EVALUATING PLANT DENSITY IN GRAIN SORGHUM USING GREENSEEKER

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EVALUATING PLANT DENSITY IN GRAIN SORGHUM USING GREENSEEKER

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Abstract: Grain Sorghum *(Sorghum bicolor(L)Moench,)* is a high yielding, drought tolerant crop commonly grown in Oklahoma and the southern Great Plains. Increased knowledge of agronomic production practices, such as planting densities, will be required to continue to increase yields in these environments. Two different trials were used to evaluate planting density. This first evaluated planting densities effects on sorghum yield and the second evaluating the potential of using remote sensing techniques to quickly evaluate sorghum plant densities. A non-significant relationship was found between NDVI and planting densities. Better relationships were found with CV of NDVI and planting densities, especially at 4 WAP ($P <.01$; $r^2= 0.61$). Grain sorghum yields were significantly impacted by planting densities. Significant yield decline was found when planting densities were decreased from 75,100 to 111,150, depending on the year, with a 30%, 55% and 12% reduction in yield for Lahoma 2019, Perkins 2019, and Perkins 2020 respectively. If producers were to consider replanting, a critical CV of NDVI value of 9.4 to 11.9% should be considered. This work shows that a model could be further developed for replanting and other management decisions.

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CHAPTER I

INTRODUCTION

Grain sorghum is a cereal grain that originated from Africa and is now being grown in the semi-arid conditions in the USA (Bandaru et al., 2006). The primary use of sorghum is for the animal feeding industry where it is used in both cattle and poultry production in the U.S. (Srinivasa et al., 2014). In the United States, most of the sorghum is harvested for grain or chopped for silage, most of which is produced in the southern Great Plains (Moges et al., 2007; Ciampitti et al., 2017). While sorghum varieties have been improved (Quinby et al., 1954), production acreages and productivity have decreased. In 2016, production was 12,199,190 Mg which reduced to 9,241,760 Mg in 2017 (*FAOSTAT*,2017). This could be a result of several factors, most notably the increased presence of sugarcane aphids and lowered price. Even with these challenges, sorghum production can be improved with better knowledge of crop production practices focused on improving productivity and economic returns.

As with most crops, management practices around planting are critical and have a large impact on yields. Manipulating agronomic practices such as planting density can be an important way to maximize productivity for sorghum in the southern Great Plains (Nik et al., 2011; Godsey et al., 2012). Higher densities occupy higher space and increase utilization of solar radiation within the canopy. However, higher densities also utilize greater amount of soil resources, such as soil moisture, which is often the most limiting factor in the southern Great plains. For sorghum, tillering can help to overcome lower planting rates. If lower planting densities are utilized and adequate resources exist, the plant produce several tillers to better utilize resources (Gerik and Neely, 1987; Kim et al., 2010). Research has suggested that decreasing tiller production can result in greater yield. Bandaru et al. (2006) showed that planting in clumps at higher densities decreased tiller production in sorghum which result in up to 100% increase in yields.

Excessive spacing, or gaps between plants occur when germination is uneven, or early-season loss of plants occurs due to unfavorable environmental conditions or pest pressure. While these non-uniform stands can cause several issues, reports on the true impact of yield have been variable. Liu et al. (2004) reported that non-uniformity of within-row plant spacing may reduce grain yield. Yield losses have been found to be greater under lower than higher population (Johnson and Mulvaney, 1980). They found out that within row plant spacing causes higher yield losses. However, Muldon & Daynard, (1981) and Erbach et al. (1972) suggested that grain yield is not affected by plant spacing.

Agriculture production systems have benefitted from incorporation of technological advances primarily developed for other industries. The modernization of agriculture has brought about many changes to the industry, including crop monitoring. Monitoring agricultural crop conditions during the growing season and relating these to crop yield potential are important and a critical component that in-field monitoring can add to production systems. Early assessment of crop growth and potential yield limitations could allow growers to develop strategic management strategies to meet crop demand and potentially minimize crop failures. Remote sensing is a way to estimate large scale plant stand density rapidly. Not only could remote sensing provide rapid detection in the early season but can provide a non-destructive method to evaluate the crop with minimum interference on the plant. An additional benefit that sensor technology adds to production agriculture is the ability to quantitatively identify variability within a field (Martin et al., 2007). Normalized difference vegetation index (NDVI) is one of the more common vegetative indice. These NDVI values are a measure of the red and near-infrared wavelength and have been shown to provide a direct relationship to crop canopy attributes such as biomass (Martin et al., 2007, Raun et al., 2007, Tucker et al., 1980, Raun et al., 2001).

Coefficient of variation (CV) was first employed as a relative measure of variation (Raun et al., 2005). A CV is affected by the value of the mean as well as by the size of the standard deviation (Mill, 1924). Variability among experimental units within experiments can be compared using CV which can be used to calculate the variability in NDVI measurements taken across a given area (Raun et al., 2007, Martin et al., 2007). Nielsen (2001) observed that in corn, for every 2.56 cm standard deviation of plant to plant spacing, there was a decrease in yield of 1.6 kg ha^{-1} from the average yield of 9.8 kg ha^{-1}. With increasing interest in grain sorghum and precision agriculture among Oklahoma farmers, the significance of yield in the state, and the vast disparity in soil and rainfall patterns, field studies are necessary for a good understanding of how grain sorghum yield responds when planted at different densities in different location. Also, the potential of using NDVI and CV of NDVI to predict plant density and making useful planting decisions should be examined. The objectives of this study are to (1) evaluate the impact of planting density on grain yield (2) quantify the response of grain sorghum yield to within -row plant spacing (3) determine the ability to utilize NDVI and CV of NDVI to estimate early season – planting densities.

CHAPTER II

REVIEW OF LITERATURE

PLANTING DENSITY

Planting density is essential to reach maximum yield potential (Godsey et al., 2012). Too high of a density can result in intraspecific competition leading to excessive above-ground growth, lodging, and subsequent yield loss. However, lower planting densities can result in increased weed competition and low light interception which can in turn result in lower yield potential. Godsey et al. (2012) noted that planting density did not correlate with the number of harvested plants in sorghum with part of these differences being associated with tiller production. They reported that under favorable growing condition, sorghum can grow tall and tiller vigorously, with a 20-30% increase in final harvested population due to tillering in most environments of the southern plains. Berenguer and Faci (2001) also reported that sorghum can take advantage of tiller production during optimal or above-average conditions leading to near optimum yields. In addition, Conley et al. (2005) also discovered the impact of head number in increasing sorghum grain yield. He reported that plant density did not have a significant impact on total head count or test weight ($P>0.05$). Head number per plant was greatest at 75,000 plants ha^{-1} and nearly double the head number per plant of other densities used (150,000, 225,000, 300,000 and 375,000 plants ha^{-1}). They also found that lower planting densities did result in lower grain yield. Additionally, Staggenborg et al. (2013) studied the effects of row spacing and planting density on grain sorghum in Kansas using 25, 50 and 76 cm rows at 75,000, 150,000 and 225,000 plants ha^{-1}. They reported increased grain sorghum yield with increasing planting density up to 150,000 with no further increase as population increased to 225,000. They mentioned that sorghum yields were stable across a wide range of plant populations and attributed this to plants ability to adjust panicle number per plant and seed number per panicle in response to the conditions encountered during the growing season.

USING NDVI AND CV OF NDVI TO ESTIMATE CROP GROWTH

Coefficient of variation (CV) is a statistical parameter of the dispersion of data from a probability distribution. The CV value is defined as the ratio of standard deviation to the mean, expressed in percentage terms, or simply the standard deviation as a proportion of the mean (Freund and Wilson, 2003).

Alharbi et al. (2019) carried out a study on prediction of maize population using normalized difference vegetative index (NDVI) and coefficient of variation (CV). The study was based on the possibility of using NDVI and CV to predict plant population. There was a significant relationship between plant population and NDVI at the V4 growth stage. A slightly weaker relationship was found at later growth stages, where the relationship significantly decreased as canopy closure occurred. This observation suggests that the early growth stages are the best time for sensor technology application for prediction of plant population. Their observation was consistent with results reported by Ahmadi and Mollazade (2009) who suggested that plant population can be correlated with NDVI. They found that NDVI increased with increasing plant populations with a coefficient of determination of 0.92. Therefore, using NDVI to predict the population could be possible at early growth stages. Trout et al. (2009) also observed a strong relationship with a coefficient of determination of 0.95 between NDVI and canopy cover, which is the percentage of the area covered by plant leaves. The results of their studies agreed that higher NDVI values indicated increasing plant biomass.

An extra advantage that sensor technology adds to cropping systems is the capacity to quantitively distinguish variability within a field. Spatial variability may be characterized as the least distance between two objects that a sensor can record. Many studies have shown that variability has some impact on the growth, development, and yield of crops (Simonett, 1983; Raun et al., 1986; Nielsen, 2001; Martin et al., 2007). Trout et al. (2009) also estimated the relationship between plant population and coefficient of variation (CV) at different vegetative growth stages V4, V6 and V8. Plant population was negatively correlated to the CV values in the growth stage V4, and the highest relationship was recorded on that stage where a coefficient of determination was 0.21. There was a weak relationship between plant population and CV at growth stages V6 and V8, and the change in CV values was stable at those stages. Results of their study suggest that when CV increased the plant population decreased, also the observation of growth stage V4 indicates that the prediction of plant population at this stage may provide the accurate estimation of plant population because it has been observed when CV was greater than 25% that plant population decreased. Their conclusion was consistent with results reported by Lukina et al. (2000), who observed that the CV of NDVI values decreased with increasing vegetation coverage. Also, results of the study correspond with another study conducted by Arnall et al. (2006), who observed that the plant density of the winter wheat was low when CVs reached around 20 at early growth stages. From the study, they were not able to reliably predict plant density at later growth stage because the canopy covered the soil with overlapping leaves.

