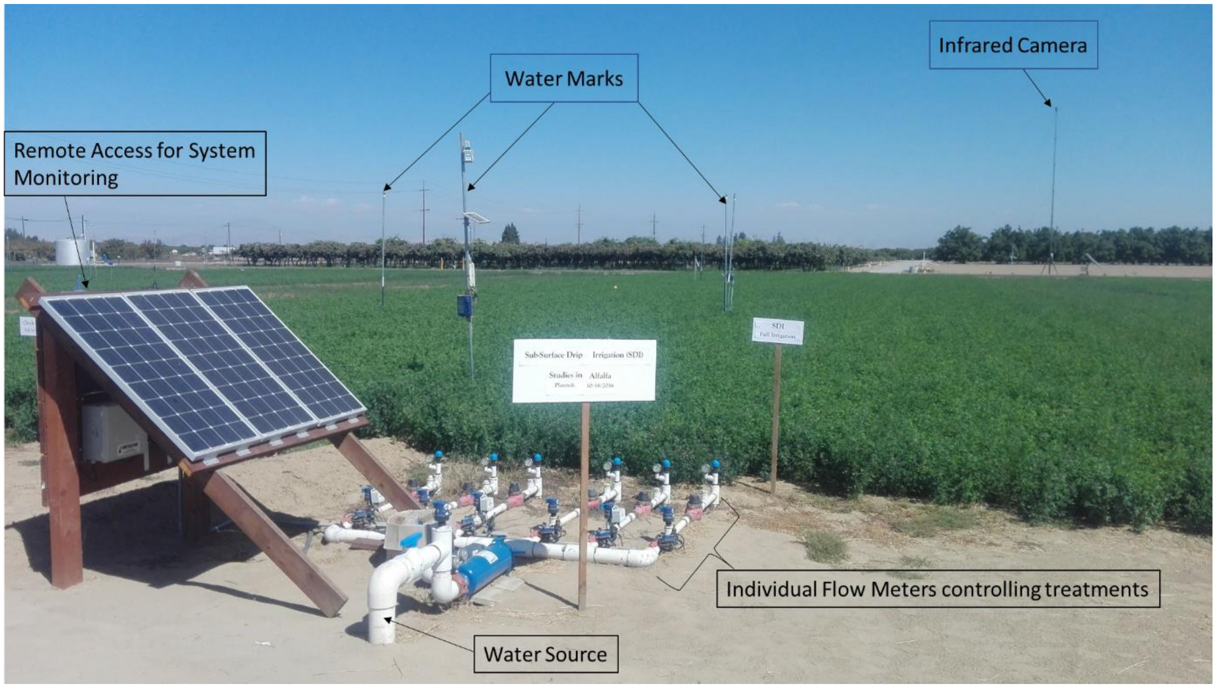


Figure 1.4. Characteristics of the SDI irrigation system equipped with individual flow meters for different treatments along with remote access for irrigation scheduling. Soil moisture sensors and infrared camera can be seen in the experiment.

Figure 1.5. Water Delivery line for each treatment connected with sub-surface drip lines

The soil profile was refilled at the beginning of each year before imposing the irrigation treatments. Soil water content was monitored using WaterMark sensors (Irrometer Company, Inc., Riverside, CA, USA). The sensors were installed in two sets (12.7 cm and 38.1 cm) from the drip tape at three different depths (30 cm, 60 cm and 120 cm) in each set within the plot. In addition to the Watermarks, soil sampling was also done using the gravimetric method to access the soil moisture content before and after each growing season.

Table 1.1. Soil physiochemical properties for Hanford Sandy Loam Soil

Sand %	**Silt %**	**Clay %**	**EC dS/m**	**pH**	**NO3-N mg/kg**	**PO4-P mg/kg**	**K mg/kg**	**OM %**	**FC %vol**	**WP %vol**	**Sat %vol**	**AW in/ft**
71	22	7	0.72	7.1	8.3	9.6	46	0.48	15.1	6.3	45.5	1.05

Irrigation scheduling was accomplished for all the treatments following an ET methodology (Snyder and Bali, 2008). Daily crop evapotranspiration (ET_c) requirements were calculated using the reference ET_o from (CIMIS Station 39) data for Parlier and appropriate crop coefficient (K_c) for alfalfa were used over the growth period. K_c values which were lower (0.35-0.40) at initial phases of crop growth (0-5 days after harvest) and increased (0.45- 1.08) as the crop develops (5-16 days after harvest) which stays fairly constant during the mid-season (16-22 days after harvest) of growth (Hunsaker et al., 2002). Tule stations were also installed in surface irrigation, SDI-Full and SDI-50% plots to monitor the actual crop evapotranspiration but due to the smaller foot print of the Tule station and close treatments, we used the calculated ET_c (Figs. 1.6 and 1.7) and the available soil water content in top 120 cm. Surface irrigation was applied following the common grower practice of 1-2 irrigations per growth cycle while drip irrigation was applied to the treatments as soon as the bales were removed till two days before the next harvest. All the plots were filled to the full profile after the first harvest of the year and irrigation was applied matching the ET_c requirements of the crop, with a targeted 10% adjustment to account for distribution uniformity (Fig. 1.3). The crop was harvested approximately every 28 days and data on harvested yield, forage quality, plant height from 30 plants in cm and water use were recorded.

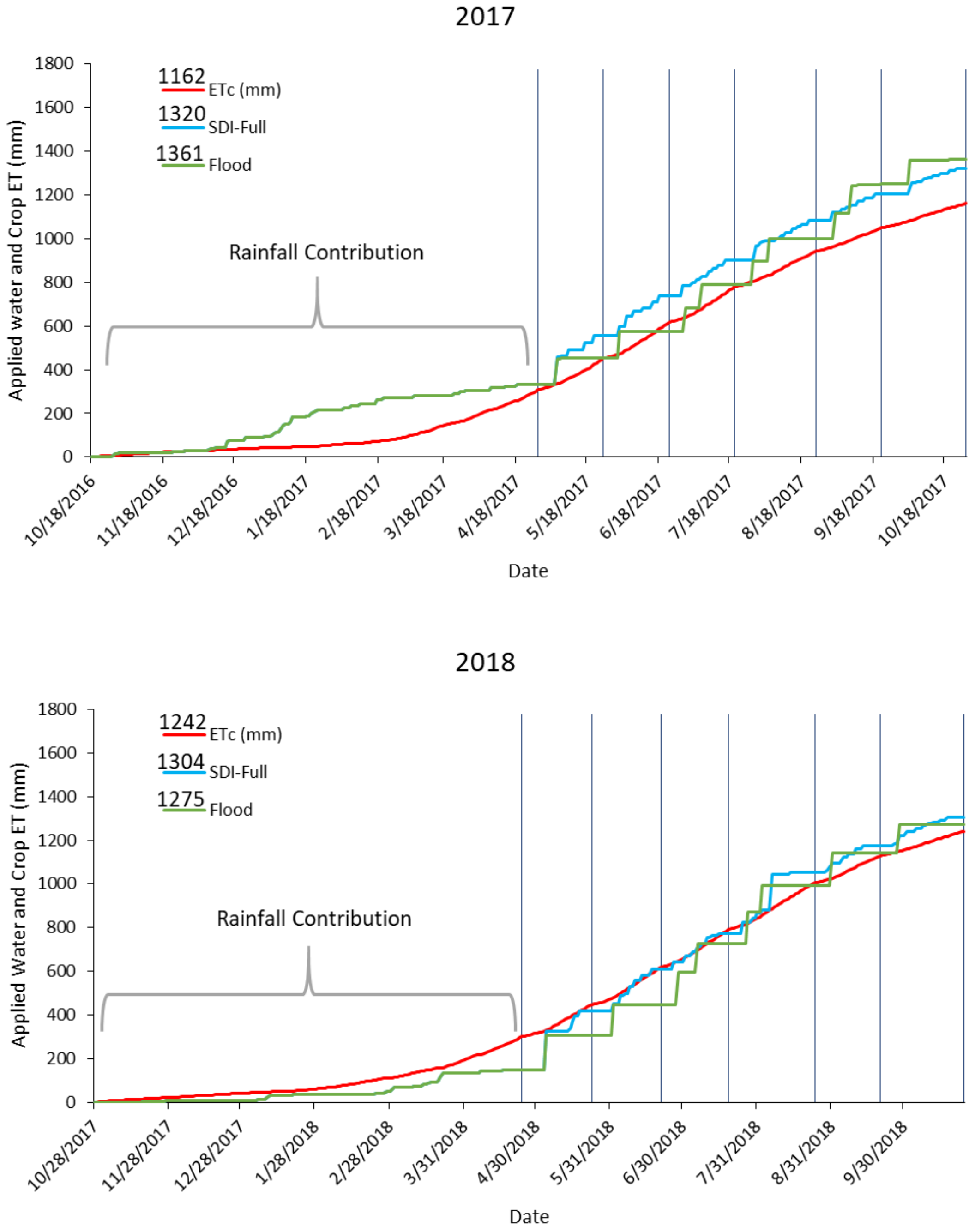


Figure 1.6. Crop evapotranspiration (red line) and cumulative seasonal applied water (mm) for the two growing seasons 2017 and 2018 to SDI-Full (blue line) and Surface irrigation (flood-green line) Full treatments while vertical lines show the harvest days. The actual applied amounts were higher than the required ET$_c$ to account for system efficiencies and distribution uniformity.

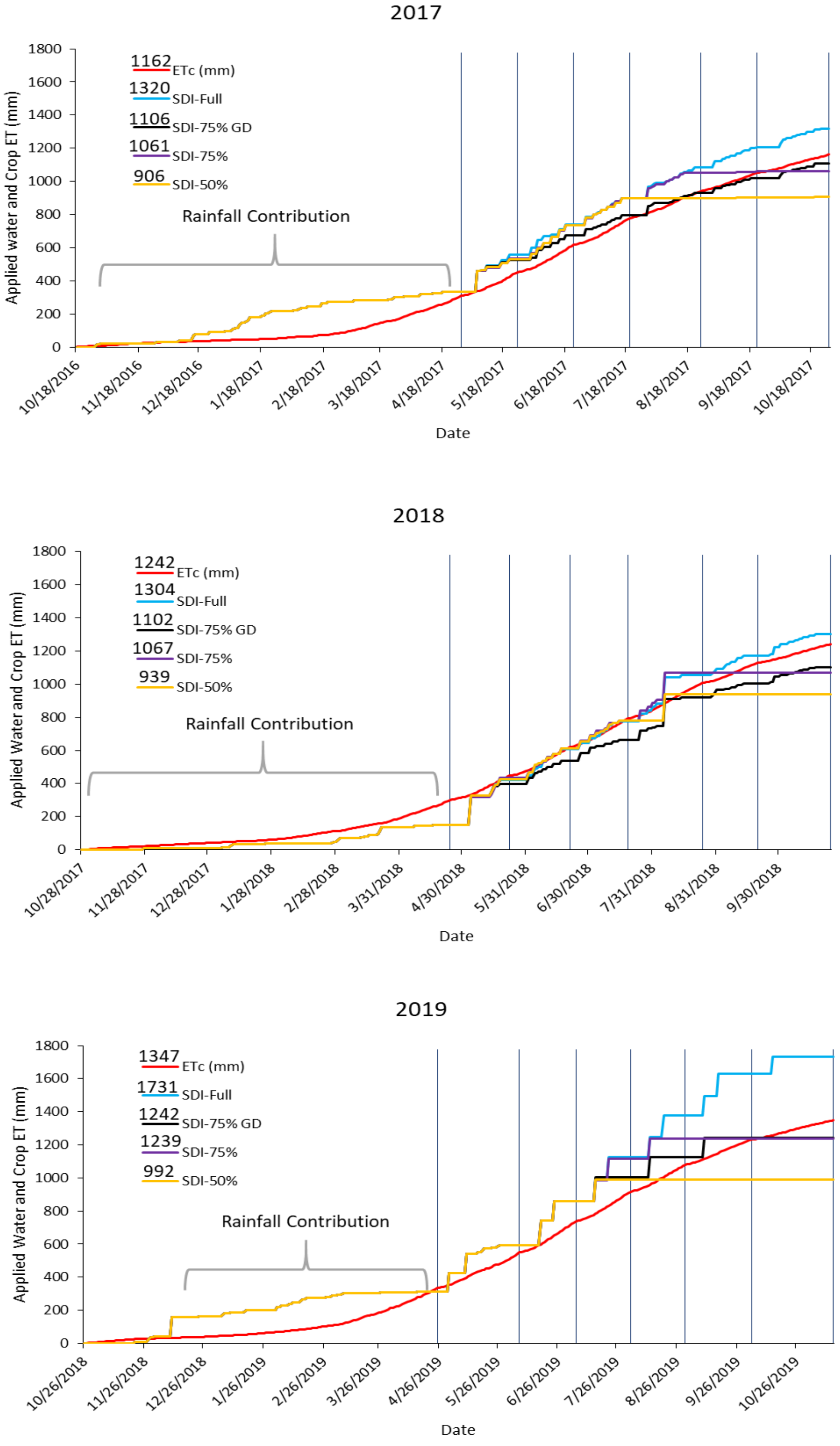


Figure 1.7. Crop evapotranspiration (red line) and cumulative seasonal applied water (mm) for the three growing seasons 2017, 2018 and 2019 to SDI-Full (blue line), SDI 75% Gradual Deficit (Black line), SDI-75% Cutoff (Purple line) and SDI-50% cutoff orange line) while vertical lines show the harvest days. The actual applied amounts were higher than the required ET$_c$ to account for system efficiencies and distribution uniformity.

The canopy temperature was monitored using an aerial fixed camera (Smartfield^{TM}, Inc., Lubbock, TX, USA). An infrared camera which collected imagery every 15 min and average the data for 30 min intervals was mounted on a 15 m high tower and was able to capture most of the research plot areas. The reference points were selected in the surface irrigation and SDI full treatments for correction of data collected by the infrared camera. The resulting output was a canopy temperature image displaying cooler to warmer canopy.

Forage quality was determined using NIR spectroscopy with a protocol developed by Jones et al., (1987). Samples were ground using a Wiley Mill to pass through a 4 mm sieve followed by a 1 mm cyclone mill grind and scanned using a Foss 6500 NIRS instrument. Crude protein (CP), acid detergent fiber (ADF), neutral detergent fiber (NDF), Ash content, digestible neutral detergent fiber at 30 hours (NDFD30) and 48 hours (NDFD48) were determined.

Water productivity (WP), and irrigation water use efficiency (IWUE) was calculated using the following formulas for the season in kg ha^{-1} mm^{-1}.

$$WP_{ET_c} = \frac{Seasonal\ Forage\ Dry\ Matter\ Yield}{Seasonal\ Crop\ Evapotranspiration} \qquad Eq.\ 1.1$$

Where crop evapotranspiration is the calculated ET_c

$$IWUE = \frac{Seasonal\ Forage\ Dry\ Matter\ Yield}{Seasonal\ Irrigation\ Water\ Applied} \qquad Eq.\ 1.2$$

Where Irrigation water applied includes irrigation water only.

1.2.1 Statistical Analysis:

Analysis of variance (ANOVA) was done using R statistical software with Agricola package (de Mendiburu, 2020). For objective 1, analysis was done using the linear model for the irrigation systems. Least significant difference (LSD) was applied for mean comparisons of irrigation systems at every harvest for studied parameters during the single year and average across the two years. Each year and cut were run separately for all the parameters. For every parameter studied, the significance level was 5% using least significance different (LSD). Regression analysis was conducted between water applied and all the dependent variables (i.e. dry matter yield, plant heights) for objective 2.

1.3 RESULTS

1.3.1 Irrigation System Comparisons:

One of the objectives of this experiment was to compare subsurface drip irrigation (SDI) with surface irrigation.

1.3.1.1 Dry Matter Yields:

Forage production under the two systems (surface irrigation and SDI) averaged over the two years was not significantly different (Fig. 1.8). The cumulative 2-year yield of 39.8 Mg ha^{-1} was achieved in SDI while in surface irrigation, the yield was 39.4 Mg ha^{-1}. In 2017 (Fig. 1.8), SDI performed slightly better than surface irrigation, while slightly higher yields were observed in 2018, but in both years, yield differences were non-significant (p<0.05). Similarly, average over the two years under the two systems also produced the non-significant differences. Yields for the individual harvests during 2017, 2018 and average across the two years are presented in Table 1.2. The two systems (surface irrigation and SDI) were found to be non-significant for nearly every harvest over the two years (Table 1.2).

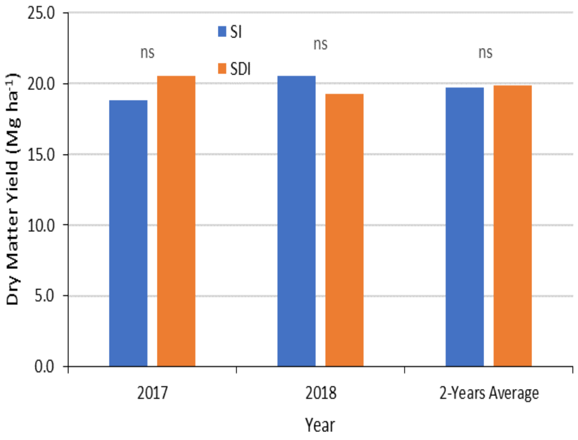


Figure 1.8. Dry matter yields for 2017, 2018 and averaged over two years. Ns represents non-significant at P<0.05

Table 1.2. Dry Matter Yields under two irrigation systems (Surface Irrigation and SDI)

Year	**Systems**	**April**	**May**	**June**	**July**	**Aug**	**Sep**	**Oct**	**Total**
		-------------------------------------Mg ha^{-1}							**--------------------------------------**
2017	SI	1.6	3.6	2.9	3.1	2.8	3.2	1.7	18.8
	SDI	1.8	4.1	3.8	3.0	3.2	2.9	1.7	20.5
	LSD	----	----	----	----	----	----	----	*2.21*
	p-value	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*0.090*
2018	SI	3.1	2.8	3.0	3.7	3.5	2.3	2.2	20.5
	SDI	3.3	3.1	3.1	2.6	3.1	1.9	2.1	19.3
	LSD	----	----	----	*1.27*	----	----	----	----
	p-value	*ns*	*ns*	*ns*	*0.070*	*ns*	*ns*	*ns*	*ns*
2-Years average	SI	2.3	3.2	2.9	3.4	3.1	2.7	2.0	19.7
	SDI	2.6	3.6	3.5	2.8	3.2	2.4	1.9	19.9
	LSD	----	*0.43*	----	----	----	----	----	----
	p-value	*ns*	*0.070*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*

Note: ns is Non-Significant SI= Surface Irrigation SDI= Sub Surface Drip Irrigation
Means sharing same letters in a column are not statistically different.
Total represents the sum across cuttings.

1.3.1.2 Plant Height:

Plant height was significantly affected by application method among the two irrigation systems during 2017, but it was non-significant for 2018 and average across the two years. Higher plant height (60 cm) was found in surface irrigation which was marginally but significantly different than SDI (58 cm) average across cuttings in 2017 (Table 1.3). During 2018, same results (Table 1.3) were found but were non-significant with higher plant heights observed in surface irrigation (67 cm) and lower in SDI (61 cm). However, differences in plant height between systems were inconsistent at each cutting, and mostly non-significant 2017 and 2018 (Table 1.3).

Table 1.3. Plant Heights under two irrigation systems (Surface Irrigation and Subsurface Drip Irrigation)

Year	**Systems**	**April**	**May**	**June**	**July**	**Aug**	**Sep**	**Oct**	**Average**
		-----------------------------------			**cm**				**-----------------------------------**
2017	SI	----	58 b	50	74 a	67	62 a	51	60 a
	SDI	----	61 a	51	68 b	65	55 b	47	58 b
	LSD	----	*2.99*	----	*4.35*	----	*3.50*	----	*1.63*
	p-value	----	*0.036*	*ns*	*0.026*	*ns*	*0.006*	*ns*	*0.018*
2018	SI	71	59	62	60	76	68	70 a	67
	SDI	63	66	58	49	66	64	62 b	61
	LSD	----	*8.07*	----	----	*12.38*	----	*7.65*	----
	p-value	*ns*	*0.073*	*ns*	*ns*	*0.077*	*ns*	*0.046*	*Ns*
2-Years average	SI	71	58 b	56	67	71	65 a	61 a	63
	SDI	63	64 a	55	59	65	59 b	55 b	60
	LSD	----	*5.24*	----	*9.11*	----	*5.06*	*5.34*	*4.51*
	p-value	*ns*	*0.052*	*ns*	*0.065*	*ns*	*0.035*	*0.037*	*0.069*

Note: ns is Non-Significant SI= Surface Irrigation SDI= Sub Surface Drip Irrigation
Means sharing same letters in a column are not statistically different.
Total represents the average across cutting.

1.3.1.3 Forage Quality:

Forage quality were significantly different among cuttings, but generally non-significant between the two systems. When averaged across the years, non-significant results were found for all the quality parameters (Table 1.4). During 2017, significant results were found for CP, NDFD30 and NDFD48 ($p < 0.01$) with SDI significantly higher than surface irrigation. In 2018 (Table 1.4), almost all the parameters were non-significant except the ash content ($p < 0.05$).

During every harvest cycle in 2017, most of the parameters were also non-significant except NDFD30 and NDFD48 which was found higher in SDI as compared with surface irrigation in a few cuttings (supplementary Table 1.10). Similar trend was seen in 2018 where during the late harvests NDFD30 and NDFD48 was found higher in SDI as compared with surface irrigation (supplementary Table 1.11). Although there was a small trend for slightly higher digestibility in the SDI treatment in year one, in general, we did not see important differences in quality between the two systems.

Table 1.4. Forage quality parameters average across the cuttings under two irrigation systems (Surface Irrigation and SDI) during 2017, 2018 and 2-years average.

Year	**Systems**	**CP**	**ADF**	**aNDF**	**ASH**	**FAT**	**NDFD30**	**NDFD48**
		--			g kg^{-1}			----------------------------------
2017	SI	261 b	274	345	82	24	367 b	474 b
	SDI	267 a	269	336	84	24	376 a	486 a
	LSD	*3.20*	----	----	----	----	*7.05*	*7.80*
	p-value	*0.009*	*ns*	*ns*	*ns*	*ns*	*0.029*	*0.017*
2018	SI	254	278	342	78 b	23	383	476
	SDI	259	276	339	81 a	23	384	484
	LSD	----	----	----	*1.81*	*0.54*	----	----
	p-value	*ns*	*ns*	*ns*	*0.018*	*0.083*	*ns*	*ns*
2-Years average	SI	257	276	344	80	24	375	475
	SDI	263	273	338	82	24	380	485
	LSD	----	----	----	----	----	----	*11.51*
	p-value	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*0.075*

Note: ns is Non-Significant SI= Surface Irrigation SDI= Sub Surface Drip Irrigation

Means sharing same letters in a column are not statistically different.

CP= Crude Protein ADF= Acid Detergent Fiber aNDF= Neutral Detergent Fiber

NDFD30= Neutral Detergent Fiber digestibility at 30 hours

NDFD48= Neutral Detergent Fiber digestibility at 48 hours

1.3.1.4 Water Productivity for Applied Water (WP_{AW}) and Irrigation Water Use Efficiency (IWUE):

Water productivity is a function both of yield and applied and available water. Over the two years average, water productivity of applied water (WP_{AW}) and irrigation water use efficiency (IWUE) were not significantly different ($p<0.05$) between the two irrigation systems. However, in 2017, SDI had the higher WP_{AW} (15.6 kg ha^{-1} mm^{-1}), significantly different than surface irrigation (13.9 kg ha^{-1} mm^{-1}) while in 2018, higher WP_{AW} was achieved in surface irrigation (Table 1.5) which was non-significant with SDI. Similarly, IWUE was significantly higher for SDI (21.1 kg ha^{-1} mm^{-1}), and surface irrigation (18.53 kg ha^{-1} mm^{-1}) in 2017 while in 2018, higher IWUE was found in surface irrigation which was non-significant with SDI (Table 1.5).

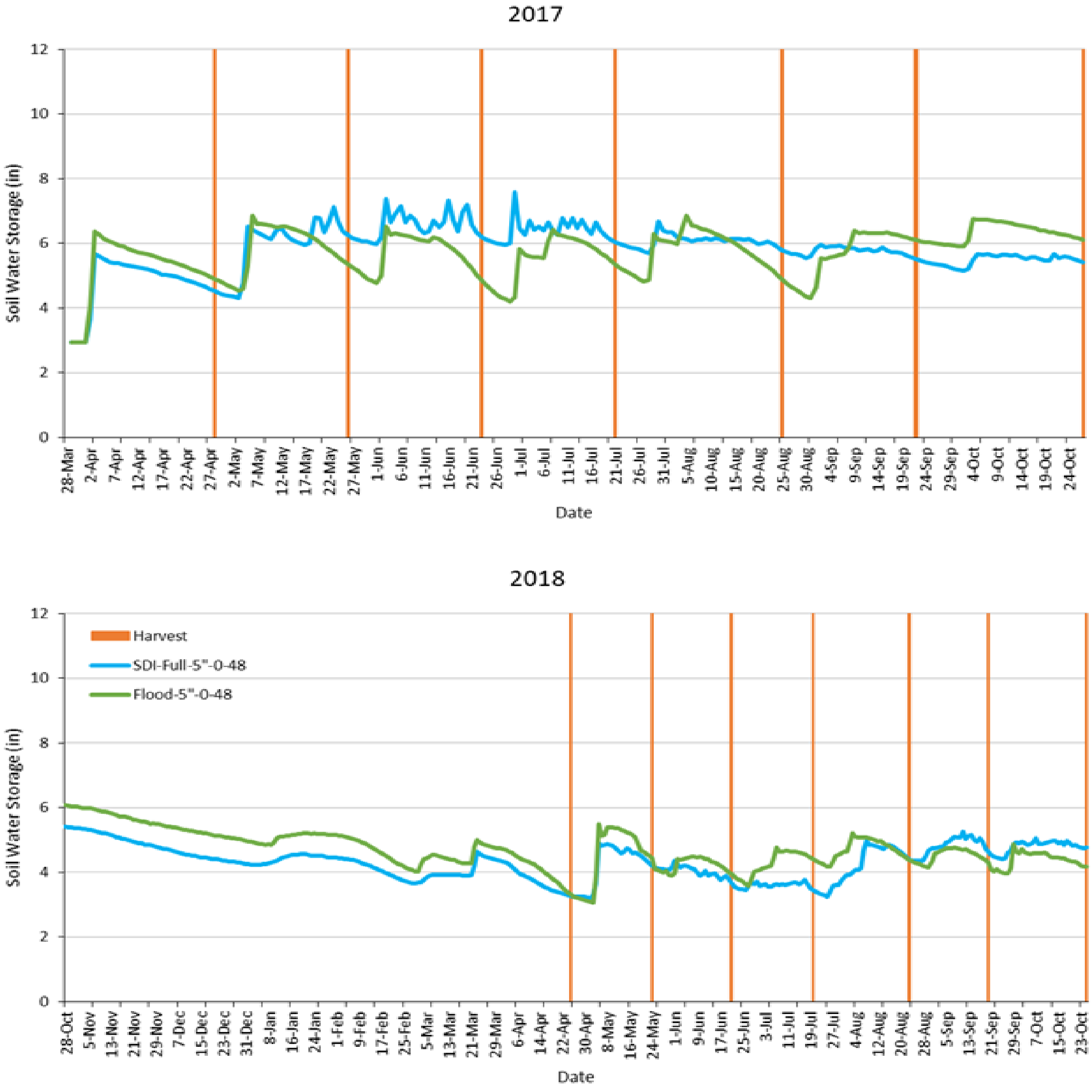
Table 1.5. End of Season Water productivity and Irrigation water use efficiency under two irrigation systems (Surface Irrigation and SDI) during 2017, 2018 and 2-years average.

Year	**Systems**	**WP_{AW}**	**IWUE**
		-----------kg ha^{-1} mm^{-1}-----------	
2017	SI	13.9 b	18.5 b
	SDI	15.6 a	21.1 a
	LSD	*1.65*	*2.21*
	p-value	*0.044*	*0.036*
2018	SI	16.1	18.3
	SDI	14.8	16.7
	LSD	----	----
	p-value	*ns*	*ns*
2-Years average	SI	15.0	18.4
	SDI	15.2	18.9
	LSD	----	----
	p-value	*ns*	*ns*

Note: ns is Non-Significant SI= Surface Irrigation SDI= Sub Surface Drip Irrigation
Means sharing same letters in a column are not statistically different.

1.3.1.5 Soil Water Availability:

There were differences found in the soil water availability under the two irrigation systems. The frequency of the SDI applications (blue line) compared with the surface applications (green line) can be seen over the growing season (Fig. 1.9). During 2017, the surface irrigation treatments had more water storage over the entire season while in 2018, SDI had the highest available. But during certain harvests in 2018, SDI had the lower water available.


2017

2018

Figure 1.9. Soil water storage (inches) in top 120 cm for surface irrigation (Green line) and SDI (Blue Line) along with harvest dates (orange verticle bars) for the year 2017 and 2018.

1.3.2 Impact of Deficit Irrigation on Forage Yield, Quality and Water Productivity:

1.3.2.1 Dry Matter Yield:

Deficit irrigation impacts over the three years of study period were significant. Under the targeted 50% deficit treatments over the three years, 82% of full yields were achieved (Fig. 1.10)., although the actual applied amounts were quite higher than the targeted deficits and ranged from 57% to 68% of full irrigation in different years. Averaged across the years, highest yields were always found in the 100% treatment, with deficits ranging from 82% to 87% of full yields (Table 1.6). Due to the fact that deficits were imposed from mid- to late-season, yield differences were primarily apparent in later cuttings (Table 1.6).

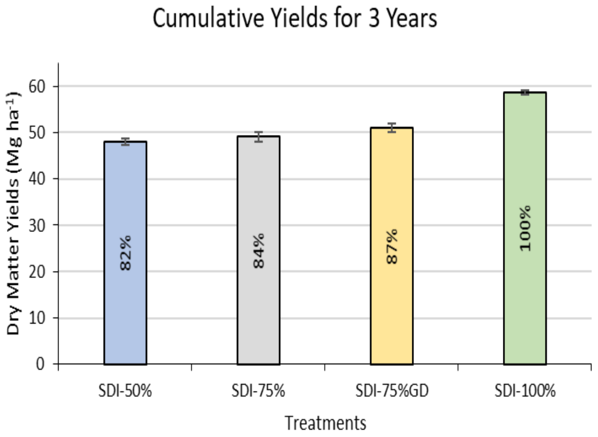


Figure 1.10. Cumulative 3-year Dry matter yields under SDI-50% deficit (blue bar), SDI-75% (grey bar), SDI-75% GD (orange bar) and SDI-100% (green bar) for year 2017, 2018 and 2019.

During 2017, cumulative yields for SDI-100% were higher which were significantly different than SDI-75%GD, SDI-75% and SDI-50%. Similar trend was found during 2018 where SDI-100% had the higher yields at par with SDI-50% and significantly different than SDI-75%GD and SDI-75% (Table 1.6). However, lowest yields were found in SDI-75% during 2018 (Fig. 1.11). Differences between treatments in 2019

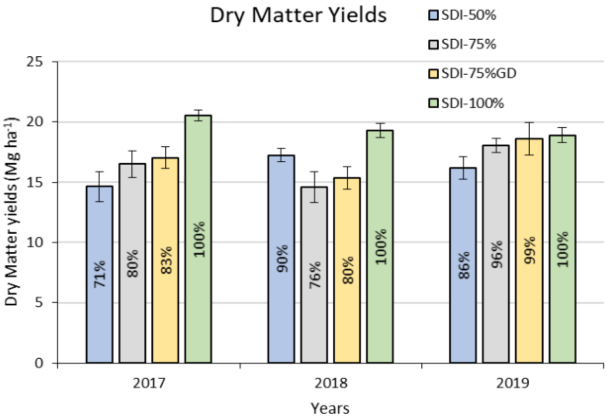


Figure 1.11. Dry matter yields under SDI-50% deficit (blue bar), SDI-75% (grey bar), SDI-75% GD (orange bar) and SDI-100% (green bar) for year 2017, 2018 and 2019. Error bars are based on replicated data for the year. The percent yields are displayed in the center of bar compared with full yields in a single year.

were less dramatic than in previous years, when the treatments were applied using surface irrigation (Table 1.6).

During the late part of the season 2017, SDI-100% produced higher yields while SDI-50% produced lowest yields (Table 1.6). During 2018, all of the harvest cycles were significant except August. SDI-50% performed well during the early part of the season with higher yields comparable with SDI-100% while the yields were lowest during the late season. During 2019, when surface irrigation was utilized, most of the harvest periods were non-significant, except for the fall cuttings (Table 1.6).

Table 1.6. Dry Matter Yields under deficit irrigation using SDI for year 2017, 2018, 2019 and 3-years average

Year	**Deficits**	**April**	**May**	**June**	**July**	**Aug**	**Sep**	**Oct**	**Total**
		---------------------------------Mg ha^{-1}---------------------------------							
2017	SDI-50%	1.9	4.0	3.5	2.8 a	1.5 b	0.6 c	0.3 b	14.6 b
	SDI-75%	1.9	4.1	3.1	2.8 a	2.9 a	1.1 bc	0.5 b	16.5 b
	SDI-75%GD	1.7	4.1	3.5	2.2 b	2.3 ab	1.9 ab	1.4 a	17.0 b
	SDI-100%	1.8	4.1	3.8	3.0 a	3.2 a	2.9 a	1.7 a	20.5 a
	LSD	-----	-----	-----	*0.44*	*0.75*	*0.78*	*0.44*	*2.40*
	p-value	*ns*	*ns*	*ns*	*0.013*	*0.002*	*0.001*	*0.000*	*0.002*
2018	SDI-50%	2.6 b	3.0 ab	3.5 a	3.1 a	2.9	1.3 bc	0.9 b	17.2 ab
	SDI-75%	2.5 b	2.8 ab	2.7 ab	2.0 bc	2.8	1.1 c	0.8 b	14.6 c
	SDI-75%GD	2.5 b	2.6 b	2.0 b	1.8 c	2.8	1.8 ab	1.9 a	15.3 bc
	SDI-100%	3.3 a	3.1 a	3.1 a	2.6 ab	3.1	1.9 a	2.1 a	19.3 a
	LSD	*0.41*	*0.40*	*1.03*	*0.74*	-----	*0.54*	*0.45*	*2.53*
	p-value	*0.002*	*0.068*	*0.050*	*0.014*	*ns*	*0.023*	*0.000*	*0.010*
2019	SDI-50%	-----	4.2	3.8	3.6	2.6	1.3 b	0.5	16.2
	SDI-75%	-----	4.3	3.8	3.7	3.1	2.0 b	1.1	18.0
	SDI-75%GD	-----	4.1	4.0	3.7	3.4	2.2 a	1.2	18.6
	SDI-100%	-----	4.0	3.6	3.8	3.5	2.3 a	1.7	18.9
	LSD	-----	-----	-----	-----	-----	*0.64*	*0.86*	*2.20*
	p-value	-----	*ns*	*ns*	*ns*	*ns*	*0.031*	*0.084*	*0.081*
3-Years Average	SDI-50%	2.2 b	3.8	3.6	3.2 a	2.3 b	1.1 c	0.6 b	16.0 b
	SDI-75%	2.2 b	3.7	3.2	2.9 ab	2.9 a	1.4 bc	0.8 b	16.4 b
	SDI-75%GD	2.1 b	3.6	3.2	2.6 b	2.8 ab	1.9 ab	1.5 a	17.0 b
	SDI-100%	2.6 a	3.7	3.5	3.1 a	3.3 a	2.4 a	1.8 a	19.6 a
	LSD	*0.26*	-----	*0.42*	*0.31*	*0.56*	*0.53*	*0.46*	*1.60*
	p-value	*0.009*	*ns*	*0.093*	*0.005*	*0.027*	*0.002*	*0.001*	*0.003*

Note: ns is Non-Significant
SDI-50%= Terminating Irrigation in July *SDI-75%= Terminating Irrigation in August*
SDI-75%GD= Irrigating 75% of ET at every irrigation *SDI-100%= Full ET$_c$ irrigation*
Means sharing same letters in a column are not statistically different.
Total represents the sum across cuttings.

