EVALUATING THE EFFECTS OF SOIL PH ON GRAIN SORGHUM (*SORGHUM BICOLOR)* AND SUNFLOWER *(HELIANTHUS ANNUUS* L.*)* PRODUCTION

By

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ABSTRACT

The transition from conventional tillage to no-tillage production systems has led to the incorporation of grain sorghum and sunflower as rotation crops; however, these crops may not perform well when grown on acidic soils. This study was conducted to determine the quantitative effect of soil pH on grain sorghum and sunflower production. The relationship of relative yield and soil pH were investigated at Lahoma, Perkins, and Haskell, OK with soil pH treatments ranging from 4.0 – 7.0. Soil pH was altered using aluminum sulfate or hydrated lime. Soil acidity negatively affected grain sorghum and sunflower yield. At soil pH 5.42 and 5.27, yield reductions of 10% were observed in grain sorghum and sunflower, respectively. Yield reductions of 20% or more were observed at soil pH 5.14 and 5.08 in grain sorghum and sunflower, respectively. Liming should be considered to increase soil pH if it is below these critical levels where grain sorghum or sunflower will be produced.

CHAPTER I

INTRODUCTION

Continuous conventional tillage winter wheat is the most widely grown crop in Oklahoma (Small Grains, 2010). Producers throughout Oklahoma are converting areas of conventional tillage to no-tillage systems (Edwards, et al., 2006). A key component of successful no-tillage production systems is the integration of crop rotations, which help break weed, disease, and insect cycles (Edwards, et al., 2006). Due to their ability to tolerate warm and relatively dry climates, grain sorghum and sunflower are well suited for crop rotations in the Central Great Plains.

Grain sorghum and sunflower have traditionally been grown on soils with a pH of >6.5 (Mask et al., 1988); however, a review of soil test results in 2005 by the Potash & Phosphate Institute observed that 46% of the tested samples in Oklahoma had a soil pH of <6.0 (PPI, 2005). The use of aluminum (Al) tolerant wheat varieties and banding of phosphorus (P) fertilizers has allowed producers to grow winter wheat in unfavorable pH conditions. Because of this, many producers are not accustomed to considering liming in their management decisions. Winter wheat can tolerate a soil pH as low as 5.5 (Zhang and Raun, 2006). With the integration of grain sorghum and sunflower into Oklahoma production systems, many of these acidic soils may need to be limed; whereas, this may not have been necessary with winter wheat.

This study focused on establishing relative yield values for grain sorghum and sunflower with respect to soil pH. Relative yields are useful for determining if there is a yield reduction associated with soil acidity, and if so, to what extent these reductions occur at varying soil pH levels. This information will be helpful for producers when determining if liming an acidic soil is economical and necessary. The use of relative yield, rather than absolute yield, allows the removal of some bias associated with multiple locations and varying growing conditions in this study. Relative yield in this study is expressed as a percentage of maximum yield potential for that location. Relative yield will be calculated as:

$$\text{Relative Yield}_{max} = [(\text{Actual yield}) / (\text{Maximum yield for that site})]$$

or

$$\text{Relative Yield}_{avg} = [(\text{Actual yield}) / (\text{Average of 3 highest yields for that site})].$$

This method of expressing yields has been used in previous extension based research. The Virginia Official Variety Test for soybean reports its results as relative yields to remove bias that occurs with multi-year averages when varieties are not tested at each location (Holhouser, 2010). Utah State University Cooperative Extension reported relative yields for various crops such as alfalfa, wheat, and barley in a water salinity publication (Hill and Koenig, 1999). With relative yields it will be possible for producers to determine the possible level of yield reduction depending on soil pH and whether liming is necessary and cost effective.

The exact quantitative effect of soil pH on grain sorghum and sunflower yield has not previously been established. The majority of research relating to soil acidity in the Central Great Plains has focused on winter wheat, while some studies have focused on determining the most acid tolerant varieties of grain sorghum and sunflower (Kariuki et al., 2007; Duncan, 1987; Krizek and Foy, 1988). Determining the behavior of grain sorghum and sunflower grown on soil varying in pH will be a useful tool for educating producers and agronomists about the importance of liming acidic soils. Without this research many producers may be satisfied with the status quo and lose yield by attempting to produce high yielding grain sorghum or sunflower on soils that may be too acidic.

CHAPTER II

REVIEW OF LITERATURE

Characteristics of Soil Acidity

Soil acidity is a major issue in production agriculture throughout the world, and an estimated 50% of the world's arable land is acidic (Kochian et al., 2004). These soils are characterized by high base cation leaching capacity, low base saturation, and low availability of P (Duncan, 1987). Soil pH is determined by the amount of H^+ in the soil solution and is expressed as the negative logarithm of hydrogen concentration. As H^+ concentration increases soil acidity also increases (USDA). As soil pH drops below 5.5, Al and manganese (Mn) become more soluble; therefore, more Al and Mn become plant available leading to the possibility of toxicities. Acid soils often have very high concentrations of Al, Mn, and iron (Fe) which may lead to nutrient imbalances and other nutrient deficiencies, including P, magnesium (Mg), and calcium (Ca) (Duncan, 1987). In acid soils a large portion of the cation exchange capacity (CEC) is occupied by Al ions leading to a high Al saturation (Haynes et al. 2001). The most prominent symptom of Al toxicity is the inhibition of root growth, which leads to nutrient deficiencies and water stress (Kochian et al., 2004).

Ohki (1987) stated that Al interferes with the uptake, transport, and utilization of Ca, Mg, P, and potassium (K). The reduced availability of P is one of the noted deficiency symptoms associated with acidic soils. The high levels of Al lead to the adsorption of P rendering it unavailable to the plant (Haynes et al., 2001). Duncan (1987) noted that soil acidity may cause injury in several different ways, such as a specific nutrient deficiency, drought susceptibility due to root damage, herbicidal injury, low temperature damage, or plant disease (Duncan, 1987). The reduction of P availability further inhibits root growth, thus exacerbating Al toxicity (Johnson and Zhang, 2004).

Causes of Soil Acidity

Soils become acidic as a result of parent material, rainfall, decay of organic matter, removal of basic cations, intense farming methods, and the use of ammoniacal nitrogen (N) fertilizers (Spies et al., 2007). Generally soils developed from calcareous parent material, such as limestone, will be less acidic than soils developed from granitic parent material (Anderson, 1988). Rainfall affects soil pH through the contribution of H^+ by the leaching of basic materials and naturally occurring acid rain forming carbonic acid in the atmosphere when water and carbon dioxide combine. As organic matter decays, carbon dioxide is produced and combines with water forming carbonic acid which releases H^+. Cations are absorbed by the plant in excess of anions leading to the removal of basic cations and contributing to soil acidity. This, however, is not a significant source of soil acidity in a non-agricultural environment where the bases in the crop residue are recycled to the soil and not removed with harvest. The addition of high rates of N fertilizers results in higher yields and an increased rate of removal of bases with the harvest of biomass. Ammoniacal N fertilizer use increases soil acidity through its biological oxidation to nitrate (NO_3^-) which produces two H^+ (Spies et al., 2007).

Neutralizing Soil Acidity

A common method used to neutralize soil acidity is applying agricultural lime. The two primary forms of agricultural lime used by producers are calcitic ($CaCO_3$) and dolomitic ($CaCO_3MgCO_3$) lime. The lime neutralizes the acidity in the soil through the addition of basic material, thus raising the soil pH. The Ca in lime replaces the H^+ on the soil particle. The acidic material then reacts with carbonate (CO_3) to form carbon dioxide (CO_2) and water (H_2O) (Zhang et al., 2005).

Grain Sorghum and Soil Acidity

The grain sorghum plant, although smaller in size, is very similar to corn in appearance and is used primarily as a source of livestock feed in the United States. Grain sorghum is typically planted in the spring and harvested in the fall and is well suited for the hot summers of the southern Great Plains. Grain sorghum typically produces at optimum levels at an average temperature of at least 27° C (Carter et al., 1989). Grain sorghum is similar to corn in that it uses large amounts of N and moderate amounts of P and K. Combines are used to harvest the grain, or silage choppers can be used for high moisture grain silage livestock feed (Carter et al., 1989).

Previous research concerning grain sorghum and soil pH determined that as reactive Al concentration increased, the symptoms of Al toxicity also increased (Ohki, 1987). Grain sorghum plants grown in higher Al concentrations were stunted and exhibited interveinal chlorosis in the newest leaves (Ohki, 1987). Ohki studied the relationship between root Al concentration and growth and found the Al critical toxicity level for grain sorghum was 54 mmol kg $^{-1}$ tissue dry matter (Ohki, 1987).

Duncan et al. (1980) observed different grain sorghum genotypes to determine their acid tolerance. This study determined that Fe, Mn, copper (Cu), zinc (Zn), and P amounts did not vary among soil pH ranging from 4.4 to 5.5 (Duncan et al., 1980). The highest Al and lowest Ca and Mg concentrations were found at soil pH 4.4. Grain yields dropped from 2,069 kg ha^{-1} at soil pH 4.8 to 163 kg ha^{-1} at soil pH 4.4. There was also a significant yield decrease from 4,279 kg ha^{-1} to 3,557 kg ha^{-1} at soil pH 5.5 to 5.1, respectively. This decrease was attributed to Al or Mn toxicity. The study indicated that the majority of plants grown at soil pH of 4.4 didn't reach the reproductive growth stage with some of the plants dying. A 35% decrease in yield was observed from soil pH 5.1 to 4.8, and a 92% decrease from soil pH 4.8 to 4.4 (Duncan et al., 1980). The objective of Duncan et al. (1980) was to determine grain sorghum elemental concentrations and elemental uptake of Al, Fe, Mn, K, P, Cu, Zn, Mg and Ca; therefore, a maximum yield plateau to determine relative yield was not established.

