Final Report: NAFA US Alfalfa Farmer Research Initiative (March 31, 2022)

Title: **Imaging Alfalfa to Predict Yield and Quality and Impacts of Water Deficits Using Innovative Overhead Irrigation Systems.**

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ABSTRACT

Prediction of alfalfa yield and quality using remote sensing can help improve decision making for enhanced profitability of alfalfa production. This may especially be the case under drought conditions. Overhead irrigation using a linear move system was used to establish a range of high-to-low- watering regimes across the field in a randomized complete block design at Davis, California on a silt clay-loam soil in 2018-2021. Our objectives were to determine the effects of Low Elevation Spray Application (LESA), and Precision Mobile Drip Irrigation (MDI) application methods on alfalfa productivity under full and deficit irrigation regimes and to develop field mapping tools that will predict the yield and quality of alfalfa. Drought treatments included targets of 100% of Evapotranspiration (ET-Full), 60% ET- (summer cutoff), 60% ET-(Sustained drought) and 40% ET- (Severe Sustained drought). As expected, yields were reduced with drought treatments, but partial season production occurred, indicating a high degree of flexibility of alfalfa grown under drought conditions, with 70-98% of full yields obtained. There were no clear consistent yield advantages for MDI or LESA systems, but the MDI system resulted in improved sub-soil moisture storage. We analyzed the pattern of spatial-temporal variability in alfalfa yields and quality at harvest using UAV systems equipped with multispectral and LiDAR sensors. Both multispectral (R^2= 0.82) and LiDAR (R^2= 0.67) imagery were able to predict the dry matter yield for alfalfa based on the trained step wise regression models for smaller harvest areas while LiDAR (R^2= 0.91) predicted better than multispectral (R^2= 0.83) for large harvest areas. Forage quality (NDF, CP, ADF) was predicted with less confidence. In these experiments, early season irrigations proved to be quite valuable in sustaining production during drought, with late-summer dry-downs recommended. Understanding within-field variation and yield limitations utilizing aerial imagery appears to be feasible and can be a useful tool in diagnosing yield limitations under field conditions and determining the effects of water deficits.

INTRODUCTION

Yield is undoubtedly the most important profit-limiting factor for alfalfa growers, with forage quality being a close second. Yields are limited by many factors, including the loss in stand, traffic damage, pests, variety, harvest schedule, soil fertility, and irrigation practices. Rapid diagnosis of yield reducing factors and their impacts on whole field yields using aerial remote sensing would be quite useful. Optimizing water supply and assuring sufficient moisture is a key aspect of maximizing yields. Approximately 50% of US alfalfa is produced under irrigation (USDA-NASS, 2022). Drought is a frequent hazard of alfalfa production in the West and nationwide. In 2021-22, over 50% of US alfalfa production was under severe to exceptional drought (Figure 1). Western states are subject to severe and debilitating periods of drought and it is challenging to cultivate alfalfa under these conditions. This has led to an interest in 'deficit irrigation strategies for alfalfa production which produce partial yields (Frate et al., 1991; Lindenmayer et al., 2011; Montazar et al., 2020; Cabot et al., 2017; Orloff et al., 2014; Ottman and Putnam, 2018; Putnam, 2021; Gull, 2021) to cope with drought conditions. This project was undertaken to understand the impacts of irrigation techniques and water deficits on alfalfa yield and quality with overhead systems and to test the ability of remotely sensed aerial images to predict yields under a range of field conditions.

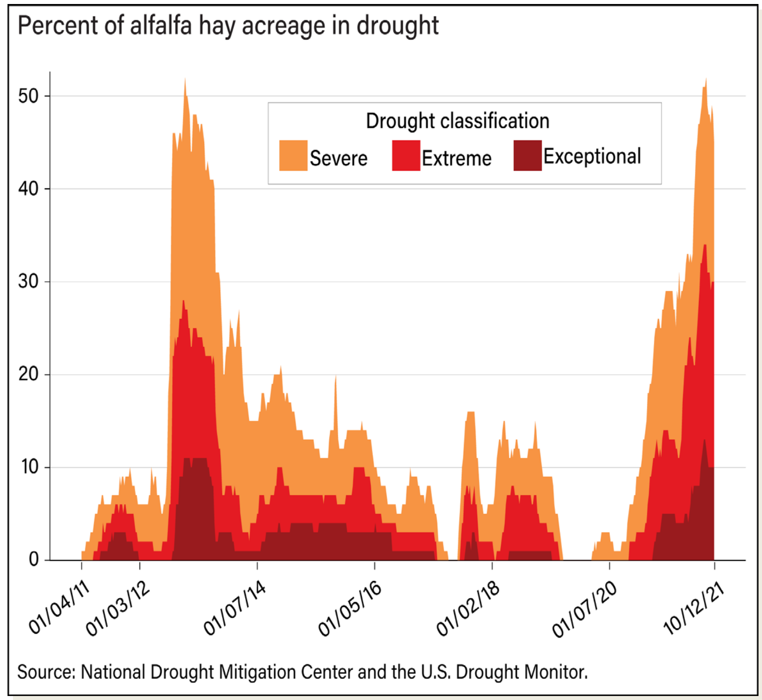

Figure 1. *Periodic drought effects on US alfalfa production over the past 10 years (USDA-ERS).*

Irrigation Techniques. Precision irrigation technologies using mechanical overhead sprinkler irrigation systems with low pressure nozzles at 30” spacing and low elevation configuration is known to increase water infiltration, reduce wind losses, reduce energy costs, and increase yields. Low Elevation Spray Application (LESA) and Mobile Drip Irrigation (MDI) (Kisekka et al., 2017) are two techniques for improving water use efficiency. These concepts require a modest investment, but growers have shown that the return-on-investment is often recovered quickly (Peters et al., 2016). In this project, we implemented several deficit irrigation strategies using these two methods, with the aim to save water under times of limited water supply.

