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Assessing suitability of modified center pivot irrigation systems in corn production using low altitude aerial imaging techniques

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This study evaluated corn (*Zea mays* var. *indentata*) canopy vigor and temperature variations using small unmanned aerial system (UAS) based spatiotemporal imagery data. The key objective was to develop understanding on site-specific suitability of the Mid Elevation Spray Application (MESA) and Low Elevation Spray Application (LESA) sprinkler systems in irrigating corn crop and potential water as well as energy savings. Aerial data was collected through small UAS flights at 100 m height above ground level and on 49, 59, 65, 77, 105, 114, 134 days after planting (DAP). Small UAS had 5-band multispectral and radiometric thermal imager on-board the platform. Custom image processing algorithms were developed to extract various vegetation indices (Normalized difference vegetation index [NDVI], Green NDVI [GNDVI] and Normalized difference red edge [NDRE]) and canopy temperature maps from the imagery data. Two sample T-test was performed on extracted data to understand significant difference, at 5% level, within the LESA and MESA treatments. For both the irrigation techniques, the crop vigor increased in the early growth stage (49, 65 DAP), peaked in the mid growth stage (77, 105, 114 DAP) and then decreased in the late growth stage (134 DAP). The MESA irrigated sections had higher vigor (NDVI, GNDVI, NDRE), but not significant, compared to LESA throughout the season. Similarly, the MESA irrigated areas had significantly (0.61–2.07 °C) cooler canopies than LESA. Such results were anticipated, in part due to the issues with the sprinkler heads used in LESA. The heads were being pulled off in the corn field, causing the weighted hose to damage the crop. A different kind of sprinkler head was used after this incident. However, some strips of corn had already been damaged. Overall, this study results confirm suitability of aerial imagery data in evaluating pertinent irrigation treatments. Additional season's data would be needed to clearly understand which technique (LESA or MESA) is more suitable for irrigating corn crop in the central part of state of Washington.

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1. Introduction

Irrigation management and associated precision technologies can improve crop production as well as irrigation efficiency. Several factors need to be considered while choosing an irrigation system to help farmers make an informed decision about investing in the same [1]. Center pivot sprinkler irrigation systems are widely recognized for their efficiency and uniformity in application of water [2]. According to Peters et al. [3], advances in center pivot systems from high-pressure impact sprinklers to Mid Elevation Spray Application (MESA) has increased irrigation efficiency from 65% to 85%. This efficiency can be further improved using Low Elevation Spray Application (LESA) [3].

About 18% more water reaches to the ground with LESA compared to MESA [3]. In MESA, water sprayer heads are positioned about midway between the mainline and the ground level. It results in water being applied above the primary crop canopy. In case of LESA, water is applied about 0.3 m above the ground and thus often sprayed underneath the primary foliage. It reduces the evaporation and drift of water particularly on hot and windy days [3]. Several factors have been studied for LESA and MESA to evaluate their field performance. Besides an increased irrigation efficiency, LESA also needs less pressure to operate and can result in pumping energy savings. In recent years, researchers have been testing variants of such systems [4–7] for several irrigated crops such as cotton, corn, sorghum, soybean, alfalfa, beans, mint, barley, potatoes and wheat. Although the initial installation cost of LESA is higher due to increased hardware, this can often be repaid over time by energy savings. Nonetheless, growers still have concerns related to water use efficiencies for crops irrigated with LESA. The effects on canopy vigor and air temperature driven evapotranspiration are also unknown. Therefore, this study focuses on evaluating crop vigor and canopy temperature for LESA and MESA systems installed in corn crop.

Crop canopy vigor can be defined as a function of canopy growth, health and the coverage on the ground. Traditionally, crop biomass estimates through ground sampling were used for assessing crop vigor. Such approach is labor intensive and time consuming. Recently, aerial multispectral imagery derived vegetation index (VI) map(s) have been established for studying crop vigor variations. VIs are combinations of the spectral characteristics of the canopy at two or more wavelengths to quantitatively and qualitatively [8] represent the crop vegetation. Teal et al. [9] reported that yield potential in corn could be accurately predicted with normalized differential vegetation index (NDVI). Panda et al. [10] have used four different VIs for predicting corn yield. Lukas et al. [11] have explored VIs derived from aerial multispectral and satellite images to monitor wheat crop vigor. For ground truth measurements, a portable spectroradiometer was used and the results had high correlation to the aerial VIs and the crop biomass. Wahab et al. [12] demonstrated that green NDVI (GNDVI) derived from small unmanned aerial system (UAS) imagery can predict corn crop vigor and yield. A study used normalized difference red edge (NDRE) to predict soybean vigor and productivity using a handheld crop scanner [13].