Kezheng and Keltjens (1995) determined that Al toxicity was evident as damage to the roots and through the reduction of Mg availability. The deficiency of Mg contributes to the poor root growth associated with sorghum grown in acid soils (Kezheng et al., 1995). Grain sorghum plants grown in acid soils may express water stress due to root damage, which can limit their ability to extract water from the soil. In this study, liming a soil with pH of 4.3 and raising it to pH 4.7 alleviated the Al toxicity but did not help the Mg deficiency. A dolomitic lime containing both calcium carbonate and magnesium carbonate will help alleviate the Mg deficiency, as well as raise the soil pH (Kezheng et al., 1995).

Previous research at the University of Georgia concluded that the acid tolerance of sorghum genotypes was not controlled by a single nutrient. The interaction of genotype, nutrient interactions, and environmental conditions all impacted the growth and development of grain sorghum grown in acid soil (Duncan, 1987).

Flores et al. (1987) conducted an experiment to determine the variations in growth and yield associated with Al saturation of the soil. They studied both susceptible and tolerant genotypes of grain sorghum grown in both 40% (pH 4.6) and 60% (pH 4.1) Al saturation. The study determined that the acid tolerant genotypes grown at 60% Al saturation had lower root mass scores and delayed flowering. There were, however no differences in yield and growth traits for the acid tolerant genotypes grown at 40% or 60% Al saturation. The susceptible genotypes showed an improvement in yield and growth traits in the lower Al saturation than the higher Al saturation. Flores et al. concluded that all sorghum genotypes grown at Al saturation above 70% performed poorly.

Sunflower and Soil Acidity

Sunflower can be used as an oil seed, birdseed, human food, and as a silage crop. Sunflower is tolerant of high temperatures but more tolerant of low temperatures; however, sunflower will produce optimally at a range of 20 to 25° C. Sunflower is not necessarily considered a drought tolerant crop, but because of its long taproot the plant can often reach water reserves deep in the soil profile. Sunflower nutrient needs are less than that of corn and wheat and has a relatively short growing season of approximately

100 days from planting to maturity. Combines are used for the harvesting of sunflower (Putnam et al., 1990).

Previous research by Blamey, et al. (1985) found that vegetative and root growth of sunflowers was reduced at soil pH 3.5 (Blamey et al., 1985). This study also observed P deficiency symptoms including non-specific growth reductions and grey-green necrotic areas on lower leaves (Blamey et al., 1985). Blamey noted that sunflower is one of the most tolerant crops to excess Mn concentrations.

A study on the effect of hydric stress and soil acidity determined that the leaf area, volume of roots, and dry matter accumulation decreased significantly in acid soils versus near neutral soils (Petcu et al., 2001). Shoot height increased as soil pH increased, and drought tolerance of sunflower was negatively affected by soil acidity (Petcu et al., 2001).

Li et al. (1996) studied the effect of soil pH on cadmium (Cd) uptake in sunflower leaves and kernels. Soil pH is an important factor concerning Cd availability in soils (Li et al., 1996). Cadmium can be a toxic element, and plant uptake of Cd is thought to be higher in acidic soils. Applying limestone to raise soil pH did not reduce sunflower Cd uptake as was expected in this study (Li et al., 1996).

A study of Mn toxicities noted that sunflowers are tolerant of high Mn concentrations, which are characteristic of acid soils, compared to other crop species (Blamey et al., 1986). However, sunflower's ability to tolerate high Mn concentrations does not imply a tolerance to soil acidity (Blamey et al., 1986). Sunflowers are also sensitive to high Al concentrations, which is a primary characteristic of acid soils (Blamey et al., 1986).

An experiment focused on the relationship of water deficit and Al toxicity determined that sunflower is very sensitive to both acid soils and extreme water deficits (Krizek and Foy, 1988). Comparisons were made to determine the effects of Al toxicity, water stress, and the interaction of both Al toxicity and water stress. Aluminum stress caused a decrease in tissue concentration of Ca, Mg, and Fe but an increase in K, Al, Cu, Mn, and Zn concentrations (Krizek and Foy, 1988). When the soil pH was raised from 4.3 to 6.3, plants under water stress exhibited an increase in leaf tissue concentrations of Ca, Mg, and Fe and a decrease in Al, Mn, and Zn concentrations (Krizek and Foy, 1988). These results suggest that water stress and soil acidity are related and some of the adverse effects of each can be ameliorated by altering the stress level of the other.

Research has been done on the selection of Al tolerant genomes for grain sorghum and sunflower, as well as the effect of soil acidity on certain aspects of the plant; however, there is not sufficient data to develop a quantitative relationship between yields and soil pH because the research was not performed at a wide enough range of soil pH levels.

CHAPTER III

OBJECTIVE

The objective of this study is to evaluate the effect of soil pH (4.0-7.0) on grain sorghum and sunflower production grown at three sites in Oklahoma. Relative yield values will be developed to quantify the effect of soil pH on grain sorghum and sunflower yield.

CHAPTER IV

METHODOLOGY

Establishment

Three sites were selected to establish the pH conditions for the study in Oklahoma in 2009. The experiments were established at the Cimarron Valley Research Station near Perkins, OK, the North Central Research Station near Lahoma, OK, and the Eastern Research Station near Haskell, OK. Soil series of each location are noted in Table 1.

Table 1. Description of soil series at Lahoma, Perkins, and Haskell, OK.

Location	Soil Series
Perkins, OK	Teller series (Fine-loamy, mixed, active, thermic Udic Argiustolls) and Konawa series (Fine-loamy, mixed, active, thermic Ultic Haplustalfs)
Lahoma, OK	Grant series (fine-silty, mixed, superactive, thermic Udic Argiustolls)
Haskell, OK	Taloka series (Fine, mixed, active, thermic Mollic Albaqualfs)

Each location utilized a 6 x 2 factorial design consisting of 6 target soil pH treatments ranging from 4.0 to 7.0 and 2 crops, grain sorghum and sunflower. Plot size was 6 m long x 3 m wide (4 rows) with 4.6 m alleys between each replication at Lahoma and Perkins and 3 m alleys between each replication at Haskell. Grain sorghum and sunflower were planted on opposite sides of the trial in 2010 to reduce potential disease pressure; however, pH treatment structure remained the same as in the 2009 season.

For each growing season soil samples were taken from each plot prior to planting to determine actual soil pH. Soil probes were used to obtain 15-20 cores from each plot to a depth of 15 cm. The soil samples were dried at 60ºC over night and ground to pass a 2mm sieve. A 1:1 soil:water suspension and glass electrode were used to measure soil pH and buffer index (Sims,1996; Sikora, 2006). 1 *M* KCl solution was used to extract soil NO_3-N and NH_4-N and quantified using a Flow Injection Autoanalyzer (LACHAT, 1994). Mehlich 3 solution was used to extract plant available P and K (Mehlich, 1984), and the amount of P and K were quantified using a Spectro CirOs ICP spectrometer (Soltanpour et al., 1996). Soil sample results were used to generate N, P, and K rates that were applied as a blanket application over each trial in 2009 and 2010.

A previous laboratory experiment determined the rates of aluminum sulfate ($Al_2(SO_4)_3$) and hydrated lime ($Ca(OH)_2$) needed to achieve a specific change in soil pH at each location. In this laboratory experiment composite soil samples were collected from each of the experimental sites. Five incremental rates of $Al_2(SO_4)_3$ and 5 incremental rates of $Ca(OH)_2$ were each added to ½ kg subsamples from each of the locations to develop a response curve which could be used to determine the amount of material needed to reach a desired soil pH. The $Al_2(SO_4)_3$ and $Ca(OH)_2$ were mixed with the soil and wetted. The soil pH of each of the sub samples was measured at 2 weeks, 3 weeks, and 4 weeks from mixing. The change in pH associated with the different rates of $Al_2(SO_4)_3$ and $Ca(OH)_2$ were used when determining the $Al_2(SO_4)_3$ and $Ca(OH)_2$ rates needed to reach target pH in this study. $Ca(OH)_2$ was applied to raise the actual pH to the target pH. $Al_2(SO_4)_3$ was applied to lower the actual pH to the target pH. The plots were cultivated to incorporate the $Ca(OH)_2$ and $Al_2(SO_4)_3$ several months prior to planting.

Herbicide applications were applied as needed throughout the season. A 6200 Monosem vacuum planter was used for all planting. Planting dates, seeding rates, and varieties are reported in Table 2.

Table 2. Planting date, variety, and seeding rate at Lahoma, Perkins, and Haskell, OK.

Location	**Crop**	**Planting Date**	**Variety**	**Seeding Rate (seeds ha^{-1})**
Perkins	Grain Sorghum	2009 Apr 22	KS 585	123,500
Lahoma	Grain Sorghum	2009 Apr 23	KS 585	123,500
Haskell	Grain Sorghum	2009 May 26	KS 585	123,500
Perkins	Sunflower	2009 Jun 3	Triumph S671	49,400
Lahoma	Sunflower	2009 May 12	Triumph S671	49,400
Haskell	Sunflower	2009 May 26	Triumph S671	49,400
Perkins	Grain Sorghum	2010 May 4	KS 37-07	123,500
Lahoma	Grain Sorghum	2010 Apr 27	KS 37-07	123,500
Haskell	Grain Sorghum	2010 May 4	KS 37-07	123,500
Perkins	Sunflower	2010 May 4	Triumph S671	49,400
Lahoma	Sunflower	2010 May 3	Triumph S671	49,400
Haskell	Sunflower	2010 May 4	Triumph S671	49,400

Additional soil samples were taken mid-season and post harvest in each growing season to determine actual soil pH during growth, as well as nutrient levels. The final set of soil samples in 2010 were analyzed for the concentration of extractable Al in the soil. A 2.0 gram subsample from each plot was extracted with 20 ml of 1 *M* potassium chloride (KCl). Samples were placed on a shaker for 30 minutes and filtered. The amount of Al extracted with 1 *M* KCl (Al_{KCl}) was quantified using inductively coupled plasma spectrometry (ICP) (Soltanpour et al., 1996).