Yield Mapping. Using aerial imagery to estimate yield and quality was a second goal of this research. The development of the relationship between captured images and water status, yield and quality using LiDAR, thermal imagery, and multispectral canopy reflectance may be useful tools for making informed decisions under limiting water resources (Noland et al. 2018). Images can also be used for diagnosing field problems (soil, pests), as well as for timing of management practices such as irrigation and harvest schedules. Plant height is a key variable (along with flowering) to predict quality as well as yield (Yuan et al., 2018). Our aim was to determine whether plant height, forage yield and quality could be non-destructively predicted using unmanned aerial vehicles (UAVs) with multi-spectral cameras and LiDAR.

Figure 2. *Linear Overhead Irrigation System was established in alfalfa at University of California Davis. Two systems (LESA and MDI were compared in separate blocks with various deficit watering regimes.*

MATERIALS AND METHODS

An 8000-series Valley four-span linear move system with variable rate irrigation (VRI) capabilities (Figure 2) was installed in 2018, and a 300' x 500' area planted to Magna715 (FD 7) alfalfa variety on October 9, 2018. The soil type was a Yolo silty clay loam (Mollic Xerofluvent). The experimental design was imposed in 2019 as a Randomized Complete Block Split Plot design with two application technologies (LESA and MDI, Figure 3 and 4) in each span in four blocks. Four irrigation levels ranging from 40% of full irrigation to 60% and 100% of full irrigation were implemented in 2019 and 2020 using both irrigation application methodologies. Deficit irrigation strategies were: 1) Sudden Cutoff or 2) Gradual Deficits. Sudden cutoff deficit irrigation was imposed by calculating the annual crop ET demand utilizing well-established crop coefficients (K_c), and following crop ET_c on a daily basis and allocating full irrigation up to the point in the season (in this case 60% of full irrigation) and then ceasing irrigation

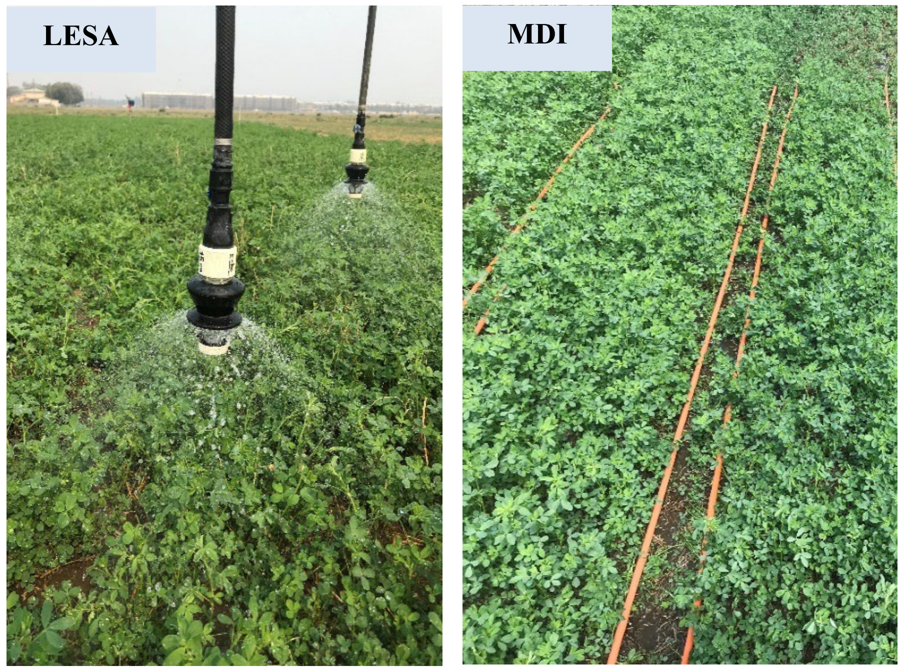

Figure 2. LESA and MDI systems in Alfalfa during operation.