A linear relationship was found between the water applied and dry matter yields produced in individual harvests during the three years of study period (Fig. 1.12). During 2017, the relationship was stronger with higher R^2 of 0.87 while it was lower during year 2018 (0.69). Substantial yields were observed with zero applications due to residual moisture on selected cuttings.

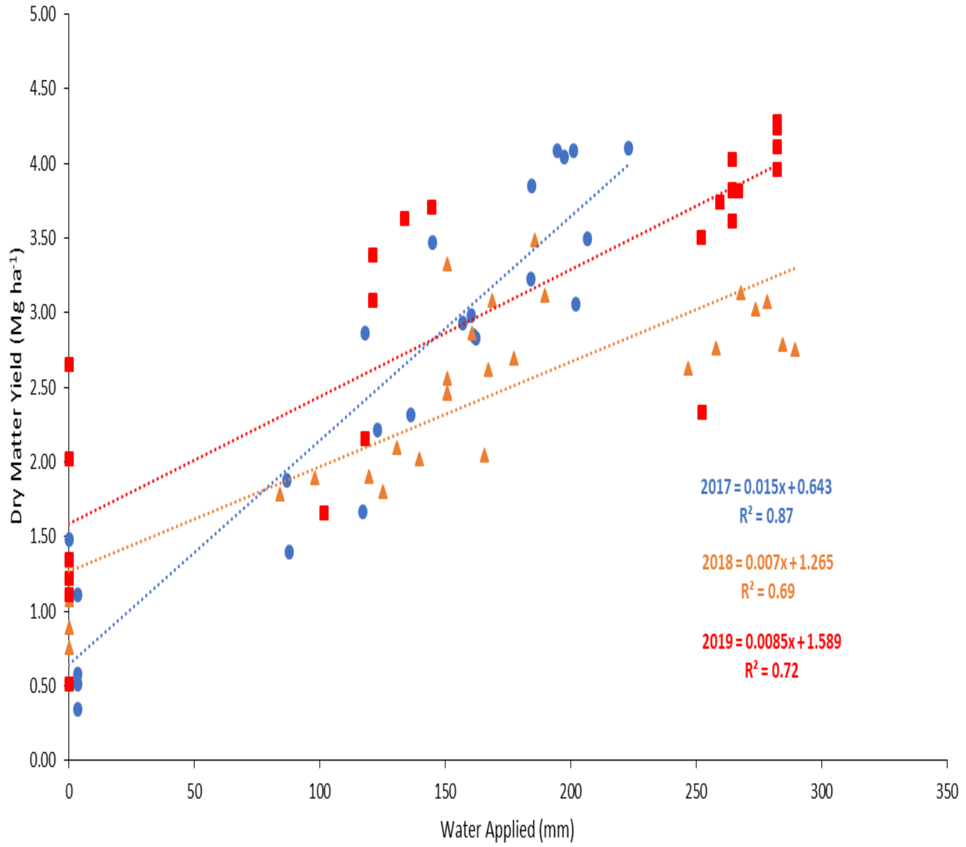


Figure 1.12. Water applied and dry matter yields of individual harvests over the entire growth season for year 2017 (blue), 2018 (orange) and 2019 (red). Scatter includes seasonal variation for each cuttina.

1.3.2.2 Plant Height:

For the three years average, significant differences in plant height due to the treatments were found (Table 1.7). Significantly higher plant heights were observed in SDI-100% followed by SDI-75%GD and SDI-75% while the lowest were found in SDI-50% over the three-season average (Table 1.7). Similar trend was found during 2017 with SDI-100% higher plant heights statistically different than SDI-75%GD and SDI-75% while lowest in SDI-50%. During 2018, SDI-100% had the higher plant heights which was statistically different than SDI-75%GD, SD-75% and SDI-50%. SDI-100% did perform well also in 2019 but it was statistically not different than SDI-75%GD and SDI-75% while significantly different than SDI-50%. During the three years, individual harvest cycles also produced the similar results with SDI-100% higher plant heights while SDI-50% lower plant heights (Table 1.7). During the latter part of the season, these differences were clearer.

Plant height was a good predictor of dry matter yields, similar to Lyons et al. (2016). Yields were positively and significantly related to DM yields in each year of our study (Fig. 1.13). The highest R^2 was found during year 2019 (0.83) while the lowest was found in year 2018 (0.40).

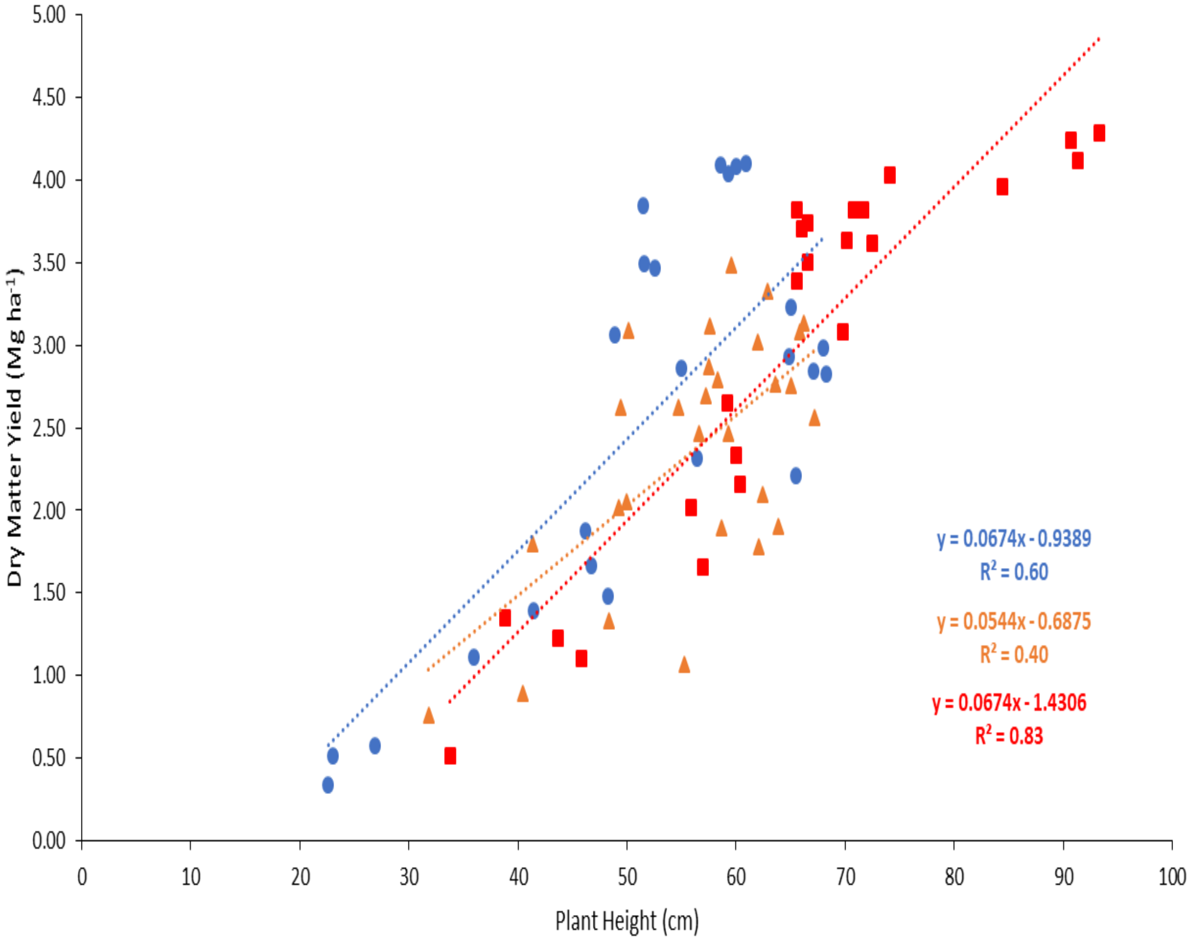


Figure 1.13. Relationships between plant height and dry matter yields at each harvest for years 2017 (blue), 2018 (orange) and 2019 (red). Data includes individual harvests from all deficit treatments fully irrigated treatments

Table 1.7. Plant heights under deficit irrigation using SDI for year 2017, 2018, 2019 and 3-years average

Year	Systems	April	May	June	July	Aug	Sep	Oct	Average
		----------------------------------			cm			--------------------------------	
2017	SDI-50%	-----	59	52	68	48 c	27 d	23 c	46 d
	SDI-75%	-----	60	49	67	65 a	36 c	23 c	50 c
	SDI-75%GD	-----	59	53	65	56 b	46 b	41 b	53 b
	SDI-100%	-----	61	51	68	65 a	55 a	47 a	58 a
	LSD	-----	-----	-----	-----	*6.88*	*7.61*	*3.24*	*2.34*
	p-value	-----	*ns*	*ns*	*ns*	*0.001*	*0.000*	*0.000*	*0.000*
2018	SDI-50%	67	62 ab	60 a	50	58	48	40 b	55 b
	SDI-75%	59	58 bc	57 a	50	65	55	32 b	54 b
	SDI-75%GD	57	55 c	49 b	41	64	62	59 a	55 b
	SDI-100%	63	66 a	58 a	49	66	64	62 a	61 a
	LSD	-----	*4.65*	*6.11*	-----	-----	-----	*11.58*	*4.50*
	p-value	*ns*	*0.002*	*0.018*	*ns*	*ns*	*ns*	*0.001*	*0.020*
2019	SDI-50%	-----	91 a	71	70 a	59 b	39 b	34 c	61 b
	SDI-75%	-----	93 a	72	67 b	70 a	56 a	46 b	67 a
	SDI-75%GD	-----	91 a	74	66 b	66 a	60 a	44 b	67 a
	SDI-100%	-----	84 b	72	66 b	67 a	60 a	57 a	68 a
	LSD	-----	*4.73*	-----	*3.28*	*6.09*	*11.85*	*6.96*	*4.55*
	p-value	-----	*0.011*	*ns*	*0.039*	*0.020*	*0.008*	*0.000*	*0.019*
3-Years Average	SDI-50%	67	71	61	63 a	55 c	38 c	32 c	54 c
	SDI-75%	59	71	59	61 ab	67 a	49 b	34 c	57 b
	SDI-75%GD	57	68	59	58 b	62 b	56 ab	48 b	58 b
	SDI-100%	63	71	60	61 ab	66 ab	60 a	55 a	62 a
	LSD	-----	-----	-----	*3.62*	*4.09*	*8.01*	*3.79*	*2.60*
	p-value	*ns*	*ns*	*ns*	*0.052*	*0.000*	*0.001*	*0.000*	*0.000*

Note: ns is Non-Significant

SDI-50%= Terminating Irrigation in July *SDI-75%= Terminating Irrigation in August*

SDI-75%GD= Irrigating 75% of ET at every irrigation *SDI-100%= Full* ET_c *irrigation*

Means sharing same letters in a column are not statistically different.

Average represents the average across cuttings.

1.3.2.3 Deficit Irrigation Effects on Forage Quality:

During the three years average, most of the quality parameters were non-significant except NDFD30 and NDFD48 (Table 1.8). Higher NDFD30 was found in SDI-100% followed by SDI-75%GD and SDI-75% while the lowest was found in SDI-50% (Table 1.8). A similar trend was found for NDFD48. During 2017, CP ($p < 0.01$), NDFD30 ($p < 0.05$) and NDFD48 ($p < 0.001$) were found higher in SDI-100% which was significantly at par with SDI-75%GD and SDI-75%

and significantly different than SDI-50% (Table 1.8). All the forage quality parameters were found non-significant during 2018 and 2019 when averaged across cuttings (Table 1.8).

During 2017, non-significant results were found during every harvest period except for CP ($p < 0.01$), NDFD30 ($p < 0.01$) and NDFD48 ($p < 0.001$) which were found significant during later harvest period (supplementary Table 1.13). Higher CP was observed for SDI-100% followed by SDI-75%GD and SDI-75% and lowest in SDI-50%. Similar results were found NDFD30 and NDFD48 which were significant in later part of the season with SDI-100% having the higher quality, followed by SDI-75%GD and SDI-75% while lowest in SDI-50% (supplementary Table 1.13).

Similarly, during 2018 significant results were found for CP ($p < 0.01$), NDFD30 ($p < 0.001$) and NDFD48 ($p < 0.001$) during later part of the season (supplementary Table 1.14). SDI-100% also had the higher quality followed by SDI-75%GD and SDI-75% while lowest quality was observed in SDI-50% (supplementary Table 1.14). During 2019, all the forage quality parameters during single harvest period were non-significant (supplementary Table 1.15) with SDI-100% had the higher quality followed by SDI-75GD and SDI-75% while lowest in SDI-50%.

Table 1.8. Forage quality parameters averaged across the cuttings under deficit irrigation using SDI for year 2017, 2018, 2019 and 3-years average.

Year	**Systems**	**CP**	**ADF**	**aNDF**	**ASH**	**FAT**	**NDFD30**	**NDFD48**
		--------------------------------g kg-1--------------------------------						
2017	SDI-50%	250 c	258	325	81	24	352 b	450 b
	SDI-75%	256 bc	263	332	82	24	362 ab	459 b
	SDI-75%GD	265 ab	266	335	83	25	373 a	484 a
	SDI-100%	267 a	269	336	84	24	376 a	486 a
	LSD	*9.65*	----	----	----	----	*14.27*	*13.80*
	p-value	*0.008*	*ns*	*ns*	*ns*	*ns*	*0.014*	*0.000*
2018	SDI-50%	254	269	331	79	23	378	469
	SDI-75%	253	265	328	81	23	378	475
	SDI-75%GD	256	273	336	80	23	378	477
	SDI-100%	259	276	339	81	23	384	484
	LSD	----	----	----	----	----	----	----
	p-value	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*
2019	SDI-50%	247	269	327	93	22	413	478
	SDI-75%	255	267	324	91	22	421	493
	SDI-75%GD	253	274	333	91	22	421	496
	SDI-100%	255	276	334	89	22	426	498
	LSD	----	----	----	*2.68*	----	----	----
	p-value	*ns*	*ns*	*ns*	*0.080*	*ns*	*ns*	*ns*
3-Years Average	SDI-50%	250	265	328	84	23	381 b	466 c
	SDI-75%	255	265	328	85	23	387 ab	476 bc
	SDI-75%GD	258	271	335	85	23	391 a	486 ab
	SDI-100%	260	274	336	85	23	395 a	489 a
	LSD	----	----	----	----	----	*9.45*	*12.32*
	p-value	*ns*	*ns*	*ns*	*ns*	*ns*	*0.035*	*0.008*

Note: ns = Non-Significant

SDI-50%= Terminating Irrigation in July *SDI-75%= Terminating Irrigation in August*

SDI-75%GD= Irrigating 75% of ET at every irrigation *SDI-100%= Full* ET_c *irrigation*

Means sharing same letters in a column are not statistically different.

CP= Crude Protein *ADF= Acid Detergent Fiber* *aNDF= Neutral Detergent Fiber*

NDFD30= Neutral Detergent Fiber digestibility at 30 hours

NDFD48= Neutral Detergent Fiber digestibility at 48 hours

1.3.2.4 Water Productivity for Applied Water (WP_{AW}) and Irrigation Water Use Efficiency (IWUE)

Over the three years average, WP_{AW} and IWUE were found significant between the deficit treatments. Higher WP_{AW}, IWUE were found statistically different in SDI-50% followed by SDI-75% and SDI-75%GD while the lowest were found in SDI-100%. However, in 2017, WP_{AW} was found to be nonsignificant amongst treatments while IWUE was also non-significant ($p > 0.05$) with higher values for SDI-50% followed by SDI-75% and SDI-75% and lowest in SDI-100% (Table 1.9). Similarly, same trend was followed in 2018 with mostly significant results for WP_{AW} ($p < 0.01$) and IWUE ($p < 0.01$), higher in SDI-50% followed by SDI-75%, SDI-75%GD and SDI-100% (Table 1.9). During 2019, lower WP_{AW} were achieved with higher for SDI-50%, followed by SDI-75%, SDI-75GD and SDI-100%. While IWUE also followed the same trend (Table 1.9).

Table 1.9. Water productivity (applied water in kg ha^{-1} mm^{-1}), irrigation water use efficiency and water productivity crop evapotranspiration for year 2017, 2018, 2019 and three year averages.

Year	**Deficits**	**WP_{AW}**	**IWUE**
		--------------kg ha^{-1} mm^{-1}	-------------
2017	SDI-50%	16.2	26.0 a
	SDI-75%	15.5	23.0 ab
	SDI-75%GD	15.4	22.3 b
	SDI-100%	15.6	21.1 b
	LSD	-----	*3.60*
	p-value	*ns*	*0.060*
2018	SDI-50%	18.4 a	21.9 a
	SDI-75%	13.7 b	15.9 b
	SDI-75%GD	13.9 b	16.1 b
	SDI-100%	14.8 b	16.7 b
	LSD	*2.33*	*2.70*
	p-value	*0.004*	*0.002*
2019	SDI-50%	16.3 a	21.8 a
	SDI-75%	14.6 a	18.2 b
	SDI-75%GD	15.0 a	18.8 b
	SDI-100%	10.9 b	12.7 c
	LSD	*1.92*	*2.47*
	p-value	*0.001*	*0.000*
3-Years Average	SDI-50%	17.0 a	23.2 a
	SDI-75%	14.6 b	19.0 b
	SDI-75%GD	14.8 b	19.1 b
	SDI-100%	13.8 b	16.8 c
	LSD	*1.37*	*1.77*
	p-value	*0.003*	*0.000*

Note: ns is Non-Significant
SDI-50%= Terminating Irrigation in July *SDI-75%= Terminating Irrigation in August*
SDI-75%GD= Irrigating 75% of ET at every irrigation *SDI-100%= Full ET_c irrigation*
Means sharing same letters in a column are not statistically different.

1.3.2.5 Soil Water Availability:

Fig. 1.14 explains the moisture conditions during the three years under SDI-50% (orange line), SDI-75% (purple line), SDI-75%GD (black line) and SDI-100% (blue line) while the vertical bars are the individual harvests. During 2017, SDI-100% and SDI-75%GD had a same soil water content at the end of the season while SDI-75% and SDI-50% experienced as steady decline in available moisture conditions. The same was true during 2018, where driest period in the start of the season impacted the lower moisture available to all the treatments but after the first irrigation, some the treatments recovered while SDI-100% had lower moisture. During 2018, SDI-75%GD had the highest moisture available while the lowest was found in SDI-75%. During 2019, SDI-75% and SDI-100% had the higher moisture available while SDI-75% and SDI-50% had the lowest water storage.

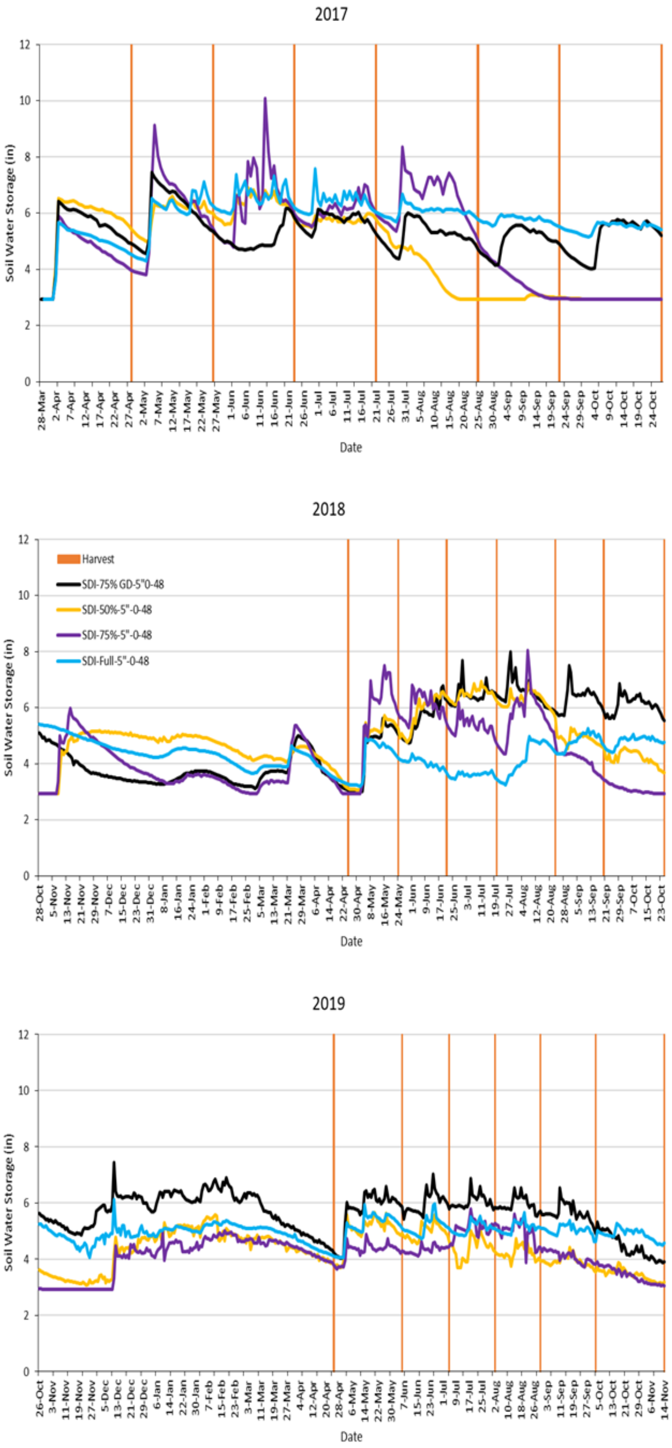


Figure 1.14. Soil water storage (inches) in top 120 cm for SDI-Full (blue line), SDI 75% Gradual Deficit (Black line), SDI-75% Cutoff (Purple line) and SDI-50% cutoff orange line) while vertical lines show the harvest days during 2017-18-19.

1.3.3 Monitoring Canopy stress in SI and SDI:

Measuring canopy temperature provides insight how much the crop is stressed and when is it least stressed. Canopy temperature was converted to the relationship Tc-Ta where Tc is the canopy temperature while Ta is the air temperature at given hour. Higher the leaf temperature, the more stressed the crop is, alternatively, a greater difference generally indicates greater crop stress (González-Dugo et al., 2006). Doing the statistical analysis for one of the harvests during the year 2017 produced some significant results in terms of treatments and day of the growth cycle. It was found that SDI had a lower average difference (8.0 °C) which was significantly different than SI (9.1 °C) at p <0.0001. During the growth cycle, higher difference was observed during the beginning of the growth cycle (16.9 °C) which was statistically different than the mid of the season (2.483 °C) and closer to the harvest at p < 0.000 (Fig. 1.15).

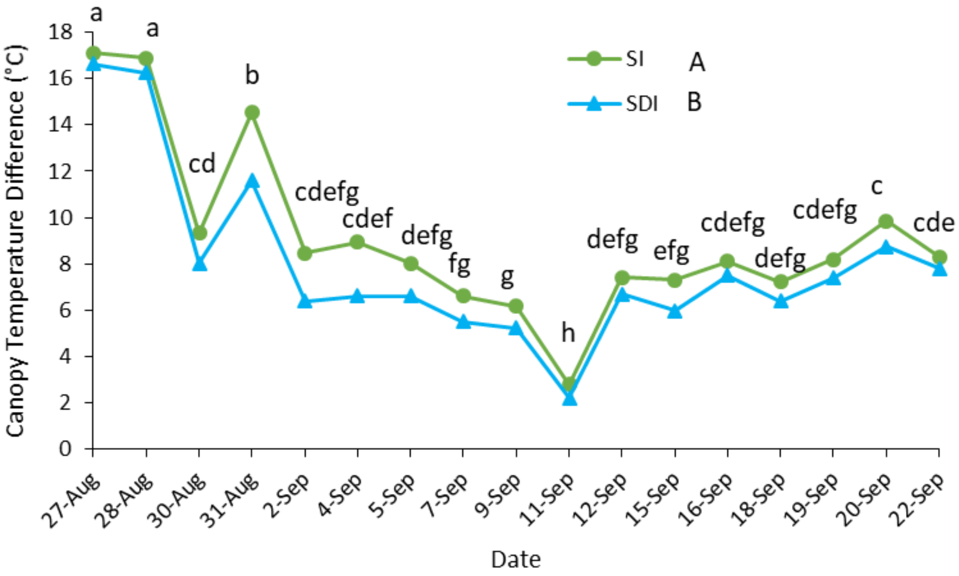


Figure 1.15. Canopy temperature differences from ambient for SDI-Full (blue line) and SI (flood-green line) during 2017. Means sharing the same small or capital letters are not significantly different.

Similar analysis was conducted for the deficit treatments. It was found that SDI-50% (11.63 °C) had the significantly higher temperature differences with ambient average across the full growth cycle followed by SDI-75% (10.8 °C), SDI-75%GD (9.0 °C) and SDI-100% (8.0 °C) at p-value < 0.000. During the 2017 growth cycle, the canopy temperature was higher during the start of the growth cycle which was significantly different than mid of the season (lowest temperature observed) and closer to the harvest (Fig. 1.16).

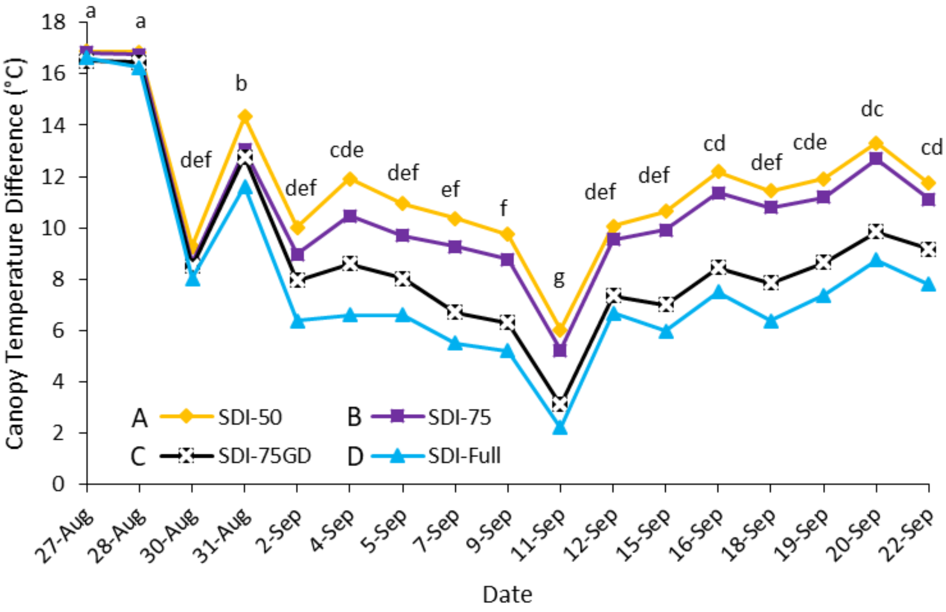


Figure 1.16. Canopy temperature differences from ambient for SDI-Full (blue line), SDI 75% Gradual Deficit (Black line), SDI-75% Cutoff (Purple line) and SDI-50% cutoff orange line) in 2017. Means sharing the same small or capital letters are not significantly different.

1.4 DISCUSSION

1.4.1 Impact of irrigation system on alfalfa forage yield, quality and water productivity:

1.4.1.1 System Comparisons:

Higher yields were achieved utilizing SDI during 2017, while in 2018 the yields were lower than SI. This primarily happened because of much drier winter in 2018 (rainfall 150 mm) compared with 2017 (rainfall 343 mm). More water was available in the root zone during 2018 for surface irrigation as multiple irrigations were applied while for SDI the water storage was not enough (Fig. 1.9). This result suggests the importance of early season irrigation 'filling the profile' that might result in better season-long production. During the start of the year, irrigation was applied to refill the profile due to a drier winter but the SDI system was not sufficient to actually refill the profile. The other reason for lower yields in SDI in year two was the result of damage to the system due to excessive rodent populations. In spite of many efforts to control leaks and rodent infestation, maintenance of this system proved difficult, and some leaks in the small (7 m wide) areas proved impactful on crop production. Surface irrigation under these experimental conditions had the advantage over SDI because of smaller irrigated areas (checks) in our controlled study, while in grower's field there is often a significant spatial variation in the application of water and flexibility using surface irrigation. Earlier studies (Hutmacher et al. 1992) has shown that SDI can potentially increase yields in alfalfa, but in our controlled study and others (Zaccaria et al. 2017), the results were not very promising, due to the system maintenance problems. Unfortunately, this is similar to many experiences on farmer's fields and the ability to control rodent damage in SDI fields is a significant barrier to its adaptation (Putnam, 2017).

Similarly, significantly higher plant heights were obtained in surface irrigation compared with SDI (Table 1.3), primarily because of smaller checks in surface irrigation and variation in distribution uniformity variation in SDI. Higher moisture during certain growth cycles also benefited the surface irrigation over SDI which had lower water available in early part of the growth cycle compared with later stage in the season. However, we found higher crude protein, NDFD30 and NDFD48 in SDI compared with surface irrigation during the year 2017 while non-significant results except ash were found in 2018, but in general, forage quality did not differ much between the two systems.

Higher IWUE was found in SDI compared with surface irrigation during the year 2017 and was lower during 2018, largely due to yield differences. This was because more water was applied to refill the soil profile and SDI was lower in water storage during early part of the season while had higher moisture content later in the season. As there was a slight increase in SDI dry matter yields over surface irrigation during 2017 and decrease during 2018, this implies to the improvement in SDI yields more while applying water following crop ET requirements.

Although this trial was designed to compare SDI with surface irrigation systems, with small-plot trials this is relatively difficult to do. There are major components of efficiency that are spatially important. There are major advantages for surface systems utilizing small plots to apply large amounts of water to fill the profile, if soil moisture is limiting. This is not the case with larger surface-irrigated fields where longer runs make it difficult to uniformly refill the profile due to ponding on lower areas in the field (Hanson and Putnam, 2004). Surface irrigation methods, depending upon the maximum flow rates available and size of field have major limitations in distribution uniformity, which was not the case in our smaller experimental units. The time required for water application and the ability to apply water uniformly is far superior with small fields compared with large fields. In this experiment, each replication that was surface irrigated was less than 0.2 acres, compared with larger (e.g. 80-100-acre fields with 1-4 acre flooding event check) units. On ‘normal’ sized fields, water distribution uniformity is circumscribed by both spatial features (length and width of run) and time elements (the amount of time it takes to irrigate a field with available flow rates). In this trial, there were advantages to increased efficiency and yields in surface irrigation which was often impossible to achieve in grower's field due to distribution uniformity over space and time (Putnam et. al, 2017). Uniform distribution is a major hurdle at the grower's field due to size of the field (Hanson and Putnam, 2004). Alfalfa forage yield was affected mainly due to soil characteristics in the SDI as well as surface irrigation but in surface irrigation, it was affected less due to refilling the profile evenly while in SDI, due to system inefficiencies, spatial patterns were observed.

1.4.2 Impact of deficit irrigation on alfalfa forage yield, quality and water productivity:

Over the three-years, deficit irrigation significantly reduced alfalfa forage yields compared to fully irrigated yields. However, the reduction over the three years in targeted SDI-50% was only 82%. This was because, most of the higher yields were observed during the early part of the season while lower yields were achieved in the later season when less or no irrigation was applied.

Plant height was lowest in SDI-50% and highest in SDI-100% over the three years average. The crude protein was found to be slightly lower in SDI-50% for year 2017 which was significantly different than SDI-75%GD and SDI-100%. Similarly, the digestibility also decreased in SDI-50% compared with SDI-75%GD and SDI-100%. This is primarily due to reduction in leaf to stem ratio and reduced transpiration as reported by (Abid et al., 2016). However, during the harvests when deficits were most severe, fully-watered alfalfa exhibited a higher ADF and NDF level than in deficit treatments (Appendix tables), which is fully in line with published studies (Frate et al., 1991; Orloff 2003; Abid et al., 2016) indicating higher fiber levels in fully-watered crops. Higher water productivities were found in SDI-50% when average across the three years which was significantly different than SDI-75%, SDI-75%GD and SDI-100%.

1.4.3 Monitoring Canopy Stress:

Monitoring canopy stress provided an insight to the stress associated with each of the treatments during an entire growth cycle. Higher temperature was observed in surface irrigation treatment compared with SDI treatment because of less available water in the root zone (Fig. 1.15). There was a lower temperature difference found within the growth cycle, which was primarily due to reduced canopy stress. But in general, higher temperatures were observed in the surface irrigation treatments compared with SDI.

Similar pattern was observed when the deficits were applied compared with full SDI treatments. Lower temperatures were observed in SDI-100% indicating less stress in fully irrigated treatments, while under deficit treatments, significant temperature rise indicated the impact of stress in the crop.

1.4.4 Opportunities and challenges:

Adopting the SDI technology for alfalfa production over the surface irrigation provides several opportunities and challenges. Firstly, SDI is beneficial when there are higher yields observed with limited water applied and the installation cost can be justified (Lamm et al., 2012). Secondly, significant maintenance is required for SDI to apply the required irrigation amount which if not maintained, can reduce the yields significantly. In our controlled study, surface irrigation had the advantage of applying irrigation more efficiently with less labor required while in practice or growers' fields, implementing surface irrigation could be challenging as certain areas of field may not be fully irrigated during the available irrigation period. The higher canopy temperatures in our controlled study under surface irrigation also explains the deficit periods within the growth cycle while SDI can maintain the soil water storage due to less evaporation from the soil surface and cooler canopy temperature can be observed. In SDI, small amount of irrigations can be applied even closer to the harvest and right after the harvest, providing the advantage of lowering crop stress. The major disadvantage for SDI in addition to cost of installation is the maintenance and rodents damage which could affect the initial investments if not properly managed.

1.5 CONCLUSIONS

In our controlled study, it was found that sub-surface irrigation (SDI) had higher yields in the first year of the study period while the yields were lower in 2017 when compared with surface irrigation. It was also found that alfalfa exhibited greater plant stress in the surface irrigation treatments when compared with SDI, indicating the advantage of more frequent irrigations in SDI compared with surface irrigation in maintaining plant growth and health. Deficit irrigation reduced alfalfa forage yields while increasing the water productivity of applied water and irrigation water use efficiency. Measured forage quality parameters were not greatly affected by irrigation system or by water deficits, though some minor differences were observed. When necessary, reducing the water applications to SDI-50% in the latter half of the season maintains yields in the early part of the season while reducing yields only in the later part of the season. If the system is well managed by controlling rodent damage, SDI had a potential of producing higher yields but when the maintenance is not done frequently, the system costs cannot be justified. Monitoring crop canopy temperature can provide insights to the stress experienced by the alfalfa crop within a growth cycle and over the season which could be beneficial in eliminating the stress before it occurs and reduce the yields. During water uncertainty periods, applying less water or cutting back the irrigations entirely for the later part of the season could prove to be a beneficial strategy when irrigation water is severely limited.