After harvest in 2010, deep soil cores were taken to 91 cm using a Giddings probe. Samples were taken from 3 plots with target soil pH 4.0, 6.0, and 7.0 at Perkins and Lahoma, OK. These samples were analyzed for soil pH to determine the variation in soil pH within the profile. Samples were not taken at Haskell, OK due to equipment and travel constraints.

The measurements used for analysis were plant counts taken 1-3 weeks after emergence, plant height taken at 7 leaf stage at Lahoma and Perkins and at 8 leaf stage at Haskell, NDVI readings taken at 2-5 leaf stage at Lahoma and Perkins and at 8 leaf stage at Haskell, number of harvested heads, and yield.

Plant counts were taken from the two middle rows of each treatment after emergence. In 2010 plant height was measured from 5 random plants within the two middle rows of each treatment. The Greenseeker^{TM} was used to collect Normalized Difference Vegetative Index (NDVI) readings from the middle two rows of each treatment in 2010. NDVI is calculated as:

$$NDVI = [(NIR-Red) / (NIR+Red)]$$

NIR and Red are near-infrared (780 nm) wavelengths and red (671 nm) wavelengths respectively (Mullen et al., 2003). These readings provide a measurement of biomass, plant health, and plant vigor. The red light emitted from the Greenseeker^{TM} is absorbed by plant chlorophyll. Healthier plants have a higher NDVI value because they absorb more red light and reflect more near-infrared light (Lan et al., 2009). The number of heads in the middle two rows of each plot was counted prior to being harvested by combine or by hand in 2010. The grain/seed was collected and weighed to calculate yield. Relative yield was calculated as: Relative $yield_{avg}$=[Actual yield) / (Average of 3 highest yields for the site)] for grain sorghum and Relative $yield_{max}$=[(Actual yield) / (Maximum yield for the site)] for sunflower.

Data analysis was generated using SAS® software, Version 9.2 of the SAS system (Copyright©2008) SAS Institute Inc. Exact target pH levels were not reached due to other soil factors so an exact replication of each pH level was not achieved; however, a range of high and low pH levels was established and allowed for the data to be analyzed using quadratic least squares regression and non-linear regression.

Grain Sorghum Harvest 2009

Grain sorghum at Perkins, OK sustained extensive bird damage. The plots were harvested by hand, and yield was estimated using a correlation coefficient of 0.6796 representing the correlation between head weight and grain weight. This correlation was determined using 2010 yield data and will be outlined in materials of the 2010 harvest. Grain sorghum at Lahoma, OK was harvested on August 27 with a Massey Ferguson 8XP experimental plot combine. The overall emergence was poor at Haskell, OK, and this location was not harvested.

Grain Sorghum Harvest 2010

Grain sorghum at Perkins, OK was harvested by hand on August 2. Grain sorghum at Lahoma, OK was harvested by hand on August 11. Grain sorghum heads were dried and threshed using a Massey Ferguson 8XP experimental plot combine. Grain was weighed to calculate yield. Grain sorghum at Haskell, OK was harvested by hand on August 16. Pest damage was extensive at Haskell, OK; therefore, yield was estimated using a correlation coefficient of 0.6796, as mentioned in the 2009 harvest. Heads were weighed, and then grain was removed and weighed. Head weight and grain weight were plotted to determine the correlation between the two variables. This correlation was used to calculate an estimated yield.

Sunflower Harvest 2009

The overall emergence was poor at Perkins, OK, and this location was not harvested. Sunflower at Lahoma, OK was harvested by hand on September 3. The sunflowers were dried and threshed using a Kincaid thresher. Total seed weight from each treatment was used to calculate yield. Pest damage was extensive at Haskell, OK; therefore, yield was estimated using a method described by North Dakota State University Extension Service (NDSU, 2010). Yield estimates were calculated using multipliers associated with plant population, head diameter, seed size, good seed set, and center seed set. Yield was calculated with the following formula:

2,450 x plant population x head size x seed size x seed count x center seed count = lbs acre^{-1}

Sunflower Harvest 2010

Sunflower at Perkins, OK was harvested by hand on August 9. Sunflower at Lahoma, OK was harvested by hand on August 11. The sunflowers were dried and threshed using a Massey Ferguson 8XP experimental plot combine. Seed was collected and weighed to calculate yield. Sunflower at Haskell, OK was harvested by hand on August 16. The sunflower heads were dried and threshed using an experimental plot combine.

CHAPTER V

FINDINGS

Ability to Reach Target Soil pH

On average, soil pH at Haskell (silt loam) deviated +/- 0.58 from the target soil pH. Soil pH of treatments at Lahoma (silt loam) deviated +/- 0.32 from target pH levels. Soil pH of treatments at Perkins (fine sandy loam) deviated +/- 0.26 from target pH. The accuracy at which target pH was reached is satisfactory considering this study was conducted in the field.

Soil Profile pH

Soil profile pH results indicate that soil pH was altered to a depth of approximately 31 cm at Perkins and Lahoma (Table 3, Fig. 1 & 2); however, soil pH varied from target pH throughout the profile. This variability could have masked the effect of high and low pH treatments as roots penetrated below the altered depth of the soil. However, this scenario is indicative of many Oklahoma acidic soils that are typically only acidic in the top 15 cm due to production practices (Gray and Roozitalab, 1976). The Lahoma location has a slight slope, and sheet erosion likely caused the treatment with target pH of 6 being much lower in the top 15 cm (Fig. 2).

Table 3. Post harvest soil profile pH at Perkins and Lahoma, OK for target pH treatments of 4.0, 6.0 and 7.0 (2010).

Location	**Depth**	**Soil pH**		
			Initial pH 4.86	
Perkins, OK		Target pH 4.0	Target pH 6.0	Target pH 7.0
	0-8 cm	3.97	6.34	7.43
	8-15 cm	3.81	4.81	4.81
	15-23 cm	4.29	5.46	4.50
	23-31 cm	4.96	5.39	4.57
	31-46 cm	5.79	5.84	5.56
	46-61 cm	6.16	6.27	5.85
	61-91 cm	6.24	6.29	6.04
	91 cm +	6.53	6.53	6.27
			Initial pH 5.50	
Lahoma, OK		Target pH 4.0	Target pH 6.0	Target pH 7.0
	0-8 cm	4.19	4.63	7.59
	8-15 cm	4.69	5.02	5.88
	15-23 cm	5.44	4.88	5.50
	23-31 cm	5.94	5.68	5.85
	31-46 cm	6.29	6.32	6.52
	46-61 cm	6.79	6.70	6.96
	61-91 cm	7.20	7.04	7.32

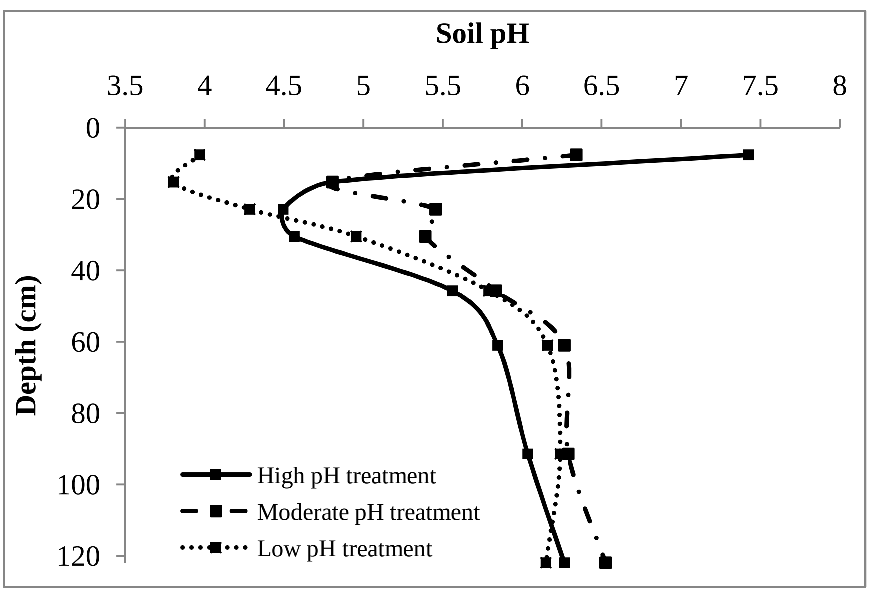

Figure 1. Post harvest soil profile pH at Perkins, OK for target pH treatments of 4.0, 6.0, and 7.0 (2010).