Raun et al. (2005) observed in a study evaluating development and spatial variability in corn using optical sensor readings, that low NDVI values were the result of sensing bare soil associated with uneven plant stands and some missing plants. They recorded the first peak in CV at V6 and reported that this is the stage where spatial variability is the greatest. A second CV peak was recorded just between VT and RI. They mentioned that the plants with more immature tassels had darker green colors and higher average NDVI. The spatial difference in colors led to increased CVs which dropped later once all the tassels had emerged due to the color detected by the sensor. These results show the potential of using NDVI readings to highly certain crop biometric, such as biomass or yield potential. Arnall et al. (2006) conducted a study on relationship between CV measured by spectral reflectance and plant density at early growth stages of wheat. The relationship between plant density and CV of NDVI readings was evaluated over the 7 site-years that was used for the study. The first peaks in CV were observed near the Feekes 6 growth stage. This coincides with the time when spatial variability is the greatest Raun et al. (2005). They reported that this suggests the time when variable rate technology could have the greatest benefit. Their result was similar to Raun et al. (2005) who observed a peak in CV in corn at the V6 stage and inferred that the peak could represent the best time to apply in-season foliar N fertilizer as that was the time when spatial variability of NDVI values were greatest. From their evaluation, a critical CV of 20 was determined using a linear-plateau model. When CV's were greater than 20, plant population was poor with < 100 plants m^{-2}, that is CV increased as plant density decreased with a R^2 value of 0.36. They concluded that adding an estimate of plant density to yield prediction models can improve the model.

Martin et al. (2007) in their study on expression of variability in corn as influenced by growth stage using optical sensor measurements discovered that, the stage with the highest correlation of CV to plant density was between V7 and V9 ($R^2 > 0.85$). At the earlier growth stages, (V3-V6) the correlation was between 0.59 and 0.77. After the V9 growth stage, coefficient of determination value decreased from 0.85 to 0.56 at V10 and continued to decrease thereafter. At V6 through V12 growth stages, NDVI was related to plant density (R^2=0.30 through 0.72, $P < 0.05$), but no statistically significant correlation was found before the V6 or other growth stages. Corn grain and biomass yields were correlated with plant density and negatively correlated with CV. The study gave a good evidence of the fact that plant density can be estimated in crops via CV generated from NDVI readings. The relationship was said to decrease dramatically as canopy closure occurred (V10 growth stage) thus suggesting that sensor technology application for assessment of density should occur before V10 in corn. They suggested that in corn, CV could allow the estimation of plant density in corn as it reveals areas yield potential cannot be reached because of how sparse the plants are. They concluded by suggesting that by combining the results found from NDVI generated with time, CV with time, yield, and plant spacing, the optimum growth stage at which remote sensors could be used can be deciphered for the various uses of remote sensors.

Arnall et al. (2006) studied the relationship between coefficients of variation measured by spectral reflectance and plant density at early growth stages in winter wheat. A critical CV range of 17 to 20% was determined. The maximum CV occurred near Feekes 6 growth stage. A low linear relationship (0.17) was found between NDVI and yield. At lower CV, 10 or less, there was not significant relationship (0.002). The highest CV observed during the study was 45 while a critical CV of 17 was found. They reported that the result from the study corresponds with the result presented by Morris et al. 2005 who observed plots of winter wheat with CV greater than 18. Also, they observed that when CVs were greater than approximately 20, the plant population was poor with <100 plants m^{-1}. In conclusion, they recommended that CVs can be used as an estimate of variation in plant stand densities.

Raun et al. (2005) studied growth stage, development and spatial variability in corn evaluated using optical sensor readings. The study was carried out to characterize expressed spatial variability as a function of physiological growth stage. Their work suggested that the point V6 whereby plant variability was best recognized should theoretically be the same time at which to sense and treat spatial variability. They noted that the peak in CVs followed by another peak in CVs as corn plants approached maturity. From V9-R4 growth stages, the variability in plant spacing/growth was masked due to overlapping leaves and canopy closure. They laid emphasis on the fact that early season NDVI readings have been highly correlated with total biomass and yield potential. Researchers have been able to successfully predict crop growth. A study by Prasad et al. (2006) on crop yield estimation model for Iowa using remote sensing and surface parameters. The study shows that they were able to develop a model which reasonably minimizes inconsistency and errors in yield prediction giving high R values and maximum accounting of variability in model. The method was effectively used to predict crop yield for crops like corn and soybeans.

CHAPTER III

METHODOLOGY

Field Trials Experiment:

Field experiments were established at OSU North Central Research Station Lahoma and Cimarron Valley Research Station Perkins in the summer of 2019 and only Cimarron Valley Research Station Perkins in 2020. Trials were established in different areas at the Cimarron Valley Research Station in different years. This was done to minimize weed pressure between two years. Temperatures and rainfall for each year and location are given in Figures 1. The dominant soil series and soil descriptions for the different site years are listed in Table 1. Prior to plot establishment, soil samples were collected across the trial areas and submitted to the Soil, Water, and Forage Analytical Laboratory at the Oklahoma State University. These samples were used to guide nutrient applications.

The field trials were arranged in a single factor randomized complete block design at each location with four replications. Six plant densities (43,225; 74,100; 111,150; 148,200; 185,250; 222,300) were utilized to evaluate influence of planting densities. Three additional planting density arrangements were evaluated, including planting density of 148,200 plants ha^{-1} with 0.3, 0.6, and 0.9 m gaps within row (Figure 2). These in-row gaps were established at approximately 30 days following planting. The layout and design of the experiment was similar across locations and years. Plots measured 9.1 by 1.5 m with two rows per plot with 76-cm spacing was planted. Agronomic management, including planting and harvest dates as well as hybrid utilized are outlined in Table 2. At planting, a combination of S-metolachlor and atrazine (Bicep Lite II Magnum- 321 g a.i. L^{-1} of atrazine and 395 g a.i. L^{-1} of S-metolachlor; Syngenta; Basel, Switzerland) were applied at the rate of 4.23 L ha^{-1}. In-season weed were managed through physical removal. Throughout the season, all agronomic management was conducted through best management practices in accordance with Oklahoma Cooperative Extension Service.

At physiological maturity and less than 30% grain moisture, all plots from other locations were desiccated using a 1,728 g a.e. ha^{-1} application of glyphosate (Roundup PowerMAX; Monsanto; St. Louis, Missouri). Fourteen days following application, plots were harvested using a Wintersteiger small plot combine (Wintersteiger; Ried im Innkreis, Austria). Plot weights were used to estimate yield on a per hectare basis.

STATISTICAL ANALYSIS

Statistical analysis was also performed in SAS 9.4 (SAS Institute Cary, NC). An analysis of variance was performed to determine the impact of planting density on grain yield using a Procedure Mixed analysis. Planting density was the only effect considered fixed while, but year and location were random. Due to significant interactions between both years and location with treatment, all site-years were analyzed separately. A post-hoc analysis was conducted using a Tukey adjustment to determine differences between individual treatment means. All analysis and mean separation were done with a α=0.05.

Sensing Methods and Techniques

A separate analysis was done to determine the potential of using remote sensing on grain sorghum planting densities. The trial outlined above was utilized as the primary plots for the analysis. However, to gather additional information, the Oklahoma Grain Sorghum Performance Trials were also utilized at Lahoma in 2019. Field procedures, experimental layout and in-season management for the planting density are above, while similar information is available for the sorghum performance trial on the Oklahoma Extension Service website (https://extension.okstate.edu/fact-sheets/grain-sorghum-performance-trials-in-oklahoma.html). Approximately thirty days after planting, stand counts were counted to determine the plants per unit area. Stand counts were taken by counting the number of plants along 30ft of row for both rows for each plot. This count was performed prior to tillering therefore each shoot was recorded as a plant. Sensor readings nor plant stands were conducted for the treatments with intentional gaps placed in-row. The number of plants in each plot was used to calculate number of on a plants per hectare basis. A GreenSeeker™ Optical sensor (Trimble Industries, Inc) was used to collect NDVI at the early stage of sorghum growth on a weekly basis. Data collection started at approximately four weeks after planting and continued for four consecutive weeks. Table 3 shows the date the NDVI data were collected. A similar protocol was utilized for the sorghum performance trials in 2019. The NDVI value was determined by scanning each row of the plot using a hand held sensor called GreenSeeker placed 75cm to 100cm above the plant to determine the reflectance of the plant at red light having a wavelength of approximately 660 nanometers and reflectance of the plant at near infra-red light having a wavelength of approximately 780 nanometer (Martin et al., 2007; Raun et al., 2005; Tucker et al., 1980).

$$NDVI = (NIR - red)/ (NIR + red)$$

Besides determining NDVI for a plot (by finding the average value for the two rows that make up a plot), the Coefficient of Variation(CV) was also calculated by performing several measurements of NDVI within a plot to determine the standard deviation and mean within the plot (Raun et al., 2005; Senders, 1958). Like NDVI, CV of NDVI was determined for each row of the plot and averaged to create a singular CV of NDVI value for each plot.

$$CV = \text{Standard deviation} / \text{Mean}*100$$

STATISTICAL ANALYSIS

Statistical procedures for the remote sensing portion of the analysis was conducted using R statistical package (R Foundations, Vienna, Austria). Furthermore, all data was processed and displayed in Microsoft Excel (Microsoft Corp., Redmond, Washington). Procedure Regression was done to perform a regression analysis to determine the relationship between planting densities and NDVI and CV of NDVI. Model components, including slope, intercept, and coefficient of determination, were taken, and transcribed on graphs produced in Excel. For all analysis an $\alpha=0.05$ was utilized.