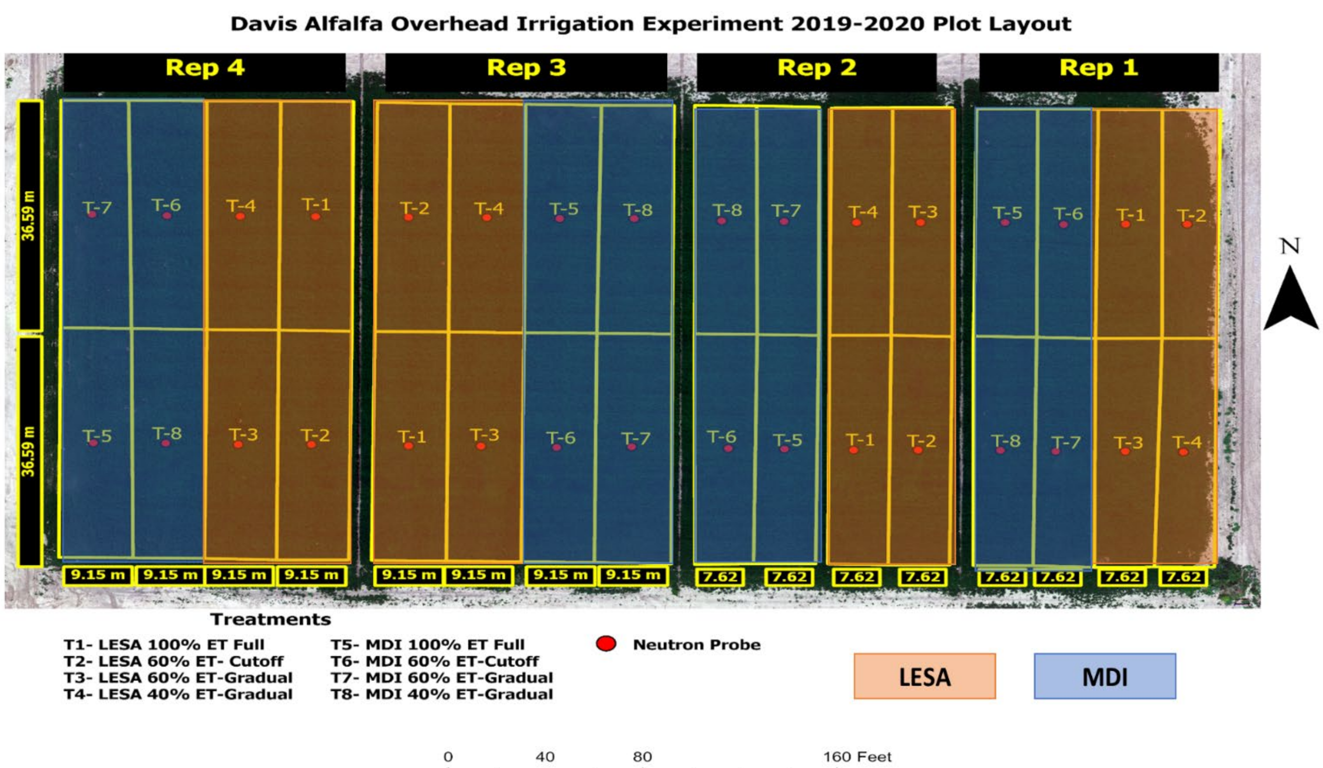

***Figure 4**. Davis Alfalfa experimental layout under LESA and MDI systems with varying amount of irrigations during year 2019 and 2020.*

altogether. Gradual deficits (SD) were imposed continuously over the growing season at the prescribed amount of water as a percentage of crop ET, calculated daily. Yields and quality measurements were taken in 2019 and 2020 using a small plot harvester in a 4' x 30' area. Additional quadrant samples were taken to develop our image-yield relationships, with 60-200 small harvests taken per cutting over a range of spatial locations to develop the image-yield-quality relationships. Forage quality was measured utilizing NIRS.

Image collection and analysis. We collected aerial images using unmanned aerial vehicles (UAVs) to record RGB, multispectral, and LiDAR images at selected harvests, and periodically during each growth period. Once the data was acquired, the images were processed using photogrammetry software specific to each technique, and not presented in detail here for brevity. The flights occurred during solar noon and clear skies. We tested various models and optimized a linear model using the observed plant height and the observed yield measurements taken. Five reflectance maps were used to create vegetation indices and yield and quality predictions utilizing appropriate formulas.

PROJECT OBJECTIVES AND CORRESPONDING RESULTS

Objectives	Results
1. Determine effects of two overhead irrigation application systems: Low Elevation Spray Application (LESA), and Precision Mobile Drip Irrigation (MDI) on Yield and Quality of Alfalfa under full and deficit irrigation regimes.	Both LESA and MDI systems performed well. LESA sprinklers did better with gradual deficits, while MDI did better under sudden cutoff deficits, likely due to better deep-soil water penetration. Yields were reduced under water deficits, but partial season yields were obtained under deficits, yielding 70-98% of fully watered yields depending upon system and year. 'Sudden cutoff' strategies are recommended with early full watering due to economic factors since late harvests are less productive. Forage quality was not greatly affected by treatments.
2. Develop mapping tools that can be used to predict the spatial distribution of alfalfa yield and quality under full and deficit irrigation strategies to maximize yield and profitability	Both LIDAR and Multi-spectral remote sensing successfully predicted plant height and yield in alfalfa with R^2 values ranging from 0.69 to 0.91. Plant height was an excellent predictor of yield. Prediction of quality (CP, NDF, ADF) was accomplished, but with more uncertainty. Spatial-temporal yield and quality variability maps were generated to assess the damage to the crop due to water deficits. These technologies are useful in predicting yield variation and diagnosing yield limitations under water stress or other yield-limiting factors.