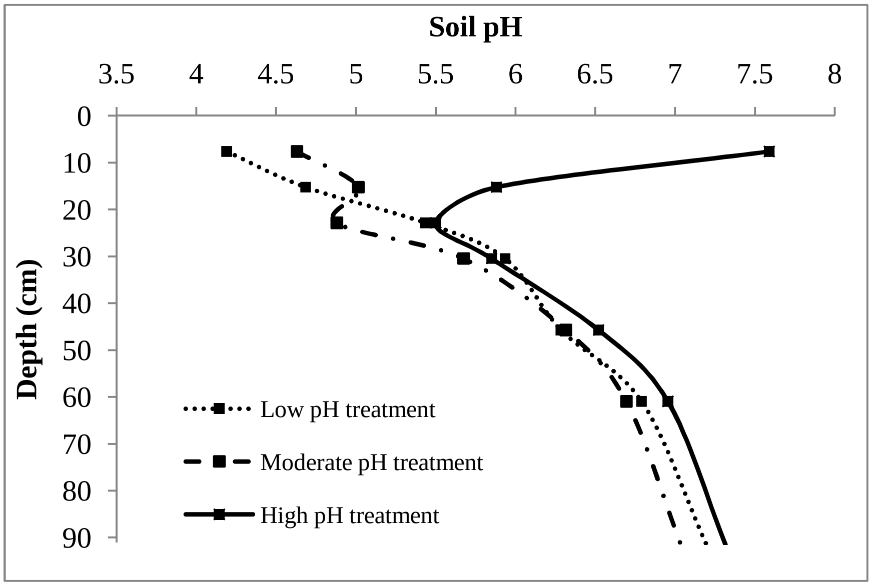

Figure 2. Post harvest soil profile pH at Lahoma, OK for target pH treatments of 4.0, 6.0, and 7.0 (2010).

Aluminum Concentration in Soil

Aluminum toxicity is one of the primary concerns when addressing soil acidity; therefore, Al_{KCl} concentration in the soil was analyzed in all plots in 2010. Soil pH and Al_{KCl} concentration in the soil were highly correlated at all sites with r^2 of 0.98, 0.93, and 0.95 at Perkins, Lahoma, and Haskell, respectively. As soil pH decreased the amount of Al_{KCl} in the soil increased (Fig. 3). The Al toxicity level varied for grain sorghum and sunflower and will be discussed later in the results.

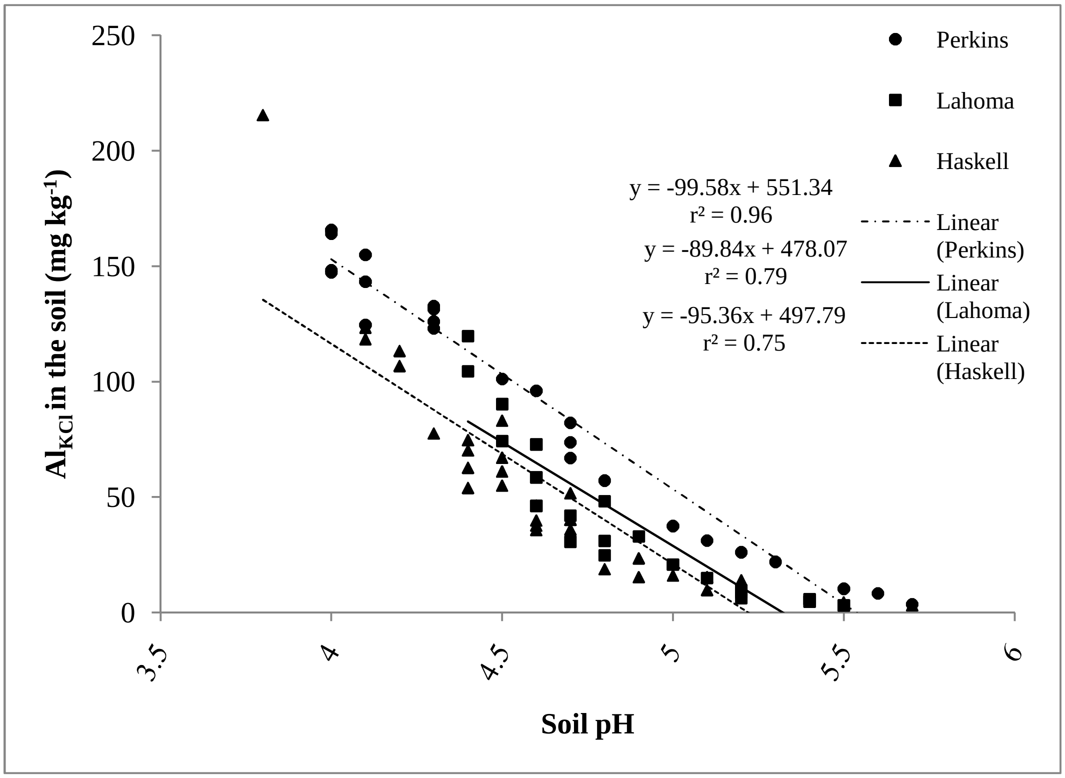

Figure 3. Quadratic relationship of Al_{KCl} concentration in the soil and soil pH from a 15 cm composite soil sample for each treatment at Perkins, Lahoma, and Haskell, OK (2010).

Grain Sorghum

In Season Growth Components

Plant emergence and soil pH was significant ($\alpha = 0.05$) when evaluated in quadratic least squares regression at five of the six grain sorghum site years but reached a plateau at two of the six site years (5.45 and 4.53), as reported in Tables 4 and 5.

Table 4. Results from quadratic least squares regression when evaluating the effect of soil pH on grain sorghum emergence (2009 and 2010).

2009	**DF**	**Mean Square**	**F**	**Prob F**	**r^2**
Lahoma	2	0.169	4.73	0.0256	0.39
Perkins	2	0.002	0.17	0.8422	0.02
Haskell	2	0.125	9.46	0.0022	0.56
All locations	2	0.209	5.37	0.0077	0.17
2010	**DF**	**Mean Square**	**F**	**Prob F**	**r^2**
Lahoma	2	0.0100	4.57	0.0282	0.38
Perkins	2	0.0634	5.54	0.0158	0.43
Haskell	2	0.0867	5.96	0.0124	0.44
All locations	2	0.1934	19.60	<0.0001	0.44

Table 5. Results from non-linear regression when evaluating the effect of soil pH on grain sorghum emergence (2009 and 2010).

2009	**Joint**	**F**	**Prob F**	**r^2**
Lahoma	-	-	-	-
Perkins	-	-	-	-
Haskell	4.53	20.91	<0.0001	0.74
2010	**Joint**	**F**	**Prob F**	**r^2**
Lahoma	5.45	4.42	0.0311	0.37
Perkins	-	-	-	-
Haskell	-	-	-	-

The correlation between plant height and soil pH was significant ($\alpha = 0.05$) when evaluated in quadratic least squares regression at all grain sorghum site years and reached a plateau at all site years (5.39, 4.93, and 5.04) (Tables 6 & 7).

Table 6. Results from quadratic least squares regression when evaluating the effect of soil pH on grain sorghum plant height (2010).

2010	**DF**	**Mean Square**	**F**	**Prob F**	**r^2**
Lahoma	2	530.8173	18.14	<0.0001	0.71
Perkins	2	1013.5939	97.48	<0.0001	0.93
Haskell	2	1277.9460	7.84	0.0047	0.51
All locations	2	1.0141	43.08	<0.0001	0.63

Table 7. Results from non-linear regression when evaluating the effect of soil pH on grain sorghum plant height (2010).

2010	Joint	F	Prob F	r^2
Lahoma	5.39	16.95	0.0001	0.69
Perkins	4.93	55.00	<0.0001	0.88
Haskell	5.04	6.91	0.0075	0.48
All locations	4.45	59.42	<0.0001	0.70

NDVI and soil pH was significant ($\alpha = 0.05$) when evaluated in quadratic least squares regression at all grain sorghum site years but did not reach a plateau at any site year, as reported in Table 8. The significance of NDVI demonstrates the reduction in biomass and plant vigor in low pH soils.

Table 8. Results from quadratic least squares regression when evaluating the effect of soil pH on grain sorghum NDVI (2010).

2010	DF	Mean Square	F	Prob F	r^2
Lahoma	2	0.0494	32.72	<0.0001	0.81
Perkins	2	0.1218	104.54	<0.0001	0.93
Haskell	2	0.0995	12.69	0.0006	0.63
All locations	2	0.9161	122.18	<0.0001	0.83

The number of heads $plot^{-1}$ at harvest and soil pH was significant ($\alpha = 0.05$) when evaluated in quadratic least squares regression at all grain sorghum site years and reached a plateau at two of the three site years (5.22 and 4.45) (Tables 9 & 10).

Table 9. Results from quadratic least squares regression when evaluating the effect of soil pH on the number of grain sorghum heads $plot^{-1}$ at harvest (2010).

2010	DF	Mean Square	F	Prob F	r^2
Lahoma	2	1043.74	9.09	0.0026	0.55
Perkins	2	15388.89	19.14	<0.0001	0.73
Haskell	2	2671.23	9.31	0.0024	0.55
All locations	2	20351.59	35.42	<0.0001	0.59

Table 10. Results from non-linear regression when evaluating the effect of soil pH on the number of grain sorghum heads plot^{-1} at harvest (2010).

2010	**Joint**	**F**	**Prob F**	**r^2**
Lahoma	5.22	8.73	0.0031	0.54
Perkins	4.45	40.37	<0.0001	0.85
Haskell	-	-	-	-
All locations	4.45	59.60	0.58065	0.70

Plant counts at emergence, plant height, and number of heads at harvest exhibited significance and reached plateaus; however, it is expected that producers are more concerned with final yield than in season growth components. When using measurements other than yield to determine critical soil pH levels it is important to consider the correlation of these measurements with final yield. The correlation of plant counts at emergence, plant height, NDVI, and number of heads at harvest are reported in Table 11. Plant height is not significant, and NDVI is significant but has a weak r^2. Plant counts at emergence and number of heads at harvest are significant and had direct influence on final grain yield.

Table 11. Regression of grain sorghum yield with emergence, plant height, NDVI, and number of heads at harvest at Lahoma, Perkins, and Haskell, OK (2010).