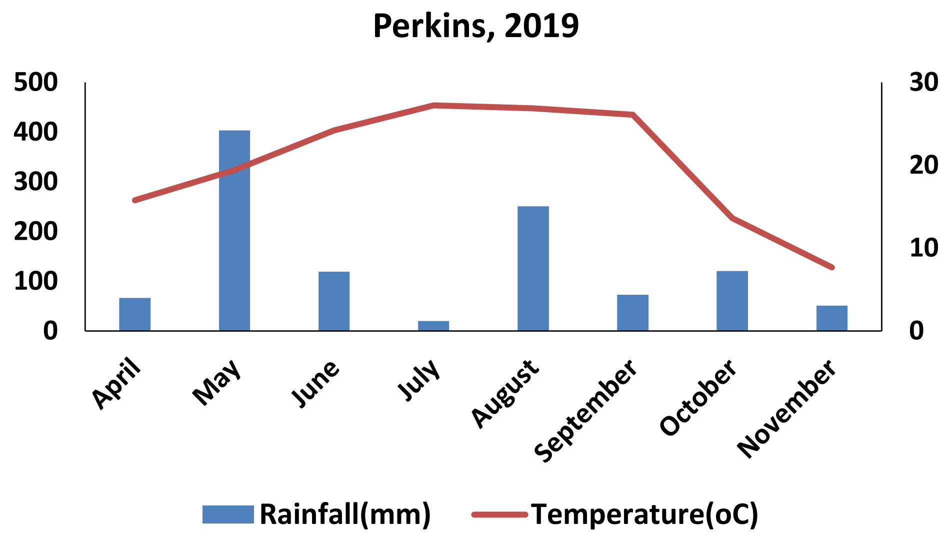
Table 1. Classification of the soils used for the experiment

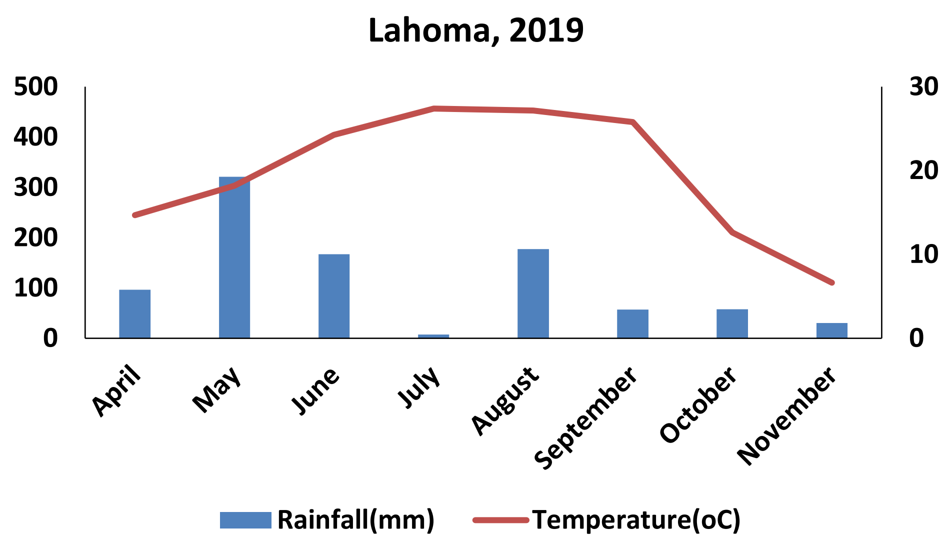
Location	Soil Classification
Perkins	Fine-loamy, mixed, active, thermic Ultic Haplustalf Teller fine-loamy, mixed, active, thermic Udic Argiustoll
Lahoma	Fine Silty, mixed, superactive, thermic, Udic Argiustoll

http://nue.okstate.edu/Soil_Classification.html

Table 2. Planting date, variety, seeding rate for all experimental sites

Location	Crop Year	Planting date	Variety	Seeding Rate (seeds ha^{-1})	Harvest Date
Lahoma	2019	04/16/2019	SP68 – 57	43,225 – 222,300	09/11/2019
Perkins	2019	05/14/2019	SP68 – 57	43,225 – 222,300	09/12/2019
	2020	05/20/2020	SP68 – 57	43,225 – 222,300	08/27/2020


Perkins, 2019
500
400
300
200
100
0
30
20
10
0
April
May
June
July
August
September
October
November
Rainfall(mm)
Temperature(oC)


Lahoma, 2019
500
400
300
200
100
0
30
20
10
0
April
May
June
July
August
September
October
November
Rainfall(mm)
Temperature(oC)

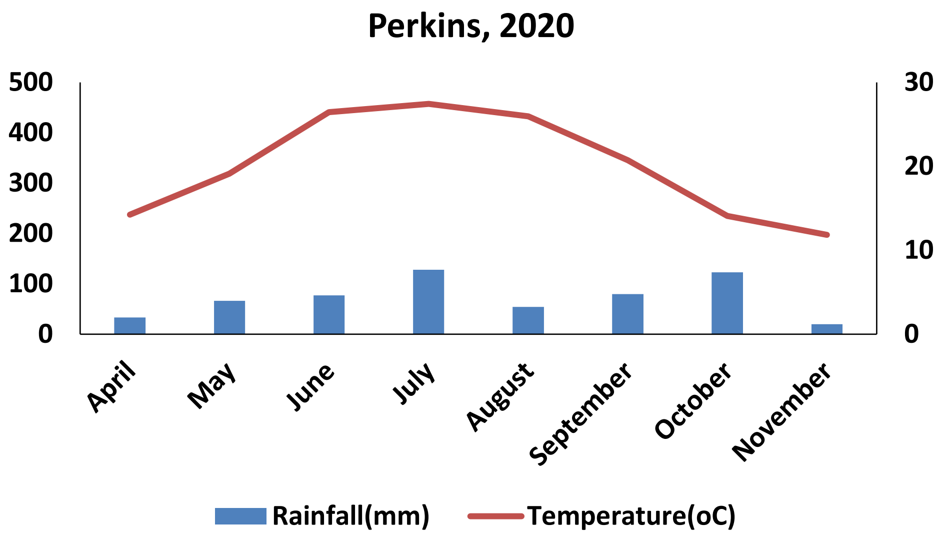


Figure 1. Temperature and rainfall observed during the 2019 and 2020 growing season at Lahoma and Perkins, Oklahoma (2019 and 2020, MESONET).

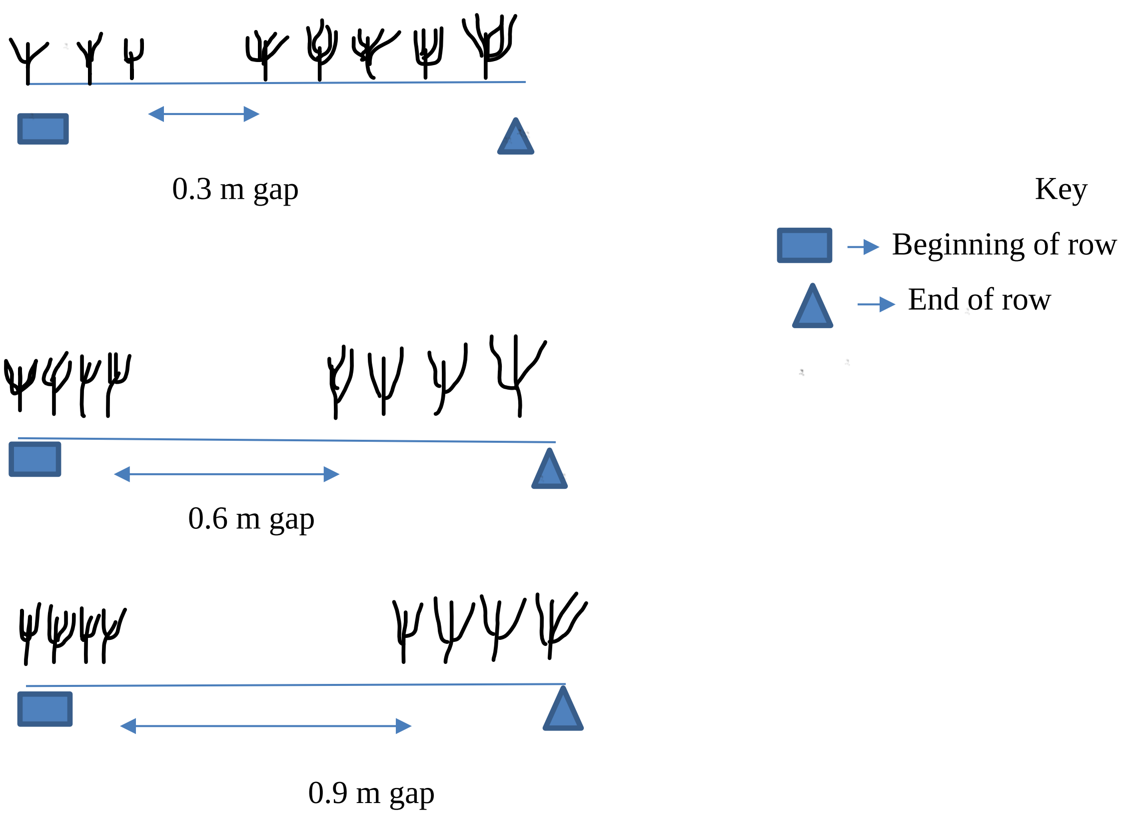


Figure 2. Hypothetical sketch of the gaps (within -row spacing) at 148,200 plants ha^{-1}.

Table 3. Location, year, and date of NDVI data collection

Location	Year	Date	Days from Planting
Lahoma	2019	05/10/2019	24
Lahoma	2019	05/15/2019	29
Lahoma	2019	05/24/2019	38
Lahoma	2019	05/31/2019	45
Perkins	2019	05/30/2019	16
Perkins	2019	06/07/2019	24
Perkins	2019	06/17/2019	34
Perkins	2019	06/26/2019	43
Perkins	2020	06/15/2020	26
Perkins	2020	06/21/2020	32
Perkins	2020	06/29/2020	40
Perkins	2020	07/03/2020	44
	Sorghum Variety Trial		
Lahoma	2019	05/15/2019	24
Lahoma	2019	05/24/2019	29
Lahoma	2019	05/31/2019	38
Lahoma	2019	06/10/2019	55
Lahoma	2019	06/19/2019	64

CHAPTER IV

RELATIONSHIP BETWEEN NDVI READINGS, CV OF NDVI AND PLANTING DENSITY

ABSTRACT

Enhancing crop production with remote sensing systems is a developing technology. This trial documented the progression of normalized difference vegetative index (NDVI) during the early growth stages of grain sorghum, estimated the spatial variability in terms of CV(calculated from NDVI readings) and the relationship between NDVI, CV of NDVI and plant density. Nine planting densities in two locations in Oklahoma were used for the study. An optical sensor was used to collect NDVI readings at the early growth stage. Low relationship was found between NDVI and planting density. The highest relationship between CV of NDVI and planting density was at 4WAP. Depending on the year, significant yield decline was noted between 75,100 and 111,150 plants^{-1} which represented 30%, 55% and 12% reduction in yield for Lahoma 2019, Perkins 2019 and Perkins 2020 respectively. A critical CV of NDVI value would range from 9.4 to 11.9%. if these values were to be used as a critical level for producers to consider replanting. The work does show that a model could be further developed to help aid in both replant and management decisions based on early season stands.

