Assessment of crop growth under modified center pivot irrigation systems using small unmanned aerial system based imaging techniques

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Abstract. *Irrigation accounts for about 80% consumptive use of water in the Northwest of United States. Even small increases in water use efficiency can improve crop production, yield, and have more water available for alternative uses. Center pivot irrigation systems are widely recognized in the irrigation industry for being one of the most efficient sprinkler systems. In recent years, there has been a shift from high pressure impact sprinklers on the top of center pivots to Mid Elevation Spray Application (MESA) sprinkler configurations and towards Low Elevation Spray Application (LESA) sprinklers. Although LESA offers range of benefits over MESA, such technologies have grower adoption concerns as the effects of these systems on the crop growth and yield are unknown. In this study, these parameters were evaluated for LESA and MESA using a small Unmanned Aerial System (UAS) integrated with multispectral and thermal imaging sensors, in corn (Zea mays* var. *indentata) and mint (Mentha spicata* and *Mentha × piperita). The field experiment was designed to have two adjacent spans of a center pivot sprinkler irrigation system with LESA and MESA in both the fields located in the state of Washington, USA. Aerial data was collected throughout the crop growing season and analyzed using image processing algorithms, custom developed in Matlab® to observe the temporal variation of the above-mentioned crop* *parameters for both sprinkler system configurations. Various vegetation indices and canopy temperature was extracted from the imaging data and compared for the LESA and MESA irrigated areas. Two sample T-test was performed to find if there was any significant difference at 5% level in the observed parameters between LESA and MESA.*

Results showed that for mint, LESA irrigated areas had more average crop vigor and similar canopy temperature during the entire crop growth season though the difference was not significant. The LESA irrigated areas had significantly more crop vigor and less canopy temperature till the mid growth season which is the phase that determines the yield, according to many prior studies. However, for corn, MESA had more crop vigor and a cooler canopy than LESA throughout the season. Though the difference in crop vigor was not significant, the MESA irrigated canopy areas was significantly cooler than LESA irrigated areas. The results were anticipated, as the sprinkler heads used in LESA were being pulled off in corn field, causing the weighted hose to damage the corn which could be observed from the aerial images. A different kind of sprinkler head was used after this incident. However, some strips of corn had already been damaged. The damaged strips could not cause any significant difference in the canopy vigor with the MESA irrigated areas. As LESA had similar effect on canopy as MESA, LESA could be installed in mint and corn fields, backed up by several benefits of this system over MESA made in other studies, improving the water efficiency. Also, the methods developed could be used for other applications related to precision and sustainable agriculture.

Keywords. *Mid Elevation Spray Application, Low Elevation Spray Application, Crop vigor, Crop water stress, Unmanned aerial system, Imaging.*

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Introduction

Center pivot sprinkler irrigation systems are widely recognized for their application efficiency and uniformity in application of water for irrigation (Rajan et al., 2015, Rogers et al., 2017). According to Peters et al. (2015), advances in center pivot systems from high-pressure impact sprinklers to Mid Elevation Spray Application (MESA) have resulted in an increase in irrigation efficiency from 65% to 85%. This efficiency can be further improved up to 96% using Low Elevation Spray Application (LESA) (Peters et al., 2015). According to the above studies, about 18% more water reaches the ground with LESA when compared to MESA. 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 (1 ft) 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 (Peters et al., 2015). 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 therefore can result in pumping energy savings as well. Although the initial costs of LESA is higher due to increased hardware expenses, over time this can often be repaid by energy savings (Peters et al., 2015). Nonetheless, growers still have concerns related to water use efficiencies for crops irrigated with LESA. The effects on crop vigor and air temperature driven evapotranspiration are also unknown.

The crop canopy vigor is normally studied using multispectral sensor data derived vegetation indices map(s). Vegetation Indices (VIs) are combinations of the spectral characteristics of the surface at two or more wavelengths to represent vegetation in a quantitative and qualitative manner (Xue and Su, 2017). They are derived using the reflectance properties of vegetation. The canopy temperature and microclimate attributes can be used as a measure of the crop's response to irrigation. Studies have shown that thermal imaging can distinguish between irrigated and non-irrigated canopies as well as between deficit irrigation treatments (Grant et al., 2006; Leinonen et al., 2006; Jones et al., 2009; Alchanatis et al., 2010; Zhou et al., 2016; Zuniga et al., 2017). Zuniga et al. (2017) demonstrated the applicability of thermal infrared images, acquired at 9.0 cm/pixel ground sampling distance (GSD) to characterize grape vine plant responses to different irrigation treatments. Results showed that thermal imaging data was able to detect differences between type of irrigation and depth of irrigation in sub-surface drip irrigation treatment.

The recent interest in small unmanned aerial systems (UAS) for crop monitoring has been motivated by the benefits of these platforms compared to manned airborne or satellite imaging. It includes high spatiotemporal resolution with lower operation costs and complexity (Khot et al., 2014). Small UAS operations are of special interest in agriculture where short revisit times 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. (2015) reviewed aerial imaging systems and the potential of using aerial imaging to evaluate crop resistance to biotic and abiotic stressors. Zhou et al. (2016) compared proximal, ground-based and aerial remote sensing for stress monitoring in pinto beans. Aerial imaging was better than ground-based imaging in a way that light variation at different times of the imaging day did not affect the aerial image quality. Overall, these studies revealed that low altitude multispectral images could be a useful approach for the spatiotemporal stress evaluation of row and field crops. Therefore, this study focusses on evaluating crop vigor and air temperature driven evapotranspiration effects for LESA and MESA using small UAS mounted with multispectral and thermal imaging sensors. Specifically, our study is focused on understanding site-specific suitability of LESA in mint and corn production.