2010	**DF**	**Mean Square**	**F**	**Prob F**	**r^2**
Emergence	1	35322392	26.35	<0.0001	0.34
Height	1	165291	0.08	0.7758	0.00
NDVI	1	13168332	7.45	0.0086	0.13
Number of heads	1	55089828	57.36	<0.0001	0.52

Plant counts at emergence were higher than the number of heads at harvest. This suggests that soil acidity had an impact on stand establishment but even more of an effect on plant mortality through the growing season in 2010. The reduction in plant counts as the season progressed is correlated with soil pH (Fig.4). Plant mortality was not reduced when soil pH >5.5, but the number of plants significantly decreased when soil pH <4.5 (Fig. 4). The plants located in treatments with lower soil pH likely had an increased amount of root pruning as a result of soil acidity. Root pruning likely prevented the roots from penetrating into the more neutral subsoil. Since these plants were not able to explore less acidic soil for nutrients, the plants did not survive. In contrast, plants located in treatments with moderate soil pH likely had less root pruning and were able to penetrate into more neutral subsoil and reach additional nutrients, thus allowing them to survive.

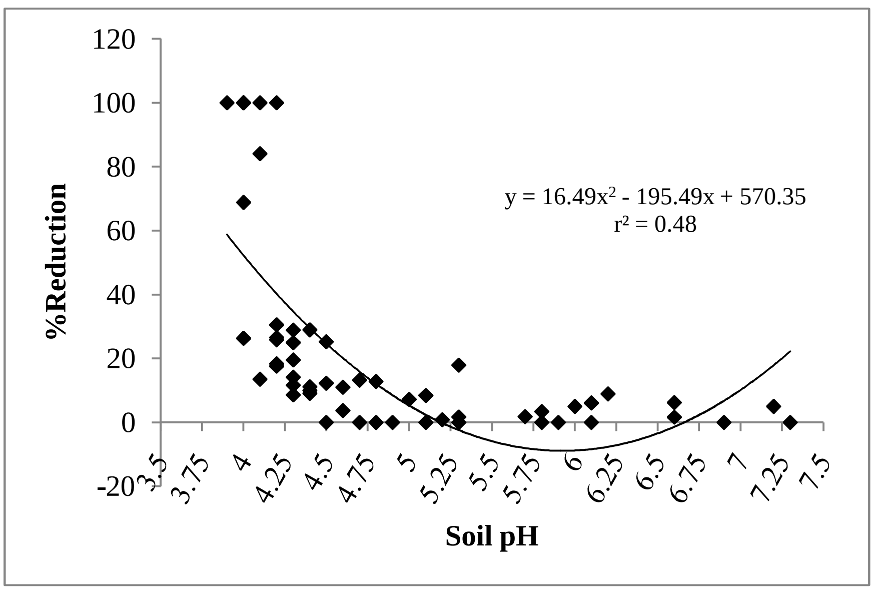

Figure 4. Percent reduction in number of grain sorghum plants from emergence to immediately prior to harvest at Perkins, Lahoma, and Haskell, OK (2010).

Relative Yield

Relative $yield_{avg}$ and soil pH was significant ($\alpha = 0.05$) when evaluated in quadratic least squares regression at two of the five grain sorghum site years (Table 12). Only two of the five grain sorghum site years reached a plateau (4.66 and 4.80) (Table 13).

Table 12. Results from quadratic least squares regression when evaluating the effect of soil pH on grain sorghum relative $yield_{avg}$ (2009 and 2010).

2009	**DF**	**Mean Square**	**F**	**Prob F**	**r^2**
Lahoma	2	0.055	2.31	0.1330	0.24
Perkins	2	0.041	0.35	0.7082	0.04
All locations	2	0.180	3.23	0.0542	0.18
2010	**DF**	**Mean Square**	**F**	**Prob F**	**r^2**
Lahoma	2	0.061	1.59	0.2371	0.17
Perkins	2	1.237	37.67	<0.0001	0.83
Haskell	2	0.252	15.65	0.0002	0.68
All locations	2	1.123	22.82	<0.0001	0.47

Table 13. Results from non-linear regression when evaluating the effect of soil pH on grain sorghum relative $yield_{avg}$ (2010).

2010	**Joint**	**F**	**Prob F**	**r^2**	**Plateau**
Lahoma	5.49	0.69	0.5155	0.08	0.77
Perkins	4.66	72.21	<0.0001	0.91	0.88
Haskell	4.80	16.34	0.0002	0.69	1.04
All locations	-	-	-	-	-

There is a considerable amount of variation in the yield response to soil pH among locations and years (Fig. 5-9). This variation is likely due to environmental impacts other than soil pH. For example, results from the 2009 season show less significance overall when compared to 2010 results. One possible explanation for this inconsistency among years could be soil moisture levels. Oklahoma Mesonet soil moisture graphs indicate that on average the period from planting to 30 days after planting in 2009 had higher fractional water index when compared to 2010 at all locations. The improved soil moisture conditions of 2009 could have masked the effect of soil pH as compared to 2010 by allowing roots to penetrate below the acidic surface soil earlier in the season.

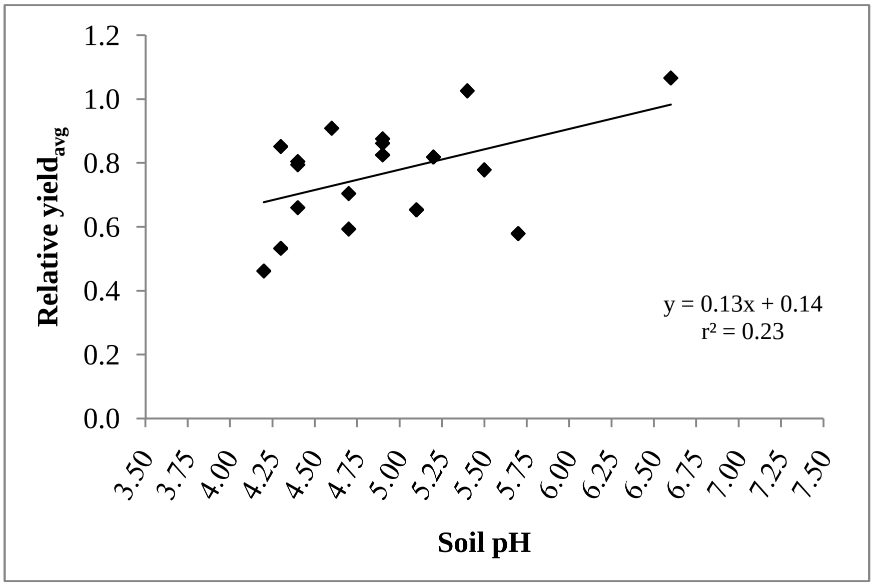

Figure 5. Relationship of grain sorghum relative $yield_{avg}$ and soil pH at Lahoma, OK (2009).

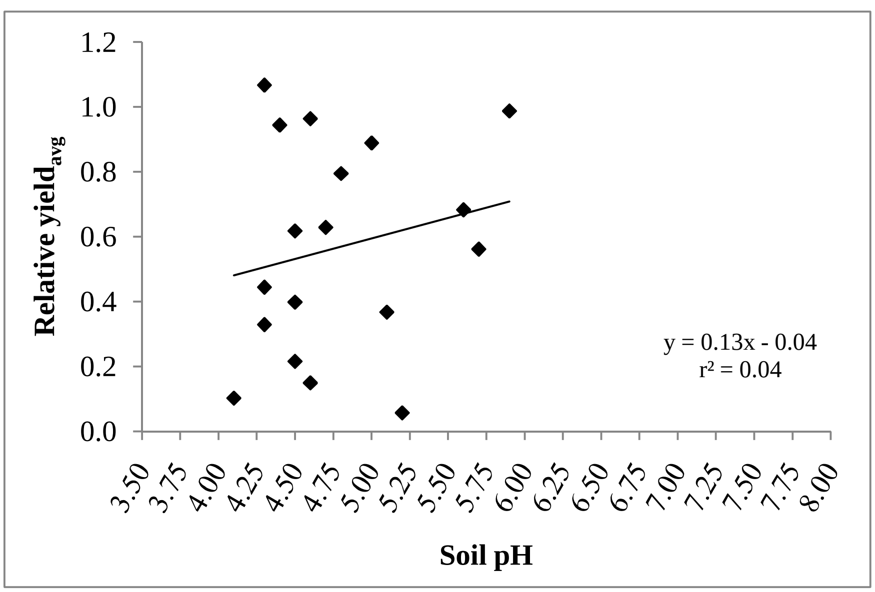

Figure 6. Relationship of grain sorghum relative $yield_{avg}$ and soil pH at Perkins, OK (2009).

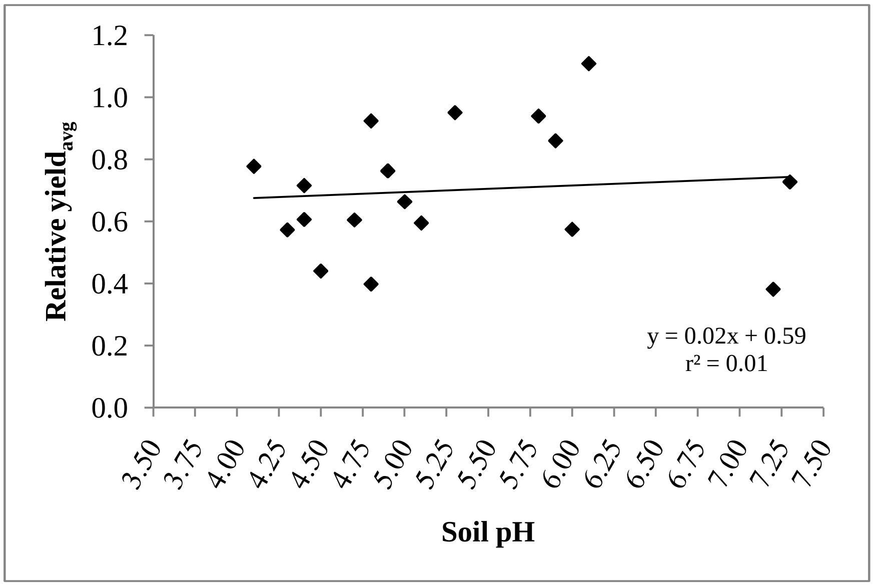

Figure 7. Relationship of grain sorghum relative yield$_{avg}$ and soil pH at Lahoma, OK (2010).