The canopy temperature and microclimate attributes can also be used as a measure of the crop's response to irrigation. For example, Canopy temperature from thermal images have shown to correlate well with ground truth temperature data from infrared thermometers in a study of wheat and maize genotypes [14]. Thermal imaging can distinguish between irrigated and non-irrigated canopies as well as between deficit irrigation treatments [15–21]. Zuniga et al. [21] have demonstrated the applicability of thermal infrared images, acquired at 9.0 cm/pixel ground sampling distance (GSD, distance between two consecutive pixel centers), in characterization of grapevine plant responses to different irrigation treatments. Results showed that thermal imaging data was able to detect differences between types of irrigation and depths of irrigation in sub-surface drip irrigation treatments.

These data can be most efficiently captured with small UAS. The recent interest in small UAS for crop monitoring has been motivated by the benefits of these platforms compared to manned airborne or satellite imaging approaches. It includes high spatiotemporal resolution and quality of the data [22]. Small UAS operations are of special interest in agriculture where short revisits are required for management applications. A range of optical sensors can be integrated with the small UAS depending on payload lift capabilities. Sankaran et al. [23] has reviewed aerial imaging systems and its potential applications to evaluate crop resistance to biotic and abiotic stressors. Zhou et al. [20] has compared proximal, ground and aerial remote sensing for stress monitoring in pinto beans. A GNDVI map acquired from multispectral images was able to discriminate between different irrigation treatments and was statistically significant at the 5% level. Aerial imaging was identified as a suitable and preferred technique over the ground-based imaging because of the frequent light variation at different times of the imaging that did not affect the quality of aerial imagery. Overall, prior studies revealed that low altitude multispectral images could be a useful approach for the spatiotemporal stress evaluation of row and field crops. Therefore, the goal of this study was to utilize small UAS based multispectral and thermal imagery-extracted information on the canopy parameters for LESA and MESA irrigated corn field to understand and assist growers in making an informed decision about site-specific installation of these irrigation systems.

2. Materials and methods

2.1. Experimental site

The experimental site was a corn *(Zea mays* var. *indentata)* field installed with modified center pivot irrigation systems, i.e., MESA and LESA (Fig. 1b). Water stress is a major yield reducing factor for this crop in the Pacific Northwest of the United States. However, corn can cope with some water stress in the early stages of growth [24,25]. The farm was located at

Fig. 1 – (a) Small UAS mission over the corn field, (b) The irrigation system showing Mid Elevation Spray Application (MESA) and Low Elevation Spray Application (LESA). The emitters of LESA, as seen, are closer to the ground than MESA. Also, the outlet spacing of emitters in LESA is less by 3–6 m.

Toppenish, Yakima County, WA (Latitude: ~46.3718°N, Longitude: ~−120.4548°W).

2.2. *Platform and sensor specifications*

In this study, a multispectral (RedEdge, MicaSense, WA, USA) and a thermal (Tau 2 640, FLIR® Systems, OR, USA) imaging sensor were used by integrating them with a small UAS (ATI AgBOT™, Aerial Technology International, OR, USA). The UAS used was a quadcopter with a maximum take-off weight of 4.7 kg. A 6500 mAh battery was used to power the UAS. It was remotely controlled with a radio transmitter (Futaba 14SG 14 channel radio, Futaba Corporation, Mobara, Japan) and an open source windows-based ground control software (MissionPlanner, version 1.3.49, Ardupilot, USA). A global positioning system (GPS) receiver (3D Robotics, Inc., CA, USA) and a light sensor (Downwelling Light Sensor, MicaSense, WA, USA) were mounted on top of the small UAS.

Fig. 2 shows the sensors used in this study. The sampling rate for the multispectral sensor was set using the ground control software with 85% frontal overlap and 70% side overlap. The thermal sensor was set to a sampling rate of 20 frames/min (sampling interval of 3 sec) which ensured 90% overlap. The specifications of the sensors are provided in the Table 1.