Materials and Methods

Experimental site

The study site for this experiment was corn *(Zea mays* var. *indentata)* and mint (*Mentha spicata* and *Mentha* × *piperita*) fields installed with modified center pivot irrigation systems, i.e., MESA and LESA (Fig. 1a). Both the farms were located near Toppenish, Yakima County, WA (Latitude:

~46.3718° N, Longitude: ~-120.4548° W)

Fig. 1. LESA and MESA installed in the study area (a) Corn field (b) spearmint field. 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 (10-20 ft).

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 unmanned aerial system (ATI AgBOT™, Aerial Technology International, OR, USA). The UAS used was a small sized and remote-controlled quadcopter with a maximum take-off weight of 4.7 kg and flight time of about 26 min. 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). The multispectral imaging sensor had five bands: blue (475 nm), green (560 nm), red (668 nm), red edge (717 nm), and near infrared (840 nm). The sampling rate for this sensor was set using the ground control software with 85% frontal and 70% side overlap. The spectral band of the thermal sensor ranged from 7.5 µm to 13.5 µm and was set to a sampling rate of 3 Hz. A GPS receiver (3D Robotics, Inc., CA, USA) and a light sensor (Downwelling Light Sensor, MicaSense, WA, USA), mounted on top of small UAS, were also used during the flights (Fig. 2)

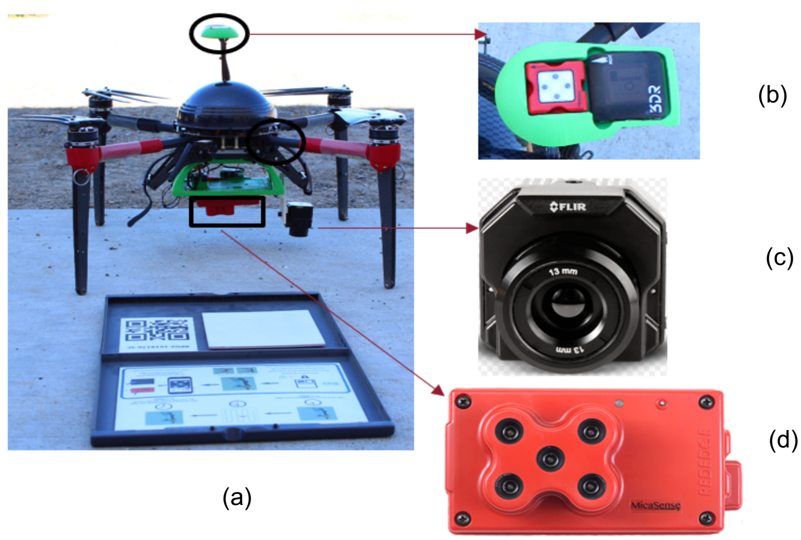


Fig. 2. The Data collection system (a) small UAS (b) a GPS receiver and downwelling light sensor (c) thermal infrared imaging sensor (d) multispectral imaging sensor.

Data acquisition

Images were acquired at a flight height of 100 m above ground level (AGL) on 7 days spread throughout the crop growing season (till harvest) in 2017 season. Initially, two flight heights (60 m and 100 m AGL) were experimented to capture images. The flight height of 100 m was chosen as at this height the study area could be captured in a shorter flight duration. Also, the GSD (distance between two consecutive pixel centers) of approximately 6 cm/pixel (4 cm/pixel for 60 m height) sufficed our application to understand the crop variability under the two irrigation treatments.

Multispectral imagery analysis

Each set of images consisted of five separate bands of images with embedded geolocation and calibration data. The software used for preprocessing was Pix4Dmapper® Pro (Pix4D, Lausanne, Switzerland). Data preprocessing steps included calibration, orthomosaic generation and quality check. Fig. 3 shows the image preprocessing workflow used in the software for multispectral imagery.