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1.8 SUPPLEMENTARY MATERIAL

Table 1.10. Forage Quality observed under two irrigation systems (Surface Irrigation and SDI) during 2017

Parameters	**Systems**	**April**	**May**	**June**	**July**	**Aug**	**Sep**	**Oct**	**Average**
		------------------------------------g kg^{-1}------------------------------------							
CP	SI	242	263	245 b	253	256	283	286	261 b
	SDI	239	276	264 a	259	257	281	296	267 a
	LSD	----	----	*12.50*	----	----	----	----	*3.20*
	p-value	*ns*	*ns*	*0.019*	*ns*	*ns*	*ns*	*ns*	*0.009*
ADF	SI	293	248	276	304	266	257	275	274
	SDI	293	243	263	295	281	253	258	269
	LSD	----	----	----	----	----	----	----	----
	p-value	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*
aNDF	SI	369	314	342	390	347	315	338	345
	SDI	369	306	326	367	356	311	318	336
	LSD	----	----	*21.29*	----	----	----	----	----
	p-value	*ns*	*ns*	*0.090*	*ns*	*ns*	*ns*	*ns*	*ns*
ASH	SI	78	78	81	79	77	94	86	82
	SDI	79	83	90	80	78	95	84	84
	LSD	----	----	*10.36*	----	----	----	----	----
	p-value	*ns*	*ns*	*0.080*	*ns*	*ns*	*ns*	*ns*	*ns*
FAT	SI	23	24	21	24	29	21	29	24
	SDI	23	25	22	23	29	21	28	24
	LSD	----	----	*1.20*	----	----	----	----	----
	p-value	*ns*	*ns*	*0.079*	*ns*	*ns*	*ns*	*ns*	*ns*
NDFD30	SI	346	378	350 b	354 b	350	397	395	367 b
	SDI	344	381	374 a	374 a	352	391	412	376 a
	LSD	----	----	*18.16*	*16.28*	----	----	----	*7.05*
	p-value	*ns*	*ns*	*0.023*	*0.027*	*ns*	*ns*	*ns*	*0.029*
NDFD48	SI	414	460	431 b	495	472	482	567	474 b
	SDI	414	468	475 a	504	482	485	575	486 a
	LSD	----	----	*16.31*	----	----	----	----	*7.80*
	p-value	*ns*	*ns*	*0.003*	*ns*	*ns*	*ns*	*ns*	*0.017*

Note: ns is Non-Significant SI= Surface Irrigation SDI= Sub Surface Drip Irrigation
Means sharing same letters in a column are not statistically different.
Total represents the average across cutting.
CP= Crude Protein ADF= Acid Detergent Fiber aNDF= Neutral Detergent Fiber
NDFD30= Neutral Detergent Fiber digestibility at 30 hours
NDFD48= Neutral Detergent Fiber digestibility at 48 hours

Table 1.11. Forage Quality observed under two irrigation systems (Surface Irrigation and SDI) during 2018

Parameters	**Systems**	**April**	**May**	**June**	**July**	**Aug**	**Sep**	**Oct**	**Average**
		----------------------------------g kg^{-1}----------------------------------							
CP	SI	227	309	245	224	237	266	266	254
	SDI	222	309	247	237	249	270	279	259
	LSD	----	----	----	*14.44*	----	----	----	----
	p-value	*ns*	*ns*	*ns*	*0.060*	*ns*	*ns*	*ns*	*ns*
ADF	SI	286	245	278	293	309	263	275	278
	SDI	287	245	292	273	330	262	246	276
	LSD	----	----	----	----	----	----	*29.77*	----
	p-value	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*0.050*	*ns*
aNDF	SI	359	305	350	355	369	319	340	342
	SDI	358	300	362	333	397	317	308	339
	LSD	----	----	----	----	----	----	*35.95*	----
	p-value	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*0.070*	*ns*
ASH	SI	77	79	72	71	77	81	90	78 b
	SDI	80	78	72	75	84	81	95	81 a
	LSD	----	----	----	----	----	----	*6.56*	*1.81*
	p-value	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*0.080*	*0.018*
FAT	SI	23	23	24	21	24	25	23	23
	SDI	22	23	23	22	22	25	24	23
	LSD	----	----	----	----	*2.32*	----	----	*0.54*
	p-value	*ns*	*ns*	*ns*	*ns*	*0.048*	*ns*	*ns*	*0.083*
NDFD30	SI	351	418	378	386	355	376	418 b	383
	SDI	345	423	376	382	347	379	438 a	384
	LSD	----	----	----	----	----	----	*13.45*	----
	p-value	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*0.016*	*ns*
NDFD48	SI	435	564	461	441	461	475	495 b	476
	SDI	440	567	460	445	464	482	528 a	484
	LSD	----	----	----	----	----	----	*26.40*	----
	p-value	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*0.028*	*ns*

Note: ns is Non-Significant SI= Surface Irrigation SDI= Sub Surface Drip Irrigation
Means sharing same letters in a column are not statistically different.
Total represents the average across cutting.
CP= Crude Protein ADF= Acid Detergent Fiber aNDF= Neutral Detergent Fiber
NDFD30= Neutral Detergent Fiber digestibility at 30 hours
NDFD48= Neutral Detergent Fiber digestibility at 48 hours

Table 1.12. Forage Quality observed under two irrigation systems (Surface Irrigation and SDI) average across two years

Parameters	**Systems**	**April**	**May**	**June**	**July**	**Aug**	**Sep**	**Oct**	**Average**
		g kg^{-1}							
CP	SI	234	286	245	239	247	275	276	257
	SDI	231	293	255	248	253	276	287	263
	LSD	----	----	----	*11.83*	----	----	----	----
	p-value	*ns*	*ns*	*ns*	*0.080*	*ns*	*ns*	*ns*	*ns*
ADF	SI	289	246	277	298	288	260	275	276
	SDI	290	244	277	284	306	258	252	273
	LSD	----	----	----	----	----	----	----	----
	p-value	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*
aNDF	SI	364	309	346	372	358	317	339	344
	SDI	363	303	344	350	377	314	313	338
	LSD	----	----	----	----	----	----	----	----
	p-value	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*
ASH	SI	77	78	77	75	77	87	88	80
	SDI	79	80	81	77	81	88	90	82
	LSD	----	----	*3.94*	----	----	----	----	----
	p-value	*ns*	*ns*	*0.046*	*ns*	*ns*	*ns*	*ns*	*ns*
FAT	SI	23	24	22	23	26	23	26	24
	SDI	23	24	23	23	25	23	26	24
	LSD	----	----	----	----	*0.71*	----	----	----
	p-value	*ns*	*ns*	*ns*	*ns*	*0.033*	*ns*	*ns*	*ns*
NDFD30	SI	349	398	364	370	353	387	406	375
	SDI	345	402	375	378	350	385	425	380
	LSD	----	----	----	----	----	----	----	----
	p-value	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*
NDFD48	SI	424	512	446	468	467	479	531	475
	SDI	427	518	467	474	473	483	552	485
	LSD	----	----	*26.69*	----	----	----	----	*11.51*
	p-value	*ns*	*ns*	*0.065*	*ns*	*ns*	*ns*	*ns*	*0.075*

Note: ns is Non-Significant SI= Surface Irrigation SDI= Sub Surface Drip Irrigation
Means sharing same letters in a column are not statistically different.
Total represents the average across cutting.
CP= Crude Protein ADF= Acid Detergent Fiber aNDF= Neutral Detergent Fiber
NDFD30= Neutral Detergent Fiber digestibility at 30 hours
NDFD48= Neutral Detergent Fiber digestibility at 48 hours

Table 1.13. Forage quality parameters per cuttings under deficit irrigation using SDI for year 2017

Parameters	**Deficits**	**April**	**May**	**June**	**July**	**Aug**	**Sep**	**Oct**	**Average**
		g kg^{-1}							
CP	SDI-50%	239	265	272	259	227 b	233 b	252 b	250 c
	SDI-75%	240	260	277	259	258 a	249 b	249 b	256 bc
	SDI-75%GD	238	276	260	256	254 a	271 a	300 a	265 ab
	SDI-100%	239	276	264	259	257 a	281 a	296 a	267 a
	LSD	----	----	----	----	*11.74*	*18.77*	*24.51*	*9.65*
	p-value	*ns*	*ns*	*ns*	*ns*	*0.001*	*0.001*	*0.001*	*0.008*
ADF	SDI-50%	294	249	258	279	261	232 b	231	258
	SDI-75%	298	271	249	282	266	238 ab	240	263
	SDI-75%GD	294	240	276	284	259	250 a	254	266
	SDI-100%	293	243	263	295	281	253 a	258	269
	LSD	----	----	----	----	----	*16.04*	----	----
	p-value	*ns*	*ns*	*ns*	*ns*	*ns*	*0.043*	*ns*	*ns*
aNDF	SDI-50%	371	312	319	351	341	297	288	325
	SDI-75%	375	336	312	355	346	301	297	332
	SDI-75%GD	369	303	340	360	338	315	319	335
	SDI-100%	369	306	326	367	356	311	318	336
	LSD	----	----	----	----	----	----	----	----
	p-value	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*
ASH	SDI-50%	80	79	90	82	72	82 c	80 bc	81
	SDI-75%	80	80	91	81	78	85 bc	78 c	82
	SDI-75%GD	80	83	87	77	77	90 ab	88 a	83
	SDI-100%	79	83	90	80	78	95 a	84 ab	84
	LSD	----	----	----	----	----	*5.58*	*5.24*	----
	p-value	*ns*	*ns*	*ns*	*ns*	*ns*	*0.003*	*0.010*	*ns*
NDFD30	SDI-50%	335	377	377	371	325	347 b	329 b	352 b
	SDI-75%	342	392	382	375	352	364 ab	326 b	362 ab
	SDI-75%GD	336	391	371	372	350	385 a	408 a	373 a
	SDI-100%	344	381	374	374	352	391 a	412 a	376 a
	LSD	----	----	----	----	----	*31.36*	*55.32*	*14.27*
	p-value	*ns*	*ns*	*ns*	*ns*	*ns*	*0.038*	*0.008*	*0.014*
NDFD48	SDI-50%	410	458	479	515	433 b	414 b	442 b	450 b
	SDI-75%	414	463	487	499	477 a	433 b	439 b	459 b
	SDI-75%GD	405	474	471	506	478 a	469 a	588 a	484 a
	SDI-100%	414	468	475	504	482 a	485 a	575 a	486 a
	LSD	----	----	----	----	*22.24*	*22.33*	*53.69*	*13.80*
	p-value	*ns*	*ns*	*ns*	*ns*	*0.002*	*0.000*	*0.000*	*0.000*

Note: ns is Non-Significant

SDI-50%= Terminating Irrigation in July *SDI-75%= Terminating Irrigation in August*

SDI-75%GD= Irrigating 75% of ET at every irrigation *SDI-100%= Full ET$_c$ irrigation*

Means sharing same letters in a column are not statistically different.

Average represents the average across cuttings.

CP= Crude Protein *ADF= Acid Detergent Fiber* *aNDF= Neutral Detergent Fiber*

NDFD30= Neutral Detergent Fiber digestibility at 30 hours

NDFD48= Neutral Detergent Fiber digestibility at 48 hours

Table 1.14. Forage quality parameters per cuttings under deficit irrigation using SDI for year 2018

Parameters	**Deficits**	**April**	**May**	**June**	**July**	**Aug**	**Sep**	**Oct**	**Average**
		---------------------------------g kg^{-1}---------------------------------							
CP	SDI-50%	221	319	255	221	250	251 b	257 ab	254
	SDI-75%	216	321	261	226	250	254 b	241 b	253
	SDI-75%GD	212	315	247	220	256	270 a	269 a	256
	SDI-100%	222	309	247	237	249	270 a	279 a	259
	LSD	----	----	----	----	----	*8.09*	*25.56*	----
	p-value	*ns*	*ns*	*ns*	*ns*	*ns*	*0.001*	*0.041*	*ns*
ADF	SDI-50%	281	237	285	296	300	250	235	269
	SDI-75%	285	232	264	272	312	249	239	265
	SDI-75%GD	297	238	269	287	304	249	265	273
	SDI-100%	287	245	292	273	330	262	246	276
	LSD	----	----	----	----	----	----	----	----
	p-value	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*
aNDF	SDI-50%	350	289	351	358	367	308	296	331
	SDI-75%	361	286	328	333	380	306	300	328
	SDI-75%GD	371	295	335	353	367	303	330	336
	SDI-100%	358	300	362	333	397	317	308	339
	LSD	----	----	----	----	----	----	----	----
	p-value	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*
ASH	SDI-50%	70 c	81	70	71	90	77 b	97 ab	79
	SDI-75%	74 bc	82	77	71	87	77 b	100 a	81
	SDI-75%GD	78 ab	80	69	70	90	83 a	90 c	80
	SDI-100%	80 a	78	72	75	84	81 ab	95 b	81
	LSD	*4.59*	----	----	----	----	*5.11*	*4.17*	----
	p-value	*0.003*	*ns*	*ns*	*ns*	*ns*	*0.069*	*0.002*	*ns*
NDFD30	SDI-50%	342	425	373	375	366	371	391 b	378
	SDI-75%	344	435	387	383	348	370	379 b	378
	SDI-75%GD	329	429	370	365	354	382	420 a	378
	SDI-100%	345	423	376	382	347	379	438 a	384
	LSD	----	----	----	----	----	----	*21.12*	----
	p-value	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*0.000*	*ns*
NDFD48	SDI-50%	428	573	455	427	487	443 b	470 c	469
	SDI-75%	431	592	478	435	475	453 b	462 c	475
	SDI-75%GD	422	582	445	421	484	482 a	501 b	477
	SDI-100%	440	567	460	445	464	482 a	528 a	484
	LSD	----	----	----	----	----	*15.12*	*27.76*	----
	p-value	*ns*	*ns*	*ns*	*ns*	*ns*	*0.000*	*0.002*	*ns*

Note: ns is Non-Significant

SDI-50%= Terminating Irrigation in July *SDI-75%= Terminating Irrigation in August*

SDI-75%GD= Irrigating 75% of ET at every irrigation *SDI-100%= Full* ET_c *irrigation*

Means sharing same letters in a column are not statistically different.

Average represents the average across cuttings.

CP= Crude Protein *ADF= Acid Detergent Fiber* *aNDF= Neutral Detergent Fiber*

NDFD30= Neutral Detergent Fiber digestibility at 30 hours

NDFD48= Neutral Detergent Fiber digestibility at 48 hours

Table 1.15. Forage quality parameters per cuttings under deficit irrigation using SDI for year 2019

Parameters	**Deficits**	**April**	**May**	**June**	**July**	**Aug**	**Sep**	**Oct**	**Average**
		---------------------------------g kg^{-1}---------------------------------							
CP	SDI-50%	----	242	261	241	240	254	242	247
	SDI-75%	----	237	264	251	254	269	256	255
	SDI-75%GD	----	240	263	240	251	270	258	253
	SDI-100%	----	244	261	239	259	262	265	255
	LSD	----	----	----	----	----	----	----	----
	p-value	----	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*
ADF	SDI-50%	----	307	283	285	282	227	229	269
	SDI-75%	----	309	274	271	291	225	229	267
	SDI-75%GD	----	309	274	297	293	241	228	274
	SDI-100%	----	306	278	295	290	251	236	276
	LSD	----	----	----	----	----	----	----	----
	p-value	----	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*
aNDF	SDI-50%	----	363	331	346	353	280	293	327
	SDI-75%	----	367	321	332	359	275	290	324
	SDI-75%GD	----	365	323	362	364	292	293	333
	SDI-100%	----	362	326	360	352	306	296	334
	LSD	----	----	----	----	----	----	----	----
	p-value	----	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*
ASH	SDI-50%	----	85	87	82	90 b	96	115	93 a
	SDI-75%	----	82	86	84	89 b	93	113	91 ab
	SDI-75%GD	----	85	84	82	93 a	89	113	91 ab
	SDI-100%	----	82	83	85	86 c	88	109	89 b
	LSD	----	*2.99*	----	----	*2.80*	----	----	*2.68*
	p-value	----	*0.065*	*ns*	*ns*	*0.003*	*ns*	*ns*	*0.080*
NDFD30	SDI-50%	----	381	431	402	436	418	407	413
	SDI-75%	----	364	440	414	453	427	430	421
	SDI-75%GD	----	374	440	402	446	432	434	421
	SDI-100%	----	377	438	398	459	428	458	426
	LSD	----	----	----	----	----	----	----	----
	p-value	----	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*
NDFD48	SDI-50%	----	480	484	465	465	486	489	478
	SDI-75%	----	463	486	489	487	521	513	493
	SDI-75%GD	----	470	500	472	487	519	527	496
	SDI-100%	----	479	490	468	489	515	548	498
	LSD	----	----	----	----	----	----	----	----
	p-value	----	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*

Note: ns is Non-Significant

SDI-50%= Terminating Irrigation in July *SDI-75%= Terminating Irrigation in August*

SDI-75%GD= Irrigating 75% of ET at every irrigation *SDI-100%= Full ET$_c$ irrigation*

Means sharing same letters in a column are not statistically different.

Average represents the average across cuttings.

CP= Crude Protein *ADF= Acid Detergent Fiber* *aNDF= Neutral Detergent Fiber*

NDFD30= Neutral Detergent Fiber digestibility at 30 hours

NDFD48= Neutral Detergent Fiber digestibility at 48 hours

Table 1.16. Forage quality parameters per cuttings under deficit irrigation using SDI average across three years

Parameters	**Deficits**	**April**	**May**	**June**	**July**	**Aug**	**Sep**	**Oct**	**Average**
		--------------------------------g kg^{-1}	--------------------------------						
CP	SDI-50%	230	275	263	241	239	246 c	250 c	250
	SDI-75%	228	273	267	245	254	257 b	249 b	255
	SDI-75%GD	225	277	257	239	253	270 a	276 a	258
	SDI-100%	231	276	257	245	255	271 a	280 a	260
	LSD	----	----	----	----	----	*9.86*	*14.04*	----
	p-value	*ns*	*ns*	*ns*	*ns*	*ns*	*0.001*	*0.001*	*ns*
ADF	SDI-50%	287	264	275	287	281	236	232 b	265
	SDI-75%	291	271	263	275	290	237	236 ab	265
	SDI-75%GD	295	262	273	290	285	247	249 a	271
	SDI-100%	290	265	277	288	300	255	247 ab	274
	LSD	----	----	----	----	----	----	*15.83*	----
	p-value	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*0.099*	*ns*
aNDF	SDI-50%	361	321	334	351	353	295	292 b	328
	SDI-75%	368	330	320	340	362	294	296 ab	328
	SDI-75%GD	370	321	333	358	356	303	314 a	335
	SDI-100%	363	323	338	353	368	311	308 ab	336
	LSD	----	----	----	----	----	----	*18.39*	----
	p-value	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*0.080*	*ns*
ASH	SDI-50%	75 b	82	82 ab	79	84	85	98	84
	SDI-75%	77 ab	81	85 a	79	84	85	97	85
	SDI-75%GD	79 a	83	80 b	76	87	87	97	85
	SDI-100%	79 a	81	82 ab	80	83	88	96	85
	LSD	*3.37*	----	*3.16*	----	----	----	----	----
	p-value	*0.053*	*ns*	*0.037*	*ns*	*ns*	*ns*	*ns*	*ns*
NDFD30	SDI-50%	339	395	394	383	376	379 b	376 b	381 b
	SDI-75%	343	397	403	391	385	387 b	378 b	387 ab
	SDI-75%GD	333	398	394	380	383	400 a	421 a	391 a
	SDI-100%	345	394	396	385	386	399 a	436 a	395 a
	LSD	----	----	----	----	----	*12.09*	*20.89*	*9.45*
	p-value	*ns*	*ns*	*ns*	*ns*	*ns*	*0.009*	*0.000*	*0.035*
NDFD48	SDI-50%	419 bc	504	473	469	462	448 c	467 b	466 c
	SDI-75%	422 ab	506	484	475	480	469 b	471 b	476 bc
	SDI-75%GD	414 c	509	472	466	483	490 a	538 a	486 ab
	SDI-100%	427 a	505	475	472	478	494 a	550 a	489 a
	LSD	*6.90*	----	----	----	----	*16.40*	*26.86*	*12.32*
	p-value	*0.010*	*ns*	*ns*	*ns*	*ns*	*0.000*	*0.000*	*0.008*

Note: ns is Non-Significant

SDI-50%= Terminating Irrigation in July *SDI-75%= Terminating Irrigation in August*

SDI-75%GD= Irrigating 75% of ET at every irrigation *SDI-100%= Full ET$_c$ irrigation*

Means sharing same letters in a column are not statistically different.

Average represents the average across cuttings.

CP= Crude Protein *ADF= Acid Detergent Fiber* *aNDF= Neutral Detergent Fiber*

NDFD30= Neutral Detergent Fiber digestibility at 30 hours

NDFD48= Neutral Detergent Fiber digestibility at 48 hours

Chapter 2. Sustaining alfalfa forage yield, quality and water productivity using Low Elevation Spray Application (LESA) and Mobile Drip Irrigation (MDI) under limited water resources in a Mediterranean Climate

ABSTRACT

Declining aquifers and the need to produce forages with limited land and water resources emphasizes the need for judicious use of water in agriculture. Alfalfa is the major forage utilized as dairy feed in the US, especially in irrigated dairy regions. A two-year study (2019-2020) was conducted to evaluate the impact of Low Elevation Spray Application (LESA) and Mobile Drip Irrigation (MDI) on alfalfa productivity under limited water regimes utilizing a linear overhead irrigation system. A Split Plot, Randomized Complete Block experiment was conducted with LESA and MDI systems as the main plots and irrigation quantities [100% ET Full (100% of required ET_c, full irrigation), 60% ET- Cutoff (60% ET of full irrigation, that is Mid-Summer Cutoff), 60% ET- Sustained (60% ET of full irrigation- imposed gradually every growth cycle), 40% ET- Sustained (40% ET of full irrigation- imposed gradually every growth cycle)] as sub plots. Required crop evapotranspiration (ET_c) was calculated using alfalfa crop coefficients multiplied by reference ET_o. Weekly neutron probe readings were collected to monitor the soil water status and to quantify the seasonal ET based on the soil water balance approach. Alfalfa was harvested every 28 days (7 cuts/year) and dry matter yield, forage quality and water use were measured. Significant differences were found for dry matter yields under varying amounts of irrigation during the 2020 season, while non-significant results were found in 2019. MDI-60% ET-Cutoff performed better (90% of full yields) than LESA-60% ET- Cutoff (73% of full yields) over the two years. However, in general, LESA outperformed MDI in all the other treatments. There were slight differences in forage quality due to water deficits but there was no effect due to irrigation system on forage quality. Reduced LAI was observed in the deficit irrigation treatments later in the season. Higher water productivity and irrigation water use efficiency was found in MDI-60% ET- Cutoff in 2020 (21.2 kg ha^{-1} mm^{-1}) while there were no significant differences found in 2019. These findings suggest that alfalfa can be cultivated under either of the two systems (LESA or MDI) but in periods of drought when deficit irrigations are required, it would be more productive under MDI 60% ET- Cutoff than in LESA-60% ET- Cutoff. This is primarily due to MDI's capability of irrigating the same area over time with reduced surface coverage. LESA outperformed MDI in all the other treatments, mainly because of high uniformity of application. The major advantage of MDI versus SDI (subsurface drip irrigation) includes reduced system repair costs from rodent damage that frequently occur with SDI.

Keywords: Alfalfa, forage quality, water productivity, LESA, MDI, deficit irrigation

2.1 INTRODUCTION

Alfalfa (*Medicago sativa* L.) is one of the most important forage crops grown worldwide, primarily as a dairy feed. It is a perennial crop with deep roots that can extract water from deep within the soil profile, enabling it to withstand extreme drought conditions. However, alfalfa does not tolerate water-logged conditions (Fernandez et al., 2019).

Approximately half of alfalfa production in the United States relies on irrigation. In the 11 western states (Arizona, California, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington and Wyoming), the acreage of alfalfa was 24% in 1970 with production 29.1% of total US alfalfa while the acreage and production increased to 39.7% and 48.9% respectively in 2020 (USDA-NASS, 2020). Different irrigation systems have been used for alfalfa forage production, including flood irrigation, wheel lines, movable pipe, overhead sprinklers, and sub-surface drip irrigation. Two innovations in overhead irrigation systems, low elevation spray application (LESA) and mobile drip irrigation (MDI), have not been widely evaluated for their ability to sustain alfalfa production under limited water conditions.

Most of the irrigation systems that have been used historically have either low cost and low efficiency (e.g., surface flood irrigation systems, ~ 60% efficiency) or high cost and very high efficiency (e.g., sub-surface drip irrigation, ~97% efficiency). Lower efficiency systems also have low cost associated with the equipment (Amosson et al. 2011; Reynolds et al., 2020) and may be sensible alternatives optimizing water usage for a given input cost. A major disadvantage of using SDI in alfalfa the initial capital costs and the high maintenance costs associated with rodent damage (Putnam et al., 2017; Zaccaria et al., 2017).

LESA has been used on center pivot irrigation systems in the Midwest and Central Plains and is an efficient way of irrigating crops with a potential efficiency of 88% or higher (Peters et al., 2016; Reynolds et al., 2020). In LESA, most of the applied water reaches the ground in contrast with Mid Elevation Spray Application (MESA) (Liang, 2019) due to reduced wind drift (Peters et al., 2016). The major advantage of LESA over other systems is the energy savings and high application efficiency compared with MESA. It also provides better irrigation uniformity than low-energy precision application (LEPA) for crop germination (Peters et al., 2016). LEPA is also considered to be a high efficiency irrigation system which utilizes the bubbler or socks to irrigate the crop very close to the ground (Peters et al., 2016; Oker et al., 2018). Both LESA and LEPA can have huge water savings ~ 18%, reduced pumping costs and better yields (Peter et al., 2016). As reported by Sarwar et. al., 2019, about 21% more water reached the ground under LESA systems, so this could be more beneficial in cultivating forages like alfalfa which requires more water to optimize production

Mobile drip irrigation is a system in which drip lines are attached to a linear-move or center pivot irrigation system. The drip lines move along with the irrigation system as it irrigates the field. A uniform wetted pattern can be observed in MDI irrigated fields, often improving soil infiltration and the deep soil profile water status. MDI is not a new technology (Kisekka et al., 2017). It was previously known as travelling trickle irrigation (O'Shaughnessy and Colaizzi, 2017), introduced during 1970s-1980s by Rawlins et al., 1974. MDI been adopted to cultivate different crops including maize (Oker et al., 2018), sorghum (Aguilar et al., 2019) but limited work has been done to explore its potential in alfalfa in the United States (Aguilar et al., 2019). MDI has an advantage of eliminating wind drift and significantly reducing soil evaporation (35%), allowing most of the water to reach to the plant roots thus improving crop water use efficiency (Kisekka et al., 2017).

Deficit irrigation studies on alfalfa production have been conducted using irrigation systems such as flood or SDI, however, little work has been done to understand the impact of deficit irrigation implemented using LESA and MDI application methods on alfalfa production. In the recent years, with the advent of improved technology, climate variability, labor shortages and other factors, the need for more efficient irrigation technologies and management practices that can sustain alfalfa production under periods of drought has become urgent. Generally, deficit irrigation strategies are not necessarily dependent on the irrigation delivery method but are impacted by the crop’s ability to utilize less water than the full ET requirement and produce acceptable yields with reduced irrigation applications over the entire season. In case of alfalfa, higher yields are produced early in the season and yields generally decrease in the later part of the season due to summer slump (Feltner and Massengale, 1965). Therefore, irrigating fully till the mid-summer and cutoff the irrigation later in the season could help conserve the water, which can be allocated to other uses (Orloff et al., 2003; Orloff et al., 2005; Hanson et al., 2009). Besides cutting off the water entirely for the late season harvests, it might be more productive to irrigate the entire season continuously with less than fully irrigated crop, although the viability of that strategy requires further testing. Research data on alfalfa response to sustained deficit irrigation for the entire season is very limited.

In this study, we hypothesized that alfalfa forage yield, quality and water productivity would be sustained using LESA and MDI and among these systems, one of the systems will have an advantage over the other under water limited conditions.

The specific objectives were to:

1. Evaluate LESA and MDI water delivery methods and their potential impacts on alfalfa forage yield, quality and water productivity.
2. Understand the impacts of deficit irrigation on alfalfa production under LESA and MDI.

3. Evaluate soil water dynamics in the root zone under the two systems and deficits irrigation strategies.

2.2 MATERIAL AND METHODS

2.2.1 Experimental Details:

The study was conducted at the University of California, Davis Land, Air and Water Resources (LAWR) Campbell Track field research facility, near Davis California. Experiments were conducted on Yolo Silt Loam soil series classified as fine-silty, mixed, superactive, nonacid, thermic Mollic Xerofluents and Reiff very fine sandy loam soil series classified as coarse-loamy, mixed, superactive, nonacid, thermic Mollic Xerofluvents (USDA-NRCS, 2020). The field was pre-irrigated prior to planting and planted with alfalfa variety Magna715 (Fall Dormancy Group 7) on October 9, 2018 (Table 2.1). The seed was pre-inoculated with *Rhizobium meliloti* strain NRG-185 (Nitragin).

Figure 2.1. Linear Move Overhead Irrigation System at University of California Davis operating in Alfalfa.

The linear-move Valley Series 8000 overhead irrigation system (Valmont Industries Inc., Omaha, NE, USA) was installed (Fig. 2.1). The system has the capability of applying water at the variable rate to different areas in the field. The linear move irrigation system had a length of 152.4 m (500 feet) long, consisting of four spans (Fig. 2.1). Each span was split into LESA and MDI application methods (Fig. 2.2). The spacing of the drop hoses was 76.2 cm for both LESA and MDI.V-Jack cable hooks (Dragon Line Inc. Ulysses, KS, USA) were used to hold the drip lines in the center of the linear-move overhead system. The V-jack was adjusted at 120 cm height to keep the drip lines in the center of the linear above the ground (Fig. 2.2). Low drift nozzles (LDN UP3) with a flowrate of 350 lph at 15 psi with 2.97 mm nozzle size (Senninger, FL, USA) were used for the LESA drops (Fig. 2.3). For MDI, the flexible hose attached to the drop hose was 1.27 cm in diameter. To keep flowrates similar to the LESA system, two drip lines spaced 15.24 cm apart were attached to each drop hose, with a total of 46 emitters (Fig. 2.3) in both drip lines. The drip lines were manufactured by Jain Irrigation Inc. (Fresno, CA, USA) with emitters spaced at 15.24 cm, flowrate 7.56 lph, 1.14 mm wall thickness, 15 mm inside and 17 mm outside diameter.

The experiment was laid out as a randomized complete block design (RCBD) with four replications with a split plot restriction on treatments (Fig. 2.4). The two irrigation systems (LESA and MDI) were the main plots, while four irrigation treatments (full plus three deficit irrigation) were subplots. The main plots were 73.2 m long × 18.3 m wide in blocks 3 and 4, and 73.2 m × 15.2 m wide in blocks 1 and 2 due to differences in span length (Fig. 2.4). Subplot areas were 36.6 × 9.2 m or 36.6 × 7.6 m, depending upon block (Fig. 2.4). The irrigation treatments were 100% ET Full (100% of required ET_c, full irrigation), 60% ET- Cutoff (irrigate 100% of ET needs, with mid-summer cutoff at 60% ET of seasonal ET demand), 60% ET- Sustained (irrigate to 60% of full ET - imposed every growth cycle), 40% ET- Sustained (40% ET of full irrigation- imposed every growth cycle).

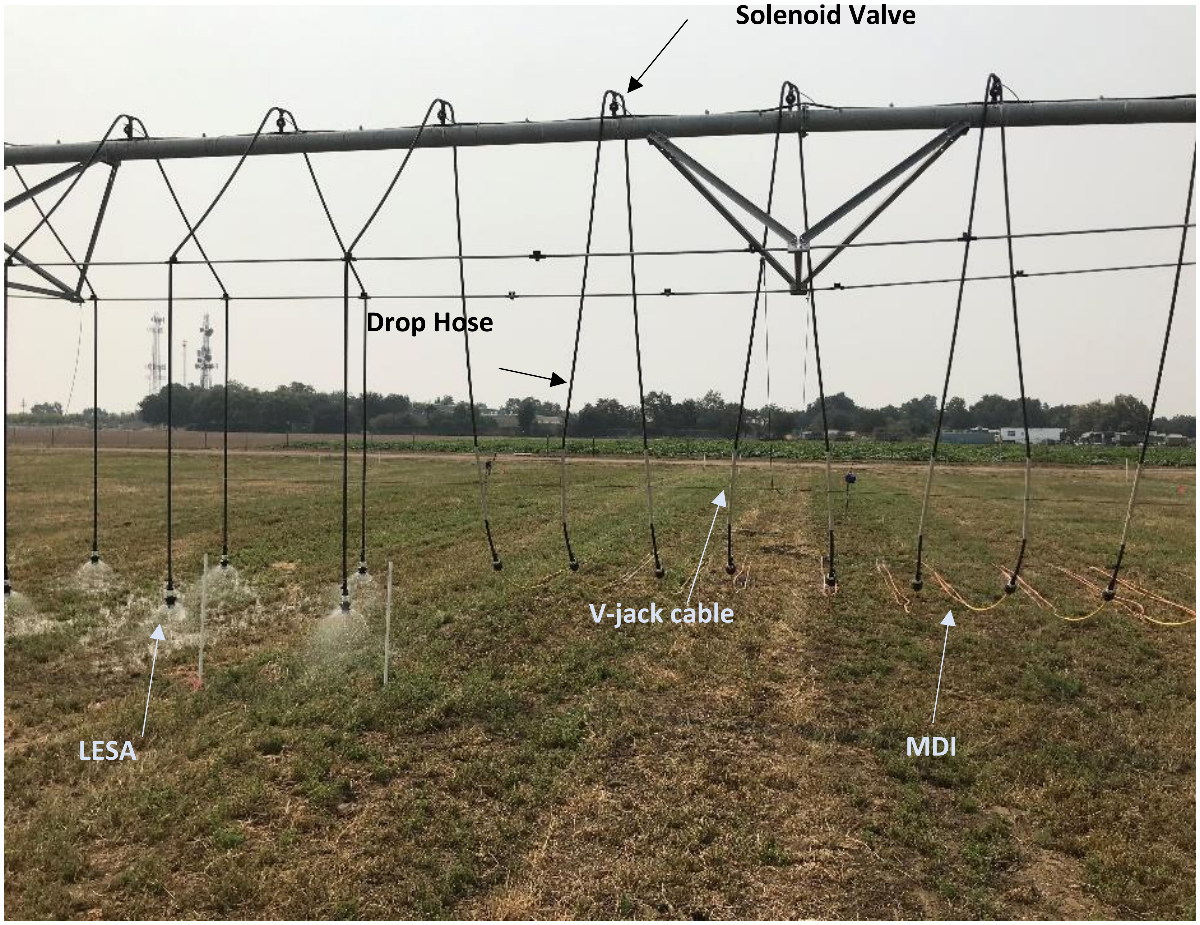

Figure 2.2. A section of linear overhead system retrofitted with low elevation spray application (LESA) on left and mobile drip irrigation (MDI) on the right. Application methods consisted of the main plots of the experiment.

Figure 2.3. LESA (left) and MDI in Alfalfa during operation.