2.3. *Data acquisition*

Images were acquired at a flight height of 100 m above ground level (AGL) on 49, 59, 65, 77, 105, 114, 134 days after planting (DAP) during the crop growing season (till harvest). The flight height was optimized based on our application. A multispec-

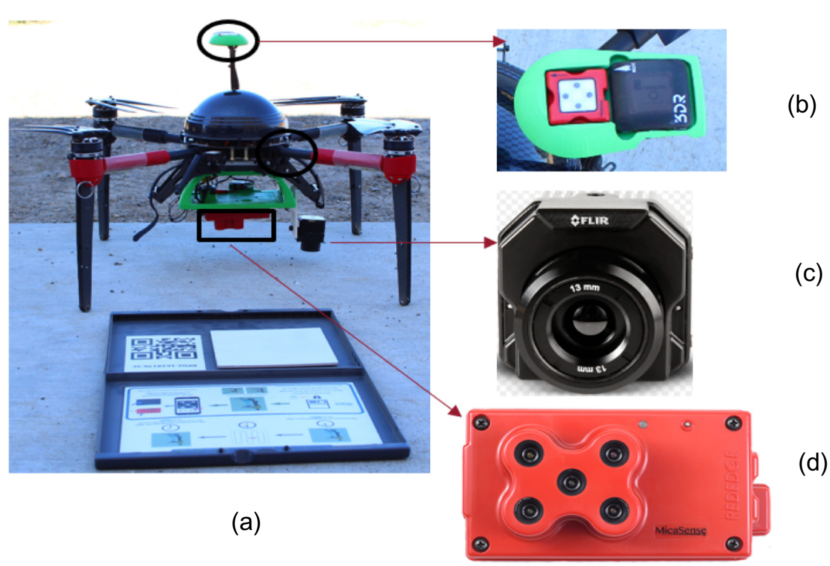

Fig. 2 – The Data collection system (a) Small UAS, (b) A GPS receiver and downwelling light sensor, (c) Thermal infrared imaging sensor, and (d) Multispectral imaging sensor.

Table 1 – Specifications of multispectral and thermal sensors used in this study.

Sensor	Multispectral	Thermal infrared
Model	RedEdge	TAU2-640
Manufacturer	MicaSense, Seattle, WA, USA	FLIR® Systems, Wilsonville, OR, USA
GSD (at 122 m above ground level, AGL), cm/pixel	8	12
Number of bands	5	1
FOV, °H × °V	47.2 × 35.4	45 × 37
Image resolution, pixels	1280 × 960	640 × 512
Focal length of lens, mm	5.5	13
Weight, gm	180	72
Input voltage, VDC	5.0 to 5.5	4.0 to 6.0

tral senor GSD of approximately 6 cm/pixel sufficed our application to understand the crop variability under the two irrigation treatments.

The corn was harvested on 155 DAP to study the yield difference between LESA and MESA. Twenty random areas of interests (ROIs) excluding the damaged strips, each of 1 m^2 measured with a hollow frame, were selected from LESA and MESA irrigated regions. The ear weight method [26,27] was used to estimate the yield potential without kernels being shelled or dried.

2.4. *Multispectral imagery analysis*

Each set of images consisted of five separate bands with embedded geolocation and radiometric calibration data. Data preprocessing was done in Pix4Dmapper® Pro (Pix4D Inc., Lausanne, Switzerland). Steps included calibration, reflectance map generation and quality check. Fig. 3 shows the image preprocessing workflow followed in this study.

The key steps for data processing are described in Fig. 4. The five reflectance bands obtained as output from preprocessing stage were used for further processing of the imagery. A custom algorithm was developed in MATLAB® (R2016a, MathWorks Inc., MA, USA) to extract crop canopy vigor indices. Fig. 4 also summarizes the key steps followed to remove the soil (background) from the reflectance maps generated at the end of pre-processing stage. Image segmentation to separate soil from canopy was performed with Otsu's method on NDVI map [28,29]. The threshold varied each day based on the canopy vigor and ranged approximately from 0.2 to 0.4. This value was used to get a binary image with two class, i.e., vegetation and soil. This image was then used as a mask on each band to remove the background (soil).

The masked bands were then used for ROI selection. Fig. 5 shows the pertinent steps of ROI selection. ROIs were selected