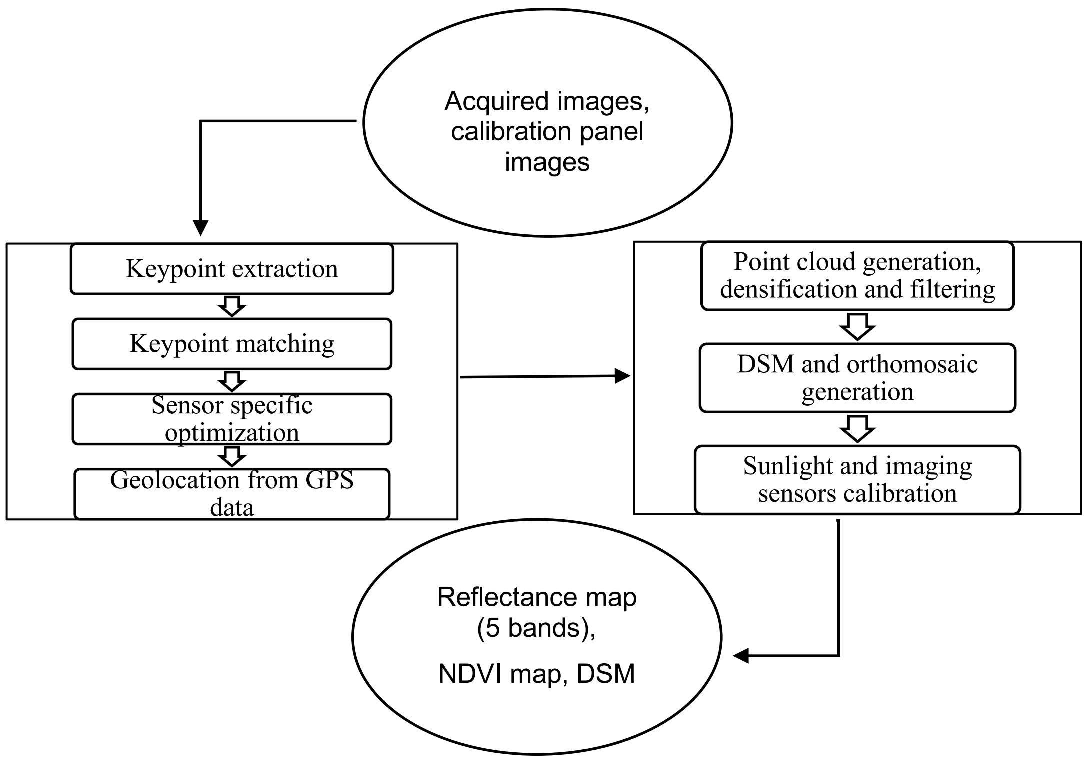
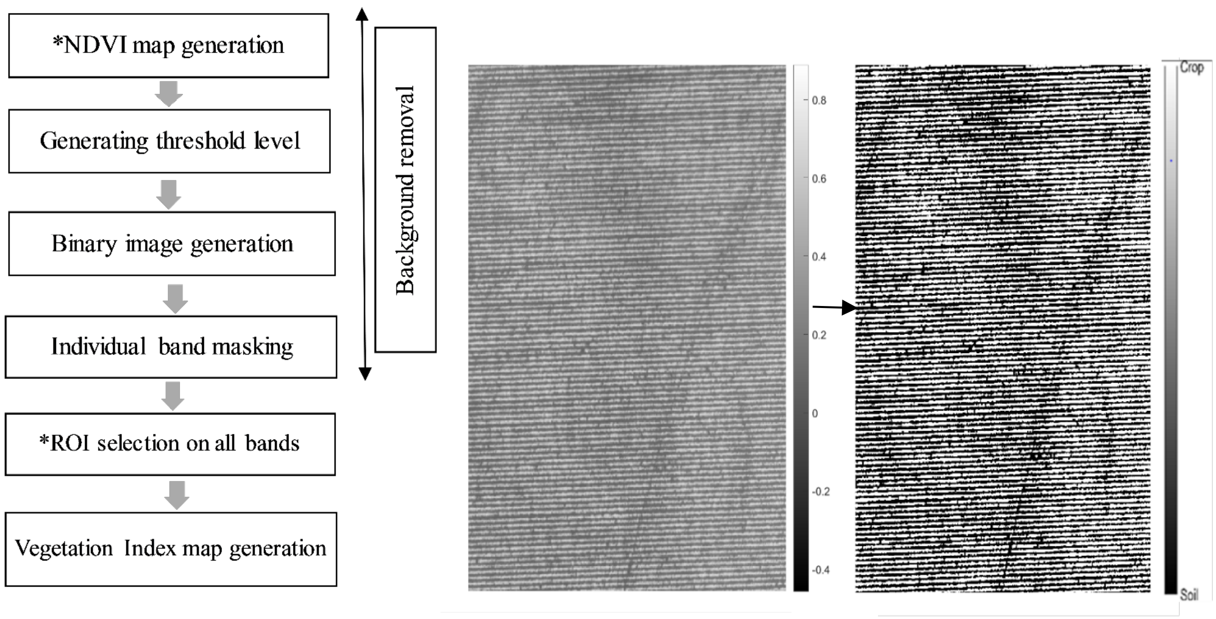


Fig 3. Image preprocessing workflow for multispectral images in Pix4D.

Data processing

The five orthomosaic bands obtained as output from preprocessing were used for further processing of the imagery. A custom algorithm was developed in MATLAB® (R2016a, MathWorks Inc., MA, USA) for processing these images to extract crop canopy vigor indices. The key steps for data processing were as reported in Fig. 4a. Fig. 4a also summarizes the key steps followed to remove the soil (background) from the orthomosaic images generated at the end of pre-processing. Image segmentation to separate soil from canopy was performed with Otsu's method on Normalized difference vegetation index (NDVI) image (Otsu, 1979, Ling et al., 1996). The threshold generated from Otsu's method, was used to get a binary image with two class, i.e., vegetation and soil (Fig. 4b). This image was then used as a mask on each band to remove the background (soil).



(a) (b)

Fig 4. (a) Flowchart for data processing (*ROI-Region of Interest, NDVI-Normalized Difference Vegetation Index) (b) NDVI map of corn field before and after background removal and masking (Image of 49 Days after Plantation i.e. DAP).

The masked bands (Fig. 4b) were then used for Region of Interest (ROI) selection. ROIs were first selected from the near infra-red (NIR) band and the same ROIs were used to select the pertinent regions from all bands. A grayscale image of the NIR band was used to avoid bias while selecting the ROIs since color produces more bias in human eyes than a grayscale image. The map was also divided into grids of 400 × 400 pixels to ensure unbiased ROIs selection. A total of 60 ROIs, i.e., 30 each for LESA and MESA, were selected from all five bands.