RESULTS AND DISCUSSION

The two irrigation applying systems (LESA and MDI) did not differ significantly in average forage production over the two years of study. These results are similar to those found by other researchers. Oker et al. (2018, 2020) and Molaei et al. (2021) reported no significant differences between LESA and MDI application technologies in maize. However, in this experiment, there was a slight numerical advantage to sprinkler application method compared with MDI averaged over treatments, with the exception of the 60% cutoff treatment, which favored MDI (Figure 5). Deficit treatments had a larger

Note: To convert Mg/ha to tons/acre, multiply by 0.446

effect in 2020, the second year of the study, vs. 2019. There were significant interactions between water deficits and irrigation systems during 2020 but the interaction was non-significant in 2019. The MDI technique proved to be superior to LESA with the 60% ET cutoff treatment, but the opposite was true in the gradual deficit treatments (Figure 5). Across the range of deficit irrigation treatments, yields from deficit treatments ranged from 70% and 98% of fully-watered yields over the two years of study, while conserving moisture, indicating the economic viability of several of these deficit irrigation strategies when water is limited. Late summer dry-downs are more generally recommended due to low late-summer yields, the lower per-cut yields of stressed alfalfa, and the economic value of stopping field operations for several months of the year.

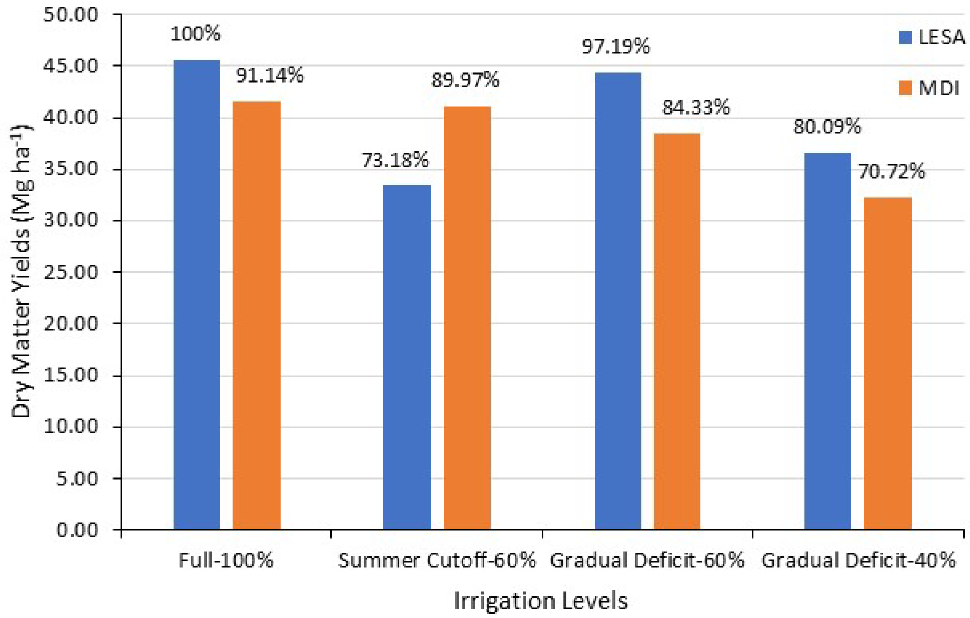

Figure 5. *Alfalfa cumulative dry matter yields summed over two years 2019 and 2020.*