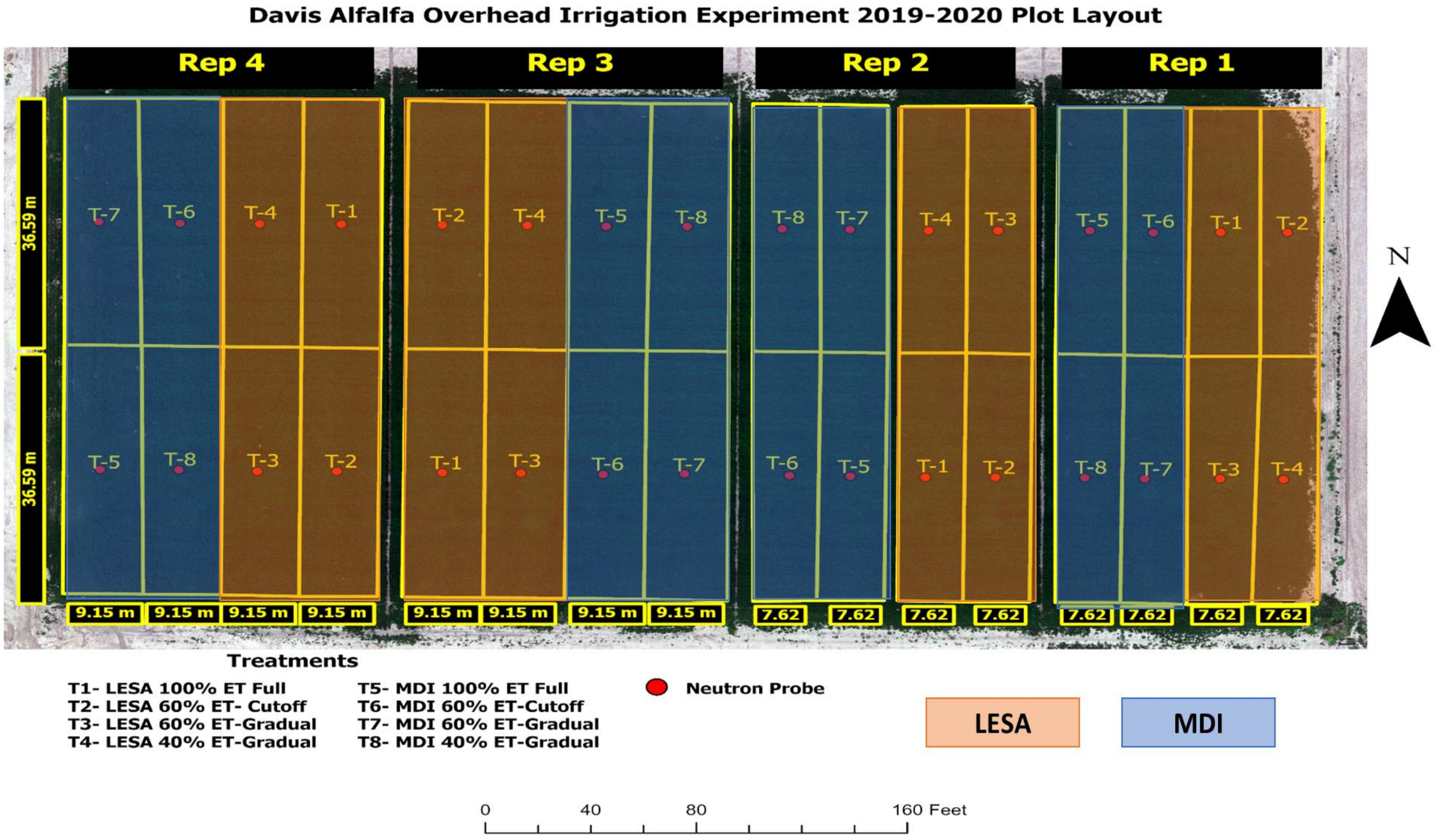

Figure 2.4. Davis Alfalfa experimental layout under LESA and MDI systems with varying amount of irrigations during year 2019 and 2020.

2.2.2 Weather:

The weather during the two-year study and long-term weather patterns (1990-2020) was obtained from the CIMIS station 6 (Davis) within 400 m of the experimental site (Figs. 2.5 and 2.6). The full irrigation requirement for alfalfa was determined by estimating the crop evapotranspiration demand (ET_c) using the daily reference ET_o from CIMIS Davis and multiplying it with the daily crop coefficient k_c values (Fig. 2.7). The ET was also calculated using the soil water balance approach by monitoring the soil water storage using a neutron probe.

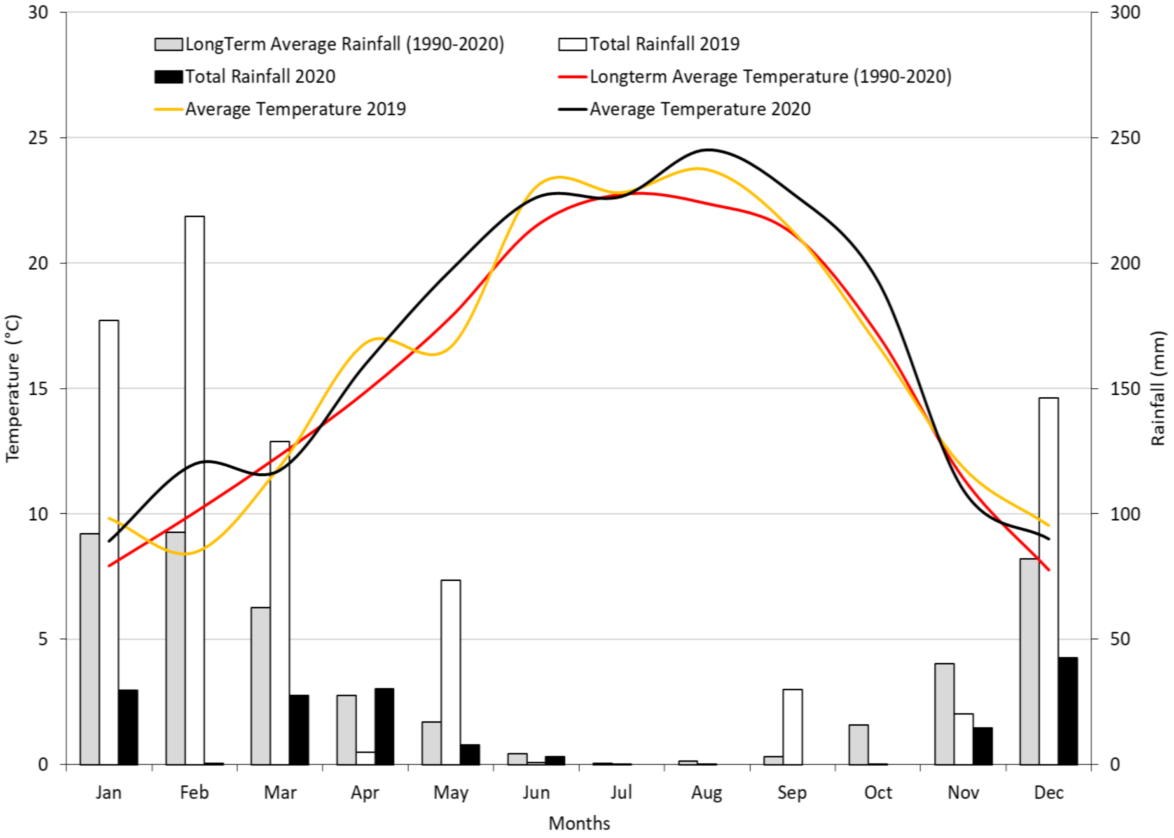

Figure 2.5. Weather patterns for Davis California, USA including long-term averages (red line-temperature and gray bars-rainfall 1990-2020) and individual study period years 2019 (orange line-temperature and white bars-rainfall) and 2020 (black line-temperature and black bars-rainfall).

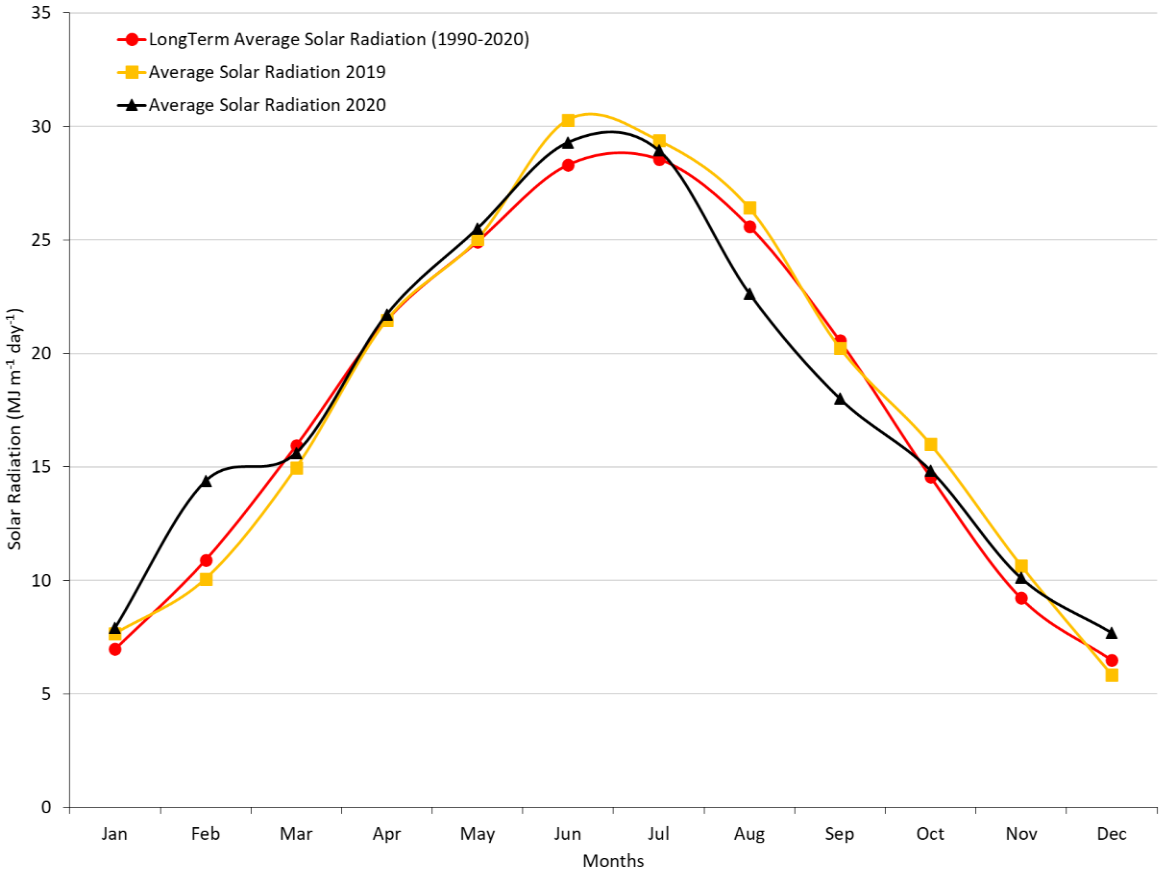

Figure 2.6. Solar Radiation for Davis California, USA including long-term averages (Red Line 1990-2020) and individual study period years 2019 (orange line) and 2020 (black line).

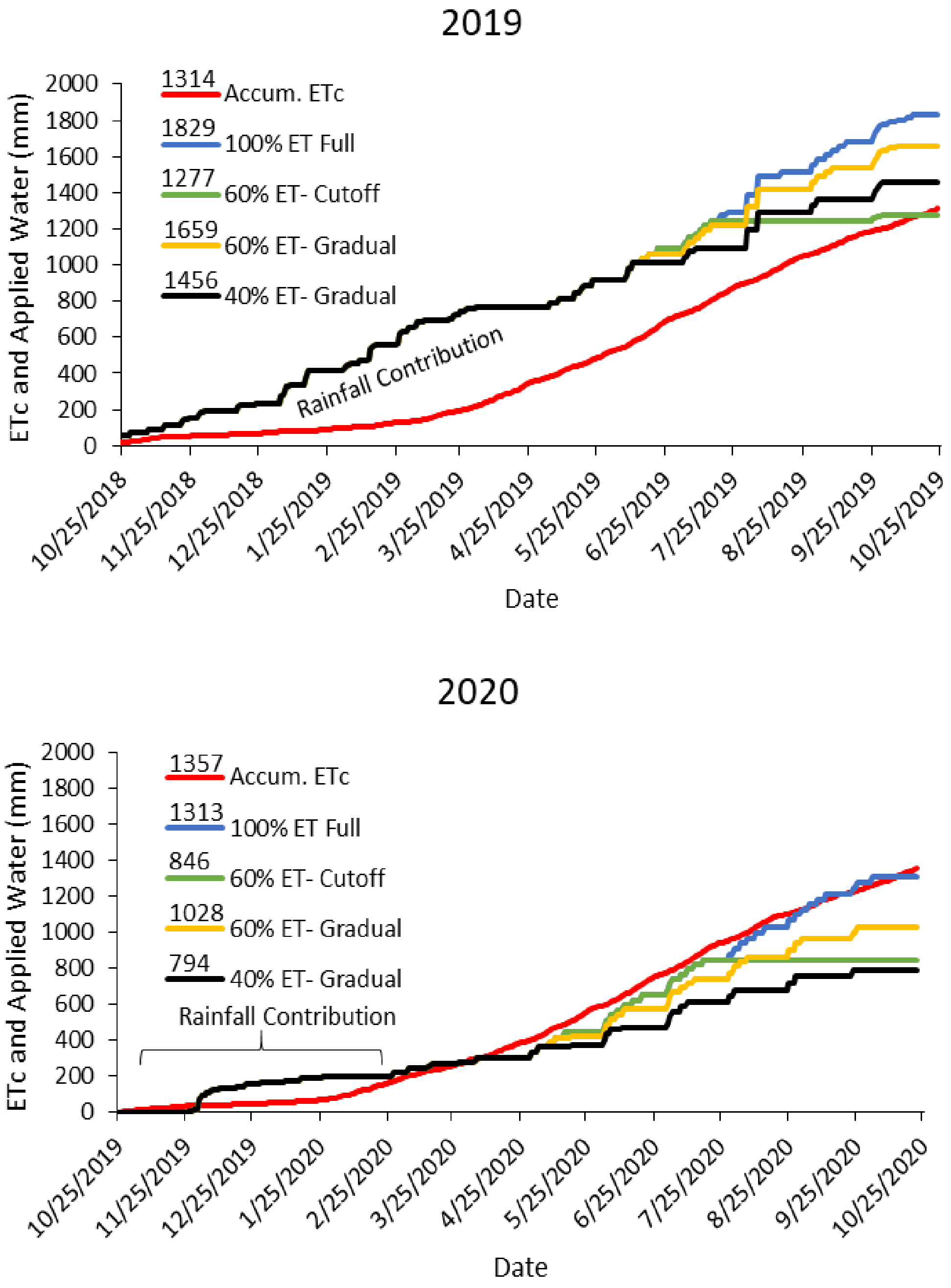

Figure 2.7. Crop Evapotranspiration (red line) and applied water (irrigation and rainfall) for the irrigation amounts (100% ET Full- blue line, 60% ET-Cutoff green line, 60% ET- Gradual orange line, 40% ET-Gradual black line) for years 2019 and 2020. The amounts shown here are for the LESA systems only.

2.2.3 Soil Moisture Monitoring:

Neutron probe access tubes were installed in the center of each plot to determine the soil water status. For this purpose, 5.08 cm diameter schedule 40 PVC pipe was installed to a depth of 300 cm using a Geoprobe® Advance 66DT model GH60 (Kejr, Inc., Salina, Kansas). The soil samples were also collected for the gravimetric water content and other soil related measurements. After the installation of the access tubes, neutron counts were taken at 30 cm intervals from the surface layer to 240 cm depth to develop the on-site calibration curve. CPN 503 Depth Moisture Gauge (Instrotek Inc. Concord, CA, USA) neutron probe was used to record the weekly soil water contents. For seasonal ET calculations, soil water balance approach was used, the beginning and ending profile soil water from the entire 240 cm soil profile from April to October in 2019 while February to October in 2020 were used. In addition to neutron probe readings, time domain transmissometry (TDT) technology sensors were placed in three replicates to monitor the continuous soil moisture data over the course of the study.

$$ET\ (mm) = Rainfall\ (mm) + Irrigation (mm) - \Delta SWC - R - D \qquad Eq.\ 2.1$$

Where ΔSWC was the soil water content difference between the beginning of season and the end of season, while R (runoff) and D (deep drainage) were assumed negligible.

2.2.4 Irrigation Management:

During each growth cycle, irrigation began as soon as feasible after the removal of baled alfalfa from the field. At the beginning of the two-year study period, the soil profile was filled. During 2019, every treatment received irrigation equally until mid-July, with treatments imposed subsequently. This was necessary to optimize the linear move overhead irrigation system sprinklers and drip lines to meet best practices in alfalfa.

Due to lack of sufficient rainfall in 2020, irrigation water was applied equally to all treatments in late winter (February and March) to recharge the profile. The drip lines were replaced with the better pressure compensating drip lines by cutting the older drip lines from the Y-connector and attaching the new drip line before starting the study period in 2020 (Fig. 2.8). The specifications of the drip lines were the same as mentioned above. The drip lines used in 2020 considered to be superior in pressure compensation and maintained adequate flowrates throughout the irrigation event. Fig. 2.2 shows the assembly of the linear system retrofitted with the LESA and MDI systems.

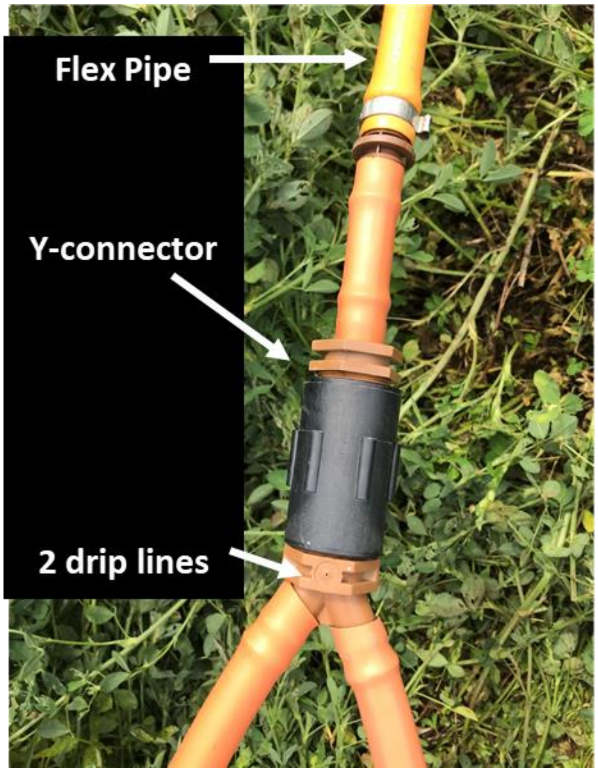

Figure 2.8. Drip lines attached with the Y-connector.

Table 2.1 shows the applied water including irrigation water (pre-irrigations in 2019 and refilling the soil profile in 2020) and rainfall in all the irrigation treatments. The crop evapotranspiration was calculated using the reference ET_o and crop coefficients.

Table 2.1. Applied water (irrigation and rainfall) to various irrigation treatments during year 2019 and 2020 in mm

Treatments	**2019**	**2020**
LESA-100% ET Full	1829	1313
LESA-60% ET- Cutoff	1277	846
LESA-60% ET- Sustained	1659	1028
LESA-40% ET- Sustained	1456	794
MDI-100% ET Full	1811	1313
MDI-60% ET- Cutoff	1277	846
MDI-60% ET- Sustained	1641	1028
MDI-40% ET- Sustained	1438	794
Rainfall	758	265
Crop Evapotranspiration (ET_c)	1314	1357

2.2.5 Crop Parameters:

The crop was harvested approximately every 28 days and data on yield, forage quality and water use were recorded. Yield was measured with a small-plot forage harvester, equipped with an electronic weight system and a cutter bar, from an area of 1.2 m wide × 9.1 m long within each plot. Prior to harvest, subsamples were hand harvested from each plot, weighted wet, placed in an oven at 60 °C until the constant weight was achieved, and weighted dry. Dry matter content was computed and used to adjust harvested yield estimates. Samples were retained for forage quality estimation. Plant height was recorded in the harvested area for each harvest date by selecting 10 mature stems in the location.

The leaf area index was measured closer to the harvested area using the LP-80 Ceptometer between 10:00 to 14:00 hours. LAI measurements were taken within 1-3 days of harvests. Following all sampling and measurements, the entire field was mown with a commercial mower conditioner, dried in the field for several days, and baled with a small square baler. Bales were immediately removed from the field and irrigation resumed.

2.2.6 Forage Quality:

Forage quality was determined using NIR spectroscopy with a protocol outlined by Jones et al., (1987). Samples were ground using a Wiley Mill to pass through a 4 mm sieve, and then finely ground to pass a 1 mm screen with a Cyclone mill. Samples were scanned using a Foss NIRS6500 model spectrophotometer. Following scanning, crude protein (CP), acid detergent fiber (ADF), neutral detergent fiber (NDF), ash content, fat content, digestible NDF at 30 hours (dNDFD30), digestible NDF at 48 hours (dNDFD48), and in vitro true dry matter digestibility (IVTDMD) based on prediction equations developed by the NIRS Forage and Feed Testing Consortium. Using NIRS predicted values, additional parameters were computed using following equations (2.3- 2.6) as reported by Jeranyama and Garcia, 2004 and Undersander et al., 2010.

$$NDFD48 = \frac{dNDF\,48}{aNDF} \qquad \textit{Eq. 2.2}$$

Where dNDF is the digestible neutral detergent fiber at 48 hours and aNDF is the apparent neutral detergent fiber.

$$DDM = \ 88.9 - (0.779 * ADF) \qquad \textit{Eq. 2.3}$$

Where DDM is the digestible dry matter.

$$DMI = 120/aNDF \qquad \textit{Eq. 2.4}$$

Where DMI is the dry matter intake (% of BW), aNDF (% of DM)

$$RFV = \frac{DDM * DDI}{1.29} \qquad Eq.\ 2.5$$

Where RFV is the relative feed value.

$$RFQ = DMI * TDN/1.23 \qquad Eq.\ 2.6$$

Where RFQ is the relative forage quality.

2.2.7 Water productivity and Irrigation Water Use Efficiency:

Seasonal water productivity was calculated using the equation 2.7.

$$WP = \frac{Forage\ DM\ Yield\ (kg\ ha^{-1})}{Crop\ Evapotranspiration\ (mm)} \qquad Eq.\ 2.7$$

where crop evapotranspiration was calculated using the soil water balance equation 2.1 from the season beginning and ending soil moisture content and forage yield was the total seasonal yields.

Irrigation water use efficiency was calculated using equation 2.8.

$$IWUE = \frac{Forage\ DM\ Yield\ (kg\ ha^{-1})}{Irrigation\ Water\ Applied\ (mm)} \qquad Eq.\ 2.8$$

where irrigation water applied is the total water applied each season and forage yield was the total seasonal yields.

2.2.8 Statistical Analysis:

Years 2019 and 2020 were analyzed separately on per cut basis and on seasonal totals for forage yield, seasonal averages for forage quality, plant height, water productivity and irrigation use efficiency using a split plot analysis of variance (ANOVA). Seasonal soil moisture content, evapotranspiration and applied irrigation were also analyzed using ANOVA. In the split-plot model, systems were the main plot while irrigation amounts were the sub-plots. Treatment factors were considered fixed, while blocks were considered as random factor. ANOVA was carried out in R statistical software version 4.0.3 (R Core Team, 2020) with Agricolae package (de Mendiburu, 2020). Means were compared using Fisher's protected least significant difference (LSD) at the 5% significance level. Regression analysis was carried between plant heights and dry matter yields, and between water applied and dry matter yields using ggplot2 package in R (Wickham, 2016).

2.3 RESULTS AND DISCUSSION

2.3.1 Weather Conditions:

During the two years, there was substantially less rainfall in 2020 compared with 2019 (Fig. 2.5). Therefore, irrigating the crop early in winter was necessary to refill the soil profile. The average temperature in 2020 was higher compared with the 30-years average and compared with 2019. Higher monthly rainfall was observed in 2019 while 2020 was relatively drier and much lower than the 30-year average rainfall (Fig. 2.5). Most of the rainfall in 2019 occurred during the first quarter (January to March, 525 mm) and the last quarter (October to December, 166 mm) while in year 2020, limited rainfall was observed in first quarter (January to March, 57.9 mm) (Fig. 2.5). Higher temperatures occurred during February 2020 with no rain and triggered the need for early irrigation in that year. Besides the higher temperatures during 2020, it was also observed that solar radiation was higher than 30-years average in February and lower during summer (July to September) which promoted substantial crop growth in February and slowed the crop growth in summer (Fig. 2.6).

2.3.2 Soil Water Content:

Soil moisture measurements taken after the first harvest (May 2019), showed that all treatments had water content higher than the maximum allowable depletion at each depth (Solid Red line, Fig. 2.9). As the season progressed, the soil water content decreased for all the deficit treatments under both irrigation systems but increased in the fully irrigated treatments during 2019 (October 2019, Fig. 2.9). During 2019-20 winter, water status for most of the treatments improved (Solid Green line, Fig. 2.9) in the top 100-120 cm but deeper depths showed considerable water depletion in the deficit treatments at the beginning of 2020 (Fig. 2.9), due to the dry winter with below average rainfall for October 2019 to February 2020 (197 mm). At the end of the 2020 season (Solid Purple line, Fig. 2.9) water content was lower than 2019 (Solid Blue line, Fig. 2.9) In general, LESA had better water status in all the treatments except in 60% ET- Cutoff where MDI had a higher water status in the top 150 cm soil profile. These results implied that MDI was successfully able to maintain the soil moisture in the soil profile while LESA had a lower content of available water deeper in the soil profile.

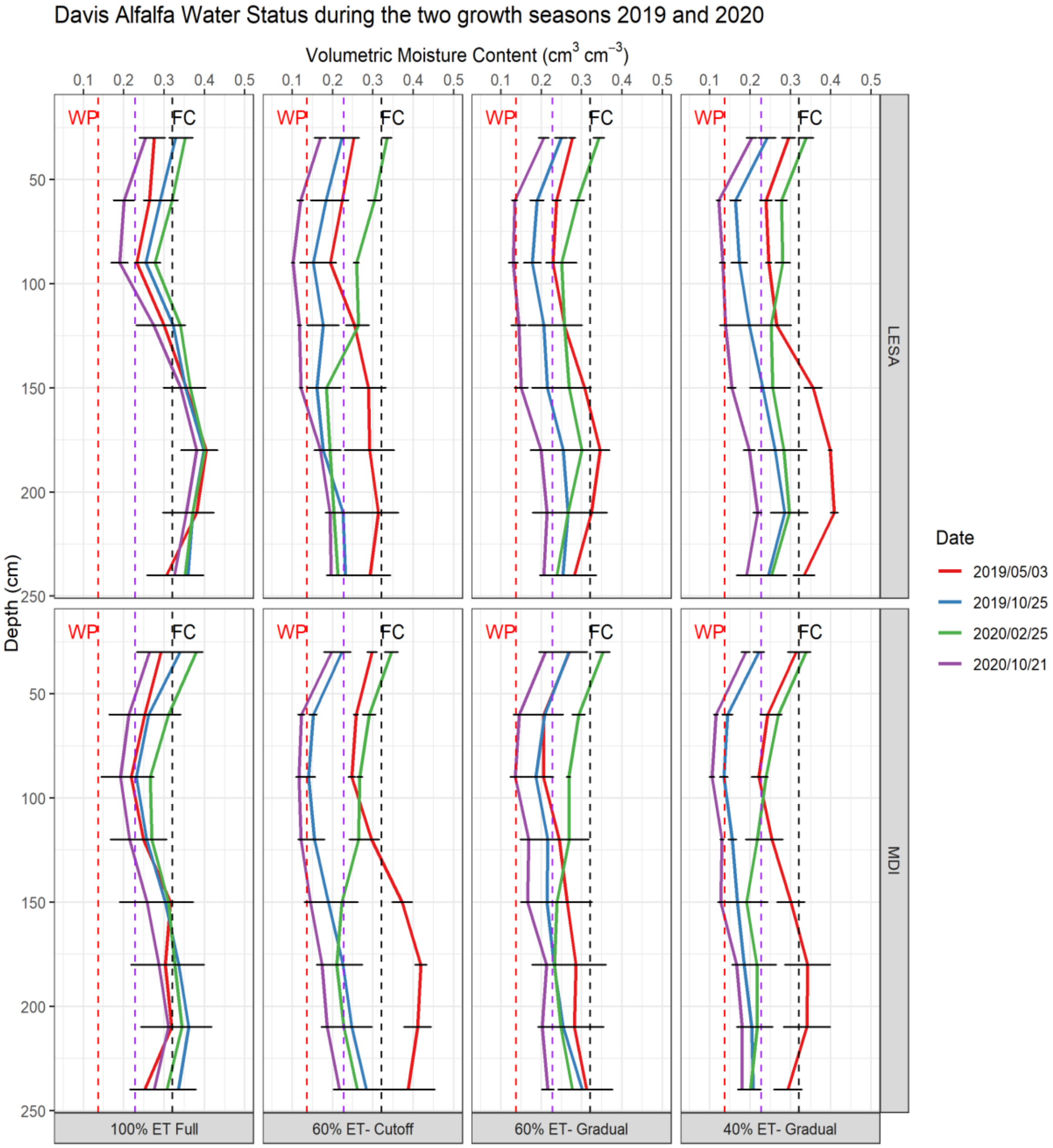

Figure 2.9. Soil Water Content in the top 240 cm soil profile for LESA and MDI under varying amount of irrigations where FC is the field capacity (black dashed line), MAD is maximum allowable depletion (purple dashed line) and WP is the wilting point (red dashed line). During 2019, solid red line shows the beginning water content while solid blue line shows the end of season water content. During 2020, solid green line shows the beginning season water content while solid purple line shows the end of season water content.Horizontal bars are the error bars on individual dates.

2.3.3 Impact of Irrigation system and irrigation amounts on

2.3.3.1 Dry Matter Yields

Very weak interactions between irrigation method and irrigation amount were observed in dry matter yields when data was averaged across two years (Table 2.7-supplmentary material). For each harvest, the two irrigation systems were not significantly different while the irrigation amounts significantly impacted yields from the June through October harvests and the total yield over the two years (Table 2.7-supplmentary material). No differences in yield due to the two irrigation systems were found for any harvest in either year, for the total yield in each year, or for averaged across the two years (Table 2.7, 2.8, 2.9-supplementary material). Cumulative yields over the two years under the two irrigation systems and irrigation amounts are provided in Fig. 2.10. There were significant differences found among the irrigation amounts in 2019 (Table 2.8-supplmentary material) for only two harvests (September and October) while overall yield was not affected by irrigation amounts. In 2020 (Table 2.9-supplementary material), significant results were found for irrigation amounts during all the harvests and total yields except the April harvest (Table 2.9-supplemenratry material). The interactions among irrigation systems and irrigation amounts were non-significant during 2019 (Table 2.8-supplmentary material) while in 2020 (Table 2.9-supplemenraty material), there were week interactions found during different harvests and total yields

An average of 90% of full yields were achieved in the MDI 60% ET- Cutoff treatment, while the LESA 60% ET-Cutoff treatment, 73% of full cumulative yields were achieved over two years (Fig. 2.10). Applied irrigation amounts for the two years under the two systems were approximately equal (Table 2.1). However, the actual applied water was slightly higher than the targeted amount of 60% ET.

During 2019, the results were non-significant as it was the first year of production and deficits were started late in the season (Table 2.8- supplementary material). The 2020 yields were lower than 2019 probably because the available soil moisture during the 2020 season were lower than the 2019 on seasonal average basis.

In 2020, yields differed among irrigation treatments at all harvests except for the first harvest and for total yield (Table 2.9-Supplementary material). Full irrigation and 60% ET Sustained were always the highest yielding treatments, with 40% ET Sustained the lowest or among the lowest, except for Sep 2020, when 60% ET Cutoff was lowest (Table 2.9). For total yield, the two 60% treatments did not differ.

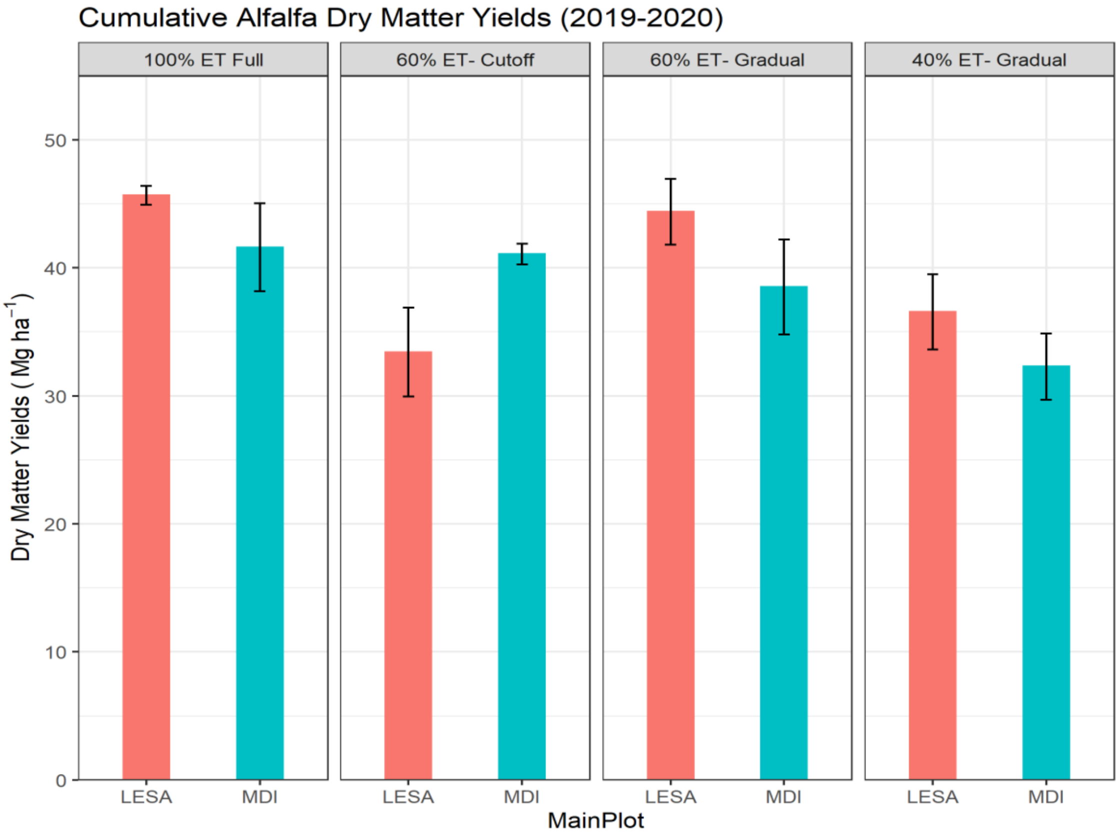

Figure 2.10. Alfalfa cumulative dry matter yields for two years 2019 and 2020.

Our results indicating no difference between LESA and MDI over all treatments are similar results to those found by other researchers. Oker et al., (2018) and Molaei et al., (2021) who reported no differences between LESA and MDI application technologies in maize (Oker et al., 2018) and peppermint/spearmint (Molaei et al., 2021). Key advantages of MDI vs. sprinkler systems is the potential reduction in wind drift losses, and the ability to apply water directly to soils so that a greater quantity ends up in the soil (Kisekka et al., 2017). Previous studies on deficit irrigation strategies used wheel-line sprinkler systems or flood irrigation (Orloff et al., 2005). They found that cutting the irrigation entirely at later harvests was economically and agronomically feasible during drought (Orloff et al., 2005). For alfalfa production under changing water scarcity scenarios, alfalfa could be cultivated under either of the systems but with summer cutoff, our data suggest that there will be slightly more reduction in yield with LESA than in MDI.

2.3.3.2 Plant Heights

Irrigation amounts had a significant impact on average alfalfa plant heights regardless of the irrigation system used (Table 2.2). In 2019, no differences were found among irrigation systems, irrigation amounts and their interaction (Table 2.2). In 2020, LESA- 100% ET Full treatment had a significantly higher plant heights ($p < 0.05$), on par with MDI- 100% ET Full, LESA-60% ET- Sustained, MDI-60% ET- Sustained, LESA-40% ET- Sustained, MDI-40% ET- Sustained and MDI-60% ET- Cutoff and significantly different than LESA-60% ET- Cutoff (Table 2.2). These results suggest that the irrigation system didn’t have much of an influence on the plant heights reduction but the irrigation amounts did significantly reduce the plant heights.