Vegetation Indices maps were then generated from the bands using the equations given in table 1. The mean values of the indices for each ROI were also extracted. Among the several vegetation indices, NDVI is the one most widely used for studying canopy health and vigor. However, NDVI tends to saturate in high vegetation conditions. Therefore, two additional vegetation indices Green normalized difference vegetation index (GNDVI) and Normalized difference rededge index (NDRE) were also extracted.

Table 1. Selected vegetation indices to represent crop vigor during various growth stages.

Vegetation Index	Formula*	Reference
NDVI (Normalized Difference Vegetation Index)	$\frac{\rho_{NIR} - \rho_{Red}}{\rho_{NIR} + \rho_{Red}}$	*Rouse et al., 1947*
GNDVI (Green Normalized Difference Vegetation Index)	$\frac{\rho_{NIR} - \rho_{Green}}{\rho_{NIR} + \rho_{Green}}$	*Gitelson et al., 1996*
NDRE (Normalized Difference	$\frac{\rho_{NIR} - \rho_{Rededge}}{\rho_{NIR} + \rho_{Rededge}}$	*Barnes et al., 2000*

Rededge Index)

Thermal imagery analysis

Thermal imagery data preprocessing included frame (single images from a video) extraction and orthomosaic generation for visual analysis. The frame extraction was done in the Thermoviewer ® software (version 2.1.4, TeAx Technology, Wilnsdorf, Germany). In this study, two frames from different parts of the field were selected in a way that they cover both LESA and MESA irrigated areas.

Similar to the multi-spectral imagery, thermal images were orthomosaiced in Pix4Dmapper® Pro by inputting the thermal jpeg images that were embedded with geolocation data. Ideally, there should be a high overlap (>90%) in the thermal images for getting an orthomosaic image of the area due to its lower resolution. In this study, the orthomosaic was created only for visualization.

Data processing

The data processing steps for the thermal image were similar to those for the multispectral image and was done in MATLAB ®. The final output after processing was the mean temperature of each ROI. The images at each step of processing are shown in Fig. 5.

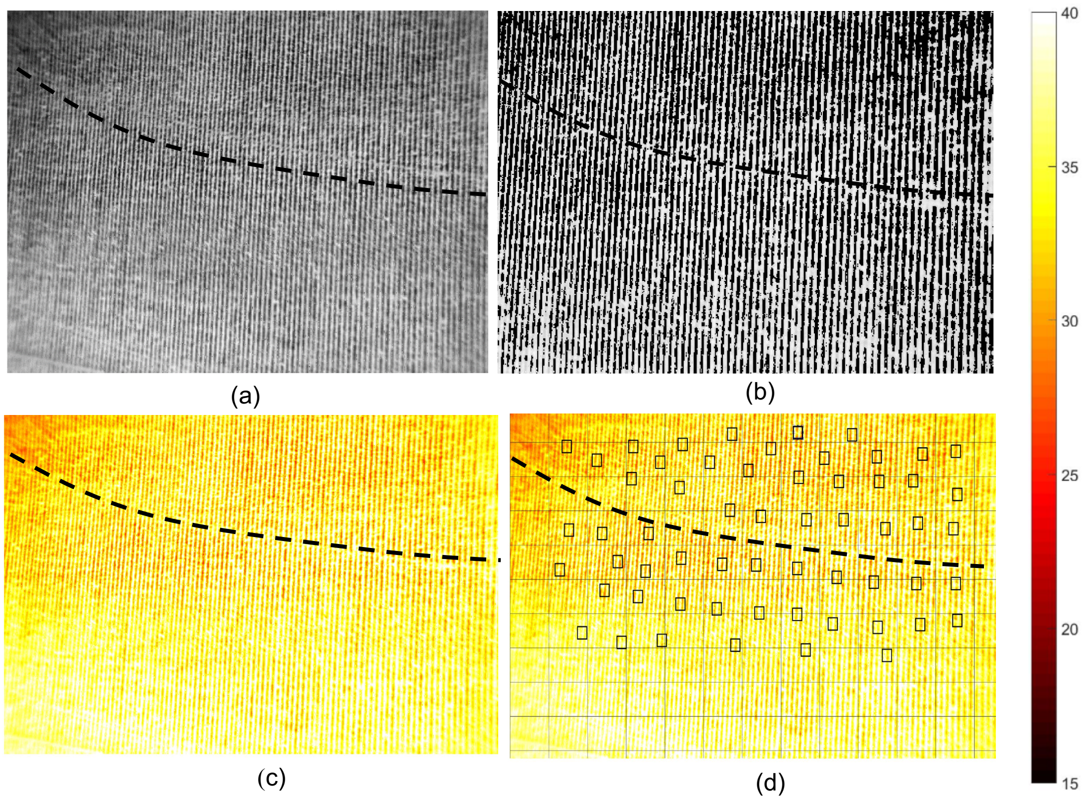


Fig. 5. Workflow of thermal imagery processing, 49 DAP corn field (a) selected thermal frame (b) frame after masking, with crop as black pixels and the soil background in white (c) colored frame, soil shown in white, red to yellow the temperature increases (15 to 40°C) (d) ROI selection, 30 from LESA and 30 from MESA. The scales are in °C. The white color represents soil in the colored frames.

Statistical analysis

Statistical analysis was conducted in R Studio (version 0.99.451, R Studio Inc., MA, USA). The data were analysed for studying: 1) temporal variation of crop vigor and the canopy temperature of parts of the field irrigated with LESA and MESA and, 2) canopy temperature difference before and after irrigation for both irrigation systems. 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 at 5% level in the observed temperatures and canopy vigor between LESA and MESA.