Results and Discussion

Relationship between NDVI readings and planting density

Planting density Trial

Overall, NDVI did not have a significant relationship with planting density. The lack of significant relationship indicated that the slope was not significantly greater than zero. This is evident by the P-Values noted in Figure 2 through 5, where there was not clear trend between planting density and NDVI. Additionally, the relationship between NDVI and planting density was extremely low (0.0037, 0.0084, 0.0074 and 0.0016 at 4, 5, 6 and 7WAP respectively) throughout the sampling period. This result is different from similar studies in other crops, such as corn (Alharbi et al., 2019 and Ahmadi & Mollazade, 2009), which found a relationship of 0.22 and 0.92 respectively at early growth stages and a significant relationship between NDVI and plant density. Corn plant has a relatively large plant height and larger number of leaves than sorghum at the early growth stage (Scarsbrook and Doss, 1973; Kiesselbach, 1999; Frank,2010). This might be the reason why a low relationship was found between NDVI and sorghum at these early growth stages.

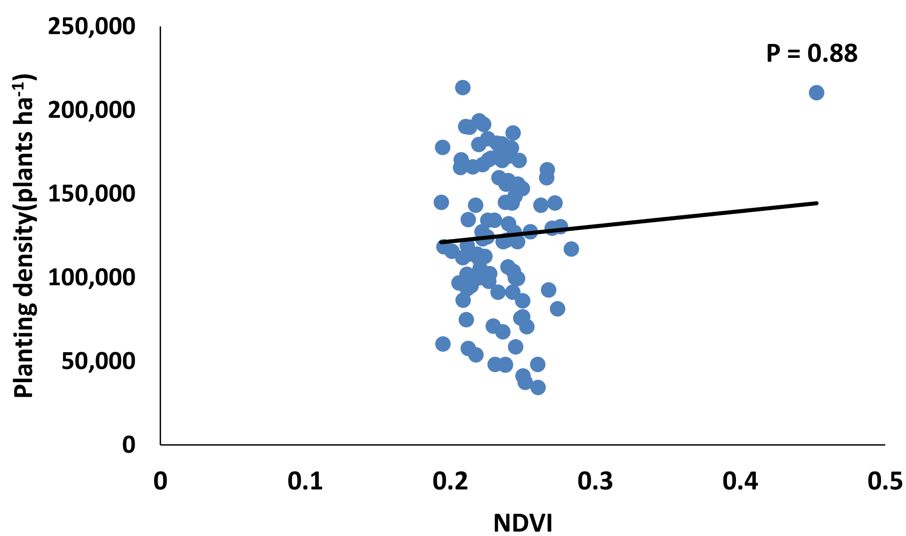


Figure 3. Relationship between NDVI readings and planting density of grain sorghum at 4 weeks after planting (4WAP) at Lahoma and Perkins in 2019 and 2020. Data for slope,

intercept, and coefficient of determination are not provided due to a lack of significant relationship, as indicated by the P-value shown.

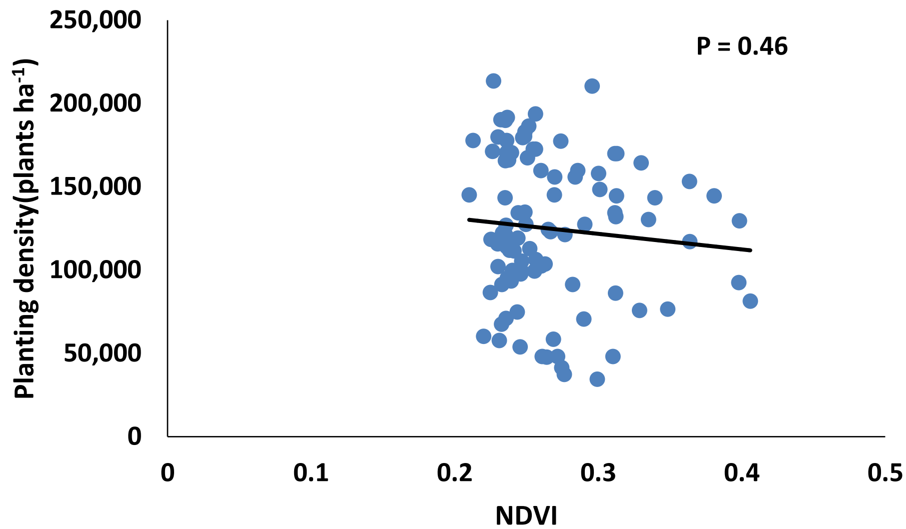


Figure 4. Relationship between NDVI readings and planting density of grain sorghum at 5 weeks after planting (5WAP) at Lahoma and Perkins in 2019 and 2020. Data for slope, intercept, and coefficient of determination are not provided due to a lack of significant relationship, as indicated by the P-value shown.

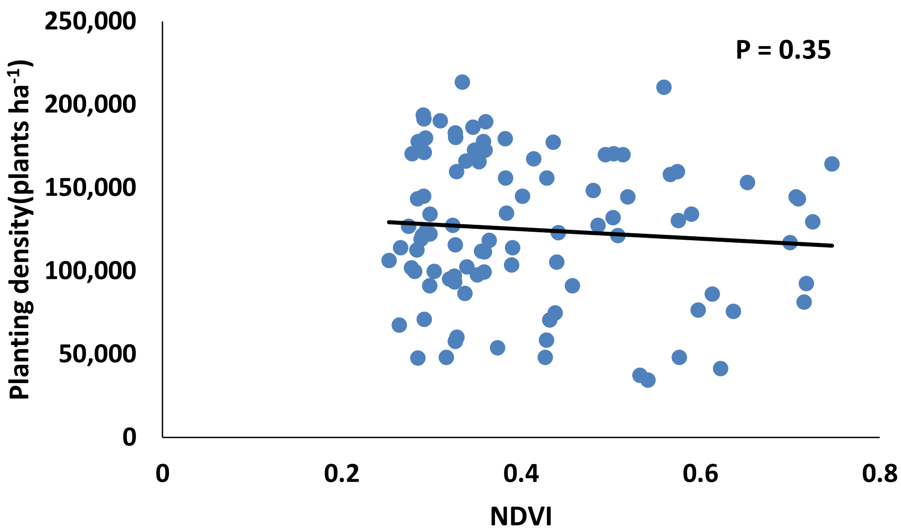


Figure 5. Relationship between NDVI readings and planting density of grain sorghum at 6 weeks after planting (6WAP) at Lahoma and Perkins in 2019 and 2020. Data for slope, intercept, and coefficient of determination are not provided due to a lack of significant relationship, as indicated by the P-value shown.

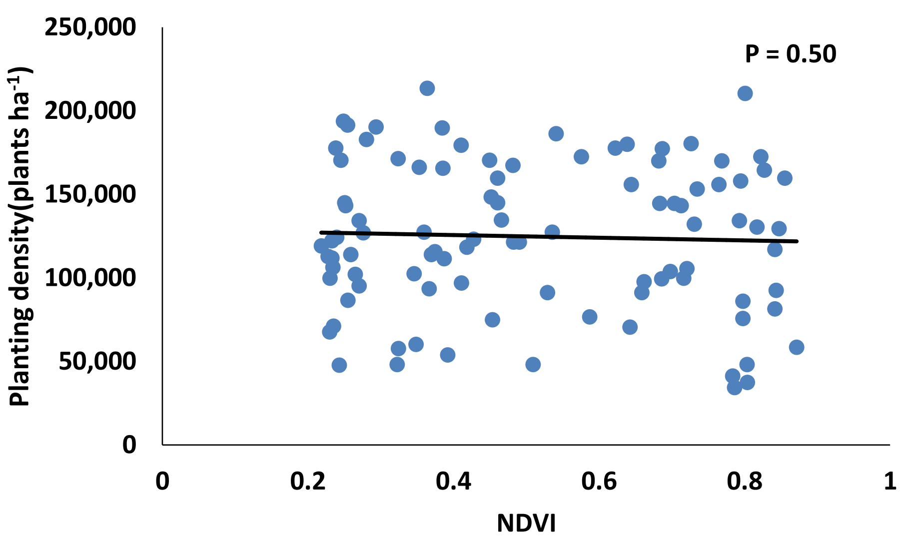


Figure 6. Relationship between NDVI readings and planting density of grain sorghum at 7 weeks after planting (7WAP) at Lahoma and Perkins in 2019 and 2020. Data for slope,

intercept, and coefficient of determination are not provided due to a lack of significant relationship, as indicated by the P-value shown.