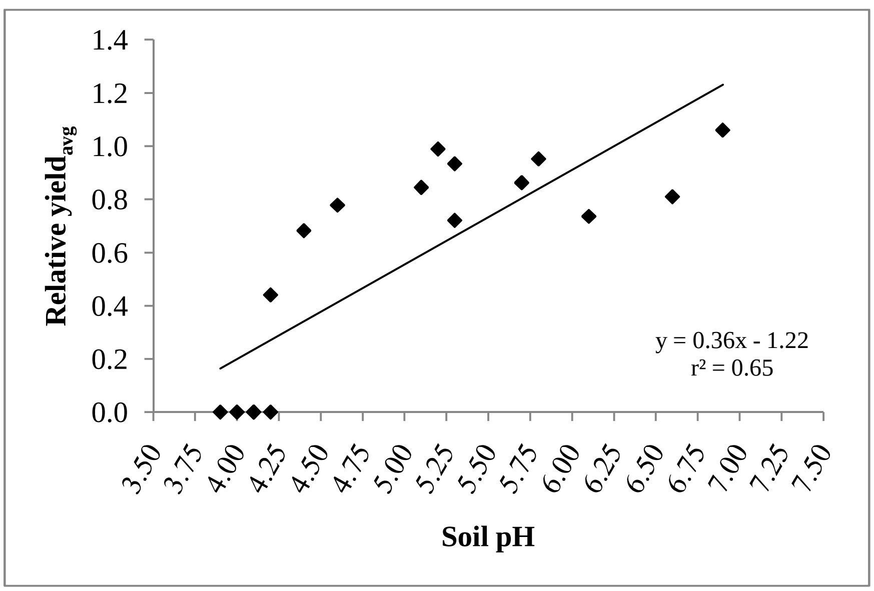

Figure 8. Relationship of grain sorghum relative yield$_{avg}$ and soil pH at Perkins, OK (2010).

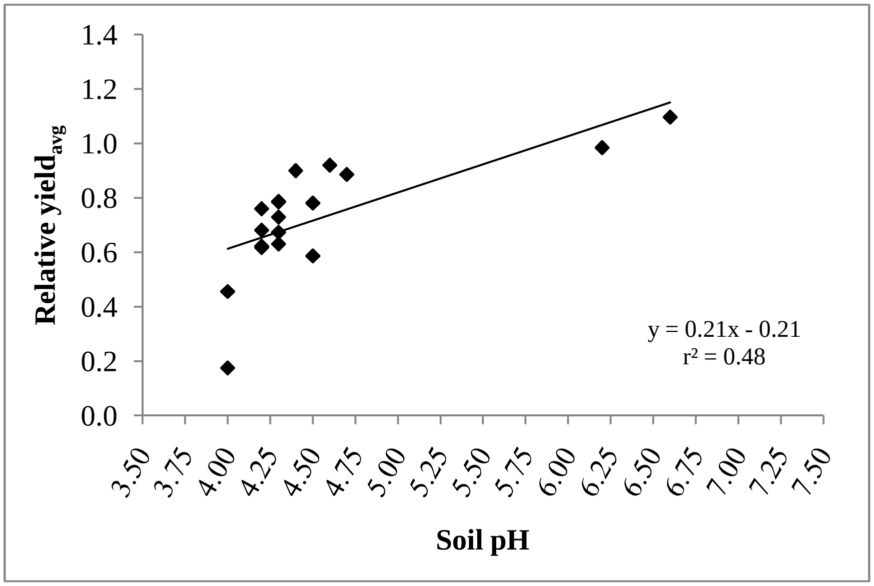

Figure 9. Relationship of grain sorghum relative yield$_{avg}$ and soil pH at Haskell, OK (2010).

Assuming that most producers would not be willing to sustain yield losses of greater than 10%, the soil pH at relative yield$_{avg}$ 0.90 was chosen as the yield plateau level. According to the equation generated from non-linear regression (y=0.3513x-1.0051) the critical soil pH at relative yield$_{avg}$ 0.90 was 5.42 (Fig. 10).

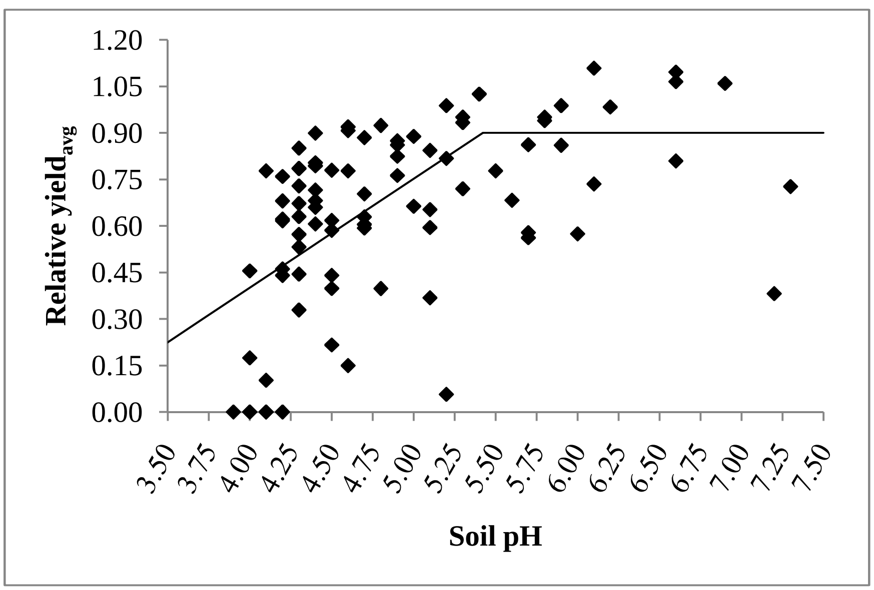

Figure 10. Relationship of grain sorghum relative yield$_{avg}$ and soil pH at Lahoma, Perkins, and Haskell, OK with yield plateau occurring at 0.90 with critical soil pH 5.42 (2009 & 2010).

In addition to using soil pH results from this study to determine relative $yield_{avg}$ values, Al_{KCl} concentration in the soil was analyzed in 2010 and was found to be highly correlated with soil pH (r^2=0.90) and relative $yield_{avg}$ (r^2=0.81). Cate and Nelson graphics method (Cate and Nelson, 1965) determined the critical level of Al_{KCl} concentration in the soil for grain sorghum in this study was 18 mg kg^{-1} (Fig. 11).

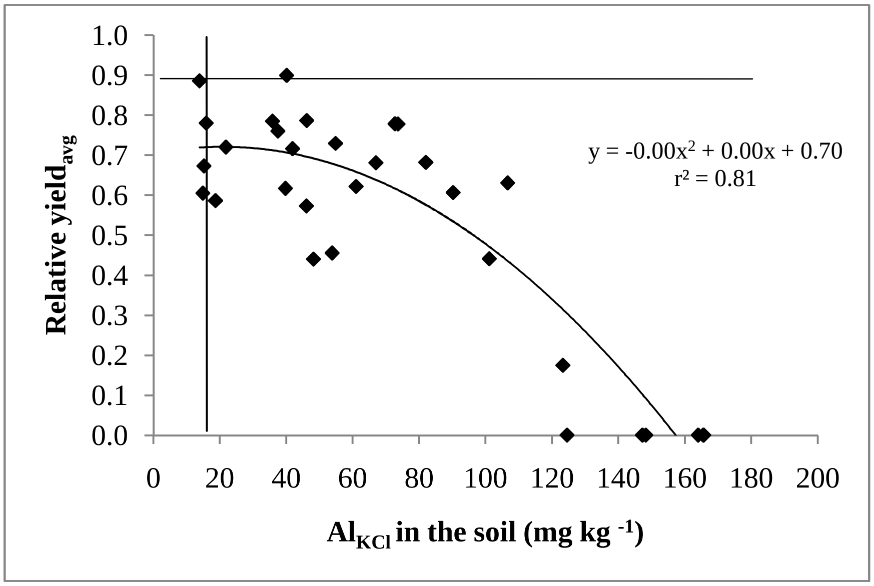

Figure 11. Quadratic relationship of Al_{KCl} concentration in soil and grain sorghum relative $yield_{avg}$ at Perkins, Lahoma, and Haskell, OK with Cate-Nelson critical point occurring at 18 mg kg^{-1} Al (2010).

According to the quadratic model of Al_{KCl} in the soil, at relative $yield_{avg}$ of 0.90, Al_{KCl} concentration in the soil was 18 mg kg^{-1} (Fig. 11). This indicates that yields were reduced by 10% at Al_{KCl} concentration of 18 mg kg^{-1} in this study. Al toxicity (18 mg kg^{-1}) in grain sorghum was reached at soil pH of 5.54, 5.25, and 5.27 at Perkins, Lahoma, and Haskell, respectively.