Results and discussion

The NDVI and temperature map for the corn and mint field on August 02 is shown in Fig. 6. Overall, for the season 2017, LESA irrigated areas demonstrated higher mean vegetation index (which is a measure of vigor) and lower temperature as compared to the MESA irrigated areas for peppermint and spearmint. However, for corn, crop canopies were more vigorous and cooler in the MESA irrigated areas as compared to the LESA areas throughout the crop growing season due to some damage caused by the sprinklers of LESA. The following sub-sections discuss the specific trends in the extracted parameters from the imagery.

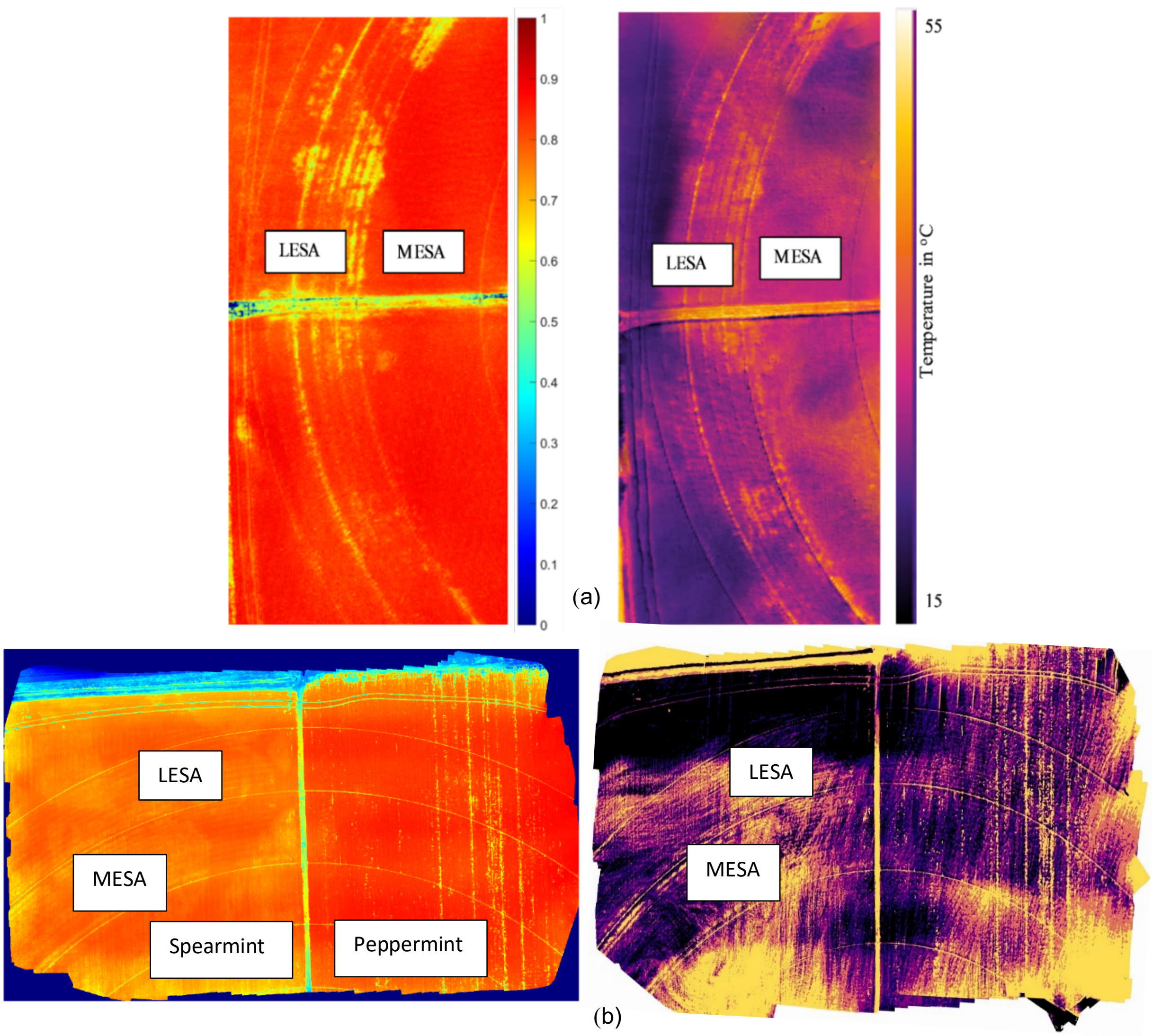


Fig. 6. Small UAS imagery based orthomosaic images showing NDVI and temperature map of the study area on August 2 (a) corn field and (b) mint field (peppermint and spearmint).

Temporal variation in crop vigor in LESA and MESA

Corn

Overall, the results suggested that for either of the irrigation technique, i.e., LESA or MESA, 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 crop where NDVI or similar indices tend to increase initially and reach to somewhat saturation during mid-growth stages (Hatfield and Prueger, 2010). 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 vegetation indices (NDVI, GNDVI, NDRE) compared to LESA (Fig. 7). NDRE was used to study the vigor as it could best depict the variation in LESA and MESA irrigated areas.

The vegetation index and thermal maps revealed some strips which had lower vegetation indices 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 a lot of damage to some of the corn. These damaged strips can be easily identified in the obtained imagery, especially the infrared image. The damaged areas show up as warmer strips in the LESA section. The sprinklers were replaced at various intervals throughout the season when they were found to be missing.