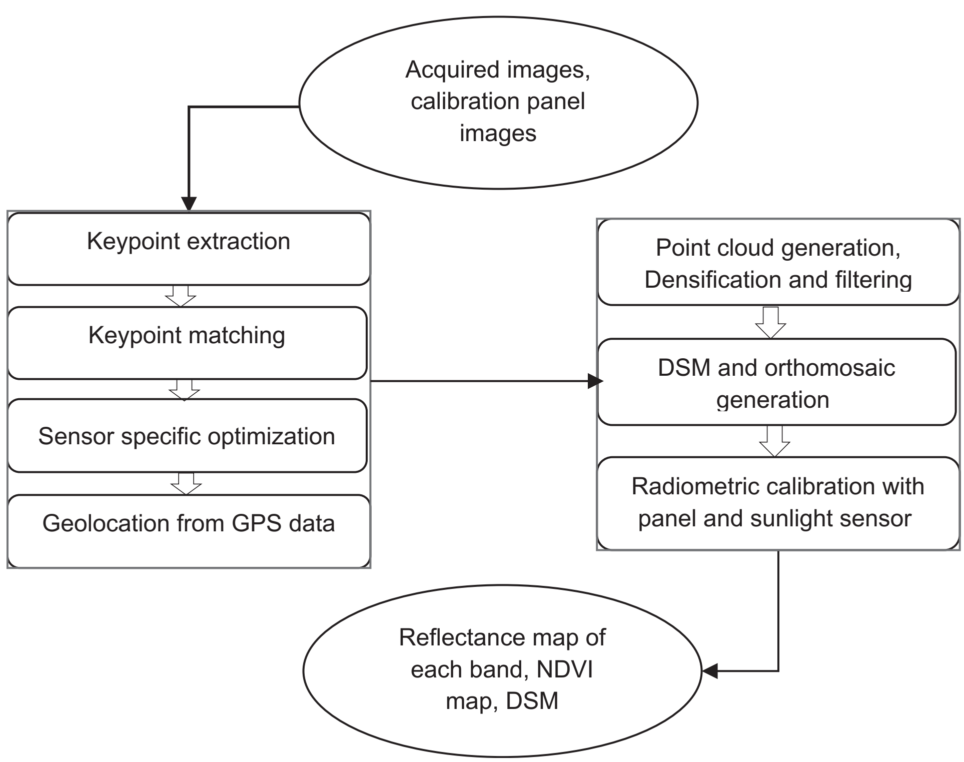

Fig. 3 – Image preprocessing workflow for multispectral image analysis.

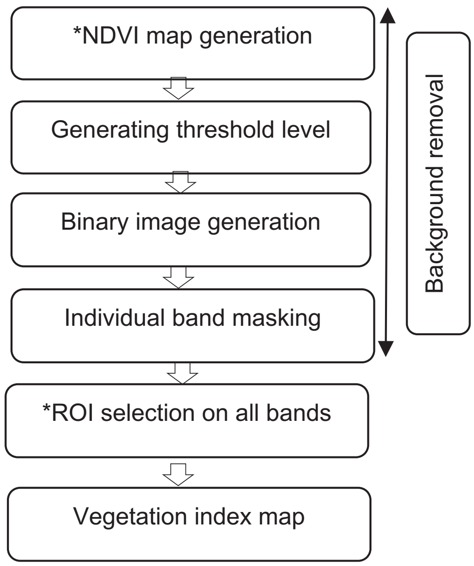

Fig. 4 – Flowchart for data processing (*ROI-Region of Interest, NDVI-Normalized Difference Vegetation Index).

from the grayscale image of near infra-red (NIR) band. The ROIs were selected manually in a random manner from all of the treatment area. The same ROIs were used to select the pertinent regions from other four bands. A grayscale image of the NIR band was used to avoid bias while selecting the ROIs since color may produce bias. There might be a tendency to always select a color that denotes higher value in the map. Such bias is reduced in a grayscale image due to its lower dynamic range. The map was also divided into grids of 400 × 400 pixels to ensure unbiased ROIs selection. A total of 60 ROIs spread over the irrigated area, i.e., 30 each for LESA and MESA, were selected from each of the five bands. Note that these ROIs were different that the ones selected from thermal imagery data and for yield assessment done later in the season. Overall, all the ROIs were selected from LESA and MESA irrigated treatment regions and should represent treatment effect, irrespective of its location within the treatment area.

Vegetation Indices maps were then generated from the bands using the equations given in Table 2. The mean values of the indices for each ROI were also extracted. Among the several vegetation indices, NDVI is most widely used for studying canopy health and vigor. However, NDVI tends to saturate in high vegetation conditions. Therefore, two additional vegetation indices GNDVI and NDRE were extracted as well.

2.5. *Thermal imagery analysis*

Thermal imagery data preprocessing included image frames extraction and orthomosaic generation for visual analysis. The frame extraction was done in the Thermoviewer software (version 2.1.4, TeAx Technology, Wilnsdorf, Germany).

Similar to the multi-spectral imagery, thermal images were orthomosaiced in Pix4Dmapper® Pro (Pix4D, Lausanne, Switzerland) using the extracted thermal ('*.rjpeg') images that were embedded with geolocation data. Due to the lack of geolocation data for some datasets, all datasets could not produce the orthomosaic and the final temperature map. Therefore, two frames from different parts of the field covering both LESA and MESA irrigated areas were selected in this study. As reported earlier, ROIs selected for the thermal frames were different than that of multispectral imagery data.