Sunflower

In Season Growth Components

Plant emergence and soil pH was significant (α = 0.05) at three of the five sunflower site years and reached a plateau at three of the five site years (5.10, 5.12 and 4.93), as reported in Tables 14 and 15.

Table 14. Results from quadratic least squares regression when evaluating the effect of soil pH on sunflower emergence (2009 and 2010).

2009	**DF**	**Mean Square**	**F**	**Prob F**	**r^2**
Lahoma	2	0.0067	0.21	0.8135	0.03
Haskell	2	0.3871	11.16	0.0011	0.60
All locations	2	0.2032	4.16	0.0245	0.20
2010	**DF**	**Mean Square**	**F**	**Prob F**	**r^2**
Lahoma	2	0.0421	0.77	0.4785	0.09
Perkins	2	0.0654	8.34	0.0037	0.53
Haskell	2	0.4777	17.41	0.0001	0.70
All locations	2	0.3634	8.85	0.0005	0.26

Table 15. Results from non-linear regression when evaluating the effect of soil pH on sunflower emergence (2009 and 2010).

2009	**Joint**	**F**	**Prob F**	**r^2**
Lahoma	-	-	-	-
Haskell	5.12	12.40	0.0007	0.62
All locations	5.46	4.25	0.0227	0.20
2010	**Joint**	**F**	**Prob F**	**r^2**
Lahoma	-	-	-	-
Perkins	5.10	8.73	0.0031	0.54
Haskell	4.93	14.78	0.0003	0.66
All locations	4.76	8.39	0.0007	0.25

The correlation between plant height and soil pH was significant (α = 0.05) when evaluated in quadratic least squares regression at all sunflower site years and reached a plateau at all site years (5.67, 4.90, and 4.52) (Tables 16 & 17).

Table 16. Results from quadratic least squares regression when evaluating the effect of soil pH on sunflower plant height (2010).

2010	**DF**	**Mean Square**	**F**	**Prob F**	**r^2**
Lahoma	2	585.8596	26.78	<0.0001	0.78
Perkins	2	420.3022	98.25	<0.0001	0.93
Haskell	2	2252.2609	4.69	0.0261	0.38
All locations	2	1.0967	68.22	<0.0001	0.73

Table 17. Results from non-linear regression when evaluating the effect of soil pH on sunflower plant height (2010).

2010	**Joint**	**F**	**Prob F**	**r^2**
Lahoma	5.67	29.28	<0.0001	0.80
Perkins	4.90	177.90	<0.0001	0.96
Haskell	4.52	6.16	0.0112	0.45
All locations	5.02	65.17	<0.0001	0.72

NDVI and soil pH was significant ($\alpha = 0.05$) when evaluated in quadratic least squares regression at two of the three sunflower site years and reached a plateau at all site years (5.36, 4.99, and 4.20) (Tables 18 & 19), once again demonstrating the reduction in biomass and plant vigor.

Table 18. Results from quadratic least squares regression when evaluating the effect of soil pH on sunflower NDVI (2010).

2010	**DF**	**Mean Square**	**F**	**Prob F**	**r^2**
Lahoma	2	0.0317	9.16	0.0025	0.55
Perkins	2	0.2667	97.42	<0.0001	0.93
Haskell	2	0.0724	3.40	0.0604	0.31
All locations	2	0.6392	33.95	<0.0001	0.57

Table 19. Results from non-linear regression when evaluating the effect of soil pH on sunflower NDVI (2010).

2010	**Joint**	**F**	**Prob F**	**r^2**
Lahoma	5.36	7.44	0.0057	0.50
Perkins	4.99	137.71	<0.0001	0.95
Haskell	4.20	6.97	0.0072	0.48
All locations	4.76	36.70	<0.0001	0.59

The number of heads plot^{-1} at harvest and soil pH was significant ($\alpha = 0.05$) when evaluated in quadratic least squares regression at two of the three sunflower site years and reached a plateau at three of the four site years (5.72, 4.78, and 5.02), as reported in Table 20 and 21.

Table 20. Results from quadratic least squares regression when evaluating the effect of soil pH on the number of sunflower heads plot^{-1} at harvest (2010).

2010	**DF**	**Mean Square**	**F**	**Prob F**	**r^2**
Lahoma	2	202.73	1.14	0.3474	0.13
Perkins	2	2670.05	57.68	<0.0001	0.88
Haskell	2	1658.57	14.96	0.0003	0.67
All Locations	2	4176.63	35.05	<0.0001	0.58

Table 21. Results from non-linear regression when evaluating the effect of soil pH on the number of sunflower heads plot^{-1} at harvest (2010).

2010	**Joint**	**F**	**Prob F**	**r^2**
Lahoma	5.72	0.38	0.6905	0.05
Perkins	4.78	119.50	0.6089	0.94
Haskell	5.02	13.33	0.0005	0.64
All Locations	4.72	34.28	0.36655	0.57

As previously discussed, in season growth components are useful for observing the different ways that soil pH affected plant growth. Plant counts at emergence, plant height, NDVI, and head counts at harvest were all significant and reached linear plateaus in the majority of site years. As previously mentioned, the relationship of these growth components with yield is important to consider. Each of the in-season growth components is related to sunflower yield (Table 22); therefore, these components were good indicators of sunflower yield in this study.

Table 22. Regression of sunflower yield with emergence, plant height, NDVI, and number of heads at harvest at Lahoma, Perkins and Haskell, OK (2010).

2010	**DF**	**Mean Square**	**F**	**Prob F**	$\mathbf{r^2}$
Emergence	1	9886154	23.06	<0.0001	0.31
Height	1	6478481	13.11	0.0007	0.20
NDVI	1	18960424	74.56	<0.0001	0.59
Counts-Harvest	1	20434138	90.44	<0.0001	0.63

Similar to grain sorghum, the relationship of sunflower plant counts at emergence was higher than head counts taken just prior to harvest (Fig. 12). Plant mortality was not reduced when soil pH >5.0 but decreased when soil pH <4.7 (Fig. 12). As with grain sorghum, this suggests that soil acidity influenced plant mortality through the growing season, as well as emergence. This reduction in plant counts as the season progressed is likely a result of root pruning, as previously discussed.

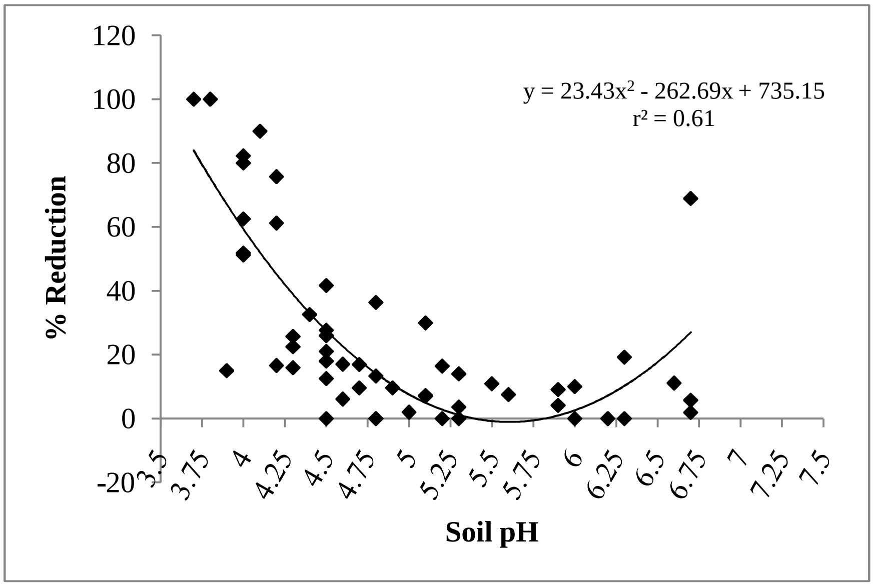

Figure 12. Percent reduction in number of sunflower plants from emergence to immediately prior to harvest at Perkins, Lahoma, and Haskell, OK (2010).

Relative Yield

Relative $yield_{max}$ and soil pH was significant in three of the five site years when evaluated in quadratic least squares regression and reached a plateau at two of the five site years (5.04 and 5.02), as reported in Tables 23 and 24. Sunflower relative $yield_{max}$ plateau occurred at 0.74 and soil pH 4.90 (Table 24). These results indicate that at soil pH of 4.90 there will be a 26% yield reduction.

Table 23. Results from quadratic least squares regression when evaluating the effect of soil pH on sunflower relative $yield_{max}$ (2009 and 2010).

2009	**DF**	**Mean Square**	**F**	**Prob F**	**r^2**
Lahoma	2	0.1413	4.56	0.0284	0.38
Haskell	2	0.0279	0.66	0.5293	0.08
All locations	2	0.0575	1.43	0.2542	0.08
2010	**DF**	**Mean Square**	**F**	**Prob F**	**r^2**
Lahoma	2	0.1021	2.08	0.1595	0.22
Perkins	2	1.1141	75.85	<0.0001	0.58
Haskell	2	0.4789	23.80	<0.0001	0.76
All locations	2	1.3525	35.11	<0.0001	0.58

Table 24. Results from non-linear regression when evaluating the effect of soil pH on sunflower relative $yield_{max}$ (2009 and 2010).

2009	**Joint**	**F**	**Prob F**	**r^2**	**Plateau**
Lahoma	-	-	-	-	-
Haskell	-	-	-	-	-
All locations	-	-	-	-	-
2010	**Joint**	**F**	**Prob F**	**r^2**	**Plateau**
Lahoma	5.31	0.62	0.5533	0.08	0.64
Perkins	5.04	136.54	<0.0001	0.95	0.88
Haskell	5.02	19.74	<0.0001	0.72	0.83
All locations	4.90	32.39	<0.0001	0.56	0.74

As with grain sorghum, there was considerable variation seen in the response of yield to soil pH among locations and years (Fig. 13-17). This variability is likely due to environmental impacts other than soil pH.