'Two-sample t-test' revealed no significant difference in the crop vigor between both the techniques. 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.

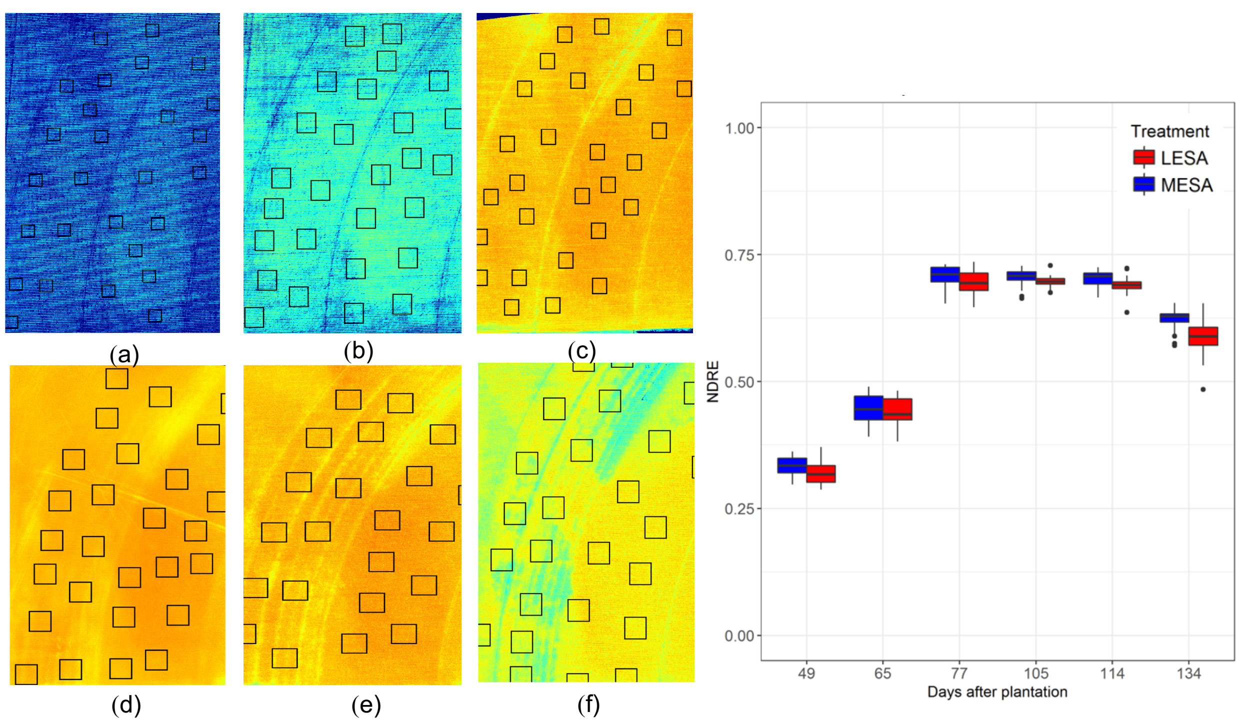


Fig. 7. NDRE map showing temporal variation in LESA and MESA, (a) through (f) represent 49, 65, 77, 105, 114 and 134 days after plantation, respectively (index) on the left. In the right, Box and whisker plots of the vegetation NDRE that relate to temporal variation in the crop vigor from 49 through 134 DAP. In the boxplot, the upper and lower whiskers represent the maximum and minimum values, the upper and lower box borders represent the 75th and 25th percentile values, respectively, and the horizontal dark line indicates the median.

Mint

GNDVI was used to study the temporal variation in mint. Overall, for the season 2017, LESA irrigated areas demonstrated higher mean GNDVI (0.62±0.23 [mean± std. dev]) than MESA irrigated areas (0.61±0.23) for peppermint. For spearmint, GNDVI for LESA was 0.7106±0.10 and that for MESA was 0.7103±0.10. Spearmint was harvested first on June 30th. Thus, for spearmint the vegetation indices decreased at the time followed by an increase (Fig. 8). However, peppermint showed an increase in GNDVI followed by a slight decrease before harvest (Fig. 9). Till mid-growth stage (July 05, 2017), LESA performed better than MESA in terms of both the parameters. However, towards the end of the growth stage, LESA had a slightly reduced performance. The reason for this still needs to be inspected. The stacked RGB images demonstrated lodging phenomenon in spearmint in MESA irrigated areas. The effect will be analyzed more precisely in the 2018 season as this phenomenon influences yield reduction.