CV of NDVI and Planting density

Planting density Trial and Sorghum Performance Trial

A significant relationship existed between CV of NDVI and planting density for both planting density trial and sorghum performance trial at 4 WAP (Figure 6). At 4 and 5 WAP in the planting density trial and 4 through 7 WAP in the sorghum performance trial, a negative relationship existed indicating that as planting density increased, CV of NDVI decreased in accordance with slope values (Appendix 1 &2 and 5 through 8). The strongest relationship was associated with 4 WAP sampling period for both trials with coefficient of determination values of 0.61 and 0.43 for planting density trial and sorghum performance trial. The major reason for the decreased in relationship at later sampling periods were due to increased variability at the higher planting density (Govaerts and Verhulst, 2010). This could partially be due to the number of tillers produced by sorghum during early growth stages. Higher tiller vegetative material, due to tillers and increased growth, could saturate the sensor with little of the background visible. Furthermore, if greater biomass has accumulated from the plants and subsequent tillers, differences in NDVI values associated with variable planting densities are reduced due to a lower impact of the soil background. This should result in CV of the NDVI values having more to do with differences in growth stage and nutrient status compared to the planting density. Similar results were reported by Arnall (2004) and Martin et al. (2007) when using a similar optical sensor to evaluate the relationship of CV of NDVI readings to plant density in wheat and corn respectively. They found out that CV of NDVI increased as plant density decreased and that the CV of NDVI measurement is related to plant density. They detailed that CV of NDVI seem to permit the estimation of plant density, in this way uncovering the areas where plants are well scanty to reach the potential of other zones with more prominent plant density. Even though there was reduction in relationship between CV of NDVI and planting density as plant grows during the sorghum performance trial (Appendix 6 through 9), significant differences were observed between planting densities and CV of NDVI throughout the study. This can be traced to a lot of varieties studied compared to what we observed in the planting density and CV of NDVI study when one variety was used where planting density had no significant difference on CV of NDVI as plant grows. Previous studies (Zulfiqar and Asim, 2002 and Ghani et al., 2015) reported the effect of varieties on sorghum biomass production. They detailed that plant phenotype is dependent on the genotype and environmental factors. The effect of genotype reflected more to show the significant differences obtained among the varieties.

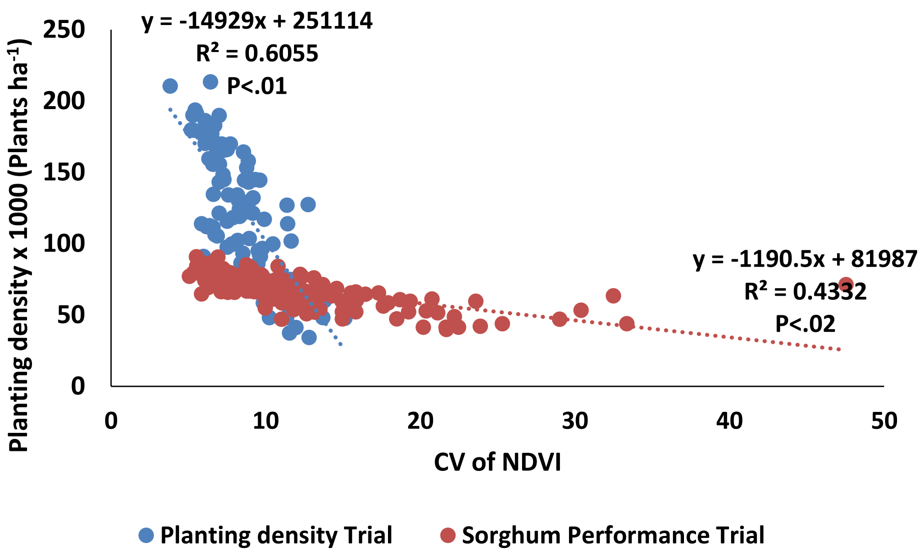


Figure 7. Relationship between CV of NDVI readings and planting density of both planting density trial and sorghum performance trial at 4 weeks after planting (4WAP) at Lahoma and Perkins in 2019 and 2020.

CONCLUSIONS

NDVI did not have a significant relationship with planting density. Additionally, the relationship between planting density and NDVI was extremely low throughout the period of study. Between 43 to 61% of variation in NDVI values can be accounted for by planting density at 4 WAP. This is the highest relationship recorded between CV of NDVI and planting density. The relationship decreased at latter growth stages as plant grows. This could be due to increased variability because of number of tillers produced by sorghum which could saturate the sensor with little of the background visible.

Varieties influenced the relationship between CV of NDVI and planting density as significant differences were found throughout the period of investigation of the sorghum performance trial when compared to planting density trial. A critical CV of NDVI values of 9.4 to 11.9% could be considered by producers for replanting, although this is also based on environmental conditions.

Additional research is required to develop a model to aid both replant and management decisions based on early season stand. This is necessary to establish a critical stand limit.

CHAPTER V

PLANTING DENSITY AND GRAIN SORGHUM YIELD

ABSTRACT

With increasing interest in grain sorghum among Oklahoma farmers, the significance of yield in the state and vast disparity in soil and rainfall patterns, field studies are necessary for a good understanding of how grain sorghum yield responds when planted at different densities in different location. This study was conducted to evaluate the impact of various planting densities on grain sorghum yield and to quantify the response of grain sorghum yield to within-row plant spacing. Field trials were carried out in Lahoma and Perkins, Oklahoma in 2019 and 2020 to investigate how grain sorghum yield responds when planted at different densities in various locations. Optimum growing conditions such as above average rainfall and temperature resulted in increasing yield with increasing planting density at Lahoma in 2019. However, at Perkins in 2019, optimum planting density were 111,150; 148,200 and 185,250 plants ha^{-1}. At Perkins in 2020, grain sorghum yield varied significantly with lowest density 43,225 and highest density 223,500 recording relatively low yield of 3.2 and 3.3Mgha^{-1} respectively. Within row spacing had no impact on grain sorghum yield at Lahoma in 2019. However, at Perkins in 2019 and 2020, extremely low yield was recorded for 0.9m gap. Planting density, location and year of planting had significant impact on grain sorghum yield. 111,150 plants ha^{-1} has been found to optimize productivity while limiting overplanting. This is a good resource for producers interested in grain sorghum.

RESULTS

Lahoma 2019

Grain sorghum yield was significantly different among the planting density. Generally, grain sorghum yield increases with increasing planting density. Lowest yield was recorded at the 43,225-planting density and was significantly different from all other planting densities. The highest yielding treated was the 185,250-planting density, which yielding 5.6Mg ha^{-1}. However, this was not significantly different from 148,200 and 223,500 plants ha^{-1} which recorded 4.9 and 5.4 Mg ha^{-1} of grain sorghum respectively. Both the 74,000 and 111,150 planting densities yielded significantly lower than the highest yielding planting densities but were not significantly different from each other (Figure 7). A numerical decrease in sorghum yield was noted in sorghum planted with gaps, with yield decreasing by just over 0.6Mg ha^{-1} with the 0.9 m gaps; however, these yield decreases were not significantly different from sorghum planted at 148,200 plants ha^{-1} with no implemented gaps (Figure 8).

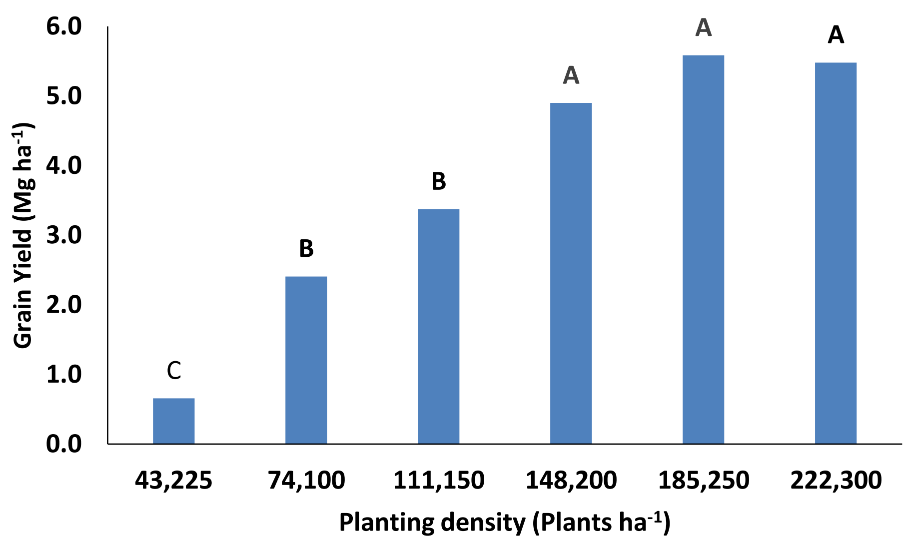


Figure 8. Grain Yield of Sorghum planted at different densities in Lahoma in 2019

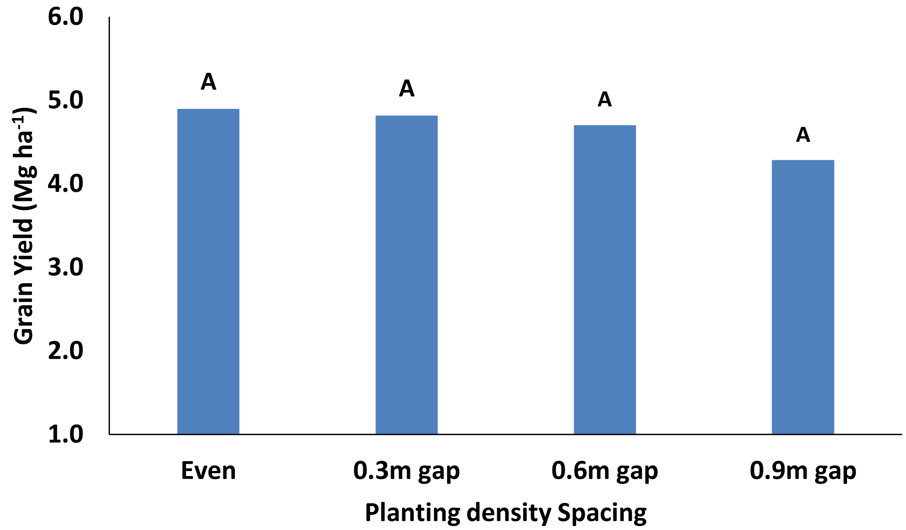


Figure 9. Grain Yield of Sorghum planted at 148,200 plants ha^{-1} planting density at different spacing in Lahoma in 2019

Perkins 2019

Significant differences were found among the planting density used for this study. Planting densities 111,150, 148,200, and 185,250 were significantly different (with yields of 3.1, 3.4 and 3.3 Mg ha^{-1} respectively) from the lower densities of 43,225 and 74,100 which recorded 0.6 and 1.4Mg ha^{-1} respectively. Yield was lower at the lowest density 0.6 Mg ha^{-1}. The primary reason for the low yield at 43,225 plants ha^{-1} was attributed to low plants to make use of the abundant soil and environmental resources. For the grain sorghum planted in gaps, a decrease in yield was recorded with increase in gaps (Figure 9). No significant difference was observed among 148,200 (Even), 0.3 m gap and 0.6 m gap where a yield of 3.4, 3.1 and 2.9Mg ha^{-1} was recorded. However, there was a significant difference between Even and 0.9 m gap which recorded 2.1 Mg ha^{-1}. The primary reason for the low yield can be attributed to extremely low plants at this density because of the wide gap in between the plants (Figure 10).