There was a significant relationship found between the plant heights and the dry matter yields across all cuttings for both irrigation systems (Fig. 2.12). This relationship was somewhat stronger in 2019 than in 2020. This could be due to varying environmental conditions during the two years and varying wetting patterns among the two systems.

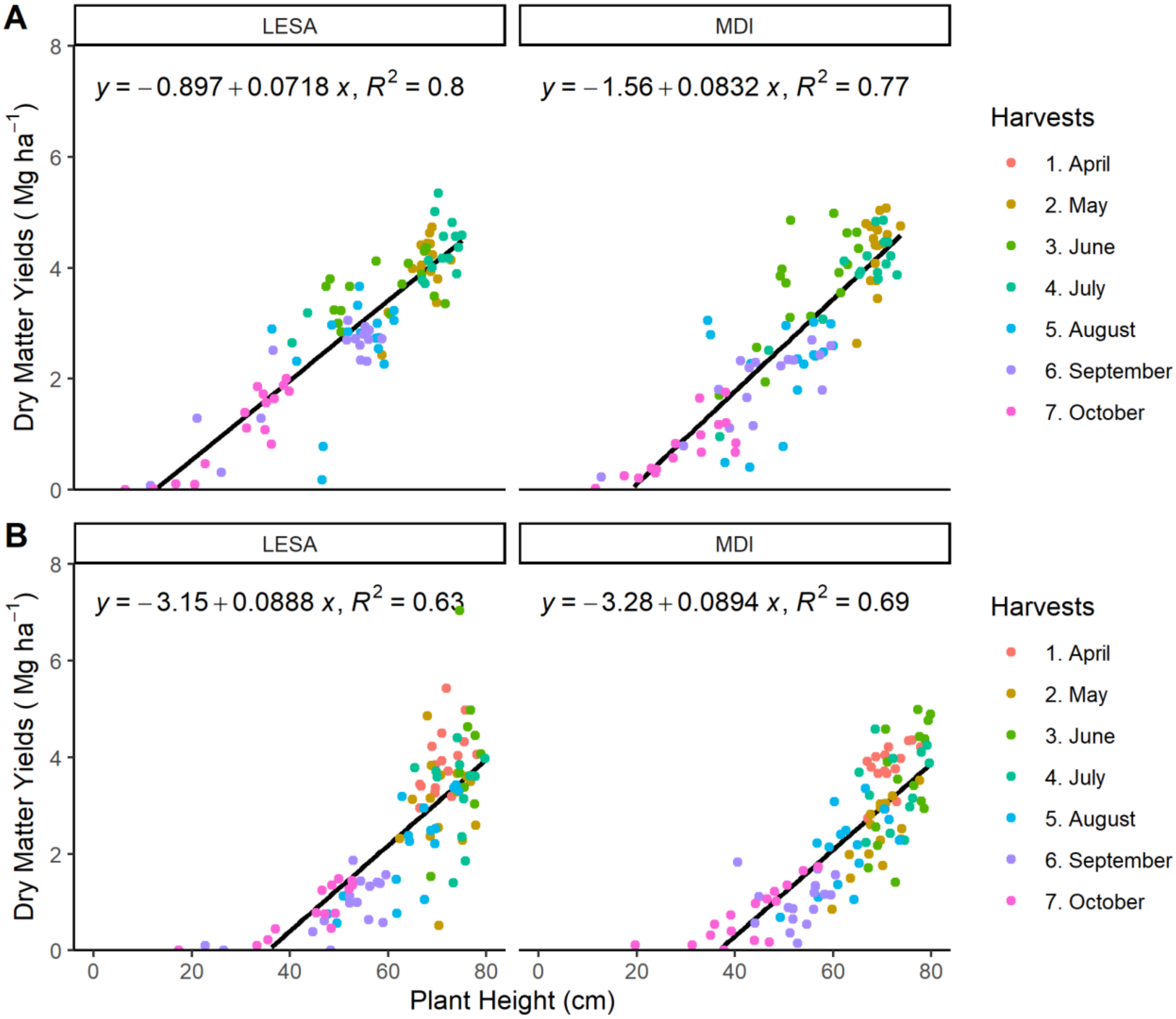

Figure 2.11. Regressions between plant heights and dry matter yields for year 2019 (A) and 2020 (B) between LESA and MDI including all the harvests for individual year.

Table 2.2. Average Plant heights in cm as affected by irrigation systems and varying irrigation levels

		2019	2020	2019-2020
Systems (S)	LESA	54	64	59
	MDI	52	64	58
	LSD	----	----	----
	p-value	*ns*	*ns*	*ns*
Amounts (A)	100% ET Full	55	68 a	62 a
	60% ET- Cutoff	48	59 c	54 b
	60% ET- Sustained	54	66 ab	60 a
	40% ET- Sustained	54	64 b	59 a
	LSD	----	*2.99*	*3.89*
	p-value	*ns*	*0.000*	*0.004*
S * A	LESA * 100% ET Full	57	69 a	63
	LESA * 60% ET- Cutoff	45	57 d	51
	LESA * 60% ET- Sustained	55	66 abc	61
	LESA * 40% ET- Sustained	57	65 bc	61
	MDI * 100% ET Full	54	67 ab	60
	MDI * 60% ET- Cutoff	51	62 c	57
	MDI * 60% ET- Sustained	53	65 abc	59
	MDI * 40% ET- Sustained	50	63 bc	56
	LSD	----	*4.23*	*5.50*
	p-value	*ns*	*0.035*	*0.053*

Note: ns is Non-Significant
LESA= Low Elevation Spray Application
MDI=Mobile Drip Irrigation

FI= Full Irrigation
CT-60%= Summer Cutoff
GD-60%= 60% of FI at every irrigation
GD-40%= 40% of FI at every irrigation

Means sharing the same letters in a column are not statistically different

2.3.3.3 Leaf Area Index (LAI)

During the study period, no irrigation system × irrigation amount interaction was present at any harvest for LAI. Leaf area index did not vary between irrigation systems but did vary among irrigation treatments (Table 2.3). The 100% ET Full treatment always had the highest LAI values and one or more of the deficit treatments had lower LAI at all time points (Table 2.3). In both years, significantly lower LAI was observed in the 60% ET- Cutoff during the late harvests regardless of the irrigation system used (Table 2.3). September and October harvests in 2020 were not measured for LAI due to low air quality form wildfire smoke in that year.

The reduction in LAI during the later harvests and in the deficit treatments is likely associated with reduced radiation use efficiency, reduced photosynthetic activity, and less leaf expansion (Liu et al., 2021).

Table 2.3. Leaf Area Index as affected by irrigation systems and varying irrigation levels during 2019 and 2020

		Leaf Area Index 2019					**Leaf Area Index 2020**					
		July	**Aug**	**Sep**	**Oct**	**Y2019**	**May**	**June**	**July**	**Aug**	**Y2020**	**Y19-20**
		--m^{2} m^{-2}---										
Systems (S)	LESA	6.2	3.2	3.9	2.6	4.0	5.8	5.6	4.2	3.0	4.7	4.3
	MDI	5.7	2.5	3.9	2.1	3.6	6.2	5.6	4.3	3.2	4.8	4.2
	LSD	----	----	----	----	----	----	----	----	----	----	----
	p-value	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*
Amounts (A)	100% ET Full	6.7	3.6	4.7 a	4.4 a	4.8 a	6.5	6.0	4.4	3.6 a	5.1 a	5.0 a
	60% ET- Cutoff	6.3	2.8	2.6 b	0.6 c	3.1 b	6.6	6.0	4.6	2.6 b	5.0 a	4.0 b
	60% ET- Sustained	5.6	2.4	4.2 a	2.5 b	3.6 b	5.6	5.4	3.8	3.2 ab	4.5 b	4.1 b
	40% ET- Sustained	5.4	2.8	4.0 a	2.1 b	3.6 b	5.4	5.0	4.3	2.9 b	4.4 b	4.0 b
	LSD	*1.05*	----	*0.86*	*1.14*	*0.90*	*1.13*	----	----	*0.70*	*0.44*	*0.56*
	p-value	*0.058*	*ns*	*0.000*	*0.000*	*0.005*	*0.081*	*ns*	*ns*	*0.034*	*0.008*	*0.004*
S * A	LESA * 100% ET Full	6.7	4.0	4.7	4.9	5.1	6.6	6.0	4.2	3.5	5.1	5.1
	LESA * 60% ET- Cutoff	6.3	2.9	2.3	0.3	2.9	6.2	5.7	4.6	2.4	4.7	3.8
	LESA * 60% ET- Sustained	6.3	2.9	3.9	2.7	3.9	5.1	5.4	3.7	3.2	4.4	4.1
	LESA * 40% ET- Sustained	5.6	3.2	4.4	2.6	4.0	5.4	5.4	4.4	3.1	4.6	4.3
	MDI * 100% ET Full	6.7	3.1	4.7	3.8	4.6	6.3	6.0	4.5	3.8	5.1	4.9
	MDI * 60% ET- Cutoff	6.2	2.7	2.9	0.9	3.2	7.0	6.2	4.6	2.9	5.2	4.2
	MDI * 60% ET- Sustained	4.9	1.9	4.4	2.3	3.3	6.0	5.5	4.0	3.3	4.7	4.0
	MDI * 40% ET- Sustained	5.2	2.4	3.5	1.5	3.1	5.3	4.6	4.1	2.7	4.2	3.7
	LSD	----	----	----	----	----	----	----	----	----	----	----
	p-value	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*

Note: ns is Non-Significant
LESA= Low Elevation Spray Application
MDI=Mobile Drip Irrigation
Year=average over the cuttings
Means sharing the same letters in a column are not statistically different

FI= Full Irrigation
CT-60%= Summer Cutoff
GD-60%= 60% of FI at every irrigation
GD-40%= 40% of FI at every irrigation

2.3.3.4 Forage Quality

In general, forage quality was not affected significantly by either method of water application or deficit treatments in this study (Table 2.4). Crude Protein (average for year 2019 and 2020), NDFD48 (average for year 2019 and 2020) and NDFD30 (average for year 2020) were only slightly affected by level of irrigation treatments, but not by irrigation system (Tables 2.4 and 2.5). Higher crude protein was found in 100% ET Full irrigated alfalfa which was statistically at par with 60% ET- Sustained deficit followed by 40% ET- Sustained deficit and 60% ET- Cutoff treatments during 2019 ($p < 0.05$, Table 2.4) and 2020 ($p < 0.001$, Table 2.5). Similar results were found for NDFD48 which was higher in 100% ET Full irrigated alfalfa while lowest in 60% ET- Cutoff in 2019 ($p < 0.01$, Table 2.4) and 40% ET- Sustained deficit in 2020 ($p < 0.01$, Table 2.5). As the studied parameters were averaged over all the cuttings during a single year, the result implied little to no change in forage quality due to water deficits which was found the same during individual harvests as well. This differs from some studies which have shown small improvements in forage quality of alfalfa due to water deficits cultivated under various irrigation systems (Lindenmayer et al., 2008; Liu et al., 2018; Montazar et al., 2020).

Table 2.4. Forage Quality parameters during 2019 as affected by irrigation systems and varying irrigation levels

		CP	ADF	aNDF	ASH	FAT	NDFD30	NDFD48	RFV	RFQ
		----------------------------------g kg^{-1}----------------------------------							-------%-----	
Systems (S)	LESA	253	288	334	98	20	433	533	191	226
	MDI	250	290	338	99	20	430	533	188	223
	LSD	----	----	----	----	----	----	----	----	----
	p-value	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*
Amounts (A)	100% ET Full	256 a	290	335	99	20 a	436	545 a	189	224
	60% ET- Cutoff	247 b	289	336	97	20 bc	429	523 c	190	225
	60% ET- Sustained	252 ab	289	337	99	20 ab	430	534 b	189	223
	40% ET- Sustained	249 b	289	337	99	20 c	430	529 bc	190	224
	LSD	*5.6*	----	----	----	*0.3*	----	*10.4*	----	----
	p-value	*0.018*	*ns*	*ns*	*ns*	*0.011*	*ns*	*0.003*	*ns*	*ns*
S * A	LESA * 100% ET Full	258	293	338	98	20 ab	438	544	187	223
	LESA * 60% ET- Cutoff	248	285	331	96	20 cd	431	519	194	229
	LESA * 60% ET- Sustained	254	285	333	99	20 ab	430	533	192	226
	LESA * 40% ET- Sustained	252	289	335	98	20 bcd	432	534	189	225
	MDI * 100% ET Full	255	287	333	99	20 a	434	546	190	226
	MDI * 60% ET- Cutoff	247	293	341	99	20 ab	428	528	187	222
	MDI * 60% ET- Sustained	249	292	341	99	20 abc	431	536	186	220
	MDI * 40% ET- Sustained	247	289	339	101	20 d	427	524	190	223
	LSD	----	----	----	----	*0.44*	----	----	----	----
	p-value	*ns*	*ns*	*ns*	*ns*	*0.025*	*ns*	*ns*	*ns*	*ns*

Note: ns is Non-Significant
LESA= Low Elevation Spray Application
MDI=Mobile Drip Irrigation

FI= Full Irrigation
CT-60%= Summer Cutoff
GD-60%= 60% of FI at every irrigation
GD-40%= 40% of FI at every irrigation

Means sharing the same letters in a column are not statistically different

Table 2.5. Forage Quality parameters during 2020 as affected by irrigation systems and varying irrigation levels

		CP	**ADF**	**aNDF**	**ASH**	**FAT**	**NDFD30**	**NDFD48**	**RFV**	**RFQ**
		---------------------------------g kg^{-1}---------------------------------							----------%----------	
Systems (S)	LESA	230	317	368	101	19	433	470	166	199
	MDI	229	315	366	103	19	432	471	166	199
	LSD	----	----	----	----	----	----	----	----	----
	p-value	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*
Amounts (A)	100% ET Full	237 a	318	367	103	19	446 a	482 a	165	199
	60% ET- Cutoff	226 b	314	366	101	19	428 b	466 b	167	201
	60% ET- Sustained	227 b	318	370	101	19	431 b	469 b	164	197
	40% ET- Sustained	225 b	313	366	102	19	423 b	463 b	167	199
	LSD	*4.81*	----	----	----	----	*10.99*	*10.73*	----	----
	p-value	*0.000*	*ns*	*ns*	*ns*	*ns*	*0.003*	*0.008*	*ns*	*ns*
S * A	LESA * 100% ET Full	238	319	368	102	20	446	482	165	199
	LESA * 60% ET- Cutoff	226	314	366	100	20	427	464	168	202
	LESA * 60% ET- Sustained	227	321	374	101	19	430	467	162	195
	LESA * 40% ET- Sustained	227	312	364	101	19	428	466	168	201
	MDI * 100% ET Full	237	317	366	105	19	446	483	166	199
	MDI * 60% ET- Cutoff	227	313	364	102	19	430	469	168	201
	MDI * 60% ET- Sustained	228	314	366	102	19	432	471	166	199
	MDI * 40% ET- Sustained	224	314	367	102	19	419	460	165	198
	LSD	----	----	----	----	----	----	----	----	----
	p-value	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*

Note: ns is Non-Significant
LESA= Low Elevation Spray Application
MDI=Mobile Drip Irrigation

FI= Full Irrigation
CT-60%= Summer Cutoff
GD-60%= 60% of FI at every irrigation
GD-40%= 40% of FI at every irrigation

Means sharing the same letters in a column are not statistically different

2.3.3.5 Water Productivity, irrigation water use efficiency (IWUE) and evapotranspiration

Water productivity did not differ due to irrigation method or deficits in 2019 but was significantly affected by water deficits in 2020 (Table 2.6). Higher water productivity was achieved under MDI-60% ET- Cutoff which was at par with LESA-60% ET- Sustained, followed by LESA-60% ET- Cutoff and LESA- 100% ET Full irrigation while lowest was found in LESA-40% ET- Sustained, MDI- 100% ET Full irrigation, MDI-60% ET- Sustained and MDI-40% ET- Sustained. Higher water productivity was found in 60% ET- Cutoff, which was about the same as the 60% ET- Sustained treatment, while lower WP was found in 40% ET- Sustained irrigation.

Irrigation water use efficiency was found to be significant affected ($p < 0.001$) by varying irrigation amounts but was found to be no different between the two irrigation systems in both years (Table 2.6). Higher IWUE were found in 60% ET- Cutoff while lowest were found in the 100% ET- Full irrigation. Similarly, statistically higher IWUE were found in 60% ET- Cutoff and lowest in 100% ET- Full irrigation ($p < 0.01$) during 2020 (Table 2.6). These results implied that alfalfa can be cultivated under either of the two systems (LESA or MDI), while there was a significant benefit in IWUE using 60% ET- Cutoff treatment, which was found higher in MDI than in LESA, when irrigation water was limited (Table 2.6).

No differences were found in crop evapotranspiration during the year 2019 among the two irrigation systems while significant differences were found among the levels of irrigation (Table 2.6). Lower ET was observed under the summer cutoffs which was significantly different ($p < 0.05$) than all the other levels. Similar trends were observed during the 2020 season where higher ET was observed for full irrigation which was statistically different ($p < 0.01$) than 60% ET- Sustained irrigation, 60% ET- Cutoff and lowest in 40% ET-Sustained irrigation.

The findings of this study are in line with findings of other researchers (Lindenmayer et al., 2008), who also found higher water productivities under limited water supplies in alfalfa. Although the targeted amounts for 60% ET- Cutoff and 60% ET- Sustained treatments were 60%, but the actual applied under the sustained treatment was slightly higher than the cutoff because of applying 60% at every irrigation during the growth cycle varied in the late summer. The same was true for 40% ET-Sustained, which was close to the 60% ET- Cutoff during the two-year study period.

Weak regressions were observed during 2019 between applied water and dry matter yields under the two irrigation systems while better regressions were observed in 2020 under the two systems with MDI performing better than LESA with R^2 of 0.58 (Fig. 2.12). The April harvests had a large effect on this relationship in 2019.

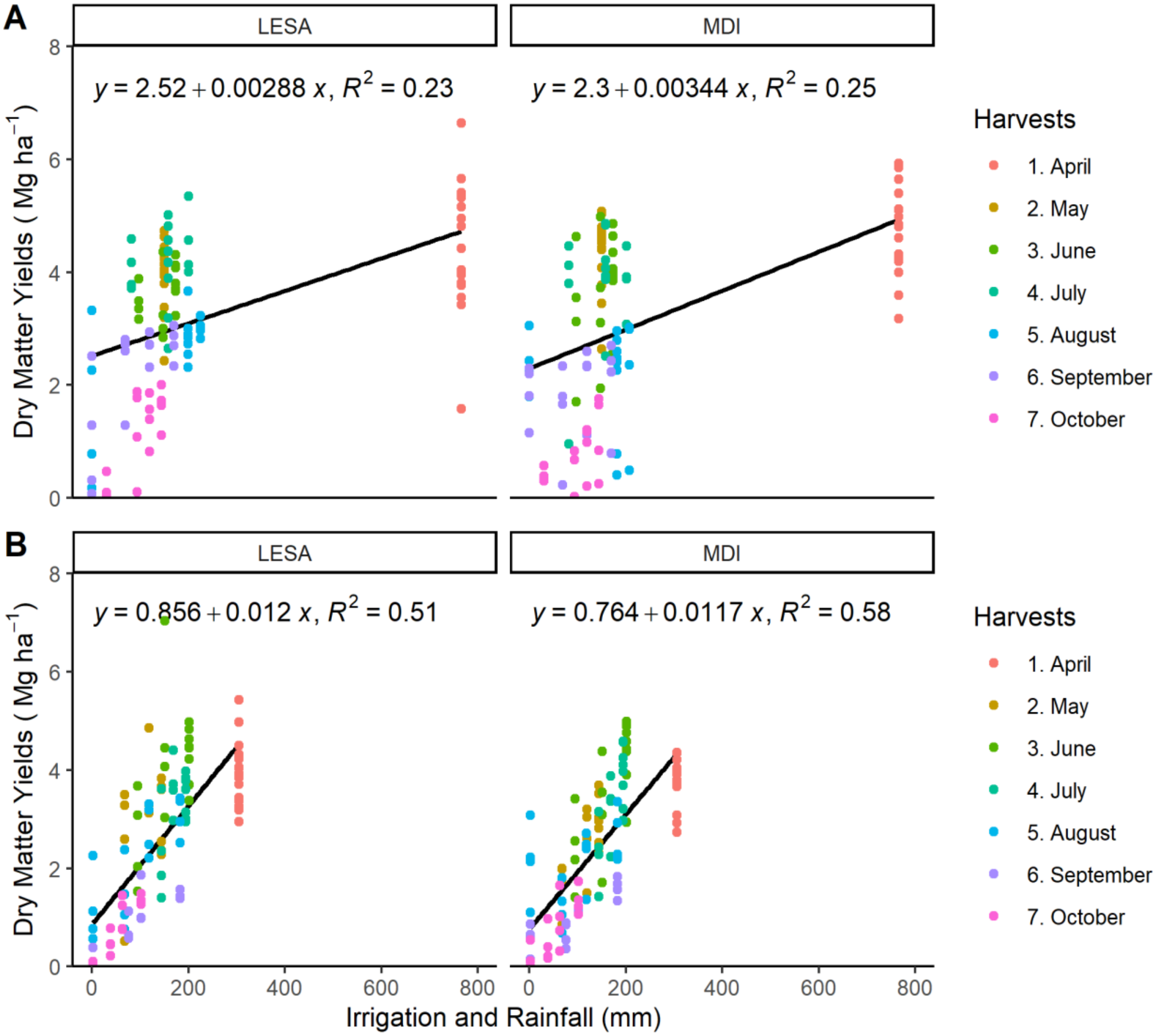

Figure 2.12. Regressions between applied irrigation including rainfall contribution and dry matter yields for year 2019 (A) and 2020 (B) between LESA and MDI including all the harvests for individual year.

Table 2.6. Seasonal Evapotranspiration from soil water balance, applied irrigation water, water productivity and irrigation water use efficiency as affected by irrigation systems and varying irrigation levels during 2019 and 2020

		2019				**2020**			
		ET	**Applied Irrigation Water**	**WP**	**IWUE**	**ET**	**Applied Irrigation Water**	**WP**	**IWUE**
		(mm)	(mm)	(kg ha^{-1} mm^{-1})		(mm)	(mm)	(kg ha^{-1} mm^{-1})	
Systems (S)	LESA	912.3	685	25.1	34.7	1022.3	730	17.4	25.0
	MDI	923.0	671	24.0	35.2	1006.8	730	17.1	24.3
	LSD	----	----	----	----	----	----	----	----
	p-value	*ns*	----	*ns*	*ns*	*ns*	----	*ns*	*ns*
Amounts (A)	100% ET Full	995.9 a	950	23.7	24.3 c	1262.6 a	1048	16.4 bc	19.6 b
	60% ET- Cutoff	763.1 b	406	27.6	50.2 a	889.3 c	581	19.1 a	29.0 a
	60% ET- Sustained	981.6 a	780	23.7	28.3 c	1067.9 b	763	18.2 ab	25.4 a
	40% ET- Sustained	930.1 a	576	23.2	37.1 b	838.4 c	529	15.4 c	24.6 a
	LSD	*147.37*	----	----	*6.06*	*110.21*	----	*2.22*	*4.73*
	p-value	*0.014*	----	*ns*	*0.000*	*0.000*	----	*0.010*	*0.006*
S * A	LESA * 100% ET Full	1014.5	959	23.8	25.2	1256.2	1048	17.1 bc	20.5 cd
	LESA * 60% ET- Cutoff	688.1	406	28.6	45.8	882.1	581	16.9 bc	25.5 bc
	LESA * 60% ET- Sustained	1030.2	788	22.5	28.9	1084.4	763	20.0 ab	28.3 ab
	LESA * 40% ET- Sustained	916.6	585	25.4	39.1	866.5	529	15.5 c	25.8 bc
	MDI * 100% ET Full	977.4	941	23.6	23.4	1269.0	1048	15.6 c	18.7 d
	MDI * 60% ET- Cutoff	838.1	406	26.7	54.6	896.4	581	21.2 a	32.5 a
	MDI * 60% ET- Sustained	932.9	771	24.9	27.8	1051.4	763	16.4 c	22.4 bcd
	MDI * 40% ET- Sustained	943.5	567	20.9	35.1	810.2	529	15.3 c	23.4 bcd
	LSD	----	----	----	----	----	----	*3.13*	*6.69*
	p-value	*ns*	----	*ns*	*ns*	*ns*	----	*0.010*	*0.057*

Note: ns is Non-Significant
LESA= Low Elevation Spray Application
MDI=Mobile Drip Irrigation

FI= Full Irrigation
CT-60%= Summer Cutoff
GD-60%= 60% of FI at every irrigation
GD-40%= 40% of FI at every irrigation

ET= Evapotranspiration
WP= Water Productivity
IWUE= Irrigation Water Use Efficiency

Means sharing the same letters in a column are not statistically different

2.3.4 Considerations comparing MDI and LESA Applications in Alfalfa under overhead irrigation including water deficits

Alfalfa is a perennial forage which can sustain periods of droughts and performs well under full crop ET conditions but also can sustain water deficits under climate change scenarios. It is clear that yields are likely to be reduced with limited irrigation water, but such reductions are likely to be inevitable under several future scenarios. So, improved irrigation strategies are important. This study indicates that we were able to successfully cultivate alfalfa in the Mediterranean conditions of California using either MDI or LESA.

LESA and MDI can equally sustain the alfalfa production under limiting water resources, but MDI had some advantages under summer cutoffs. As this was a controlled study, we had limited area available under each treatment with two drip lines in case of MDI dragging with the overhead irrigation system and small field area made it somewhat difficult to eliminate the edge effects from the treatments. Sometimes, the kinking of drip lines (Fig. 2.13) occurred while reversing the linear overhead system, this was primarily because of the small area under the experiment. Such problems are unlikely to occur (or may be different) with longer drip lines or longer irrigation sets.

Figure 2.13. Kinked MDI drip line and moving away from center.

As stated earlier, LESA is one of the more efficient irrigation systems in use with either center pivots or the linear overhead irrigation systems (Amosson et al. 2011). In this study, it also performed well for alfalfa production but certainly producing less dry matter yield under some of the severe water deficits compared with MDI. This supports the possibility that

MDI might provide longer water storage and deeper soil water buildup compared with LESA (Oker et al., 2020, Kisekka et al., 2017).

LESA had the advantage of irrigating uniformly on the entire surface (Peter et. al., 2016) when compared with MDI, which only irrigated in a certain path limiting the wetted pattern. Thus, LESA systems may be superior for stand establishment since the soil surface is uniformly wetted. However, surface runoff may be more severe with sprinklers vs. surface drip (Kisekka et al., 2017). Due to flat elevation in this study, there was limited runoff observed in the trial under either system, but differences in runoff may be observed in sloped fields, depending upon application rate and soil infiltration rate. In this experiment, we analyzed only the MDI and LESA systems, but for future work, it would be interesting to see how these systems perform when compared with other high efficiency irrigation systems. It will also be beneficial to do a comparative study to evaluate the systems using the economic cost-benefit analysis for production on the large acreage.

MDI provided a continuous wetted pattern which helped in improving the soil water storage in certain deficit treatments while LESA was not able to perform as well in those deficits partly because of infiltration issues and large area wetting pattern which promoted some evaporative loss. Wind losses, and evaporative losses from wetted plant foliage are a disadvantage of all sprinkler systems, but LESA systems are generally superior to mid-level sprinkler elevation. LESA when compared with MESA saved ~18% more water which reached the crop canopy and into the root zone (Peters et. al., 2016). We didn’t evaluate wind losses in this study. MDI had a clear advantage over the subsurface drip (SDI) systems, as in our study, we did not observe any rodent damage or the cost of repairing the MDI drip lines. While cultivating alfalfa under SDI generally requires a lot of drip repairs and maintenance because of rodent damage. However, there are significant power requirement differences between higher pressure overheads sprinklers vs. low pressure SDI systems.

2.4 CONCLUSIONS

Alfalfa can be successfully produced under either the LESA or the MDI irrigation systems. In general, LESA performed better than MDI in the full irrigation and some deficit treatments, but there was an advantage of the MDI in the more severe 60% ET- Cutoff treatment. Under these severe water deficits (60% ET- Cutoff), the yields were higher under MDI vs. LESA methods. Either sustained deficits (less water at every growth period) or sudden summer cutoff at 60% of seasonal water needs resulted in similar yields, with slight advantage to the sustained deficit strategy. However, low yields in late cuttings may be non-economic. In the 40% sustained deficit treatment, yields were significantly affected late in the season. Under limited water availability, it would be economical to cutoff irrigation entirely in the late season for alfalfa grown under MDI but yields will be reduced most in the LESA in that treatment. There was little to no change in the forage quality under either of the systems but under severe water deficits, the quality was slightly improved. Higher water productivity and IWUE were found in the 60% ET- Cutoff while the water applications were lower. This research explored the potential of LESA and MDI retrofitted to a pressurized linear-overhead irrigation system for sustaining alfalfa productivity under limited water scenarios. In this study there were no differences among the two systems but MDI may have advantages under high wind conditions and with limited water infiltration rates. Compared with sub-surface drip (SDI), MDI can be easily retrofitted on existing pivots or linear systems, but also reduces the risk of rodents damage to the drip lines which is quite high in SDI. Due to differences in wetting patterns, LESA is likely to irrigate the surface more uniformly, but our subsurface soil data suggests that MDI enables greater sub-surface moisture under water deficits. Both systems (LESA and MDI) are effective application systems for alfalfa production under full irrigation scenarios as well as conducive to water deficit strategies.

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2.7 SUPPLEMENTARY MATERIAL

Table 2.7. Dry Matter Yields average across two years (2019-2020) as affected by irrigation systems and varying irrigation levels

		April	**May**	**June**	**July**	**Aug**	**Sep**	**Oct**	**Total**
		--------------------------------Mg ha^{-1}-------------------------------							
Systems (S)	LESA	4.2	3.5	3.8	3.7	2.3	1.6	1.0	20.1
	MDI	4.3	3.4	3.6	3.6	2.1	1.4	0.7	19.2
	LSD	----	----	----	----	----	----	----	----
	p-value	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*
Amounts (A)	100% ET Full	4.1	3.6	4.1 a	3.9 a	2.7 a	2.0 a	1.4 a	21.8 a
	60% ET- Cutoff	4.0	3.6	4.2 a	4.0 a	1.8 b	0.9 c	0.2 c	18.6 bc
	60% ET- Sustained	4.4	3.5	3.7 a	3.7 a	2.5 a	1.8 a	1.1 a	20.7 ab
	40% ET- Sustained	4.3	3.1	2.9 b	3.0 b	1.9 b	1.3 b	0.7 b	17.2 c
	LSD	----	----	*0.52*	*0.59*	*0.59*	*0.40*	*0.32*	*2.53*
	p-value	*ns*	*ns*	*0.000*	*0.012*	*0.009*	*0.000*	*0.000*	*0.005*
S * A	LESA * 100% ET Full	4.1	3.8	4.3	4.1	3.0	2.1 a	1.5	22.8 a
	LESA * 60% ET- Cutoff	3.8	3.4	3.9	3.6	1.4	0.6 c	0.1	16.7 d
	LESA * 60% ET-Sustained	4.3	3.8	4.0	4.0	2.8	2.0 a	1.2	22.2 ab
	LESA * 40% ET-Sustained	4.4	3.1	3.0	3.2	2.1	1.5 ab	0.8	18.3 cd
	MDI * 100% ET Full	4.2	3.4	4.0	3.7	2.4	1.8 a	1.2	20.8 abc
	MDI * 60% ET- Cutoff	4.2	3.7	4.4	4.4	2.3	1.2 b	0.3	20.5 abc
	MDI * 60% ET-Sustained	4.4	3.3	3.3	3.5	2.2	1.6 ab	0.9	19.2 bcd
	MDI * 40% ET-Sustained	4.1	3.2	2.8	2.8	1.6	1.1 bc	0.5	16.1 d
	LSD	----	----	----	*0.84*	*0.84*	*0.57*	----	*3.58*
	p-value	*ns*	*ns*	*ns*	*0.094*	*0.046*	*0.037*	*ns*	*0.041*

Note: ns is Non-Significant

LESA= Low Elevation Spray Application

MDI=Mobile Drip Irrigation

Total is the sum over the cuttings

FI= Full Irrigation

CT-60%= Summer Cutoff

GD-60%= 60% of FI at every irrigation

GD-40%= 40% of FI at every irrigation

Means sharing the same letters in a column are not statistically different

Table 2.8. Dry Matter Yields during 2019 as affected by irrigation systems and varying irrigation levels

		April	**May**	**June**	**July**	**Aug**	**Sep**	**Oct**	**Total**
		--------------------------------Mg ha^{-1}-------------------------------							
Systems (S)	LESA	4.4	4.0	3.6	4.2	2.6	2.2	1.1	22.1
	MDI	4.7	4.3	3.7	3.8	2.2	1.9	0.7	21.4
	LSD	----	----	----	----	----	----	----	----
	p-value	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*
Amounts (A)	100% ET Full	4.5	4.2	3.9	4.2	2.6	2.4	1.4 a	23.1
	60% ET- Cutoff	4.3	4.3	4.0	4.1	2.0	1.5	0.3 c	20.4
	60% ET- Sustained	4.6	4.0	3.4	4.0	2.5	2.4	1.2 ab	22.1
	40% ET- Sustained	4.9	4.2	3.4	3.7	2.4	1.9	0.9 b	21.4
	LSD	----	----	----	----	----	*0.76*	*0.47*	----
	p-value	*ns*	*ns*	*ns*	*ns*	*ns*	*0.056*	*0.001*	*ns*
S * A	LESA * 100% ET Full	4.1	4.3	3.8	4.5	3.0	2.7	1.6	24.1
	LESA * 60% ET- Cutoff	4.1	4.0	3.9	3.8	1.6	1.0	0.1	18.6
	LESA * 60% ET- Sustained	4.1	4.0	3.4	4.4	2.9	2.7	1.4	22.8
	LESA * 40% ET- Sustained	5.2	3.8	3.5	4.1	2.8	2.4	1.2	22.9
	MDI * 100% ET Full	4.8	4.0	4.0	3.8	2.2	2.0	1.1	22.0
	MDI * 60% ET- Cutoff	4.4	4.6	4.1	4.4	2.4	1.9	0.4	22.2
	MDI * 60% ET- Sustained	5.2	4.0	3.4	3.7	2.1	2.1	0.9	21.4
	MDI * 40% ET- Sustained	4.6	4.7	3.2	3.3	2.0	1.5	0.6	19.9
	LSD	----	----	----	----	----	----	----	----
	p-value	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*

Note: ns is Non-Significant	*FI= Full Irrigation*
LESA= Low Elevation Spray Application	*CT-60%= Summer Cutoff*
MDI=Mobile Drip Irrigation	*GD-60%= 60% of FI at every irrigation*
Total is the sum over the cuttings	*GD-40%= 40% of FI at every irrigation*

Means sharing the same letters in a column are not statistically different

Table 2.9. Dry Matter Yields during 2020 as affected by irrigation systems and varying irrigation levels