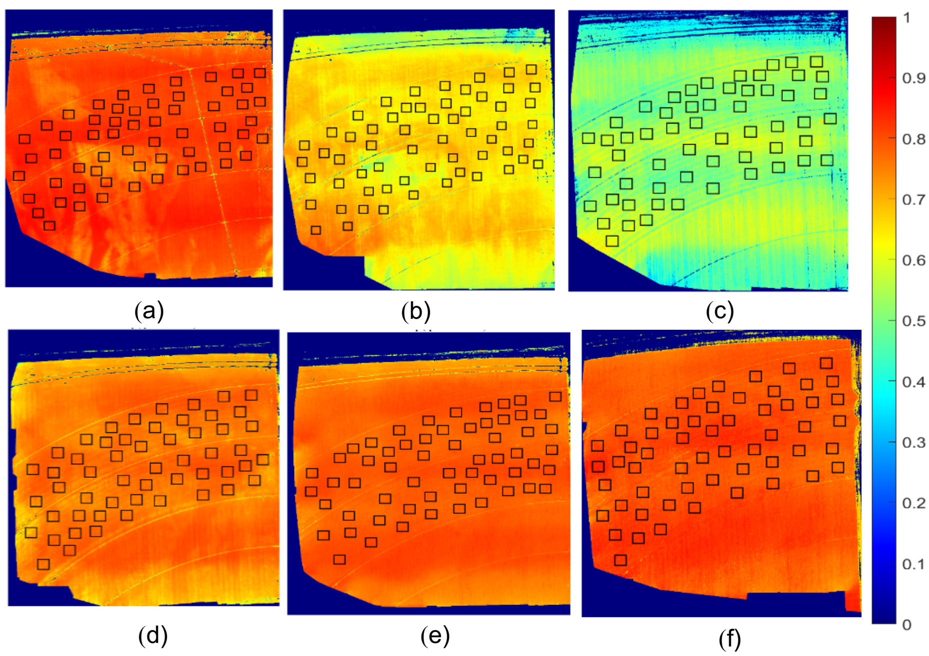


Fig. 8. GNDVI map of spearmint at 98 and 115 days after emergence (until first harvest) and 5, 33, 42 and 62 days after emergence (after first harvest), from a to f, respectively.

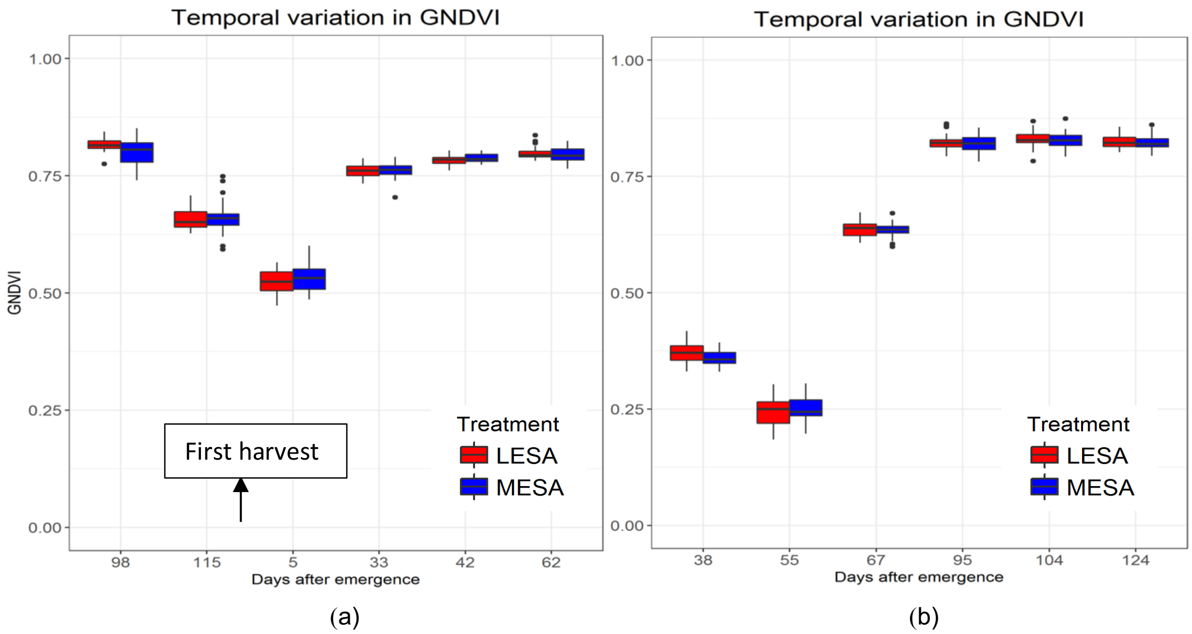


Fig. 9. Temporal variation in crop vigor through GNDVI in (a) spearmint, first harvest was done 122 days after emergence. (b) Peppermint.

Temporal canopy temperature assessment

Corn

It is evident from the plots that the temporal variation of canopy temperature does not follow a trend like the crop vigor. The sudden increase of temperature at 105 DAP (Fig. 10) 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 solar radiation during from 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 event. However, the canopies were cooler for MESA than LESA throughout the growing season. The difference of mean temperature between MESA and LESA sites 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 for MESA ([mean± std. dev.] 28.69°C±1.37°C) and LESA (39.65°C±0.73°C). Thus, MESA kept the crop canopy cooler than LESA which is indirectly a measure of high stomatal conductance for the corn sites installed with MESA.

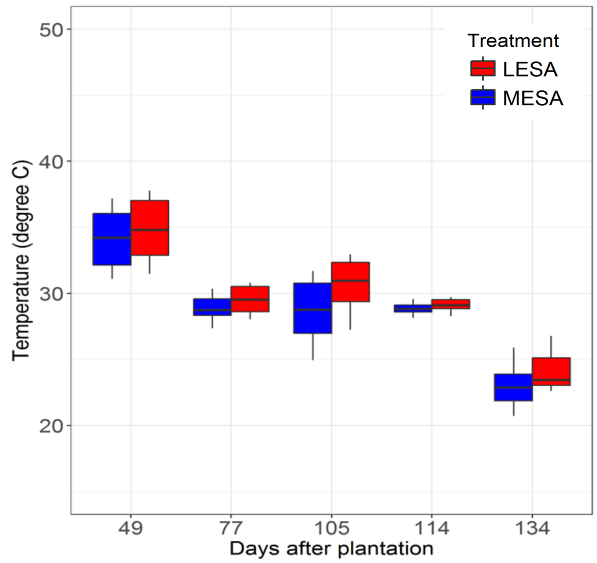


Fig. 10. Box and whisker plots of canopy temperature from 49 through 134 DAP.