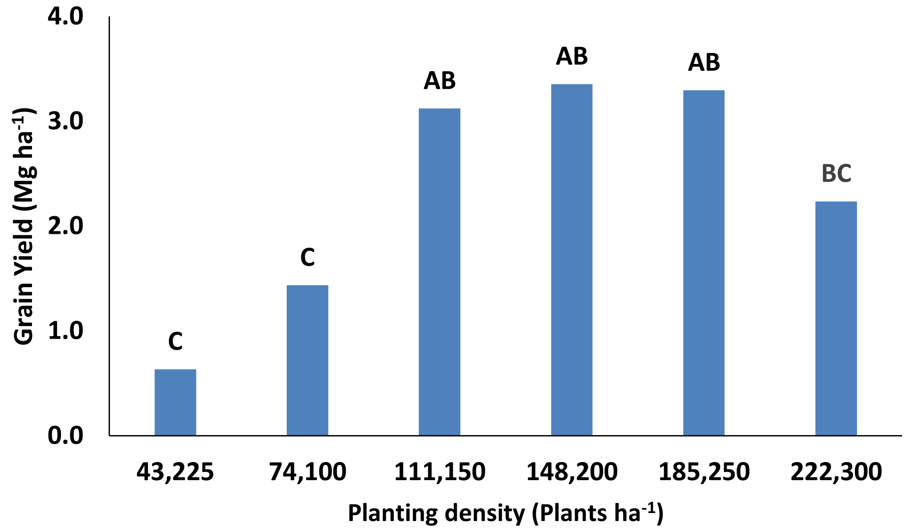


Figure 10. Grain Yield of Sorghum planted at different densities in Perkins in 2019

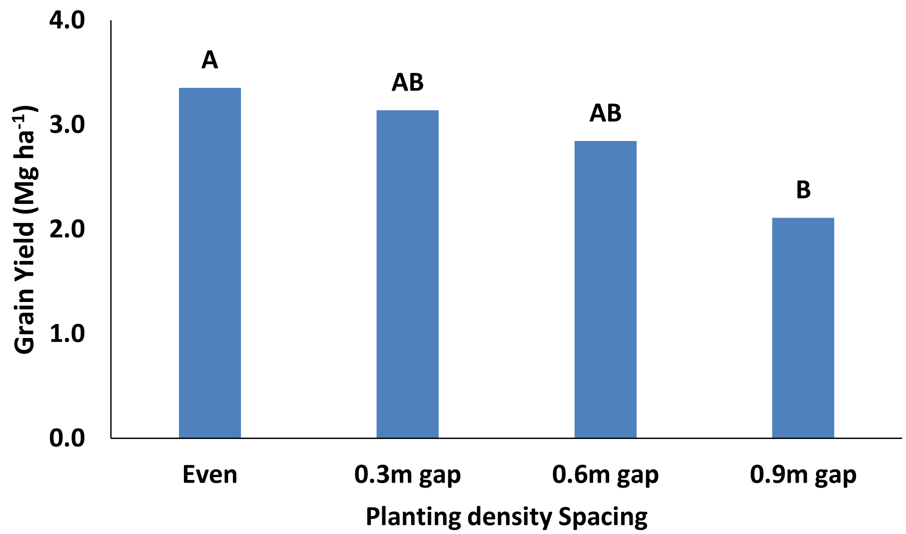


Figure 11. Grain Yield of Sorghum planted at 148200plants ha^{-1} planting density at different spacing in Perkins in 2019

Perkins 2020

A significant difference was found among the grain sorghum yield across the densities. At Perkins in 2020, 111,150 planting density was the highest yielding treatment at 4.9 Mg ha^{-1}, which was significantly higher than all other treatments (Figure 11). No significant difference was found among 74,100, 148,200 and 185,200 planting densities. Also, 43,225 and 223,500 plants ha^{-1} recorded yields that were not significantly different, yielding 3.2 and 3.3 Mg ha^{-1} respectively. Significant differences were found among 148,200 planting density planted in gaps (Figure 12). 4.2, 4.3, 4.3 and 3.7 Mg ha^{-1} were recorded for even, 0.3m gap, 0.6m gap and 0.9m gap respectively.

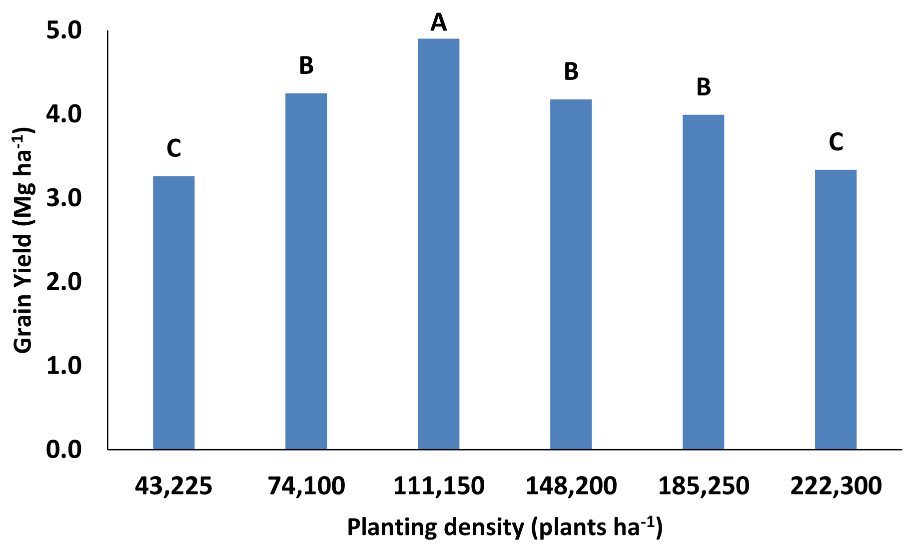


Figure 12. Grain Yield of Sorghum planted at different densities in Perkins in 2020.

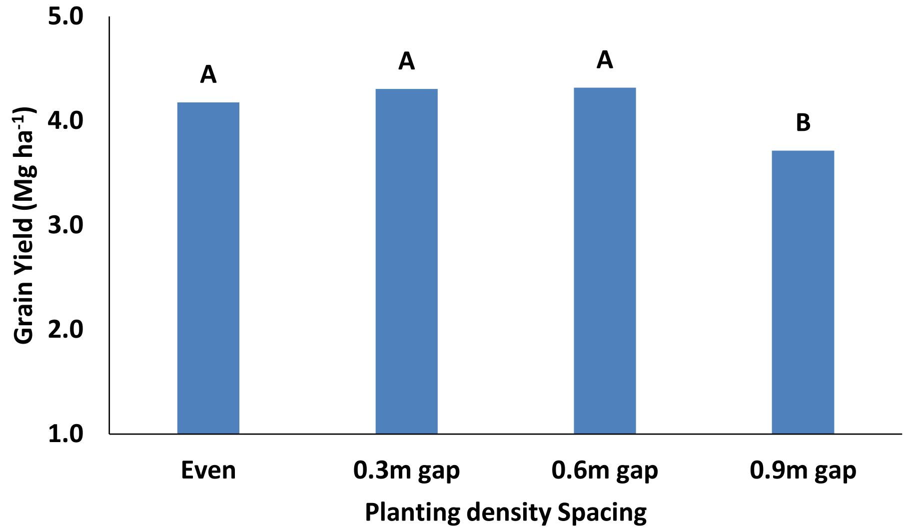


Figure 13. Grain Yield of Sorghum planted at 148200plants ha^{-1} planting density at different spacing in Perkins in 2020.

DISCUSSION

The higher yields at highest planting densities at Lahoma in 2019 were not expected due to this location typically being associated with hotter and drier conditions during critical growth stages. This would often result in a greater benefit of lower planting densities and the crop being able to take advantage of tiller production during optimal or above-average conditions (Berenguer and Faci, 2001). However, optimum conditions, such as above average rainfall and temperatures, can result in increasing yields with increasing planting densities (Welch et al., 1966; Staggenborg, 2013). Lahoma recorded very high rainfall during the active growing season. Total rainfall during active growing season were above the normal (10 years average). This higher rainfall did result in early-season flooding. While this did not impact the integrity of the site location, the lower planting densities were more severely impacted by delayed emergence, low early-season growth, and greater late-season weed pressure. High yield at high density could be because of accumulation of individual plant yield to give bigger yield. This result is like Welch et al. (1966) and

Staggenborg (2013) observation. They reported that in the presence of adequate growing condition, production of grain sorghum increased with increasing density.

At Perkins in 2019, tillering in sorghum did not compensate for the low density because number of plants per unit area is too low for the area of land. Optimum planting density were 111,150, 148,200 and 185,250 plants ha^{-1} as yield decreased to 2.2 Mg ha^{-1} at 223,500 plants ha^{-1}. Similar result was reported by Staggenborg et al. (2013), which observed sorghum yield was steady over a wide range of plant populations with either consistent or decreased yields at higher planting densities. They attributed the ability to maintain consistent yields over a wide range of planting densities to plant's capacity to alter panicle, number of plants, and seed number per panicle in response to growing conditions during development. In July 2019, during the boot stage and grain filling stage, Perkins experienced excessive water deficit compared to 2020.This might be the reason why low yield was recorded in 2019. Inuyama et al. (1976) reported a decrease in yield because of water stress during booting and grain filling periods and they accorded this to greater effect on limiting head size. They reported that severe deficit during boot stage reduced grain yields to a much greater extent than during earlier vegetative development because of greater effect on limiting head size. Other investigators reported critical stages of drought stress in grain sorghum. This include milk stage (Plaut et al., 1969), heading through grain filling (Musick et al., 1971), heading through bloom (Shipley et al., 1970), and boot through bloom (Lewis et al., 1974).