The data processing steps for the thermal images were also implemented in MATLAB®. Otsu's method was used to create a binary image of soil and canopy for each day. The binary image was used to create a mask by multiplying it with the thermal frame to create a resulting map where the soil pixels were assigned as not a number ('NaN') and the canopy pixels contained the temperature values. The final output

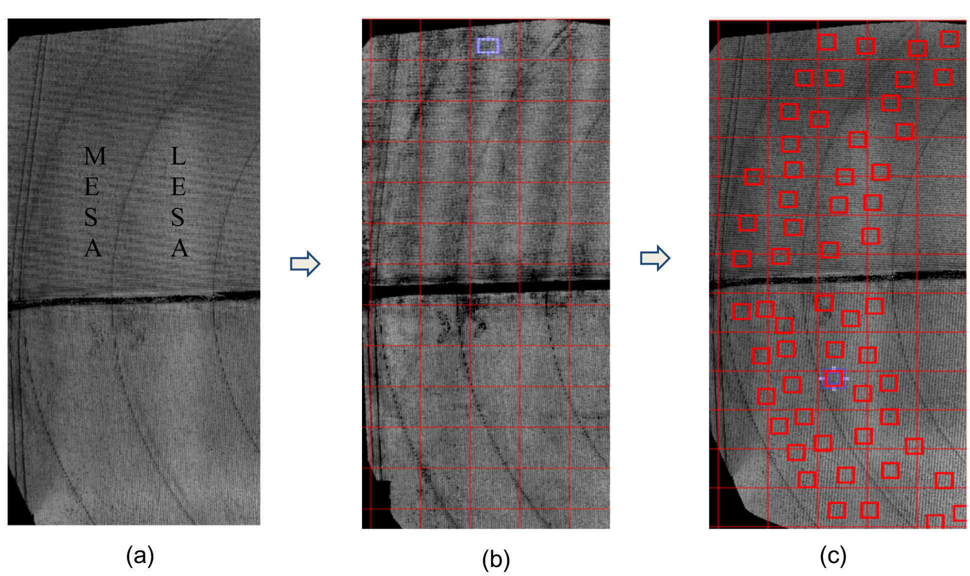

Fig. 5 – Region of interest selection process flow with (a) NIR band showing LESA and MESA in the corn field, (b) Dividing the map into grids, and (c) Selecting 30 ROIs from each of the LESA and MESA irrigated field plots (Images of 49 DAP).

Table 2 – Selected vegetation indices to represent crop vigor during various growth stages.

Vegetation Index	Equation	Reference
Normalized Difference Vegetation Index, NDVI	$\frac{\rho_{NIR}-\rho_{Red}}{\rho_{NIR}+\rho_{Red}}$	[30]
Green Normalized Difference Vegetation Index, GNDVI	$\frac{\rho_{NIR}-\rho_{Green}}{\rho_{NIR}+\rho_{Green}}$	[31]
Normalized Difference Rededge Index, NDRE	$\frac{\rho_{NIR}-\rho_{Rededge}}{\rho_{NIR}+\rho_{Rededge}}$	[32]