		April	May	June	July	Aug	Sep	Oct	Total
		--------------------------------Mg ha^{-1}-------------------------------							
Systems (S)	LESA	3.9	3.0	4.0	3.2	2.1	0.9	0.8	18.0
	MDI	3.8	2.5	3.6	3.3	2.1	1.0	0.7	17.0
	LSD	----	----	----	----	----	----	----	----
	p-value	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*
Amounts (A)	100% ET Full	3.8	3.1 a	4.4 a	3.6 a	2.9 a	1.5 a	1.4 a	20.6 a
	60% ET- Cutoff	3.8	2.8 a	4.3 a	3.8 a	1.7 b	0.3 d	0.1 d	16.9 b
	60% ET- Sustained	4.1	3.1 a	3.9 a	3.4 a	2.5 a	1.2 b	1.0 b	19.3 ab
	40% ET- Sustained	3.7	2.1 b	2.5 b	2.3 b	1.3 b	0.7 c	0.5 c	13.0 c
	LSD	----	*0.68*	*0.82*	*0.58*	*0.55*	*0.26*	*0.31*	*2.91*
	p-value	*ns*	*0.015*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
S * A	LESA * 100% ET Full	4.0	3.3	4.7	3.6	3.1 a	1.4	1.4	21.5 a
	LESA * 60% ET- Cutoff	3.5	2.8	3.9	3.3	1.2 d	0.1	0.0	14.8 cde
	LESA * 60% ET- Sustained	4.5	3.6	4.6	3.7	2.8 ab	1.3	1.1	21.6 a
	LESA * 40% ET- Sustained	3.7	2.5	2.6	2.3	1.4 cd	0.7	0.5	13.7 de
	MDI * 100% ET Full	3.6	2.9	4.0	3.5	2.7 ab	1.6	1.3	19.6 ab
	MDI * 60% ET- Cutoff	4.1	2.9	4.7	4.3	2.1 bc	0.6	0.2	18.9 abc
	MDI * 60% ET- Sustained	3.7	2.6	3.2	3.2	2.2 b	1.2	0.9	17.1 bcd
	MDI * 40% ET- Sustained	3.7	1.6	2.4	2.3	1.2 d	0.7	0.4	12.4 e
	LSD	*0.75*	----	*1.15*	*0.82*	*0.78*	----	----	*4.11*
	p-value	*0.061*	*ns*	*0.058*	*0.094*	*0.040*	*ns*	*ns*	*0.039*

Note: ns is Non-Significant	*FI= Full Irrigation*
LESA= Low Elevation Spray Application	*CT-60%= Summer Cutoff*
MDI=Mobile Drip Irrigation	*GD-60%= 60% of FI at every irrigation*
Total is the sum over the cuttings	*GD-40%= 40% of FI at every irrigation*

Means sharing the same letters in a column are not statistically different

Table 2.10. Plant heights during 2019 as affected by irrigation systems and varying irrigation levels

		April	May	June	July	Aug	Sep	Oct	Total
		------------------------------cm------------------------------							
Systems (S)	LESA	----	67	58	68	53	46	29	54
	MDI	----	69	55	65	50	45	29	52
	LSD	----	----	----	----	----	----	----	----
	p-value	----	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*
Amounts (A)	100% ET Full	----	69	56	68	54	51 a	34 a	55
	60% ET- Cutoff	----	68	56	64	49	33 b	20 b	48
	60% ET- Sustained	----	68	53	68	51	52 a	33 a	54
	40% ET- Sustained	----	68	61	65	52	45 a	30 a	54
	LSD	----	----	----	----	----	*11.11*	*7.43*	----
	p-value	----	*ns*	*ns*	*ns*	*ns*	*0.007*	*0.003*	*ns*
S * A	LESA * 100% ET Full	----	69	57	70	56	54	36	57
	LESA * 60% ET- Cutoff	----	66	56	58	52	24	16	45
	LESA * 60% ET-Sustained	----	68	54	73	48	56	34	55
	LESA * 40% ET-Sustained	----	66	67	70	56	49	33	57
	MDI * 100% ET Full	----	69	56	66	52	48	32	54
	MDI * 60% ET- Cutoff	----	69	56	70	47	42	25	51
	MDI * 60% ET-Sustained	----	68	52	64	54	48	32	53
	MDI * 40% ET-Sustained	----	70	54	60	48	41	28	50
	LSD	----	----	----	----	----	*15.71*	----	----
	p-value	----	*ns*	*ns*	*ns*	*ns*	*0.060*	*ns*	*ns*

Note: ns is Non-Significant	*FI= Full Irrigation*
LESA= Low Elevation Spray Application	*CT-60%= Summer Cutoff*
MDI=Mobile Drip Irrigation	*GD-60%= 60% of FI at every irrigation*
Average=average over the cuttings	*GD-40%= 40% of FI at every irrigation*

Means sharing the same letters in a column are not statistically different

Table 2.11. Plant heights during 2020 as affected by irrigation systems and varying irrigation levels

		April	May	June	July	Aug	Sep	Oct	Total
		-------------------------------cm------------------------------							
Systems (S)	LESA	71	71	78	75	64	50	38	64
	MDI	71	70	75	75	63	53	42	64
	LSD	----	----	----	----	----	----	----	----
	p-value	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*
Amounts (A)	100% ET Full	71	74 a	79 a	74	70 a	56 a	51 a	68 a
	60% ET- Cutoff	71	70 b	78 a	75	58 b	43 b	22 b	59 c
	60% ET- Sustained	72	69 b	76 ab	75	67 a	54 a	47 a	66 ab
	40% ET- Sustained	71	70 b	74 b	75	60 b	53 a	43 a	64 b
	LSD	----	*3.49*	*3.52*	----	*6.49*	*6.32*	*8.47*	*2.99*
	p-value	*ns*	*0.039*	*0.042*	*ns*	*0.002*	*0.002*	*0.000*	*0.000*
S * A	LESA * 100% ET Full	73	74 a	80	77	71	58 a	51	69 a
	LESA * 60% ET- Cutoff	69	68 cd	79	76	57	36 b	13	57 d
	LESA * 60% ET-Sustained	72	69bcd	77	74	69	54 a	49	66 abc
	LESA * 40% ET-Sustained	71	75 a	76	75	60	54 a	42	65 bc
	MDI * 100% ET Full	70	73 ab	78	72	69	54 a	51	67 ab
	MDI * 60% ET- Cutoff	73	72 abc	76	75	58	50 a	31	62 c
	MDI * 60% ET-Sustained	72	69 cd	74	77	64	55 a	44	65 abc
	MDI * 40% ET-Sustained	71	65 d	72	76	59	53 a	44	63 bc
	LSD	----	*4.93*	----	----	----	*8.94*	*11.98*	*4.23*
	p-value	*ns*	*0.004*	*ns*	*ns*	*ns*	*0.032*	*0.049*	*0.035*

Note: ns is Non-Significant

LESA= Low Elevation Spray Application

MDI=Mobile Drip Irrigation

Average=average over the cuttings

FI= Full Irrigation

CT-60%= Summer Cutoff

GD-60%= 60% of FI at every irrigation

GD-40%= 40% of FI at every irrigation

Means sharing the same letters in a column are not statistically different

Table 2.12. Plant heights average across two years (2019-2020) as affected by irrigation systems and varying irrigation levels

		April	May	June	July	Aug	Sep	Oct	Total
		-------------------------------cm------------------------------							
Systems (S)	LESA	71	69	68	71	59	48	34	59
	MDI	71	69	65	70	56	49	36	58
	LSD	----	----	----	----	----	----	----	----
	p-value	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*
Amounts (A)	100% ET Full	71	71	68	71	62 a	53 a	42 a	62 a
	60% ET- Cutoff	71	69	67	70	53 b	38 b	21 b	54 b
	60% ET- Sustained	72	68	64	72	59 ab	53 a	40 a	60 a
	40% ET- Sustained	71	69	67	70	56 b	49 a	36 a	59 a
	LSD	----	----	----	----	*5.38*	*7.24*	*6.48*	*3.89*
	p-value	*ns*	*ns*	*ns*	*ns*	*0.020*	*0.001*	*0.000*	*0.004*
S * A	LESA * 100% ET Full	73	71	68	73	64	56 a	43 a	63
	LESA * 60% ET- Cutoff	69	67	67	67	54	30 b	14 c	51
	LESA * 60% ET-Sustained	72	69	66	73	58	55 a	41 a	61
	LESA * 40% ET-Sustained	71	70	72	73	58	51 a	37 a	61
	MDI * 100% ET Full	70	71	67	69	60	51 a	41 a	60
	MDI * 60% ET- Cutoff	73	71	66	72	52	46 a	28 b	57
	MDI * 60% ET-Sustained	72	68	63	70	59	51 a	38 a	59
	MDI * 40% ET-Sustained	71	67	63	68	53	47 a	36 ab	56
	LSD	----	*3.72*	----	----	----	*10.24*	*9.16*	*5.50*
	p-value	*ns*	*0.084*	*ns*	*ns*	*ns*	*0.016*	*0.042*	*0.053*

Note: ns is Non-Significant

LESA= Low Elevation Spray Application

MDI=Mobile Drip Irrigation

Average=average over the cuttings

FI= Full Irrigation

CT-60%= Summer Cutoff

GD-60%= 60% of FI at every irrigation

GD-40%= 40% of FI at every irrigation

Means sharing the same letters in a column are not statistically different

Table 2.13. Forage Quality parameters average across two years (2019-2020) as affected by irrigation systems and varying irrigation levels

		CP	**ADF**	**aNDF**	**ASH**	**FAT**	**NDFD30**	**NDFD48**	**RFV**	**RFQ**
		---------------------------------g kg^{-1}---------------------------------							----------%--------	
Systems (S)	LESA	241	302	351	100	20	433	501	178	212
	MDI	239	302	352	101	20	431	502	177	211
	LSD	----	----	----	*1.90*	----	----	----	----	----
	p-value	*ns*	*ns*	*ns*	*0.088*	*ns*	*ns*	*ns*	*ns*	*ns*
Amounts (A)	100% ET Full	247 a	304	351	101	20 a	441 a	514 a	177	212
	60% ET- Cutoff	237 b	301	351	99	20 ab	429 b	495 c	179	213
	60% ET- Sustained	240 b	303	353	100	20 ab	431 b	502 b	177	210
	40% ET- Sustained	237 b	301	351	101	19 b	427 b	496 bc	178	212
	LSD	*4.36*	----	----	----	*0.26*	*6.84*	*7.10*	----	----
	p-value	*0.000*	*ns*	*ns*	*ns*	*0.031*	*0.002*	*0.000*	*ns*	*ns*
S * A	LESA * 100% ET Full	248	306	353	100	20	442	513	176	211
	LESA * 60% ET- Cutoff	237	299	349	98	20	429	491	181	215
	LESA * 60% ET- Sustained	241	303	353	100	20	430	500	177	211
	LESA * 40% ET- Sustained	239	300	350	100	20	430	500	179	213
	MDI * 100% ET Full	246	302	349	102	20	440	514	178	212
	MDI * 60% ET- Cutoff	237	303	353	100	20	429	499	177	211
	MDI * 60% ET- Sustained	239	303	353	100	20	431	503	176	210
	MDI * 40% ET- Sustained	236	302	353	101	19	423	492	178	211
	LSD	----	----	----	----	----	----	----	----	----
	p-value	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*

Note: ns is Non-Significant	*FI= Full Irrigation*
LESA= Low Elevation Spray Application	*CT-60%= Summer Cutoff*
MDI=Mobile Drip Irrigation	*GD-60%= 60% of FI at every irrigation*
	GD-40%= 40% of FI at every irrigation

Means sharing the same letters in a column are not statistically different

Chapter 3. Estimating alfalfa forage yield and quality using multispectral and LiDAR imagery cultivated under abiotic stress

ABSTRACT

Forages are an important part of livestock operations around the world, particularly alfalfa (*Medicago sativa* L.). Alfalfa is primarily used in the feed rations for high producing dairy animals. However, remote estimation of available forage could help in improved decision making for sustainable forage production. Besides overall yield estimation, there are significant yield gaps in an individual alfalfa fields which could reduce economic returns for alfalfa growers. These yields gaps could result from the improper management of limited water resources, increased saline conditions, soil compaction, limited nutrients availability or cultivar selection. In this research, the objectives were to determine whether reflectance data utilizing two methods (LiDAR and multispectral) would be successful in prediction of yield, quality, plant height, and to detect differences due to drought conditions over space and time. We analyzed the pattern of spatio-temporal variability in alfalfa yields and quality at harvest using unmanned aerial vehicle systems (UAVs) equipped with multispectral and LiDAR cameras in a drought-affected research field. The research plots were established with different levels of drought treatments including 100% ET Full, 60% ET- Cutoff, 60% ET-Sustained and 40% ET-Sustained). In this experiment, LiDAR and multispectral cameras were used before selected harvests in 2020. Plant samples and measurements were taken after the aerial imagery acquisition for determining the biomass yields and forage quality parameters and plant heights. Models were created using step wise regression and the model was compared with random forest (RF) and support vector machine (SVM) algorithm. For multispectral imagery, it was found that the step-wise regression model predicted the dry matter yield better than the RF and SVM with an R^2 =0.82, 0.79 and 0.81, respectively. The model also performed well for predicting yield in an area of 11.15 m^2 with an R^2=0.83 (n=190). LiDAR also performed well and predicted the yield with slightly lower R^2 (0.67) for 0.09 m^2 (n=252) but performed better with R^2 (0.91) for 11.15 m^2 area (n=126). Both multispectral and LiDAR imagery was able to predict the dry matter yield for alfalfa-based on the trained models, but care needs to be taken while carrying out sampling surveys as the results may be biased due to low area sampled. Yield variability can be understood while creating the yield maps from aerial imagery and management decisions can be modified as needed. In our research, aerial images enabled a better understanding of the variability in forage yield as affected by drought treatments. Alfalfa yield patterns over the season were detected utilizing both methods, with higher early season while lower later in the season. The higher yields due to full irrigation were easily detected utilizing both methods, compared with deficit irrigation treatments. Imaging technologies were successful at identifying yield differences in alfalfa and could be utilized to better manage alfalfa fields for maximum production, but differences due to scale and timing of image capture within growth periods and over the season would need to be considered.

Keywords: Alfalfa yield and quality, UAV remote sensing, yield prediction, field diagnostics, drought, Multispectral, LiDAR

3.1 INTRODUCTION

Alfalfa is among the top forage crops grown worldwide primarily as a potential feed for dairy animals. In the United States, alfalfa holds third place in economic production (USDA-NASS 2020). As forage hay, alfalfa production adds value to the US economy of around $8.4 billion (USDA-NASS 2020). It is well suited in Mediterranean environments due to its deep-rooted characteristics, ability to extract water from deep in the profile, providing soil health benefits while improving nitrogen and carbon sequestration and can be deficit irrigated under limiting water resources (Russell et al., 2005; Fernandez et al., 2019). However, the yield estimates from one's own experience could limit the maximum attainable yields. In an alfalfa field, there is a 2-to-three-fold yield gap (Russell, 2013). Therefore, it is important to understand the yield variability using advanced technology and minimize the yield gap that may be present in an alfalfa field.

Unmanned aerial vehicle systems (UAVs) has gained much popularity in the recent years both as a research tool and for surveillance purposes. These have been used in many agricultural operations including pesticide applications, crop growth monitoring, crop water stress detection, irrigation system malfunctioning, crop phenotyping, and biomass estimations in different crops (Eugenio et al., 2020; Gebremedhin et al., 2019; Wang et al., 2018). UAVs have the capability of carrying multiple sensors to a maximum of its payload based on application (Zheng et al., 2018). With the advancement in technology, multiple cameras including RGB, multispectral and thermal cameras are available off the shelf from many manufacturers (Zheng et al., 2018). Using multispectral imagery can provide insight into crop management practices including abiotic stresses.

Light detection and ranging (LiDAR) is a technology that can be used for plant canopy height estimation and predicting biomass (Yuan et al., 2018), however, it is considered costly compared with multispectral imagery. It is also a challenge to deal with a large volume of data captured during a single flight and processing millions of point clouds to achieve the results (Yuan et al., 2018). However, utilizing such technology could provide accurate estimations of alfalfa forage yields, though limited research has been done with alfalfa utilizing LiDAR.

Recent studies have used multiple sensors in predicting alfalfa forage yield and quality. Most of these studies have either utilized the stationary LiDAR (Noland et al., 2018) or lower altitude flights (Dvorak et al., 2021) with 3D photogrammetry but did find the potential of using such technologies in alfalfa for predicting yield and quality. Very few studies had investigated the multispectral approaches and examined the available indices for alfalfa yield and quality (Chandel et al., 2021; Noland et al., 2018; Tang et al., 2021). Most of these studies had focused on breeding lines grown under the field conditions but none has investigated the deficit irrigation impact on alfalfa yields and predicting yields under such conditions using UAVs multispectral and LiDAR sensors.

In this study, we explored the potential of multispectral imagery and LiDAR to understand the yield variability in alfalfa as affected by limited irrigation through an entire growing season with multiple harvests. The specific objectives for this study were to

- Develop an image to yield relationship using multispectral and LiDAR imagery for alfalfa
- Create a yield and quality map for understanding spatial variability at different times during the growing season.
- Identify the best models to estimate alfalfa yield and quality.

3.2 MATERIAL AND METHODS

3.2.1 Experimental Details

3.2.1.1 Drought Experiment (Davis, CA)

A detailed description of the experiment is provided in Chapter 2 of this dissertation. In general, the experiment was a randomized complete block design with a split-plot restriction. The two irrigation systems (LESA and MDI) were in the main plots while the irrigation amounts (100% ET Full, 60% ET- Cutoff, 60% ET-Sustained, and 40% ET-Sustained) were in the subplots. The crop was harvested after approximately 28 days, and the irrigation was resumed as soon as the bales were removed from the field. 100% ET full was applied following the crop evapotranspiration (ET_c), 60% ET-Cutoff was irrigated fully till mid-July and the irrigation was ceased after it for the entire season 2020. 60% ET- Sustained and 40% ET-Sustained were irrigated at 60% and 40% ET demands of the crop at every irrigation during every growth cycle. These irrigation treatments created a spatial pattern of well-watered and water-stressed areas in the field that could be identified visually and utilizing reflectance data.

The soil was classified as Yolo Silt loam soil series. Soil water status was monitored using the calibrated neutron probe for the site weekly. The plant height and biomass sampling measurements from 0.09 m^2 quadrat were carried to determine the yield (Mg ha^{-1}) and quality (crude protein (CP%) and neutral detergent fiber (NDF%)) parameters at harvest. For validation purposes, a separate larger 11.15 m^2 area was harvested using a small plot forage harvester and the GPS location was recorded. Yields were adjusted for dry matter by subsampling and drying the samples to a constant weight in an oven at 60°C. To compare the irrigation treatments, block averages as predicted by multispectral and LiDAR were also calculated.

3.2.2 Image acquisition and processing using Multispectral Camera

Aerial imagery was collected one to two days before the harvest using the quadcopter equipped with Micasense RedEdge (Micasense, Inc., Seattle, WA, USA) camera during 2020. The flights were conducted between 10:00 to 14:00 hours with front and side overlaps of 85% at an altitude of 30 m. The flight parameters were set in a Micasense web browser. Auto-pilot flight was conducted after creating a flight path in the mission planning app. The flight pattern was created in DJI Ground Station Pro (GS Pro) using Zenmuse X3 camera as primary camera. The flight was autonomous with front and side overlap of 85%. Ground control points were recorded using the handheld GPS Trimble Geo7x (Trimble®, Sunnyvale, CA, USA) which were used later for georeferencing for some of the flights. The GPS was also used to record the biomass sampling locations. Once the data was acquired, the images were processed in a photogrammetry software Pix4Dmapper (Pix4D S.A., Prilly, Switzerland) to obtain an orthomosaic and obtain reflectance map along with digital surface models (DSM). The five multispectral bands (blue (B), green (G), red (R), near-infrared (NIR) and red-edge (Re)) in an electromagnetic spectrum were primarily used. As the sensor is a passive sensor, it was essential to conduct the flights during the solar noon and clear skies. All the flights were registered in the University of California Drone Web app system with appropriate approvals. Before each flight, the aircraft was checked thoroughly to make sure it was safe for the flight and the weather was checked as well. The imagery acquisition details are provided in Table 3.1 for multispectral imagery.

We used the multispectral DSMs for each date and extracted the soil pixels to determine the bare ground model or the digital terrain model (DTM). The soil pixels were interpolated in ArcGIS pro to obtain the bare ground layer. Later, both DSM and DTM were used to calculate the canopy height model (CHM) or simply the plant height separately for each date. We created a linear model using the observed plant height and CHM, so the plant height for the entire raster could be predicted. The five reflectance maps were used to create the vegetation indices using the formulas provided in Table 3.2. The predicted plant height in the table is from the model described before.

Once all the vegetation indices and predicted plant heights were calculated, the indices were masked to a specific threshold by using the NDVI layer (a universally accepted index). It was essential to remove all the bare ground pixels, so the resulting index is only the alfalfa plant or canopy. Indices and predicted plant heights were extracted using the harvested quadrats which comprised of areas of the field with differing yield levels in the field (Fig. 3.1.)

Table 3.1. Image acquisition details using Micasense Rededge and LiDAR in alfalfa during 2020

Harvest Date	**Flight Date**	**Sensor Used**
April 23, 2020	------------------	------------------
May 28, 2020	May 26, 2020	Micasense Rededge
	May 27, 2020	LiDAR
June 25, 2020	June 24, 2020	Micasense Rededge
July 23, 2020	July 22, 2020	Micasense Rededge
	July 21, 2020	LiDAR
August 20, 2020	August 19, 2020	Micasense Rededge
September 17, 2020	September 16, 2020	Micasense Rededge
	September 16, 2020	LiDAR
October 22, 2020	October 20, 2020	Micasense Rededge
	October 20, 2020	LiDAR

3.2.3 Imagery acquisition and processing using LiDAR:

LiDAR imagery was collected and pre-processed by Digital Agriculture Lab, University of California Davis. The flight was conducted a day or two before the harvest as provided in Table 3.1. The flight was conducted at an altitude of 60 m. As LiDAR is an active sensor, the time of day was not an issue. For our flights, we did all the flights between 9-11 am. The output of the pre-processing was the raster containing the height information for the entire field. The soil pixels were masked from the raster to report only the canopy pixels. We used this raster to create the linear model between the observed and LiDAR height in m. The absolute LiDAR plant height was used to create the model for predicting dry matter yields. The yield maps for the entire field were created with the predicted dry matter yields. Once the yield maps were created, observed dry matter yields from the 0.09 m^2 and 11.15 m^2 were compared with the predicted dry matter yields from LiDAR. Dry matter yields were adjusted from LiDAR using the linear model equation obtained from the relationship between predicted and observed dry matter yields from 11.15 m^2. The modified model was used to calculate the block averages and comparing the irrigation treatments. An illustration of the observed data used in the model development and validation is provided in Fig. 3.1.

Electromagnetic induction may induce electric current in the soil and measures the soil apparent electrical conductivity (Brevik et al., 2006). It could be used as a proxy for estimating soil salinity, soil texture, soil physical and chemical properties and soil moisture (Brevik et al., 2006). We also conducted the EM38 surveys to measure the spatial variability in moisture conditions. These surveys were conducted right after the harvest for multiple harvests. Initially, EM38 was calibrated with neutron probe moisture data and then the moisture maps were created using the EM38 surveys.

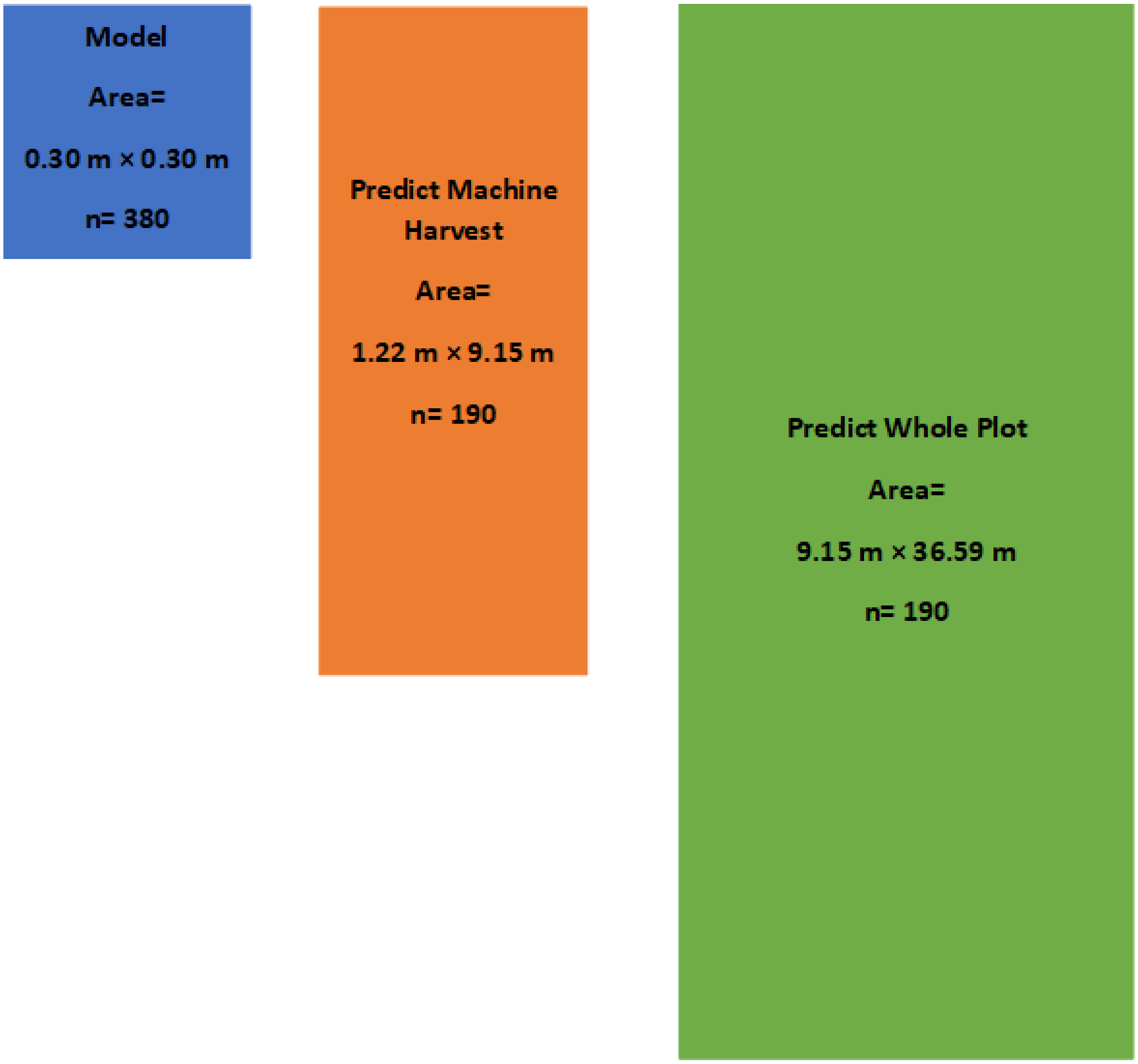

Figure 3.1. An illustration of observed data collected from 0.09 m^2 (blue square), 11.15 m^2 (orange rectangle) and estimated whole plot 334.45 m^2 (green rectangle). Harvested DM yields were measured in small (blue square) and large (orange rectangle) and yields were predicted utilizing either multispectral or LiDAR methods for the whole sub-plot (green rectangle)

3.2.4 Statistical Analysis:

All the analyses were carried out in R statistical software version 4.0.3 (R Core Team, 2020) with R Studio version 1.3.1093. Image processing was done in ArcGIS Pro (ver. 2.7.3) as well as R with the following packages: caret (Kuhn, 2021), raster (Hijmans, 2020), ggplot (Wickham, 2016), sf (Pebesma, 2018), hydroGOF (Bigiarini, 2020), rgdal (Bivand et al., 2021), Hmisc (Harrell Jr et al., 2021). For machine learning, the following packages were used in R: kernlab (Karatzoglou et al., 2004), randomForest (Liaw and Wiener, 2002). Correlation maps between the indices and observed data were created by corrplot (Wei and Simko, 2017), ggpubr (Kassambara, 2020). For multispectral data, correlation maps were created to determine the significant indices along with plant height and observed dry matter yields. The highest correlated indices, above 0.4, were kept in the reduced models which was used later to develop the step-wise regression model for dry matter yields. Multiple variables were included in the model and excluded using the step-wise model until the highest R^2 was achieved. The step-wise regression model (STEP) was also compared with random forest (RF) and the support vector machine (SVM) to determine the important variable for predicting the yield. 70% data was split into training the model dataset while 30% data was used for model testing purposes. 9-fold cross-validation was performed to test the models.

For LiDAR data, linear regression model between the LiDAR estimated plant height and observed dry matter yields was developed. The model was used to predict the dry matter yields. Before creating the model, the raster images were masked for the soil pixels and considering the plant heights only above 0.08 m to reduce the mixed canopy and soil pixels.

Model performance was evaluated using the coefficient of determination (R^2) root mean squared error (RMSE), mean absolute error (MAE) (Ewald, 2013) and normalized root mean squared error (nRMSE) using the following equations. These metrics were also calculated using the performance, caret, and hydroGOF packages referenced earlier.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Predicted - Observed)^2}{n}} \qquad \textit{Eq. 3.1}$$

$$MAE = \frac{\sum_{i=1}^{n}|Predicted - Observed|}{n} \qquad \textit{Eq. 3.2}$$

$$nRMSE = \frac{RMSE}{sd(observed)} \qquad \textit{Eq. 3.3}$$

Where predicted is from the UAV or LiDAR, observed is from the observed data, n is the number of observations.

Table 3.2. Vegetation indices evaluated and utilized in this study for developing a prediction model (adopted from Tang et al., 2021)

Indices	Abbreviation	Formula
Chlorophyll Index of Green	ClGreen	(NIR-Green)/(Green)
Chlorophyll Index of Red Edge	ClRe	NIR-RedEdge/RedEdge
Chlorophyll Vegetation Index	CVI	(NIR*Red)/(Green*Green)
Enhanced Vegetation Index	EVI2	2.5*(NIR-Red)/(NIR+(6*Red)-(7.5*Blue)+1)
Excess Green	ExG	2*Green-Red-Blue
Green Leaf Index	GLI	(2*Green-Red-Blue)/(2*Green+Red+Blue)
Green Normalized Difference Vegetation Index	GNDVI	(NIR-Green)/(NIR+Green)
Green Red Blue Vegetation Index	GRBVI	((Green^2)-(Blue*Red))/((Green^2)+(Blue*Red))
Green Ratio Vegetation Index	GRVI	NIR/Green
Leaf Chlorophyll Index	LCI	(NIR-RedEdge)/(NIR-Red)
Modified Chlorophyll Absorption in Reflectance Index	MCARI	((RedEdge-Red)-0.2*(RedEdge-Green))*(RedEdge/Red)
Normalized Difference Red Edge Index	NDRE	(NIR-RedEdge)/NIR+RedEdge)
Normalized Difference of Vegetation Index	NDVI	(NIR-Red)/(NIR+Red)
Normalized Green-Red Difference Index	NGRDI	((Green-Red))/((Green+Red))
Ratio Vegetation Index	RVI	(Red/NIR)
Simple Ratio	SR	(NIR/Red)
Triangular Vegetation Index	TVI	60*(NIR-Red)-100*(Red-Green)
Visible Atmospherically Resistant Index	VARI	(Green-Red)/(Green+Red-Blue)
Wide Dynamic Range Vegetation Index	WDRVI	(0.1*NIR-Red)/(0.1*NIR+Red)
Predicted Plant Height	PH	Relationship between Observed and UAV

3.3 RESULTS AND DISCUSSION

3.3.1 Model Calibration

To build the model calibration, the relationship between predicted plant height and observed plant heights was created.

3.3.1.1 Multispectral Data

Plant height was predicted successfully utilizing both multispectral and LiDAR methods, with a slightly better prediction with multispectral methods than the LiDAR dataset (Fig. 3.2 and 3.3 respectively). Note that the multispectral dataset utilized six harvest timings while the LiDAR method used 4 harvest timings. In the multispectral dataset (Fig. 3.2), predicted plant height was obtained from the difference of DSM and DTM (soil pixels interpolation) which was considered as predicted plant height and fitted well with the observed plant height from the 0.09 m^2 area. Plant height from multispectral was predicted using the relationship between observed and CHM but the CHM from multispectral was lower than the observed plant height. So, we decided to re-predict the plant height by creating the above relationship. The predicted plant height was then used in the model development including all the vegetation indices mentioned in Table 3.2.

For multispectral data, firstly, the full model was created using the vegetation indices and predicted plant height (Table 3.2) and the correlation of these parameters was checked with dry matter yields (DMY). The individual parameters had lower correlation with DMY but when the full model with all the indices and plant height created, it was higher. We created the correlation map to further investigate the relationship and significance based on p-value (Fig. 3.4), it was found that all the indices except CVI and ExG had a lower correlation (less than 0.4). We excluded these two parameters and created the reduced model with all the remaining indices and plant height. Step-wise regression model was then created, and the R^2, RMSE, MAE and nRMSE was

0.79, 0.694, 0.502 and 0.455 respectively (Fig. 3.5). Equation 3.4 shows the yield prediction equation based on selected vegetation indices and plant height from UAV using step wise regression model.

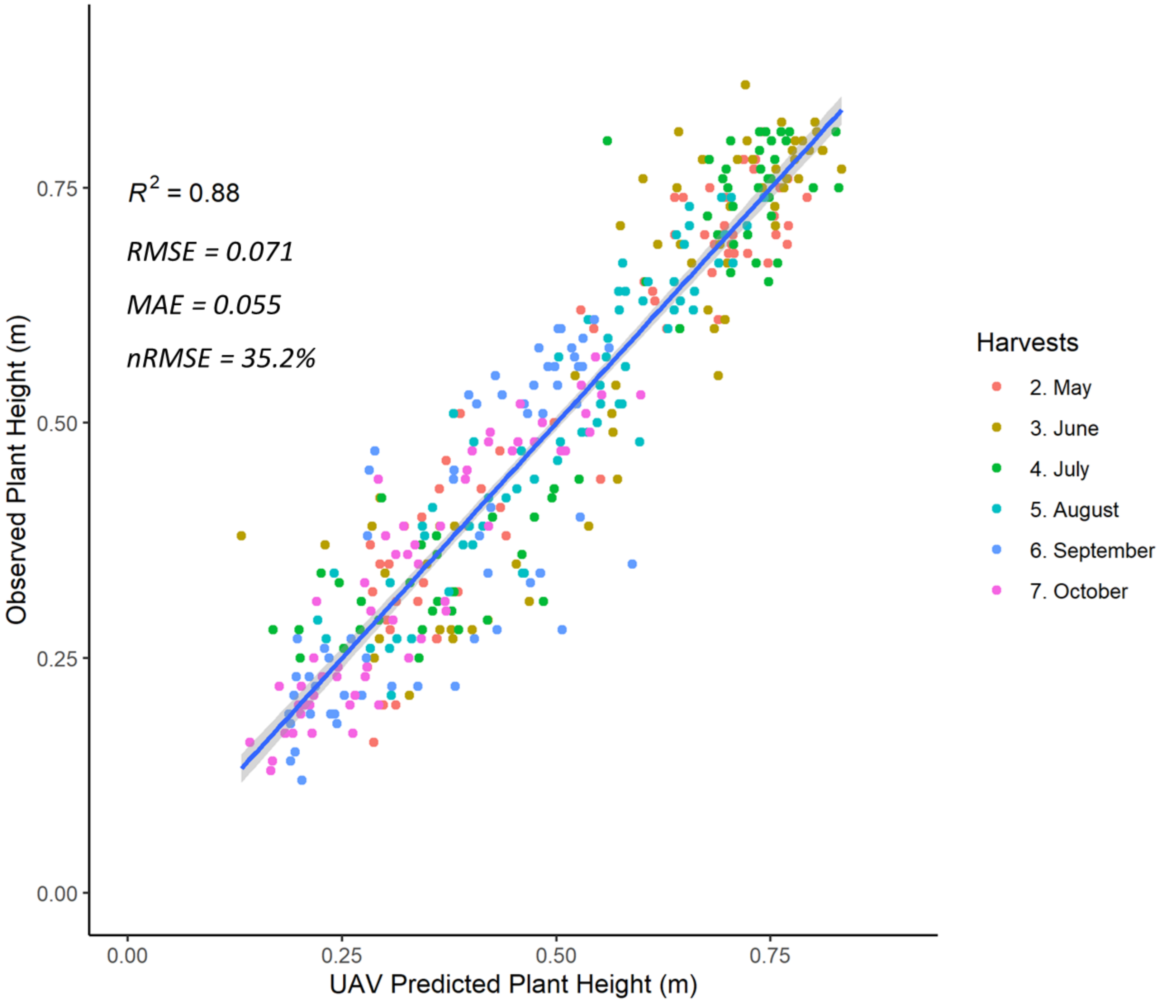

Figure 3.2. Linear regression between the estimated plant height from UAV (multispectral) and the observed plant height from 380 small (0.09 m^2) samples.