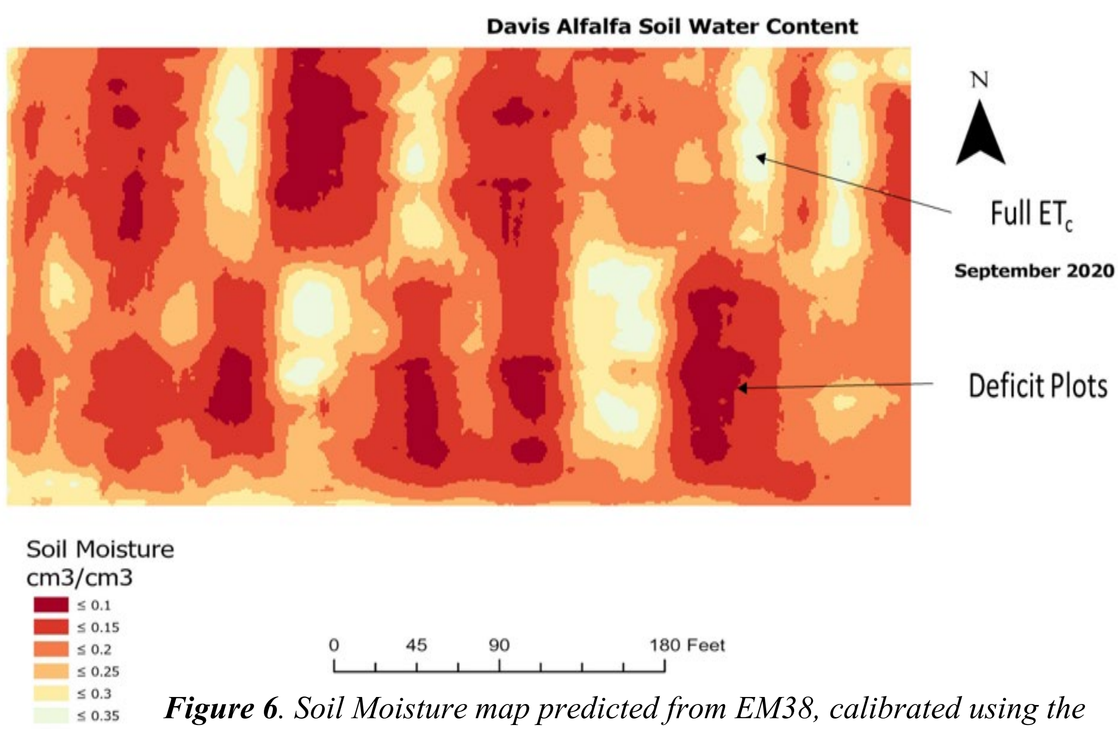

Figure 6*. Soil Moisture map predicted from EM38, calibrated using the neutron probe moisture data set at 1.5 m soil profile for September 2020 at the completion of the trial.*

Soil Water. This experimental design created a range of soil moisture conditions over the growing season that were most intense at the completion of the trial (Figure 6). These soil moisture conditions were predicted using EM38 instrument which predicts apparent soil bulk electrical conductivity (ECa) (Figure 6). Changes in EM38 measurements were a function of soil moisture, clay content of the soil, compaction, and soil salinity. Neutron probe measurements to 8-foot depths indicated a drying pattern over the season, as the crops utilized moisture deep in the profile as a function of treatments (Figure 7). These data indicated that the soil moisture content of the MDI treatments resulted in deeper moisture content vs. sprinkler systems at the 60% Sudden Cutoff treatment.

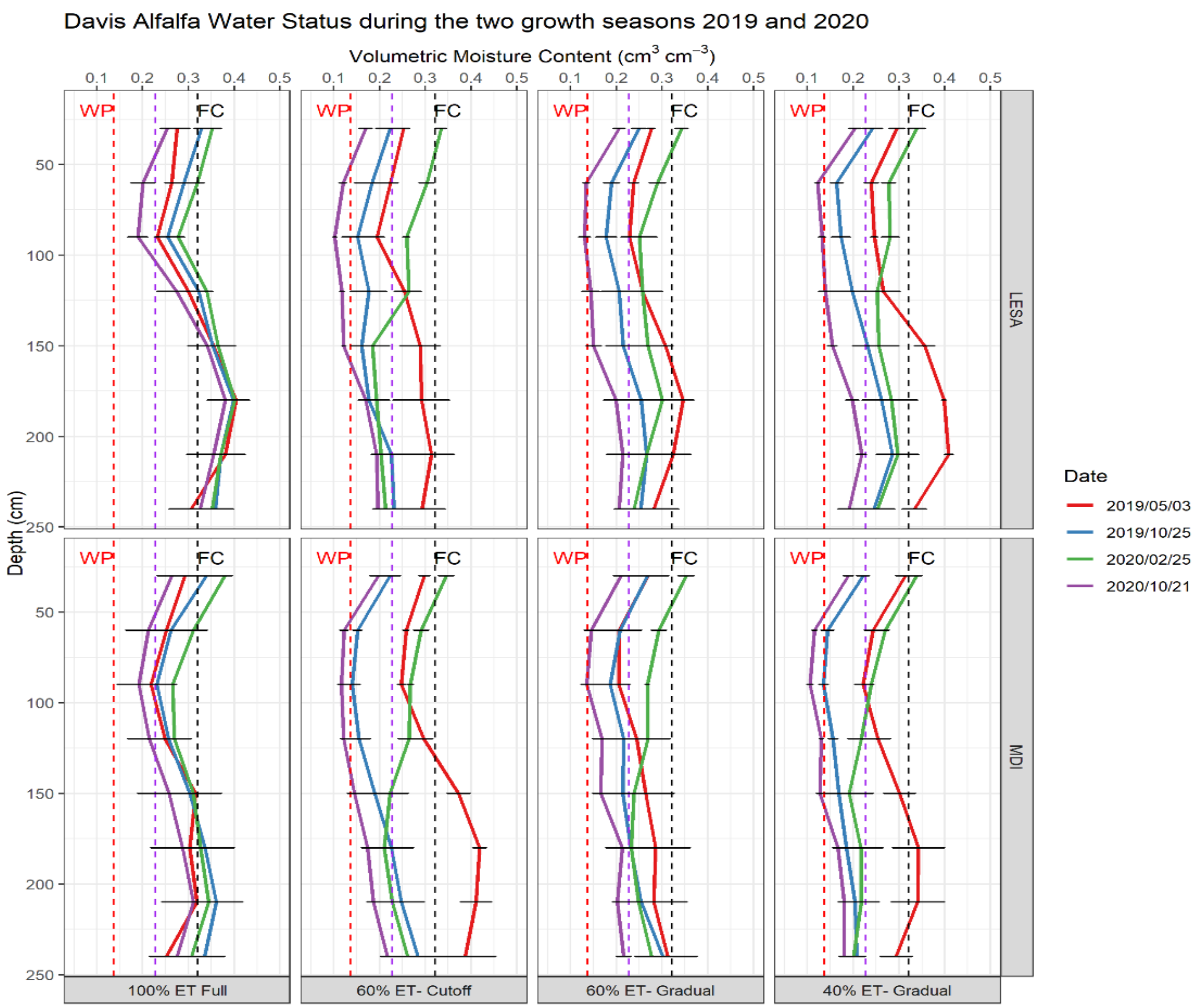

Figure 7. *Neutron Probe measurements of soil water content in the top 240 cm soil profile for LESA and MDI under varying amount of irrigations where FC is the field capacity (black dashed line), MAD is maximum allowable depletion (purple dashed line) and WP is the wilting point (red dashed line). During 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.*