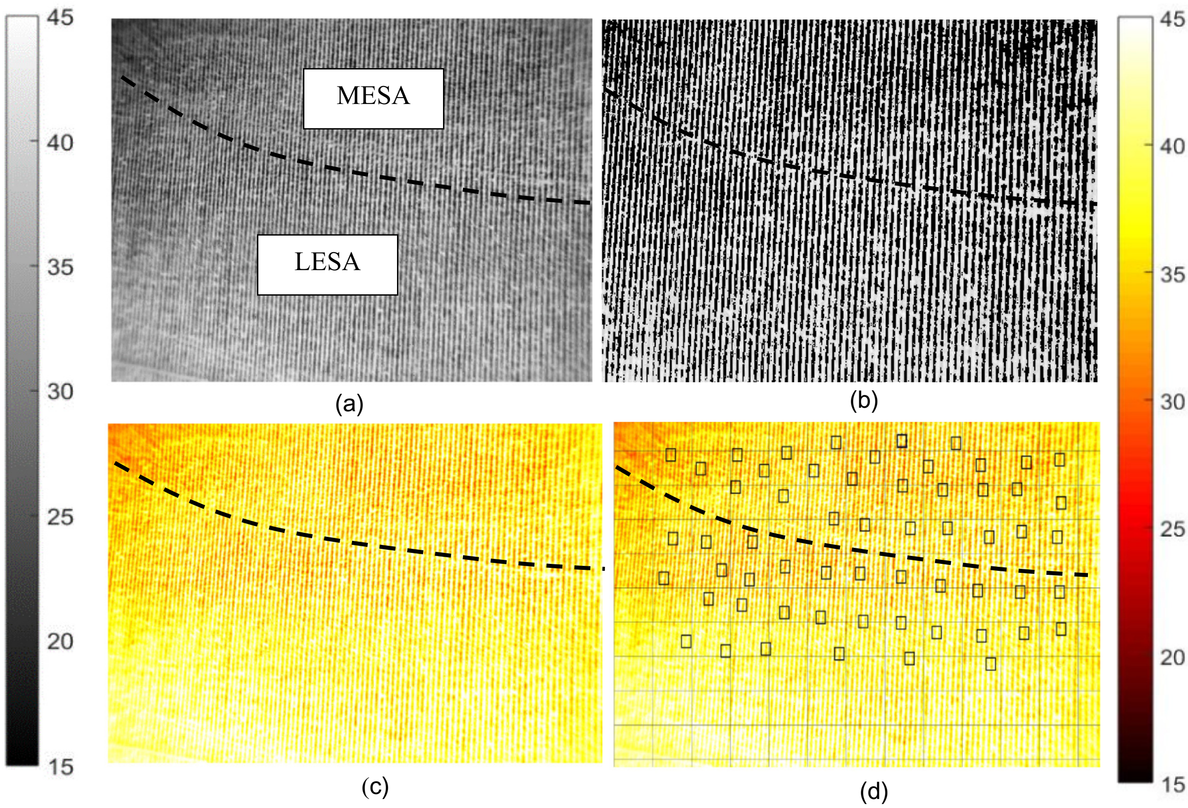

Fig. 6 – Workflow of thermal imagery processing, 49 DAP corn field (a) Selected thermal frame, (b) Frame after masking, with crop as black pixels and the soil background in white, (c) Color masked frame, with the temperature scale (15–45 °C) on right (d) Region of interest selection from LESA and MESA. The scales are in °C. The white color represents soil in the colored frames and pertinent pixels were assigned 'NaN' in the analysis.

after processing was the mean temperature for each ROI. The typical images at each step of processing are shown in Fig. 6.

2.6. *Statistical analysis*

Statistical analysis was conducted in R Studio (version 0.99.451, R Studio Inc., MA, USA). The data was analysed for studying temporal variation of crop vigor and the canopy temperature for parts of the field irrigated with LESA and MESA. To visually represent the data, box and whisker plots were created. A 'two sample t-test' was conducted to find if there was any significant difference between LESA and MESA irrigated areas at 5% level. Yield data was also analysed to determine if the yields for LESA and MESA were significantly different.

3. Results and discussion

The NDVI and temperature map for the corn field at 134 DAP is shown in Fig. 7. Overall, crop canopies were more vigorous and cooler in the MESA irrigated areas as compared to the LESA areas throughout the crop growing season. The following sub-sections discuss the specific trends in the extracted parameters from the aerial imagery.

3.1. *Temporal variation in crop vigor: LESA vs MESA*

Overall, for both the irrigation techniques, the crop vigor increased in the early growth stage (49, 65 DAP), peaked in the mid growth stage (77, 105, 114 DAP) and then decreased in the late growth stage (134 DAP). This is typical for a corn