We also examined the model performance with other machine learning algorithms in R, namely, random forest and support vector machine (SVM). The k-fold cross-validation (9-fold cross validation resampling approach) was used to split the data into 70% training dataset and 30% testing dataset. The results of the comparison are provided in Table 3.3 with step wise regression model performed well for the testing data (30%) with higher R^2, lower RMSE, MAE and nRMSE.

$$\begin{aligned} Yield\left(\frac{Mg}{ha}\right) = {} & -35.772 - 0.660 \times ClG + 8.188 \times ClRe + 19.242 \times GLI \\ & - 18.275 \times GNDVI + 58.159 \times LCI - 4.921 \times MCARI \\ & - 115.297 \times NDRE + 58.406 \times NDVI - 29.124 \times NGRDI \\ & + 0.334 \times SR + 0.118 \times TVI + 5.942 \times PH \end{aligned} \qquad \text{Eq. 3.4}$$

Table 3.3. Machine Learning Models testing data set using multispectral imagery data.

Testing Data (30%)				
Models	**R^2**	**RMSE**	**MAE**	**nRMSE**
Random Forest (RF)	0.791	0.738	0.532	0.459
Support Vector Machine (SVM)	0.812	0.709	0.499	0.441
Step Wise Regression	0.822	0.692	0.486	0.430

We used the same step-wise model to re-predict the yields at individual harvests within year 2020. The model performed well for the individual harvests with R^2 ranging between 0.61 to 0.73 for different harvests (Fig. 3.6). This implied the model could be further used to create the yield map for the entire field. We used the model to create the yield map for individual harvests to understand the yield variability within each individual harvest and the effects of our drought treatments on the alfalfa yield. Fig. 3.7 illustrates the yield map predicted from the model. It was found that there was a yield variation observed within the same field. The maximum yield range was between 2.50 to 4.50 Mg ha^{-1} for May, between 2.00 to 4.5 Mg ha^{-1} for June, between 1.75 to 3.75 Mg ha^{-1} for July, between 1.00 to 3.00 Mg ha^{-1} for August, between 0.75 to 2.00 Mg ha^{-1} for

September, and between 0.25 to 1.5 Mg ha^{-1} for October. It was noted that within the fully irrigated treatments, there was quite a bit of yield variation, even though, full irrigation was applied. It could be due to the variation in soil properties or soil water holding capacities (Fig. 3.8).

We also created the model for predicting forage quality (Crude Protein, CP and Neutral Detergent Fiber, NDF in g kg^{-1}) using several vegetation indices and plant height from UAVs. The relationship between the predicted CP and observed CP had a lower R^2 (Fig. 3.9), with RMSE of 13. 481 g kg^{-1}, but the relationship between predicted NDF and observed NDF was slightly more successful (Fig. 3.10) than CP. It could be due to environmental changes for each harvest cycle which are likely to have influenced the variation in forage quality. Equation 3.5 and 3.6 was used to estimate the CP and NDF in g kg^{-1}. Forage quality maps were created based on the model to see the within harvests forage quality variation for CP and NDF. It was observed that both CP and NDF were different for different cuttings. Fig. 3.11 illustrates the CP map while Fig. 3.12 shows the NDF map.

$$\begin{aligned} CP\left(\frac{g}{kg}\right) = & -425.737 - 38.889 \times ClRe - 378.851 \times ExG \\ & + 158.397 \times GRBVI + 197.557 \times LCI + 31.267 \times MCARI \\ & + 601.748 \times NDVI + 715.871 \times RVI - 65.783 \times VARI \\ & - 78.210 \times PH \end{aligned} \qquad \textit{Eq. 3.5}$$

$$NDF\left(\frac{g}{kg}\right) = -3514.520 - 19.655 \times ClG + 752.495 \times EVI + 6100.948 \times GLI - 2913.020 \times GNDVI - 2013.533 \times GRBVI - 95.540 \times MCARI + 6462.359 \times NDVI - 7181.329 \times NGRDI + 5298.779 \times RVI + 16.220 \times SR - 11.395 \times TVI + 2444.007 \times VARI + 247.464 \times PH \quad \textit{Eq. 3.6}$$

3.3.1.2 LiDAR Data

The linear relationship (Fig. 3.3) between the LiDAR plant height and observed plant height was also highly correlated but it was slightly lower than the multispectral relationship. LiDAR underpredicted the plant height primarily because the relationship was averaged over the entire season rather than an individual cutting as the environmental and management operations were different in each cutting. The same was true for the multispectral dataset but due to many indices included in the model, it may have improved the relationship (Fig. 3.2). Absolute height was used as an input raster and soil pixels were removed from the final calculations of the plant height. The LiDAR plant height was then used to create a relationship between observed dry matter yield and plant height. It was found that the relationship was not very strong for predicting dry matter yield as the R^2 was lower for small squares (0.09 m^{-2} each sample area). Using equation 3.7, we predicted the dry matter yield (Mg ha^{-1}) for the entire field (Fig. 3.14) during the individual harvests. It was found that LiDAR successfully predicted the dry matter yield for individual harvests with yield variation within each harvest period. The maximum yield variation ranged was between 3.75 to 4.75 Mg ha^{-1} during May, between 2.75 to 4.75 Mg ha^{-1} during July, between 2.00 to 2.75 Mg ha^{-1} during September and between 1.50 to 2.50 Mg ha^{-1} during October. This season-long decline in alfalfa yield is an important aspect of yield prediction for this crop, and it was interesting that both the LiDAR and multispectral approaches predicted seasonal yield decline.

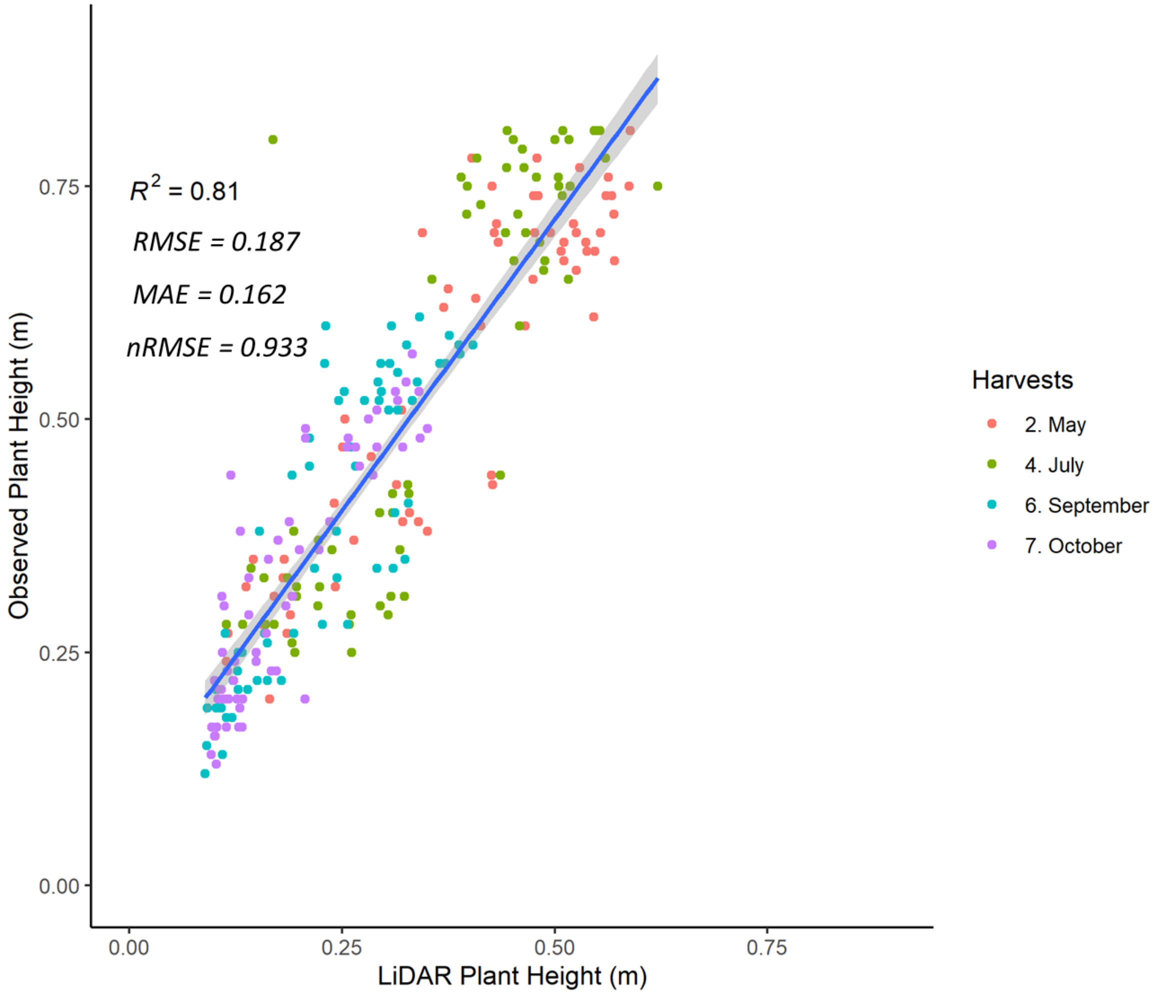

Figure 3.3. Linear regression between the estimated plant height from LiDAR and the observed plant height from 252 small (0.09 m^2) samples.

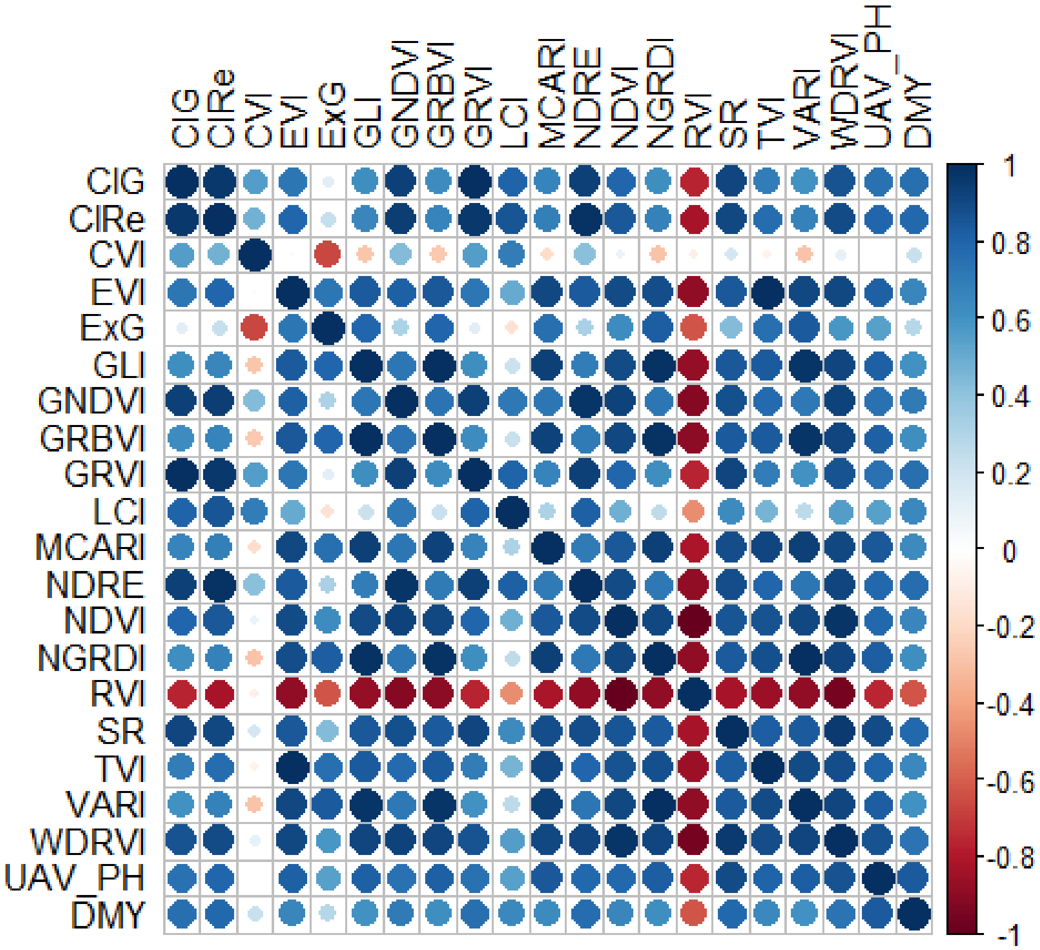

Figure 3.4. Correlation map between vegetation indices, UAV plant height and dry matter yields for Alfalfa

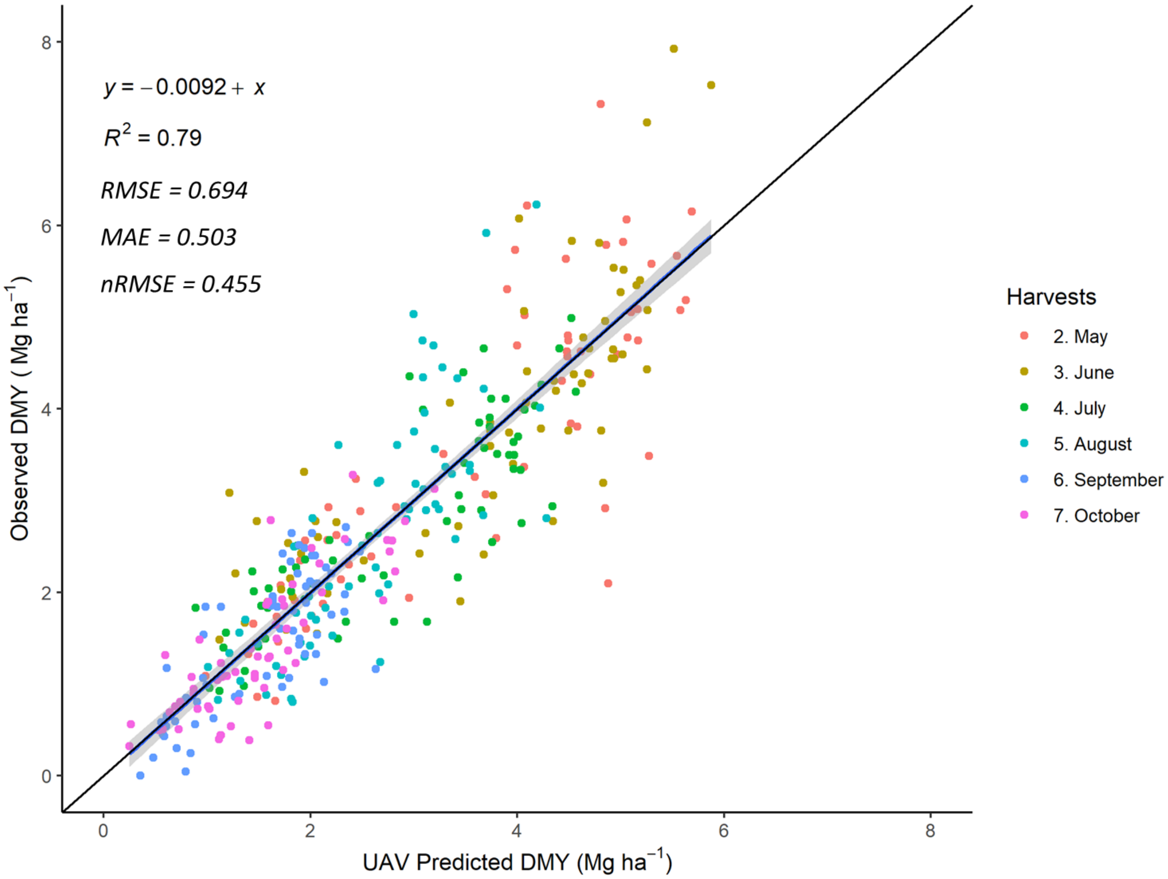

Figure 3.5. Relationship between dry matter yield (DMY) predicted by the UAV extracted vegetation indices, predicted plant heights, and observed DMY from 0.09 m^2 (n= 380).

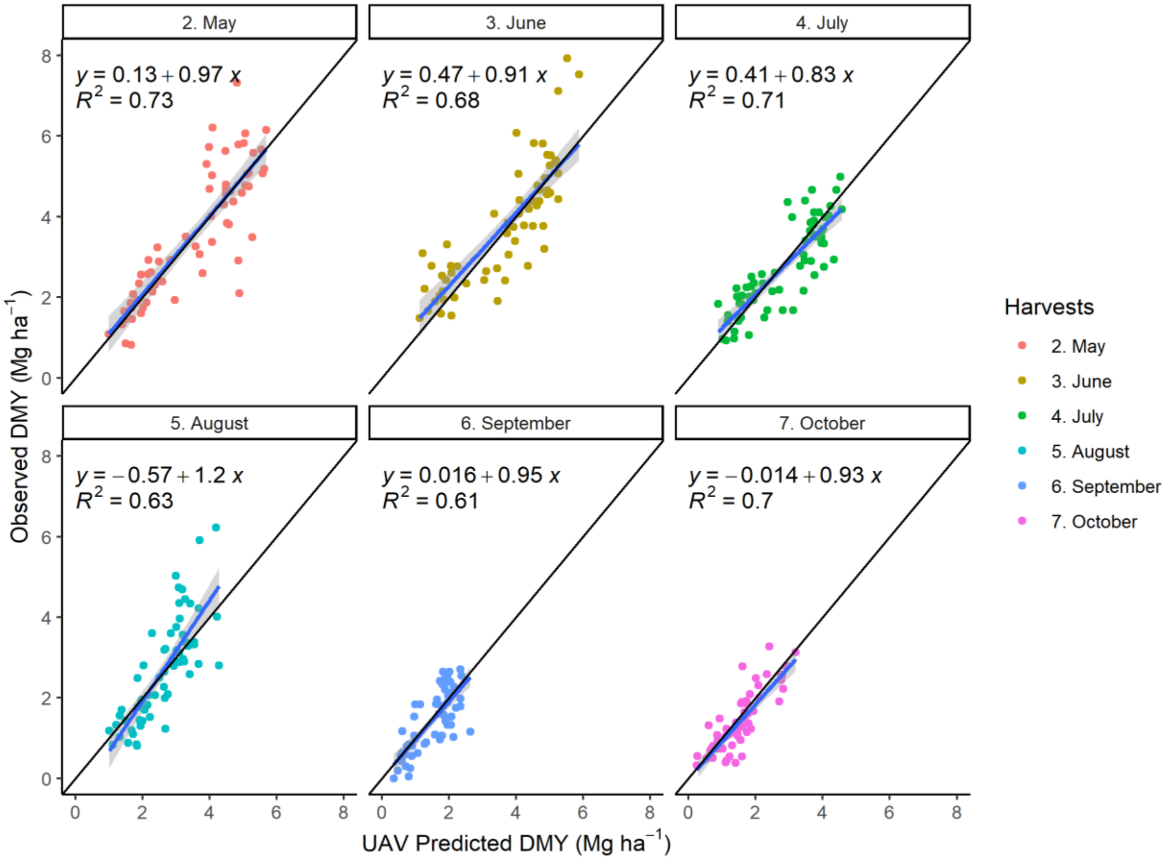

Figure 3.6. Relationship between predicted dry matter yields (Mg ha^{-1}) for individual harvests using the step wise regression model trained on mean data form the all the harvests. Sampling area 0.09 m^2 (n= 380).

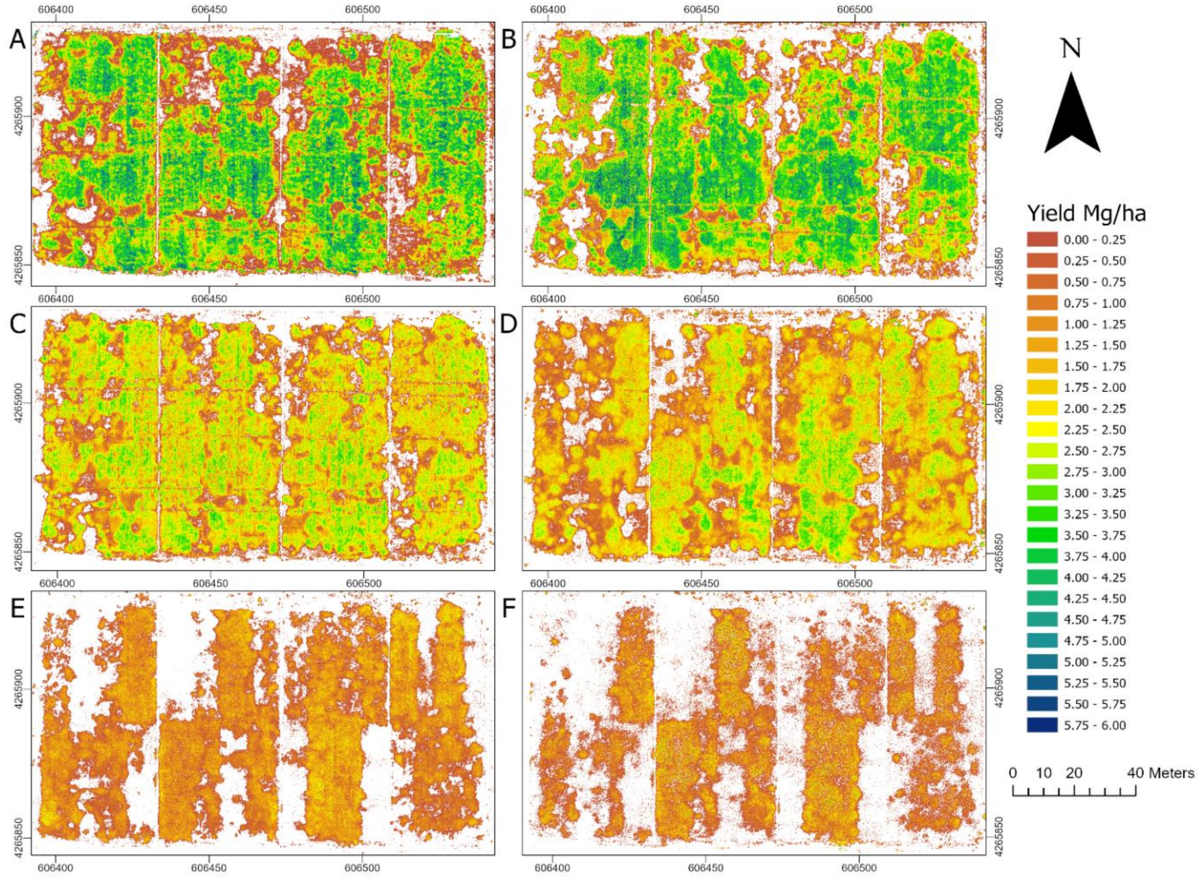

Figure 3.7. Alfalfa Yield map using the UAVs for multiple harvests (A- May, B- June, C-July, D- August, E- September and F- October) during the year 2020

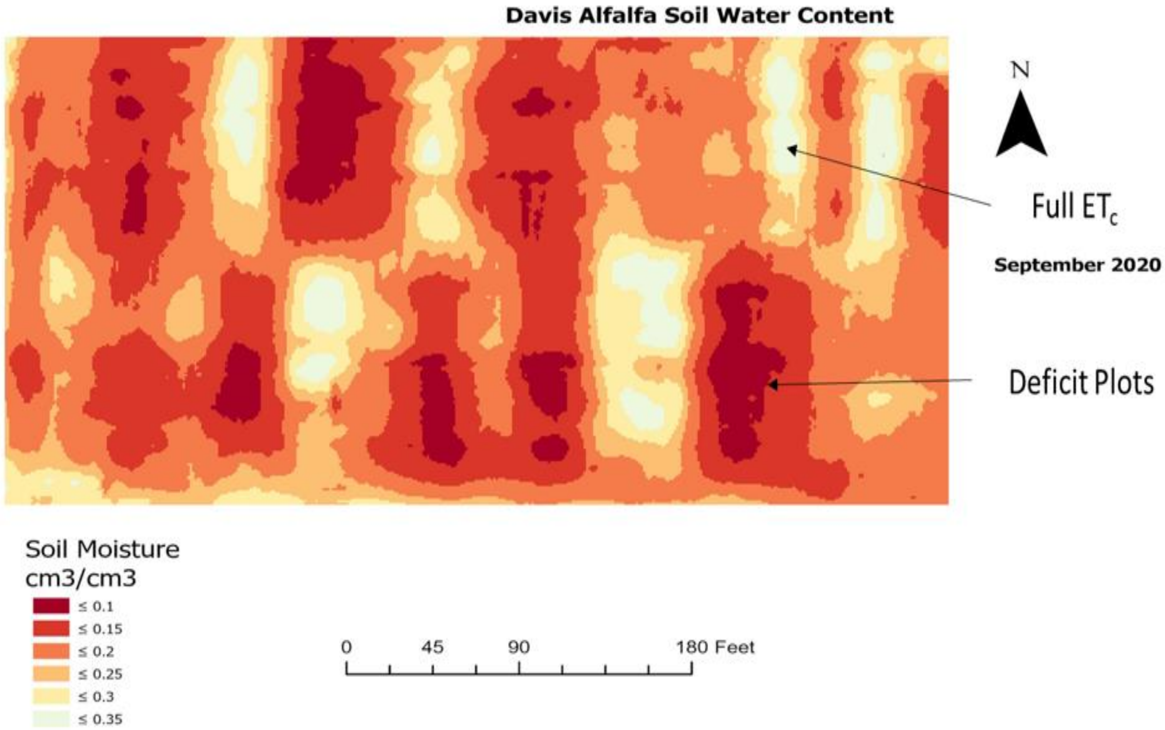

Figure 3.8. Soil Moisture map predicted from EM38, calibrated using the neutron probe moisture data set at 1.5 m soil profile for September 2020.

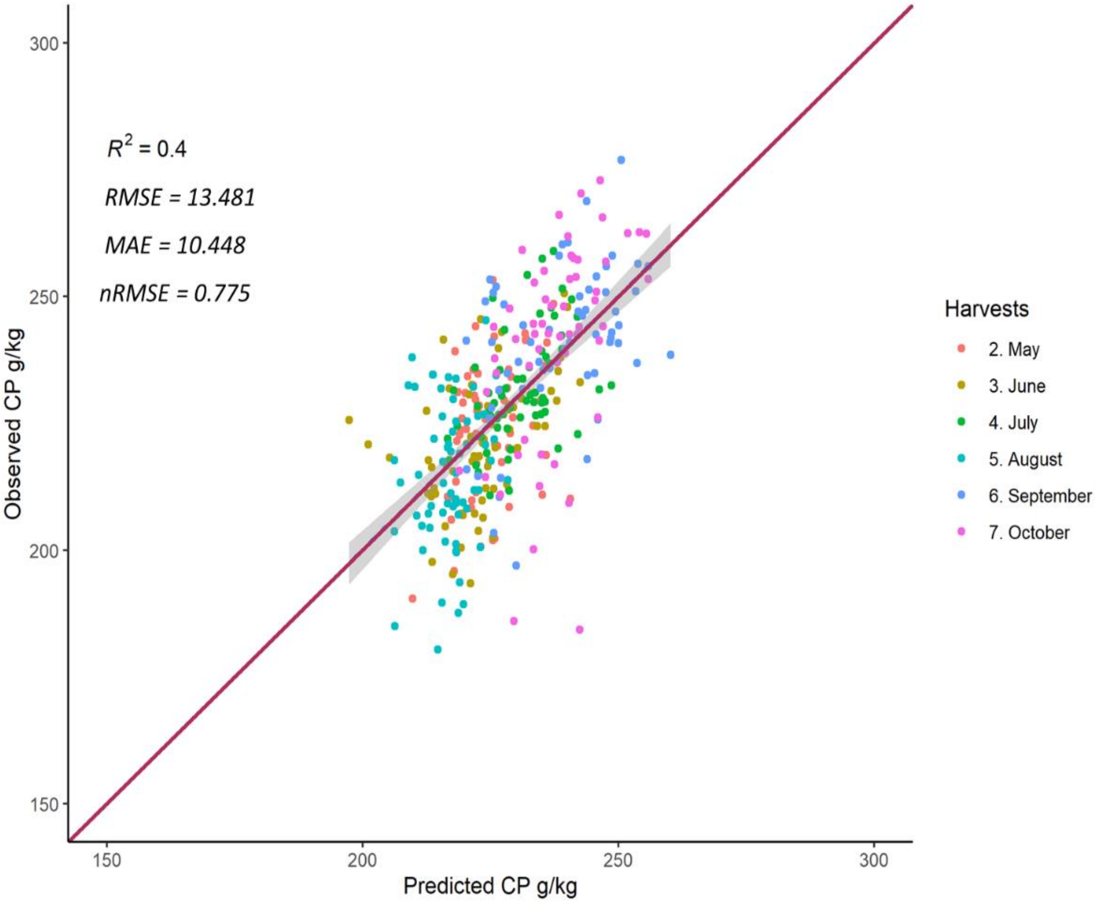

Figure 3.9. Relationship between predicted CP and observed CP for multiple harvests in 2020 (n= 370, 0.09 m^{-2}). Predicted CP was obtained from step wise regression model from multispectral imagery.

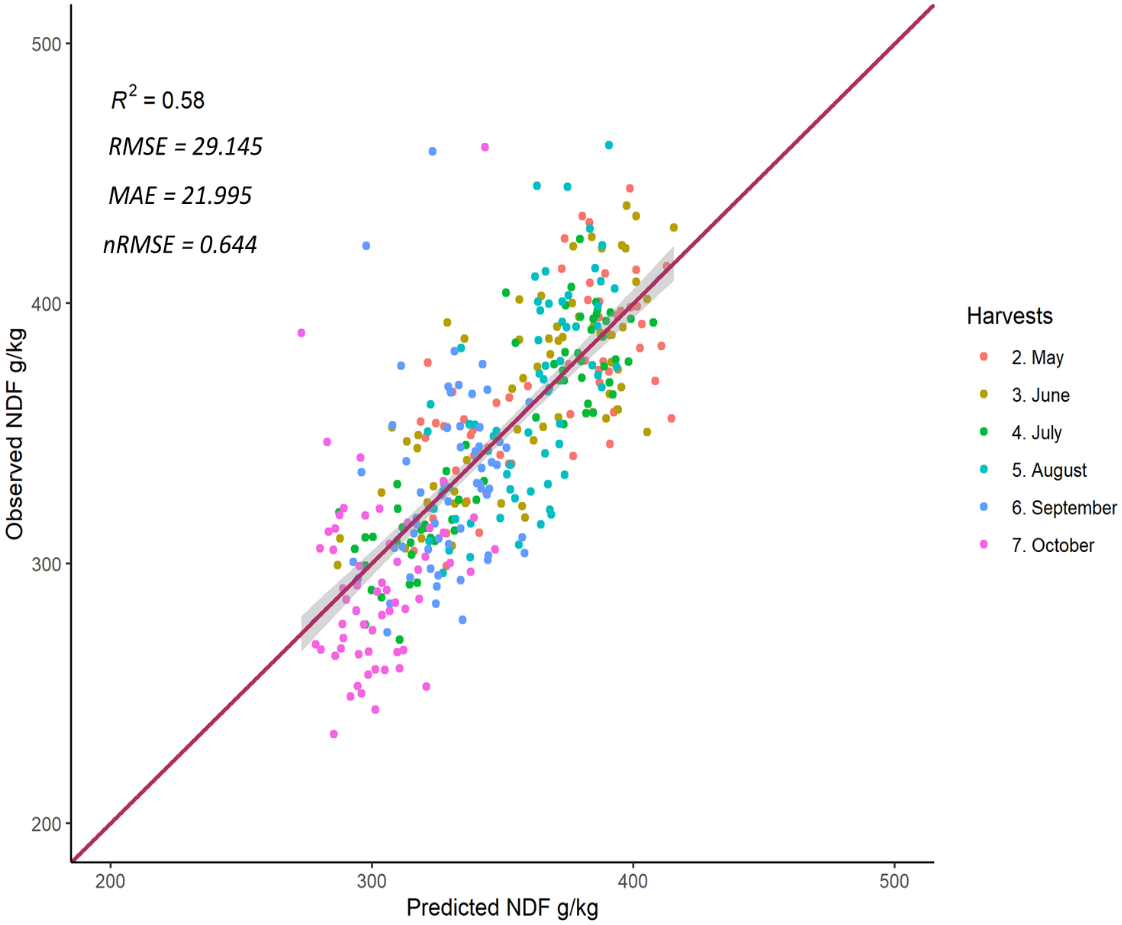

Figure 3.10. Relationship between predicted NDF and observed NDF for multiple harvests in 2020 (n= 376, 0.09 m^{-2}). Predicted NDF was obtained from step wise regression model from multispectral imagery.