Yield and Quality Mapping and Prediction using Aerial Images. Two types of images (Multi-spectral and LIDAR) were examined to determine their utility for the prediction of plant characteristics. After aerial images were collected, a range of indices were developed to understand the optimum mathematical treatment of the pixel images that result in the best fit for yield prediction. Data from multispectral cameras were highly successful at predicting plant height (R^2= 0.88) and yield (R^2= 0.79) over multiple harvests (Figures 8 and 9 respectively). Season-long yield mapping in these research plots shows the progression of crop growth from higher-yielding early cuts to lower (or zero) yields later harvests during the cropping season (Figure 10). Other sources of variation include the time of year (cutting), soil and compaction variation, and random sources of variation (stand loss, gophers, etc.). LIDAR prediction equations were also highly successful at prediction of yield, with prediction equations having R^2 values of 0.91 averaged over the multiple cuttings (Figure 11). Prediction equations were somewhat less successful at the prediction of forage quality (Figures 12, 13). Due to the higher cost of LIDAR vs. multi-spectral drone flights, only four harvests were taken in 2020.

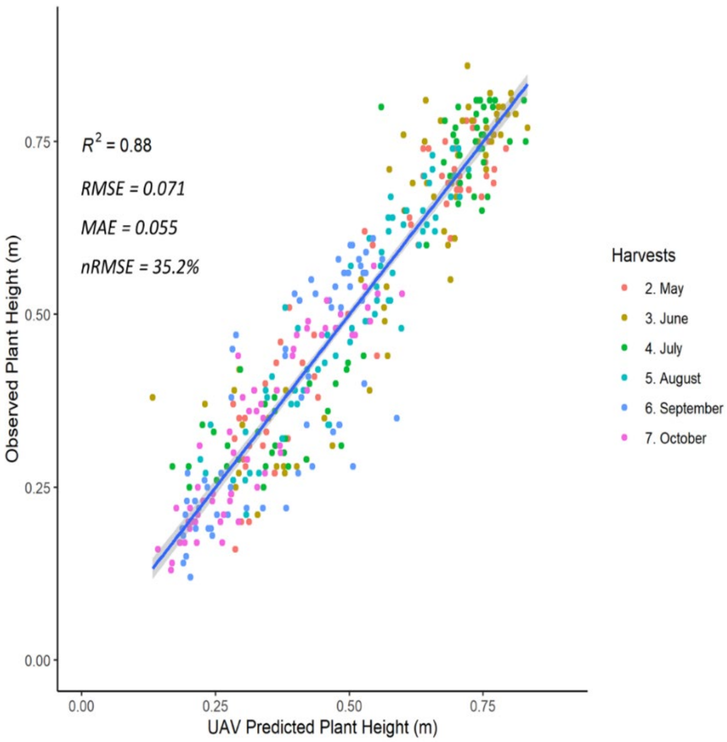

Figure 8. Linear regression between the estimated plant height from UAV (multispectral) and the observed plant height from 380 small (0.09 m^2) samples.

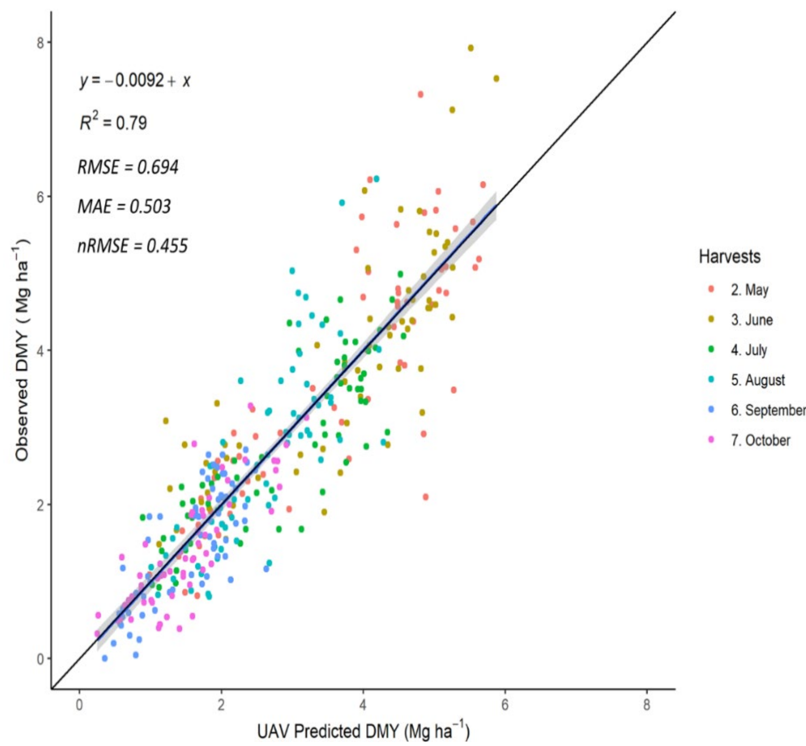

Figure 9. Relationship between predicted and observed dry matter yield (DMY) by UAV-extracted vegetation indices, predicted plant heights, and observed DMY from 380 (0.09 m^2).