At Perkins in 2020, grain sorghum yield varied significantly with lowest density 43,225 and highest density 223,500 recording relatively low yield. The primary reason for this is that at lower density, sorghum tillers and produce more grain because of lower competition for nutrient and other environmental resources. While at higher density, competition for nutrient and other resources makes the plant produce much lower than their potential (Kim, 2010). This might be the reason why there was no significant difference between the yield of the lowest and highest planting density. Better yields were recorded in Perkins in 2020. Though sorghum is a drought tolerant crop, however rainfall was higher during the most critical growing season when compared to 2019. This could be the reason why better yield was recorded. Similar results were reported by Grischar, 2007. He observed variations in the effect of planting density in soybean. He also reported that effect of planting density on soybean yield varied from year to year depending on variety and rainfall received during the growing season in a location.

The within-row spacing responded differently based on their location. At Lahoma in 2019, the within-row spacing had no significant impact on grain sorghum yield. The reason for this might be tillering at the highest spacing or the spacing was not big enough to cause a significant difference in this high yielding location. However, at Perkins in 2019 and 2020, extremely low yield was recorded for 0.9 m gap. This was significantly lower from others in 2020 where even, 0.3 m gap, 0.6 m gap and 0.9 m gap yielded 4.2, 4.3, 4.3 and 3.7 Mg ha^{-1} respectively. However, 0.9m gap was only significantly different from even planting density spacing in 2019. The primary reason for extremely low yield at 0.9 m gap is because plants were too low at that density. This is related to Vanderlil et al., 1988 and Caravetta et al., 1990 who reported significant yield reduction as plant spacing variability increased in corn and sorghum respectively.

Conclusion

Higher yield with increasing planting density at Lahoma in 2019 was not expected due to the location being associated with hotter and drier conditions during critical growth stages. The high yield was because of very high rainfall recorded during the active growing season. The optimum planting density recorded were 111,150; 148,200 and 185,250 plants ha^{-1} as yield decreased to 2.2 Mg ha at 223,500 plants ha^{-1} at Perkins in 2019. In addition, tillering in sorghum did not compensate for the low density because the number of plants per unit area is too low for the area of land. At Perkins in 2020, relatively low yield was recorded at 43,225 and 223,500 plants ha^{-1}. Within row spacing had no significant influence on yield at Lahoma in 2019. However, 0.9 m gap differed significantly from others at Perkins in 2019 and 2020.

In conclusion, 111,150 plants ha^{-1} has been found to optimize productivity while limiting overplanting. Optimum yield is dependent on the environmental conditions prevalent in a location in a particular year.

CHAPTER VI

SUMMARY AND CONCLUSIONS

Determining critical CV of NDVI value

The work highlighted above shows that remote sensing, specifically the variation of NDVI values could be used to determine plant density if measured early in the season. An important use of this would be to determine if fields need to be replanted. This is a little more difficult of a task, as a critical value for both plant density as well as CV of NDVI would need to be determined. Based on the field trial, significant yield declines were noted between 75,100 and 111,150 plants ha^{-1}, depending on the year. This yield reduction represented a 30%, 55%, and 12% reduction in yields for Lahoma 2019, Perkins 2019, and Perkins 2020, respectively. If these values were to be used as a critical level for producers to consider replanting, critical CV of NDVI value would range from 9.4 to 11.9%. These values are much lower than the 20 CV found by Arnall et al. (2006). Previous work has noted that nearly a 30% stand reduction from optimum is needed to significantly reduce stands (Larson and Vanderlip, 1994). Furthermore, it has been shown in this study that optimum planting populations vary on the year based on environmental conditions, which are often not known until past the ability to make replant decisions. Therefore, the work does show that a model could be further developed to help aid in both replant and management decisions based on early season stands; however, a known critical stand limit needs to be established.

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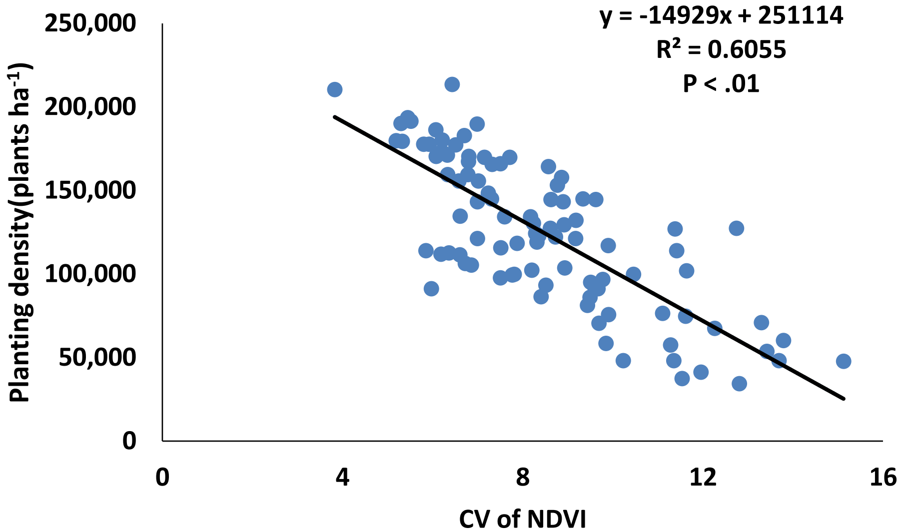
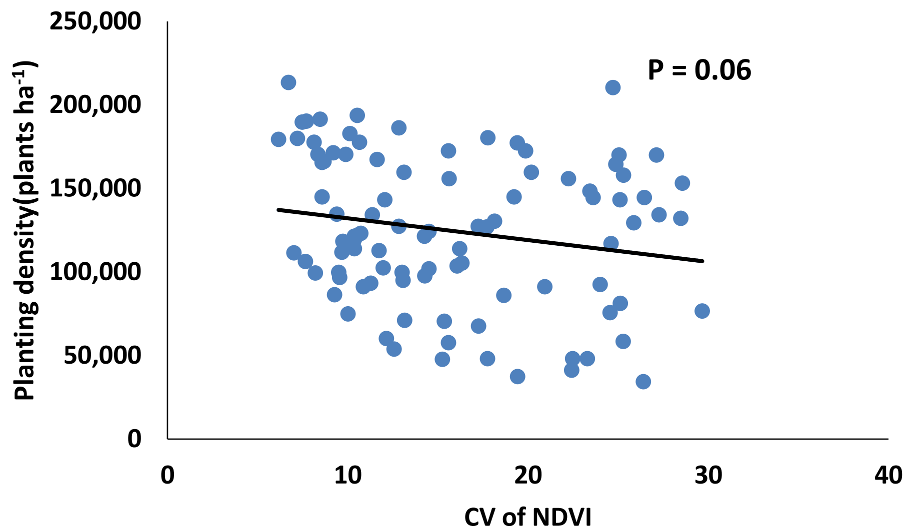
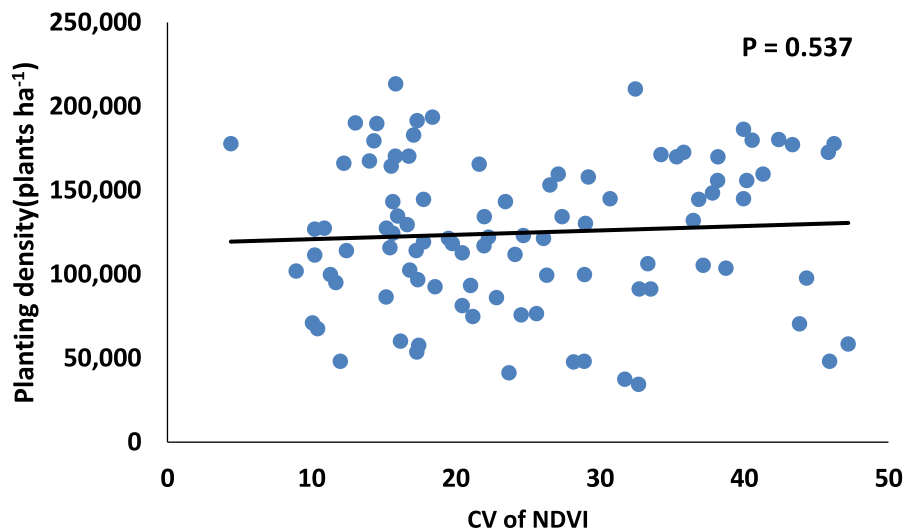
APPENDIX



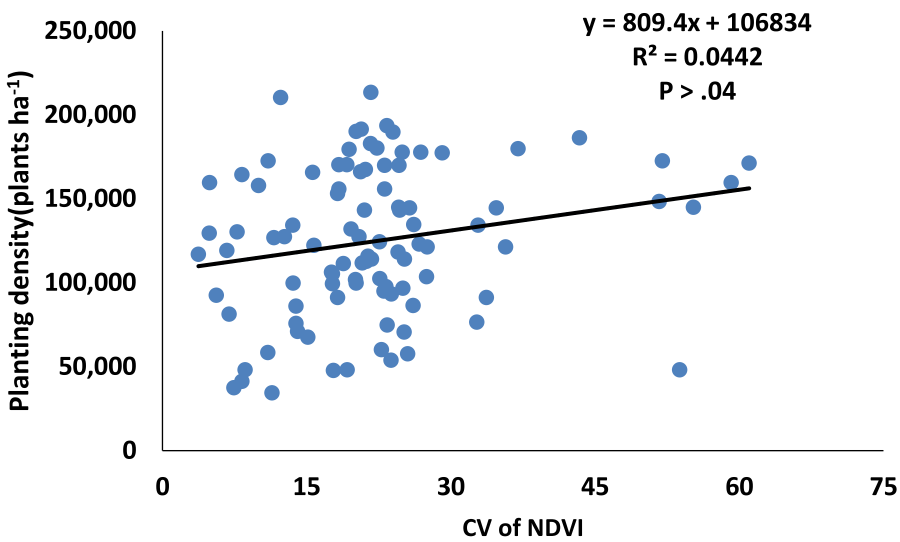
Relationship between CV of NDVI readings and planting density of grain sorghum at 4 weeks after planting (4WAP) at Lahoma and Perkins in 2019 and 2020.