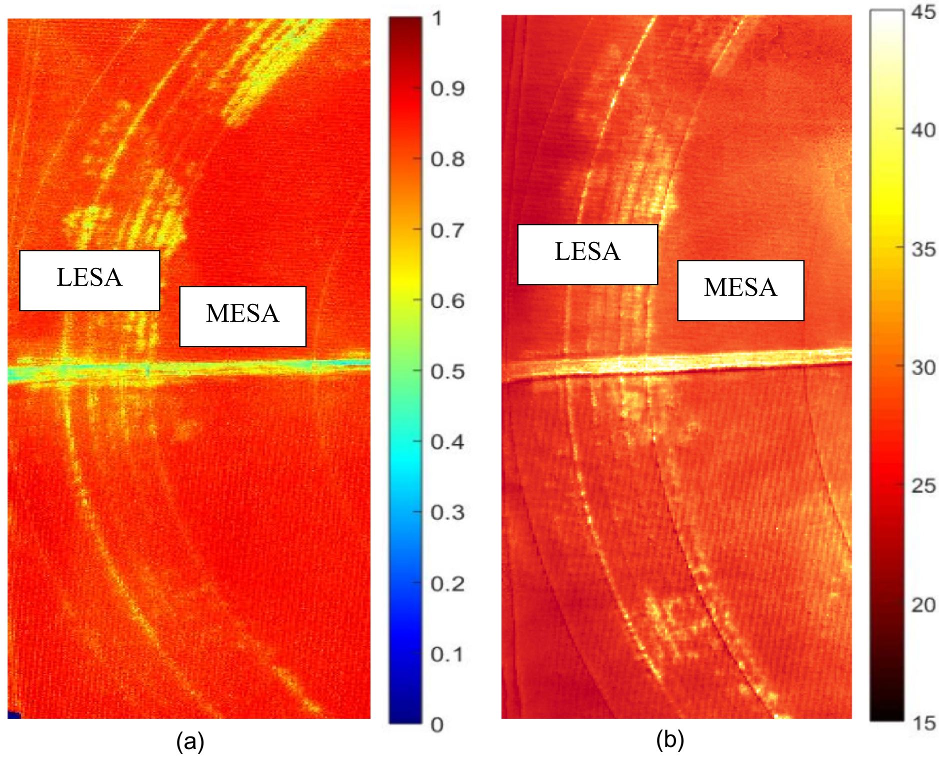

Fig. 7 – Small UAS imagery based orthomosaic images showing (a) NDVI and (b) Temperature (scale in °C) map of the study area on 134 DAP.

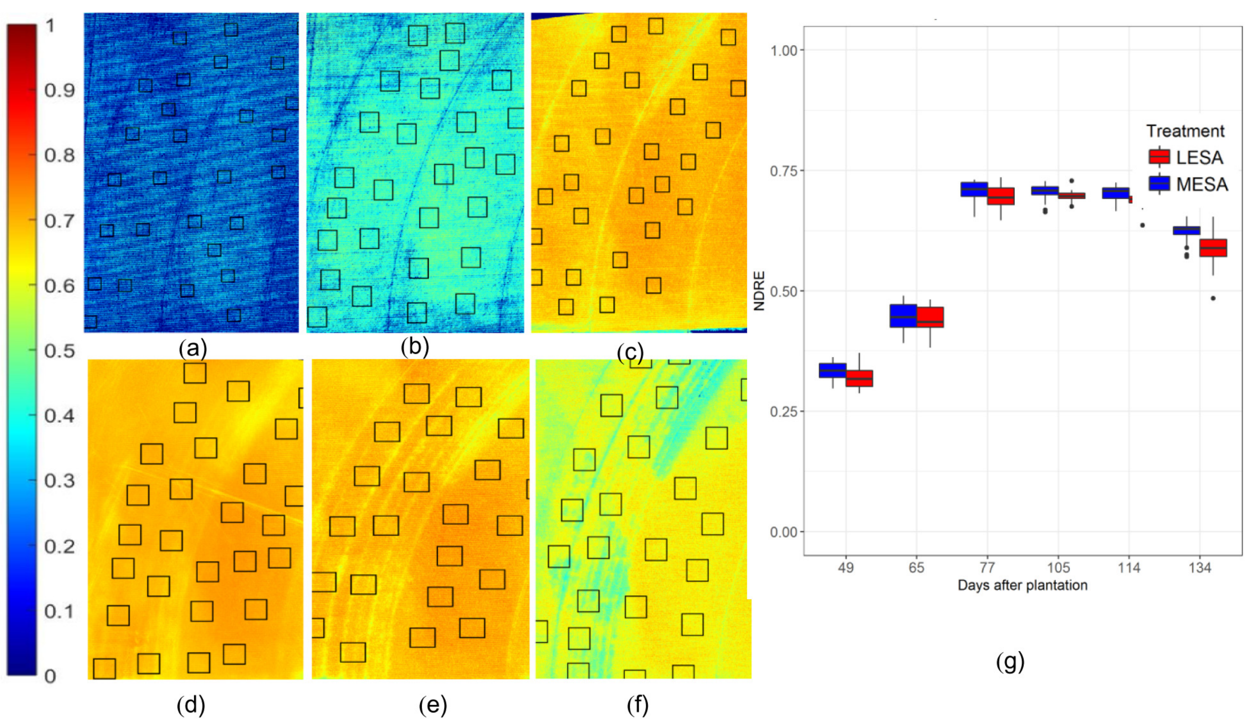

Fig. 8 – NDRE map showing temporal variation in LESA and MESA, (a) through (f) represent 49, 65, 77, 105, 114 and 134 days after plantation, respectively. On the right, Box and whisker plots (g) of the NDRE index relates to temporal variation in the crop vigor from 49 through 134 DAP. In the boxplot, the upper and lower whiskers represent the maximum and minimum, the upper and lower box borders represent the 75th and 25th percentile, respectively, and the horizontal dark line indicates the median.

crop where NDVI or similar indices tend to increase initially and tend to saturate during mid-growth stages [33]. Decreased vigor at later stages can be related to maturation and beginning of crop senescence. However, for all image acquisition dates, MESA irrigated sections had higher vigor (NDVI, GNDVI, NDRE) compared to LESA (Fig. 8, see NDRE maps).