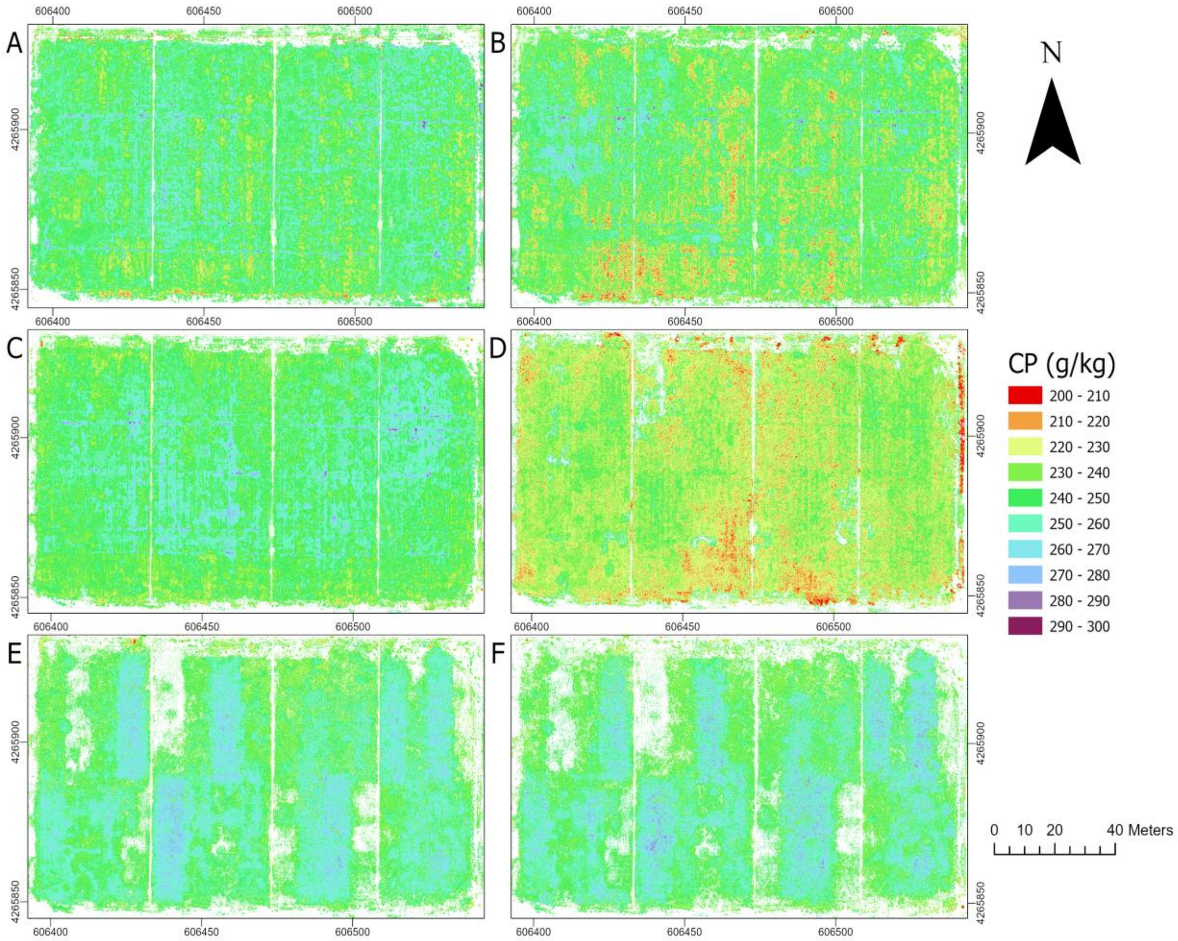

Figure 3.11. Alfalfa forage quality (CP g kg^{-1}) predicted using the UAVs for multiple harvests (A- May, B- June, C- July, D- August, E- September and F- October) during the year 2020

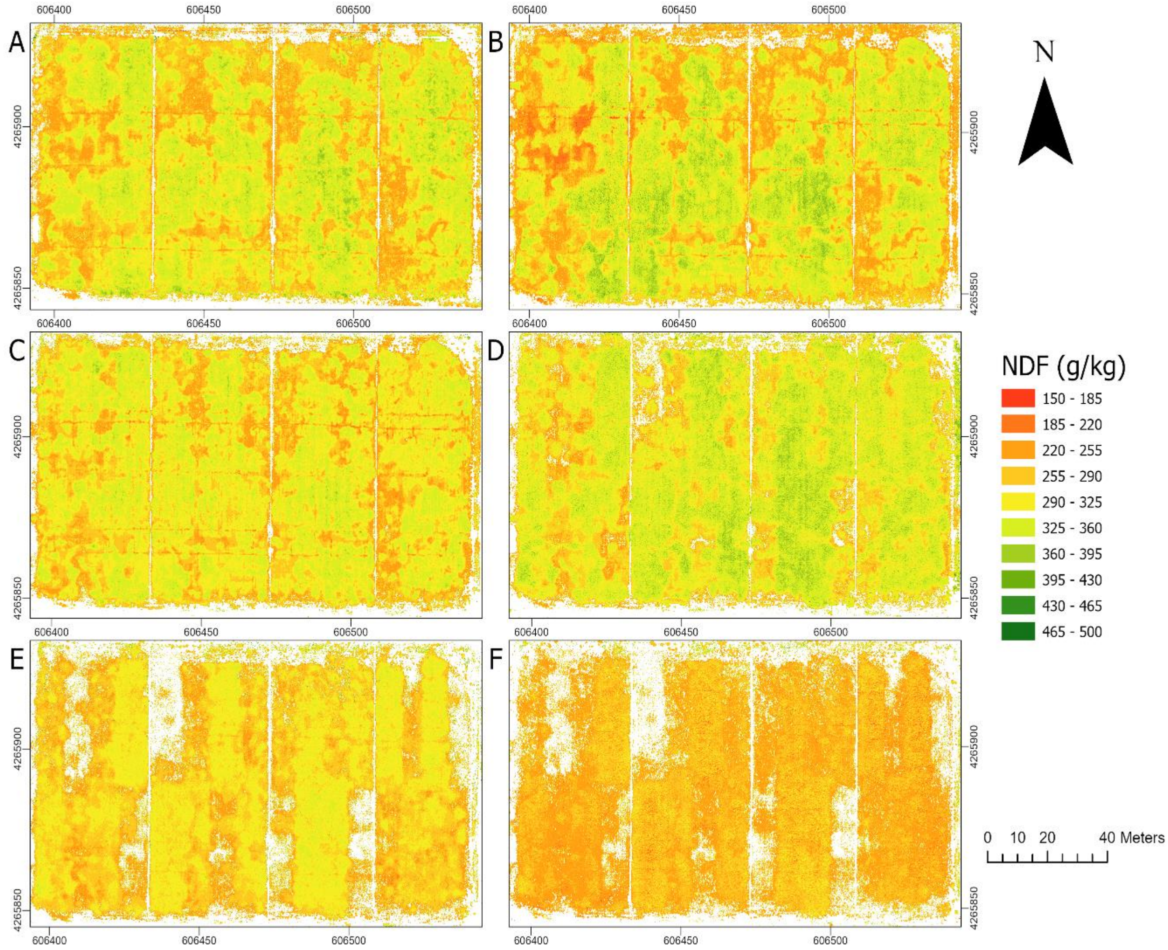

Figure 3.12. Alfalfa forage quality (NDF g kg^{-1}) predicted using the UAVs for multiple harvests (A- May, B- June, C- July, D- August, E- September and F- October) during the year 2020

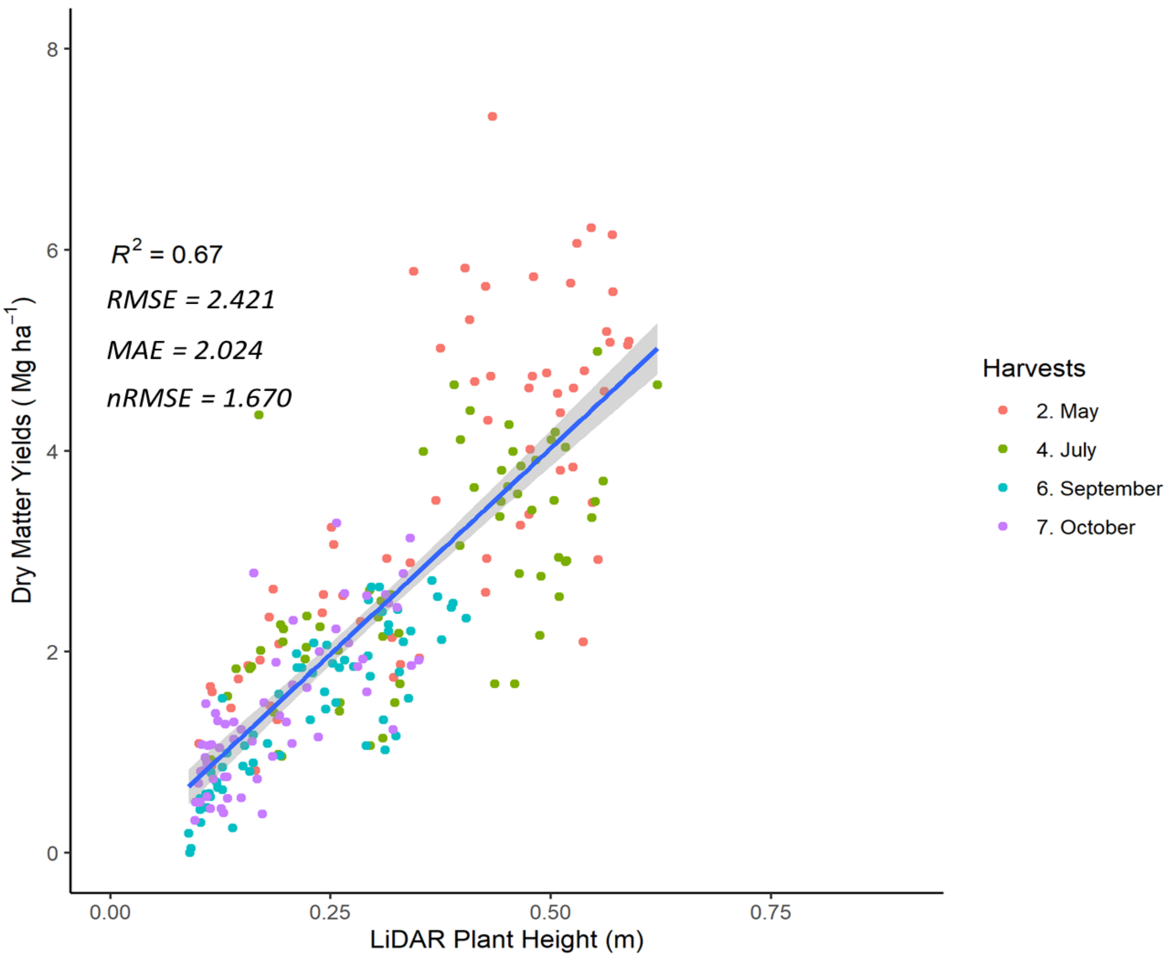

Figure 3.13. Linear regression between the LiDAR plant height and the observed dry matter yield from 252 small (0.09 m^2) samples.

$$Yield \left(\frac{Mg}{ha}\right) = -0.071 + 8.198 \times LiDAR\ PH \qquad Eq.\ 3.7$$

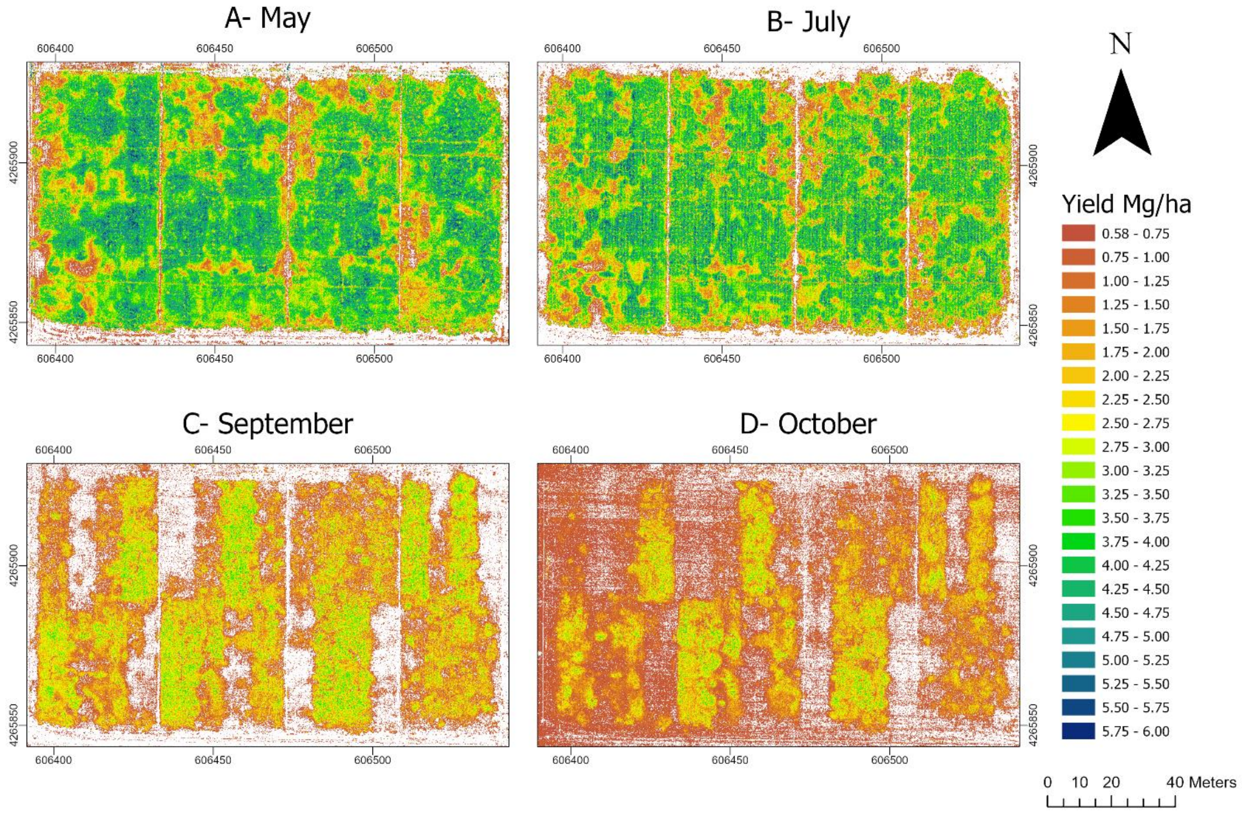

Figure 3.14. Alfalfa Yield map using the LiDAR for multiple harvests (A- May, B- July, C- September and D- October) during the year 2020.

3.3.2 Model Validation

The model for both multispectral and LiDAR was tested against the large plot area (11.15 m^2 (machine harvested) and 334.45 m^2 (complete plot in a block)) to see how well the model performed. The multispectral model was able to predict the unknown plot areas and when compared with observed data, results were promising (Fig. 3.15 and Fig. 3.16). However, UAV multispectral data underpredicted dry matter yields for high yielding areas while LiDAR predicted yields were adjusted to match the 1:1 line. For both, the models were trained on small high yielding and low yielding areas and may have over-represented low-yielding areas in the sampling procedure. This may have introduced a bias and under predicted yields in the larger measured areas. The other reason could be environmental conditions and sampling procedure, which may have impacted the yield estimation from smaller samples and resulted in a bias for the large plot areas. LiDAR predicted the yield of the larger areas (11.15 m^2, n=126) with higher R^2, lower RMSE, lower MAE and nRMSE compared with multispectral.

Both models were used to predict the plot averages in a block and treatments were compared. Fig. 3.17 and 3.18 illustrate the treatment means for individual harvests under LESA and MDI, predicted from multispectral and LiDAR imagery respectively. Based on predicted yield from multispectral and LiDAR imagery, no differences were observed in yield between LESA and MDI in alfalfa, but significant differences were found due to deficit irrigation treatments. Highest yields were achieved in 100% full irrigation throughout the season while the lowest was observed in 40% sustained deficit in the early season and the 60% summer cutoff in the late season. This was also observed from the LiDAR predicted yields as well with the exception that predicted yields were higher as compared with multispectral imagery.

The relationship between predicted dry matter yields from multispectral imagery and predicted forage quality were examined to determine whether there was a yield-quality tradeoff as often found in previous studies. Fig. 3.19 (A) illustrates the relationship between predicted dry matter yield and predicted NDF, while Fig. 3.19 (B) illustrates the relationship between predicted dry matter yield and predicted CP. In (A), DMY and NDF were inversely correlated i.e., higher the dry matter yield lowers the fiber content and vice versa. This was likely due to less leaf to stem ratio later in the growth cycle (Ball et al., 2001). It reduced the forage quality in high yielding treatments but may have slightly improved the forage quality in the lower yielding treatments. For crude protein, no relationship with yield was observed, possibly because within each harvest period, the quality changes due to environmental and management factors over the season (the higher crude protein can be readily seen in cut one).

The UAVs predicted yield and forage quality estimations provided the ease of these measurements which could be beneficial for understanding yield variability in an alfalfa field. Due to higher costs associated with LiDAR sensors (Yuan et al., 2018), this method might be impractical to use on every single alfalfa field by the growers, although it may provide better estimates when tested on multiple fields and multiple years. The size of sampling is an important factor to consider when training the model. In our study, we found the smaller sampling size may have introduced some bias. This may have been due to overrepresentation of lower yielding (or higher yielding) areas using small sample size. The number of samples used in training the model may be another consideration to improve the model training and testing results. In this study, we selected areas based on higher yield and lower yielding areas within a drought affected field, but the selection of such areas may be biased in one harvest compared with the next harvest.

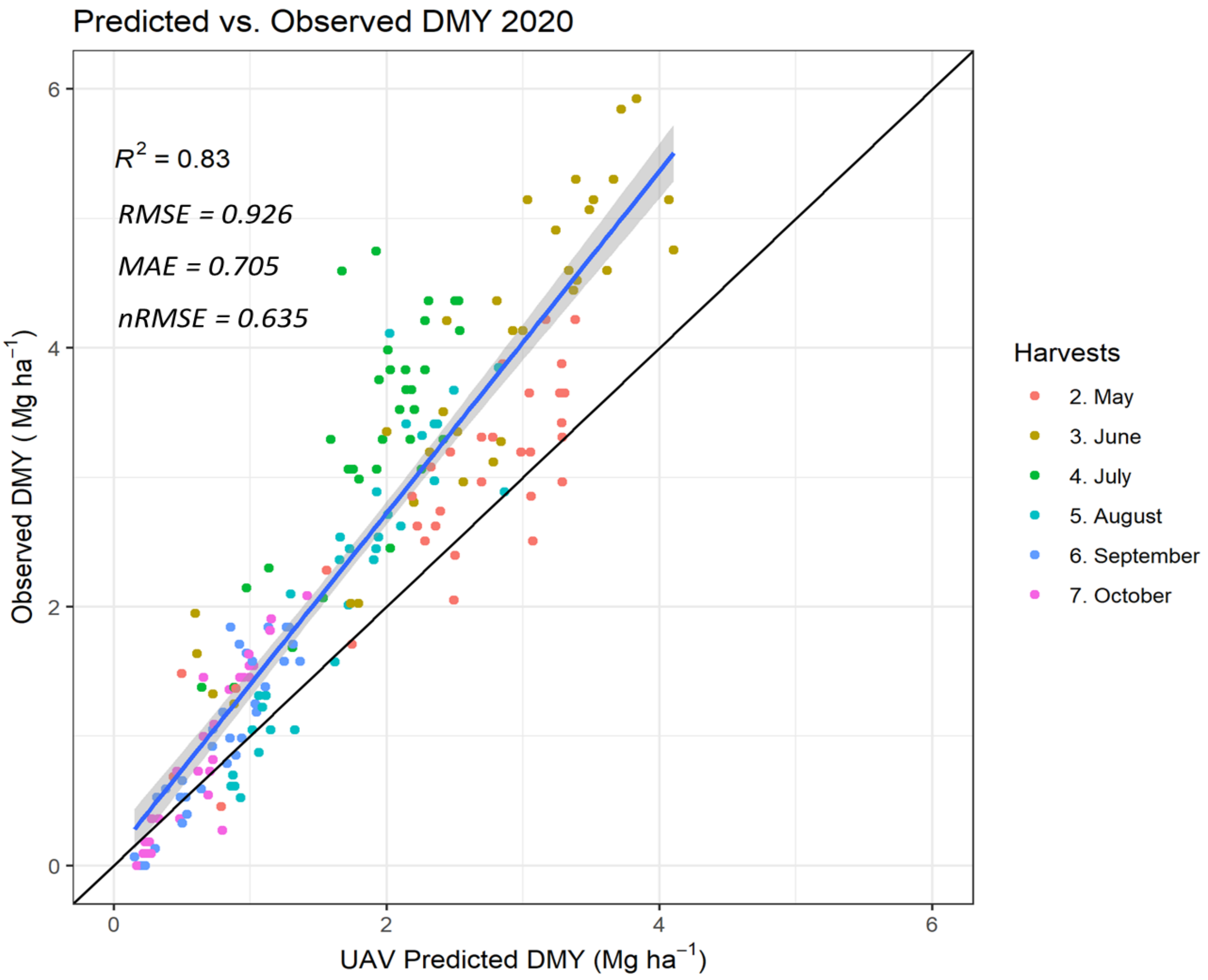

Figure 3.15. Relationship between dry matter yield (DMY) predicted by the UAV and observed DMY from 11.15 m^2 (n= 190).

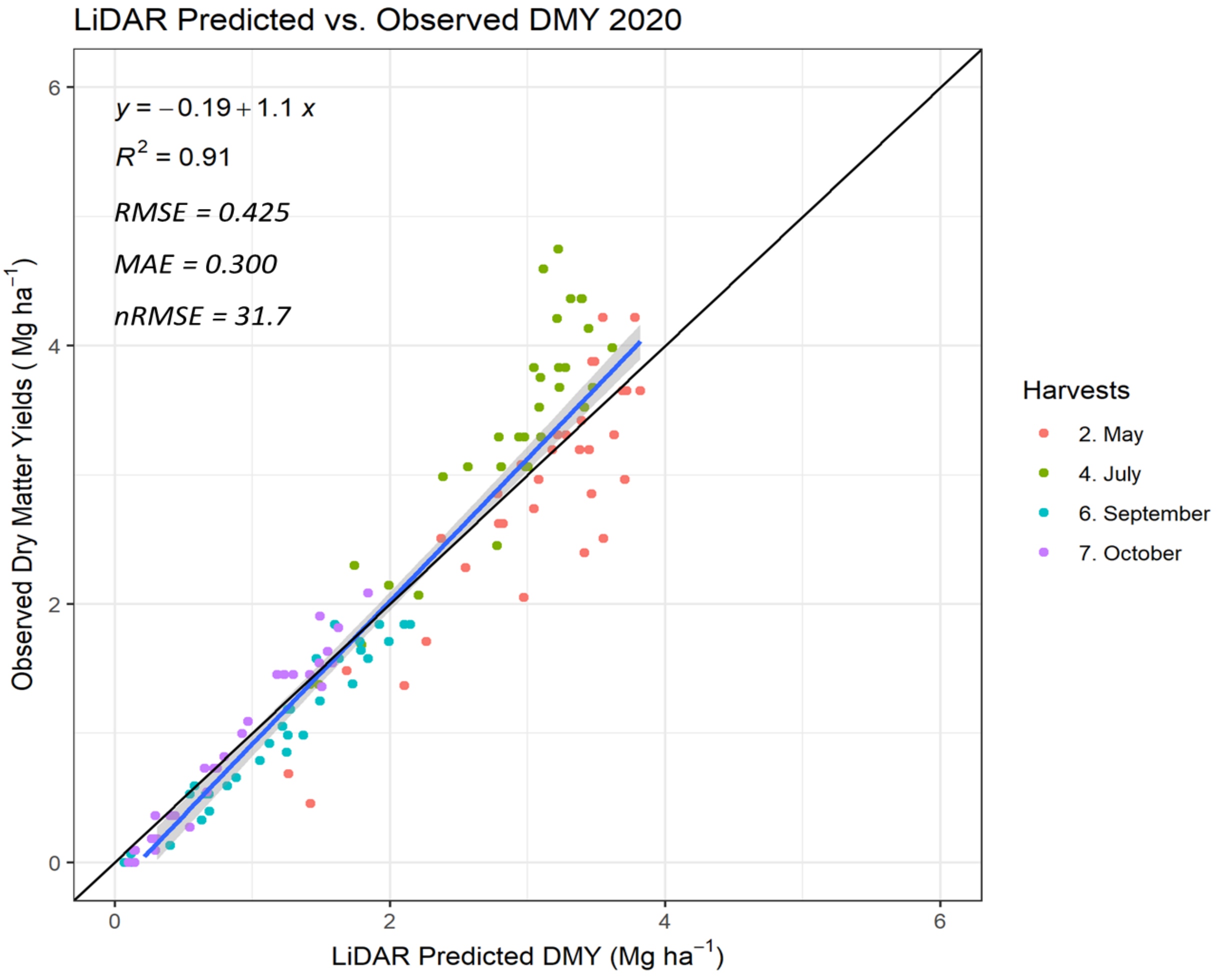

Figure 3.16. Relationship between dry matter yield (DMY) predicted by the LiDAR (adjusted) and observed DMY from 11.15 m^2 (n= 126).

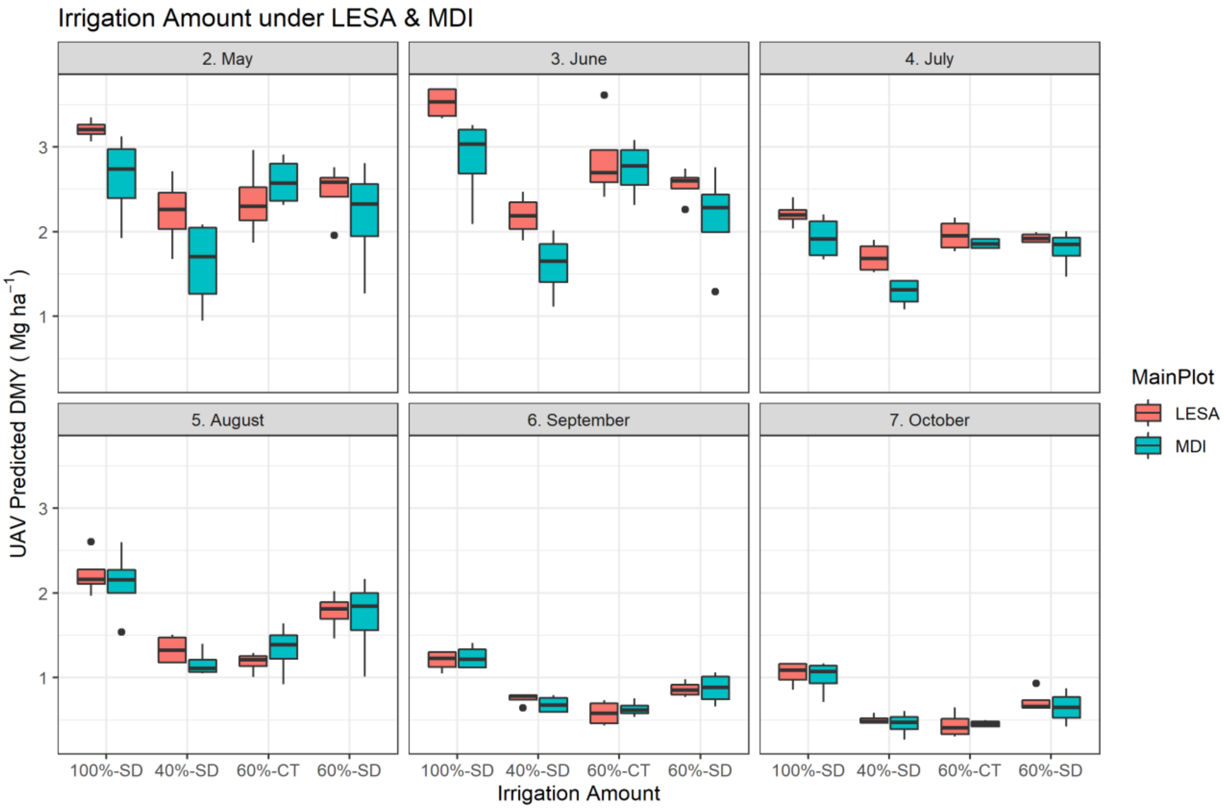

Figure 3.17. Yield prediction using multispectral imagery for LESA (red box) and MDI (blue box) under 100%-SD (Full Irrigation), 40%-SD (40% of FI at every irrigation), 60%-CT (Summer Cutoff) and 60%-SD (60% of FI at every irrigation) during May, June, July, August, September, and October harvests in 2020.

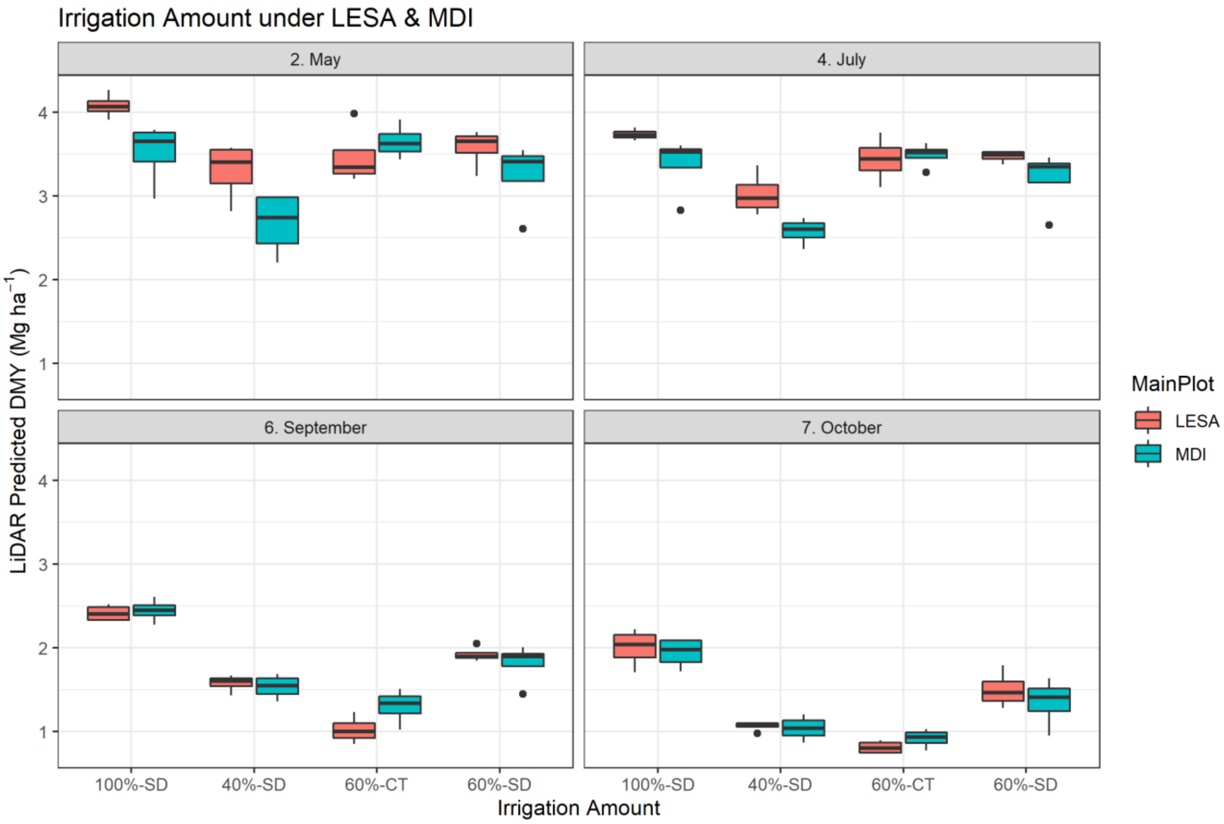

Figure 3.18. Yield prediction using LiDAR imagery for LESA (red box) and MDI (blue box) under 100%-SD (Full Irrigation), 40%-SD (40% of FI at every irrigation), 60%-CT (Summer Cutoff) and 60%-SD (60% of FI at every irrigation) during May, July, September, and October harvests in 2020.

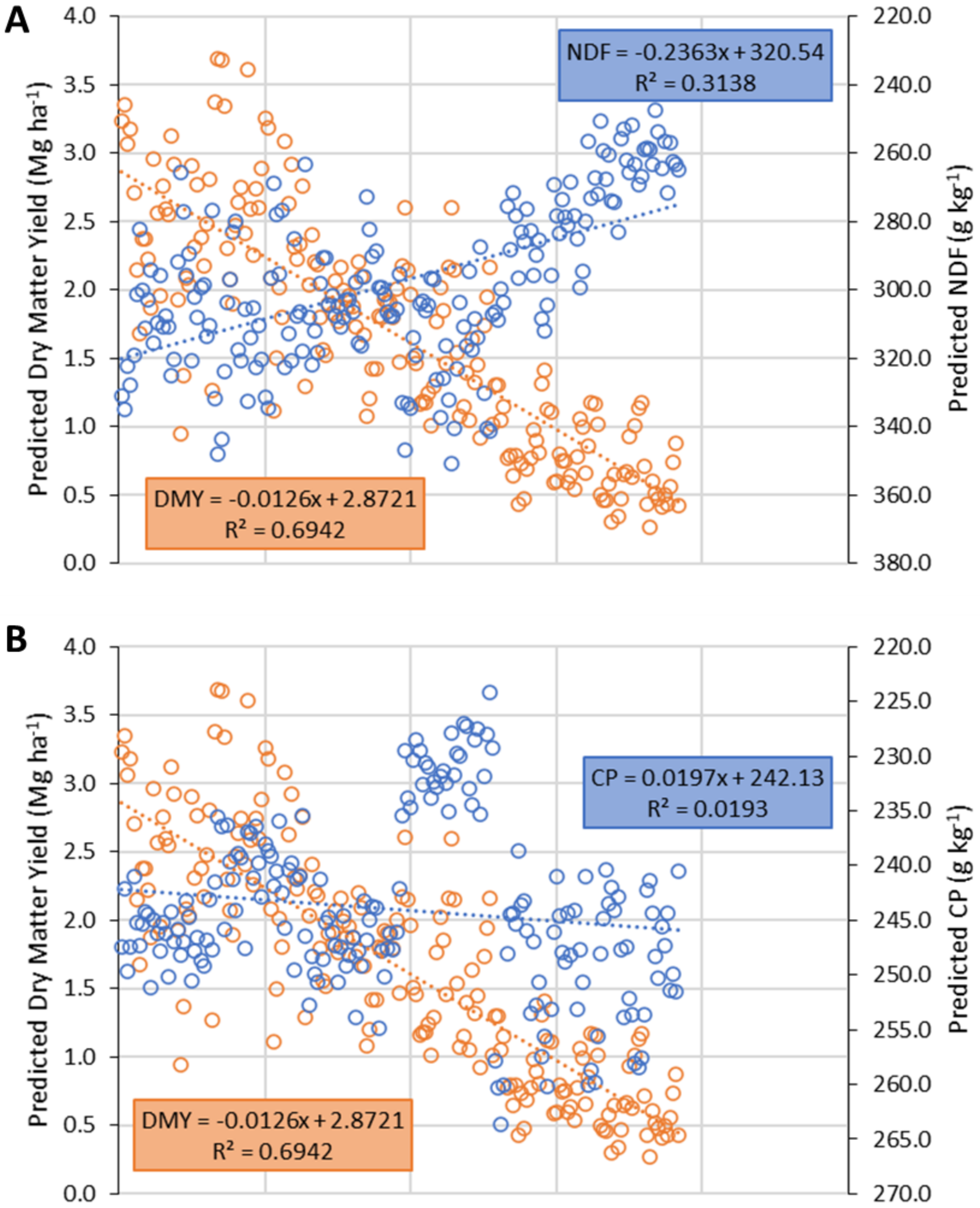

Figure 3.19. Relationship between predicted dry matter yield (Mg ha^{-1}), predicted NDF in g ka^{-1} (A) and predicted CP in g kg^{-1} (B) for an individual plot in the study area including all the harvests. n= 192 with an area of 334.45 m^{2} each from multispectral imagery

3.4 CONCLUSIONS

Alfalfa dry matter yield and forage quality (NDF and CP) were successfully predicted using either the multispectral or LiDAR imagery in a drought-affected research field. Both multispectral and LiDAR imagery could predict yield with an R^2 of 0.88 and 0.67, respectively. Prediction of quality parameters was somewhat less successful than predictions of yield. The two imagery techniques have their pros and cons, primarily because one is a passive sensor (multispectral) and the other is an active sensor (LiDAR). LiDAR tends to be (currently) more expensive and demanding of computer resources. Environmental conditions and growth stage need to be considered when using either of these technologies in predicting alfalfa forage yield. These technologies provide promising and timely results which could be essential in managing alfalfa fields for yield variability, analyzing yield reducing factors, and providing guidance for rectifying problems. Such technologies can help in diagnosing the field problems and the growers can modify their decisions based on the timely results of these image technologies. Additionally, in patchy drought-affected areas, irrigation decisions could be made to target greater or lesser irrigation amounts to specific areas of the field using site-specific overhead irrigation techniques. Our model prediction based on step-wise regression model provided comparable results for multispectral and LiDAR imagery when an unknown dataset was fitted with the predicted yields. Lower R^2 (0.83) was observed in multispectral while higher (0.91) was observed using the LiDAR imagery dataset for larger areas. Our model has limitations due to tested only in single field. It may be checked in other fields to confirm the wider applicability. Both technologies can be utilized in estimating alfalfa forage yield and quality with some care to take while selecting the sample size and number.

3.5 ACKNOWLEDGEMENTS

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3.6 LITERATURE CITED

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