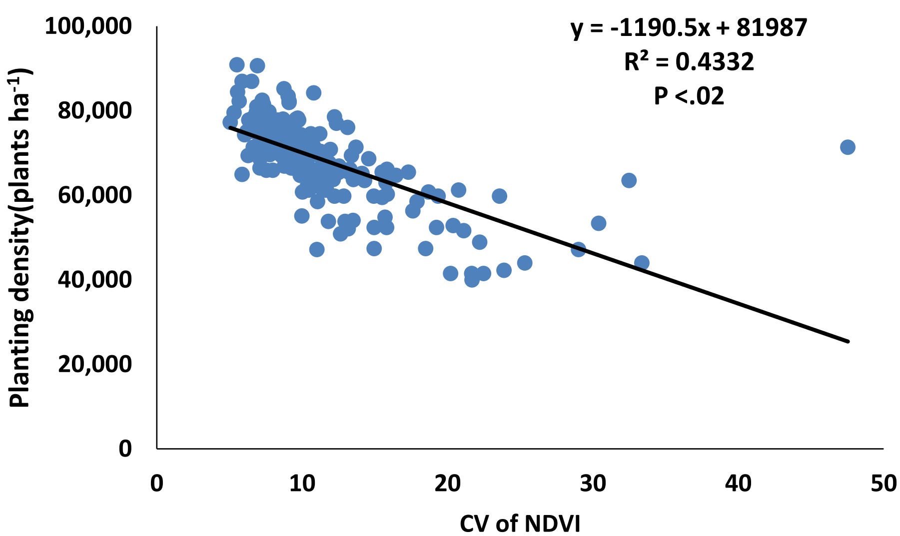
Relationship between CV of NDVI readings and planting density of grain sorghum at 5weeks after planting (5WAP) at Lahoma and Perkins in 2019 and 2020. Data for slope, intercept, and coefficient of determination are not provided due to a lack of significant relationship, as indicated by the P-value shown.



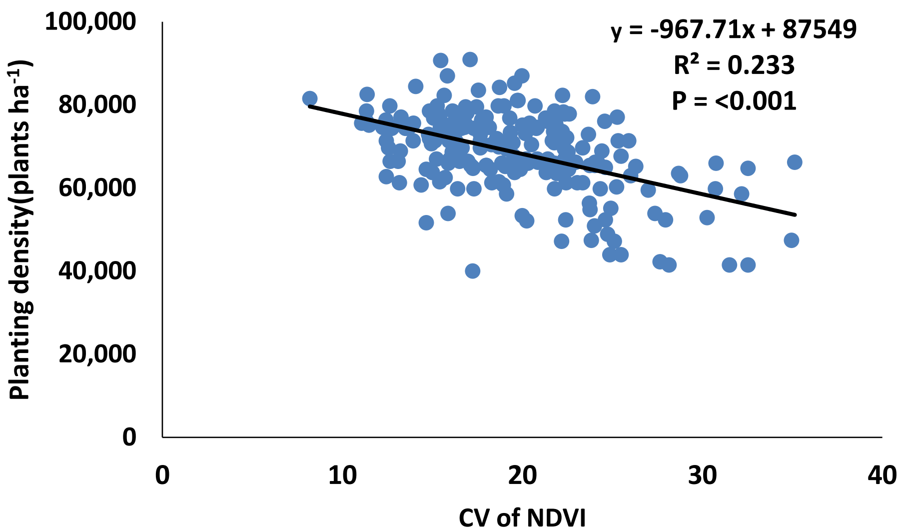
Relationship between CV of NDVI readings and planting density of grain sorghum at 6weeks after planting (6WAP) at Lahoma and Perkins in 2019 and 2020. Data for slope, intercept, and coefficient of determination are not provided due to a lack of significant relationship, as indicated by the P-value shown.



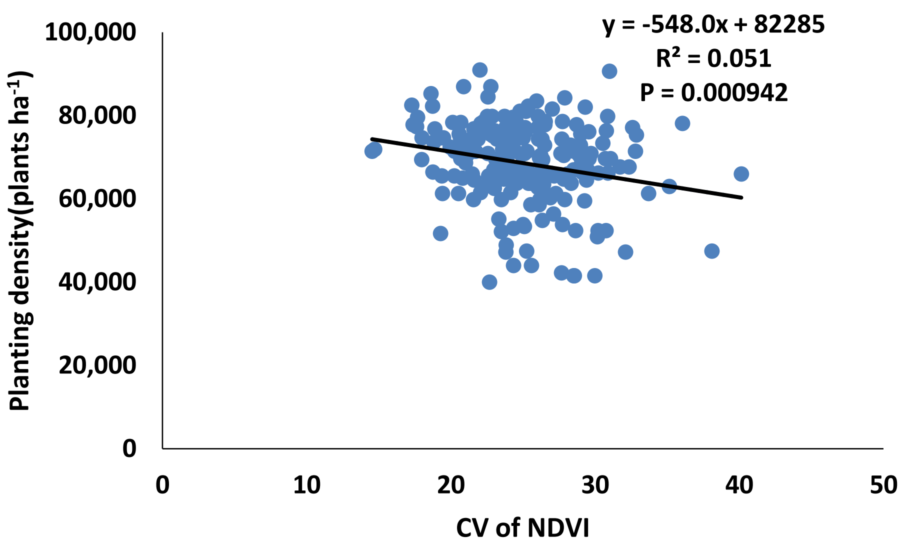
Relationship between CV of NDVI readings and planting density of grain sorghum at 7weeks after planting (7WAP) at Lahoma and Perkins in 2019 and 2020.



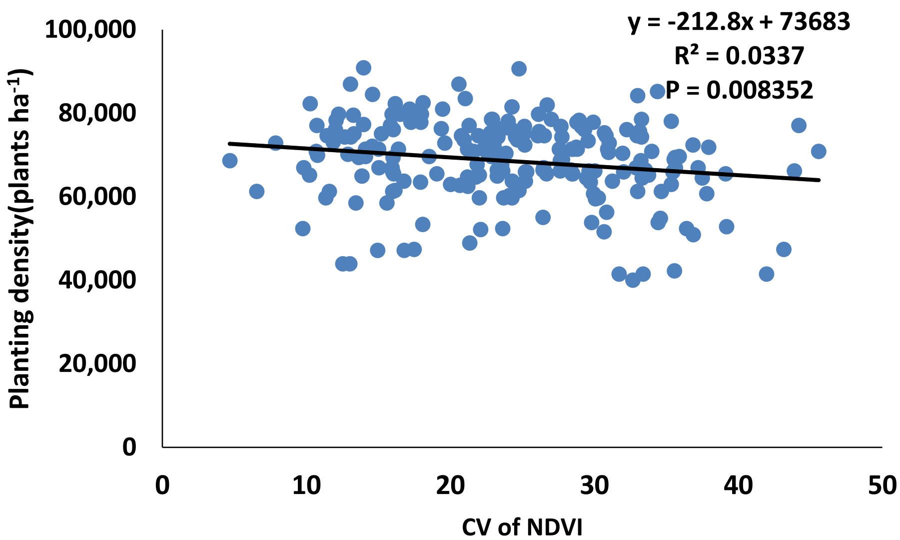
Relationship between CV of NDVI readings and planting density of grain sorghum at 4weeks after planting (4WAP) at Lahoma in 2019.



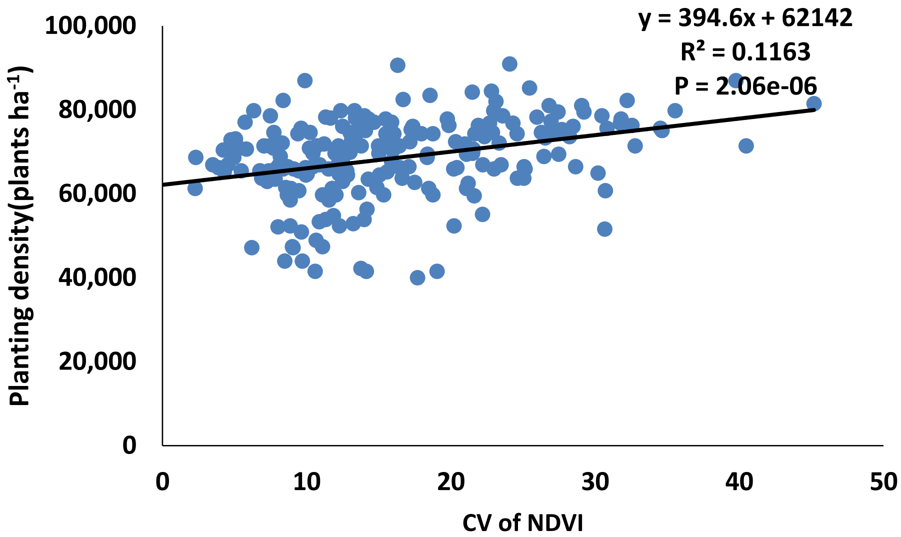
Relationship between CV of NDVI readings and planting density of grain sorghum at 5weeks after planting (5WAP) at Lahoma in 2019.



Relationship between CV of NDVI readings and planting density of grain sorghum at 6weeks after planting (6WAP) at Lahoma in 2019.



Relationship between CV of NDVI readings and planting density of grain sorghum at 7weeks after planting (7WAP) at Lahoma in 2019.



Relationship between CV of NDVI readings and planting density of grain sorghum at 8weeks after planting (8WAP) at Lahoma in 2019.

VITA

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