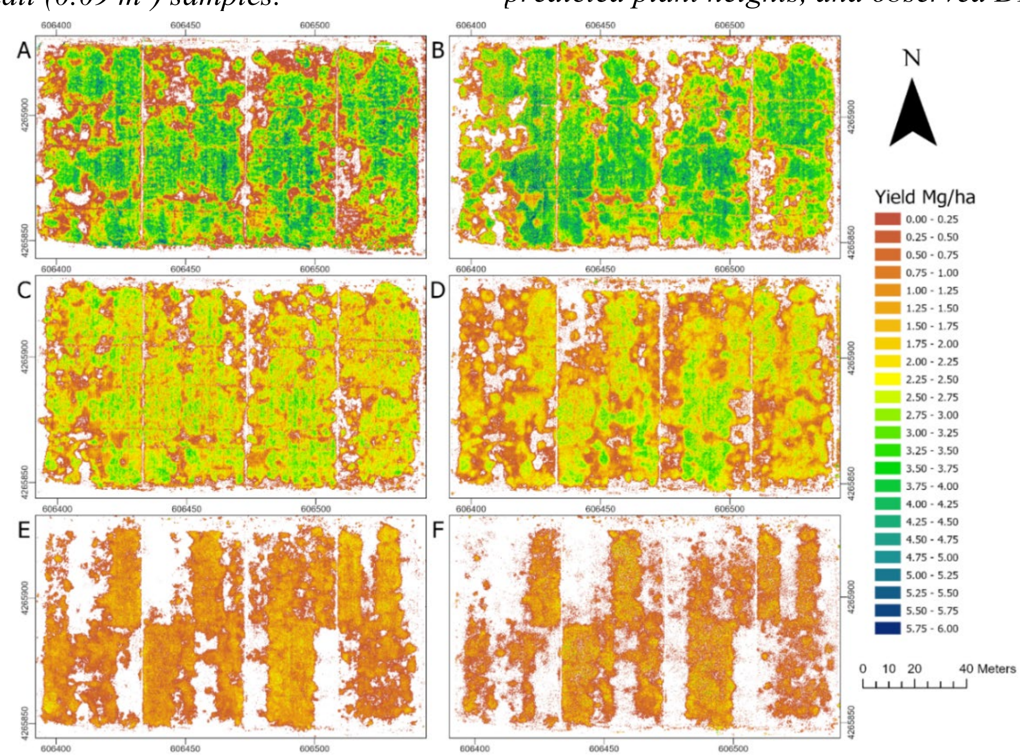

***Figure 10.** Alfalfa Yield map over the season using the UAVs for multiple harvests (A- May, B- June, C- July, D- August, E- September and F- October),*

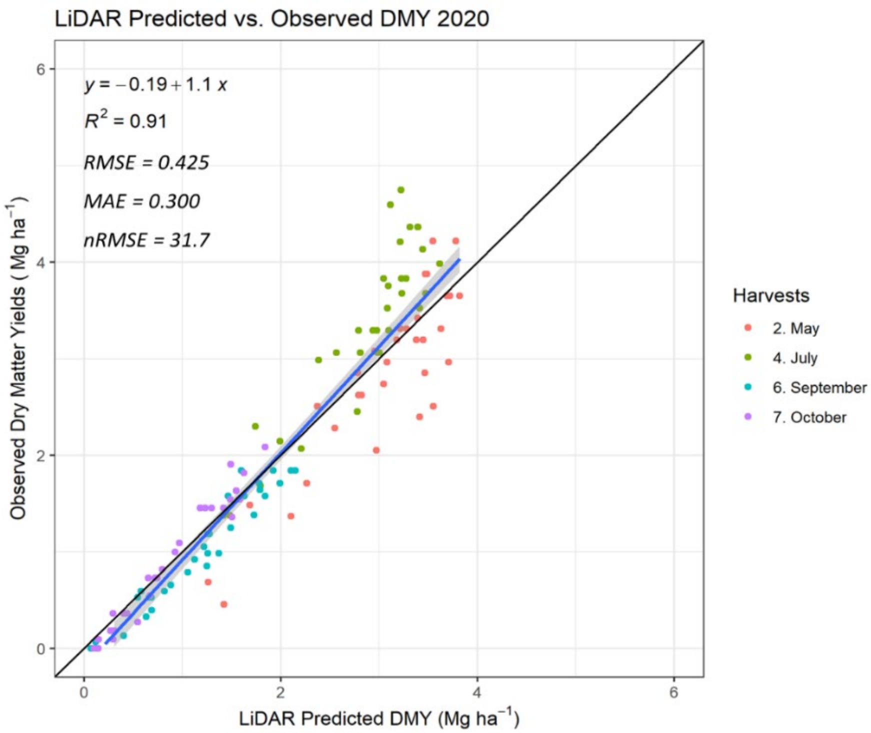

Figure 11. *Relationship between dry matter yield (DMY) predicted by the LiDAR (adjusted) and observed DMY from 11.15 m^2 (n= 126).*