Mint

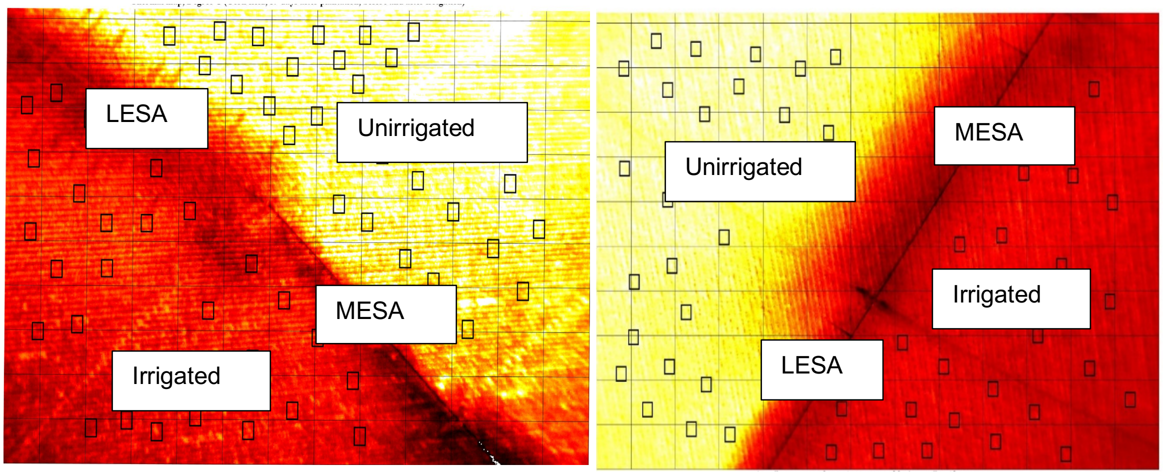
The mean canopy temperature was 34.26˚C±4.97˚C for LESA and 34.19˚C±5.08˚C for MESA in peppermint. The canopy temperature for spearmint was 31.91˚C±10.40˚C for LESA and 31.72˚C±9.97˚C for MESA. As seen from the t-tests (table 2), there is no significant difference at 5% level in the crop vigor and canopy temperature for LESA and MESA (both spearmint and peppermint).

Table 2. Welch's T test showing that there was no significant difference in LESA and MESA for canopy vigor as well as temperature.

Welch's Two sample T test				
	Spearmint LESA	Spearmint MESA	Peppermint LESA	Peppermint MESA
mean NDVI	0.820	0.816	0.642	0.638
95% CI NDVI, p value	0.041 to 0.033, 0.846		-0.055 to 0.063, 0.891	
mean GNDVI	0.711	0.710	0.622	0.619
95% CI GNDVI, p value	-0.019 to 0.019, 0.977		-0.046 to 0.052, 0.906	
mean NDRE	0.496	0.492	0.408	0.407
95% CI NDRE, p value	-0.015 to 0.023, 0.681		-0.040 to 0.042, 0.950	
mean Temperature	31.919	31.722	34.262	34.192
95% CI Temp, p value	-2.396 to 2.789, 0.881		-2.396 to 2.789, 0.881	

Efficacy of LESA and MESA irrigation

In this study, aerial images were captured on 69 DAP and 41 DAP at the time of irrigation application, for corn and peppermint, respectively. One side of the center pivot was being irrigated and the other side was unirrigated. Thus, images were able to capture before and after irrigation scenario for both MESA and LESA. Fig. 11 shows LESA and MESA sites before and after irrigation. Overall, canopies were cooler after irrigation as expected, with MESA having cooler canopy for both the irrigated and unirrigated sites in corn and LESA had a cooler canopy in mint. However, the mean temperature difference of MESA and LESA sites (both corn and peppermint) reduced after irrigation. This is because canopy temperature is indicative of plant water status under well-developed stress (Sudhakar et al., 2016).



(a) (b)

Fig. 11. Thermal map showing the conditions of the field before and after irrigation in (a) corn (b) Peppermint.

Conclusion

Previous studies revealed that LESA can save water and energy as well it has more uniformity of application than MESA. However, since the effects of this irrigation system on the crops are unknown, growers are still concerned about the adoption of this system. This study was conducted to evaluate other parameters like crop vigor and canopy temperature that relates to water-use efficiency and crop growth in these two irrigation systems.

The following has been concluded from this study. For both peppermint and spearmint, the crop vigor (studied through various vegetation indices) was higher, and canopy temperature was nearly the same for LESA irrigated areas as compared to MESA though the difference was not significant at 5% level. For corn, MESA irrigated areas had more vigor and cooler canopies than LESA throughout the season. The NDVI and thermal maps in corn revealed some strips which had lower NDVI and higher temperature in LESA. On further investigation, problems were found with the sprinklers used in LESA that damaged the corn crop. Secondly, in both irrigation techniques and for both the crops, canopy became cooler after irrigation with temperature difference reduction between LESA and MESA.

Further studies need to be conducted with different types of sprinkler head to conclude which center pivot system performed better in terms of crop vigor and canopy temperature in corn. Since the effects on canopy of both the irrigation systems were not significantly different, MESA can be replaced by LESA in mint as well as corn fields, backed up by all other benefits of LESA revealed in other studies.

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