The vegetation index and thermal maps revealed that some strips had lower vigor and higher temperature in LESA. On further inquiry, it was discovered that there were problems with the types of LESA sprinklers being used. Because of the configuration of the sprinklers, they were catching in and were being pulled off the hose by the corn stalks. This resulted in the hose whipping about with the sprinkler weight still attached. Such movement of the hose and sprinkler weight caused damage to some of the corn. These damaged strips can be easily identified in the obtained imagery, as warmer strips, especially the infrared images. The sprinklers were replaced at various intervals throughout the season when they were found to be missing.

Overall, data revealed no significant difference in the crop vigor between both the techniques. However, difference in crop vigor for MESA and LESA was more prominent during the late growth stage due to the damage caused by the sprinkler heads in LESA.

3.2. *Temporal canopy temperature assessment*

Temporal variation of canopy temperature (Fig. 9) did not follow a trend like the crop vigor. The sudden increase of temperature at 105 DAP could be a result of changes in air temperature, solar radiation, wind, vapor pressure, soil moisture content, irrigation schedule and combination of other parameters. The cause of the increase was studied by understanding the weather data obtained from WSU AgWeatherNet (https://weather.wsu.edu/). The built up of temperature and

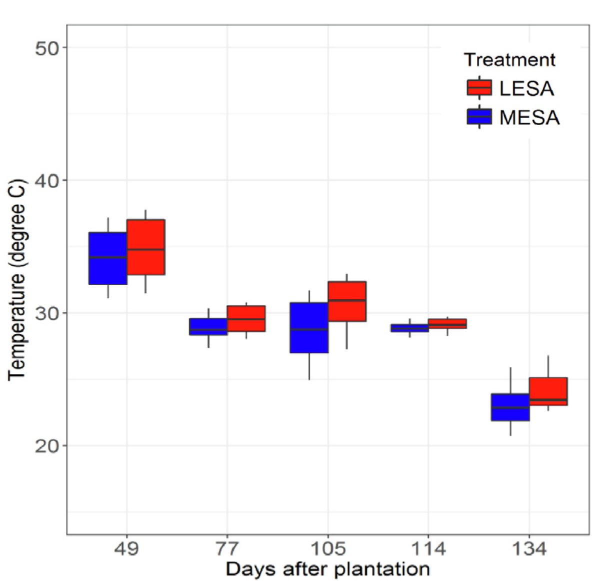

Fig. 9 – Box and whisker plots of canopy temperature from 49 through 134 DAP.

solar radiation during 77 DAP to 105 DAP was the highest. This might be the reason for the canopy temperature increase. However, the canopy temperature increase was more in LESA, because of the corn strips damaged by the weighted hoses at that time. The type of sprinkler heads used was changed following the pertinent events. However, the canopies were cooler for MESA than LESA throughout the growing season. The difference of mean temperature between MESA and LESA areas varied from 0.61 °C to 2.07 °C throughout the season, with a normal distribution. Furthermore, statistical analysis confirmed a significant difference ($p < 0.05$) in temperature of MESA and LESA irrigated areas.

3.3. *Relationship between canopy vigor, temperature and yield*

The response variable (yield) behaved quite differently from the vegetation indices and canopy temperature over the season. LESA (22,338 ± 1450 kg/ha [mean ± standard deviation]) had higher yield compared to MESA (20,881 ± 3187 kg/ha) but the difference was not significant ($p = 0.2118$). Note that in LESA, corn was not harvested from the damaged strips. Thus, LESA might have improved corn yield with greater crop vigor and lower canopy temperature if different sprinkler heads were used from the beginning.

Further studies need to be conducted with suitable sprinkler heads for corn to derive any further conclusion on site-specific adoption of LESA. In a previous study [1] on crop production with full irrigation capacity, MESA resulted in the greatest yield of corn compared to various modern pressurized irrigation systems. They also mentioned that identical yield response should not be expected for different field locations or seasons.

4. Conclusions

Small UAS based multispectral and thermal imagery data adequately understood the irrigation treatment effects. Throughout the season, MESA irrigated areas had more vigor and cooler canopies than LESA. The small UAS based imagery was also able to identify the crop damage due to sprinkler heads in LESA. Those strips had lower vigor (lower NDVI) and higher temperature gradients. Such damage would otherwise go unnoticed via ground scouting methods. This further elaborates the role of small UAS based imagery in scientific evaluation of field research treatments. Based on the study results, we recommend additional studies with different types of sprinkler heads to determine which center pivot irrigation system performs better for corn production in the state of Washington. Also, it is recommended to have additional datasets to develop the robust relationship between irrigation treatments related crop vigor variations and resulting crop yield.

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