CONCLUSIONS

Systems Comparison. Alfalfa can be successfully produced under either the LESA or the MDI irrigation systems, and both methods are conducive to water deficit strategies. There was a slight advantage to LESA sprinkler systems averaged across treatments, but under the most severe water deficits (60% ET- Cutoff), the yields were higher under MDI vs. LESA. Both 'sustained' deficits (gradual) and 'sudden cutoff' deficits reduced yield, but sudden cutoff methods are likely to be more economically viable since a grower could reduce late harvest costs. 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. Both MDI and LESA represent significant improvements over mid-elevation widely-spaced overhead sprinkler systems due to the ability to 1) reduce or eliminate wind losses, 2) improve distribution uniformity, and 3) ability to push water deeper into the profile. The appropriateness of each system depends upon soil type (infiltration rate), slope, wind risk, economics and other factors. Both systems are likely to produce excellent water-use efficiency under drought conditions.

Yield Prediction. Alfalfa dry matter yield and forage quality (NDF and CP) were successfully predicted using either the multispectral or LiDAR imagery in a drought-affected field. Prediction of quality parameters was less successful than predictions of yield. Our model prediction based on step-wise regression provided comparable results for multispectral and LiDAR imagery when an unknown dataset was fitted with the predicted yields. Lower R^2 (0.79) was observed in multispectral while higher R^2 (0.91) was observed using the LiDAR imagery dataset. 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, whereas multi-spectral drone-mounted cameras are widely accessible. Our model was tested only in single field with a wide-range of drought conditions, so the prediction equations developed here would need to be tested more widely to confirm wider applicability.

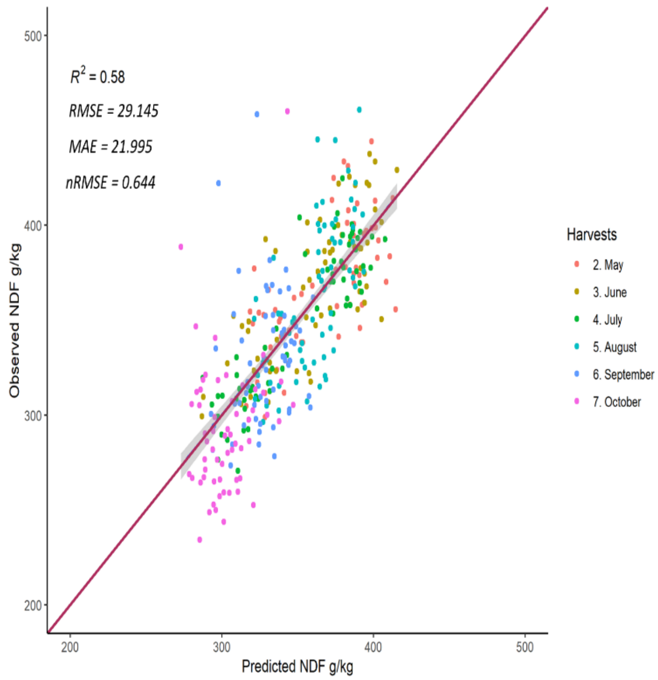

Figure 12. *Relationship between predicted NDF and observed NDF for multiple harvests in 2020 using multi-spectral cameras (n= 376, 0.09 m^{-2})*

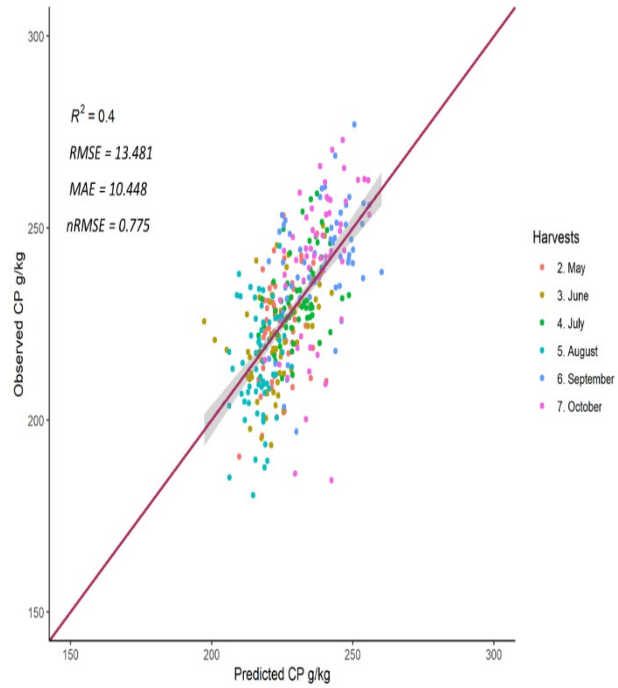

Figure 13. *Relationship between predicted CP and observed CP for multiple harvests in 2020 (n= 370, 0.09 m^{-2})*

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