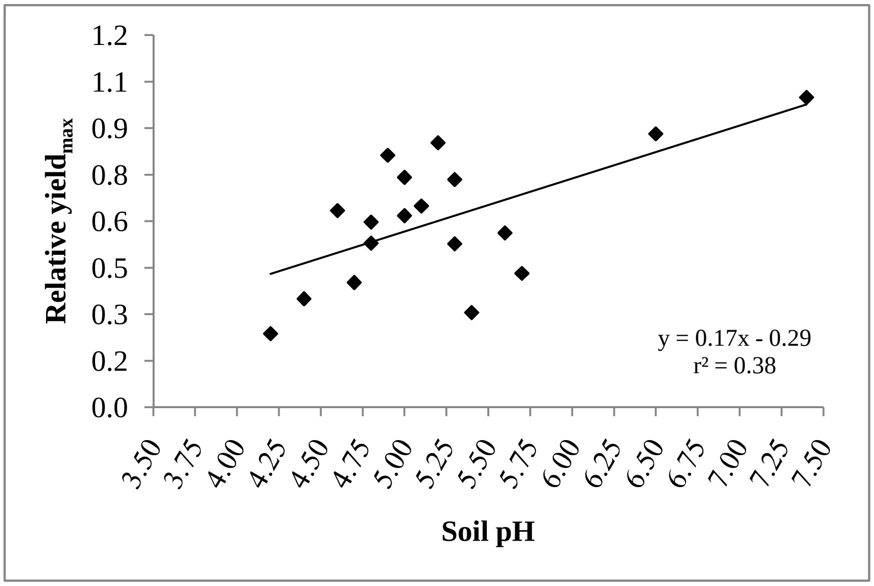

Figure 13. Relationship of sunflower relative yield$_{max}$ and soil pH at Lahoma, OK (2009).

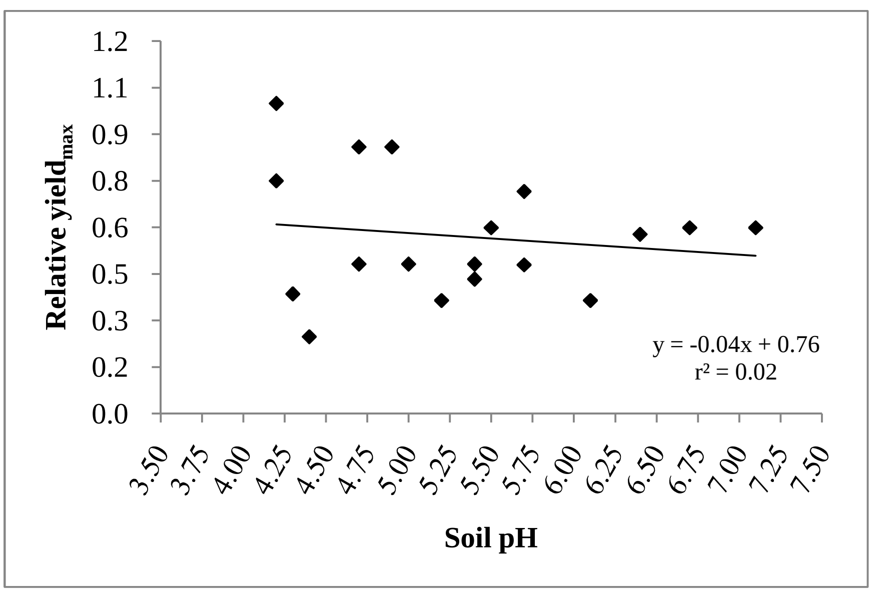

Figure 14. Relationship of sunflower relative yield$_{max}$ and soil pH at Haskell, OK (2009).

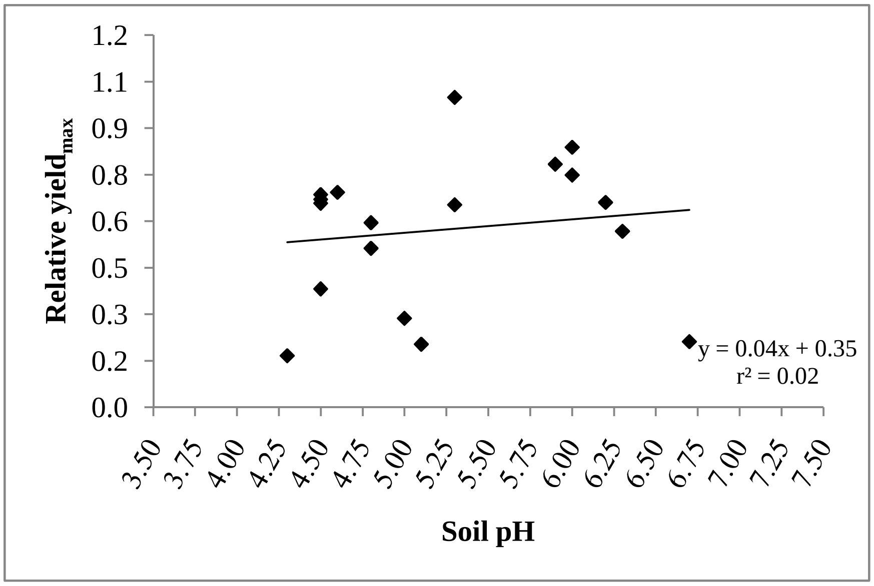

Figure 15. Relationship of sunflower relative yield$_{max}$ and soil pH at Lahoma, OK (2010).

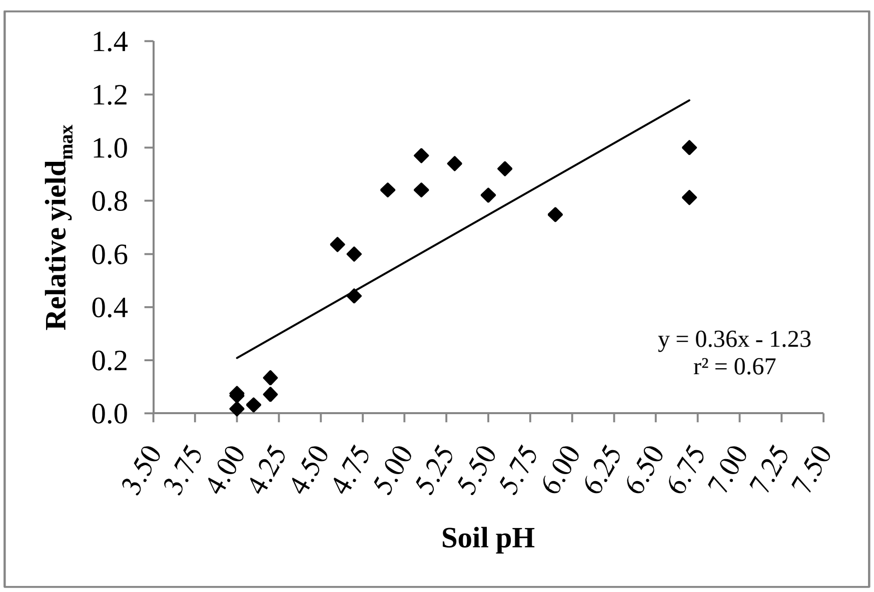

Figure 16. Relationship of sunflower relative yield$_{max}$ and soil pH at Perkins, OK (2010).

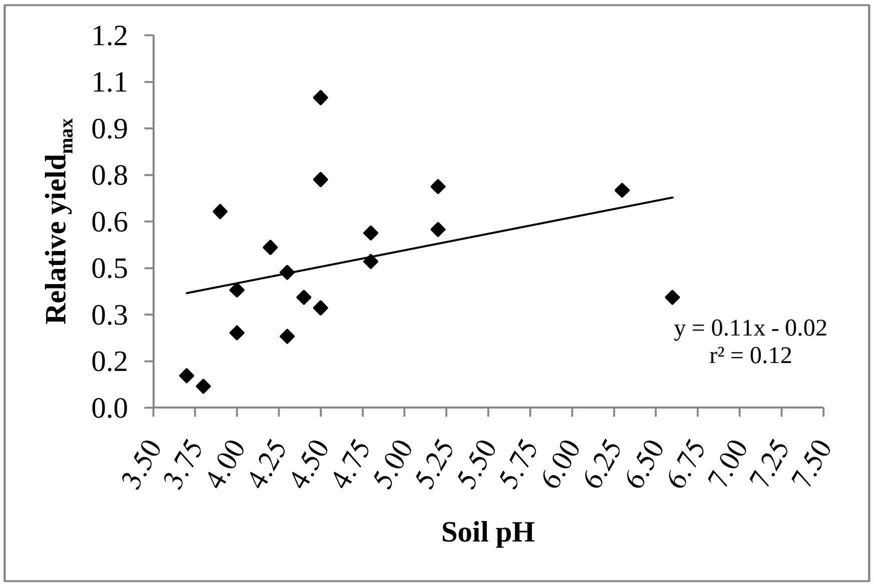

Figure 17. Relationship of sunflower relative yield$_{max}$ and soil pH at Haskell, OK (2010).

Similar as grain sorghum, relative yield$_{max}$ 0.90 was chosen as the yield plateau level. According to the equation generated from non-linear regression (y=0.5180x-1.8298) the critical soil pH at relative yield$_{max}$ 0.90 was 5.27 (Fig. 18).

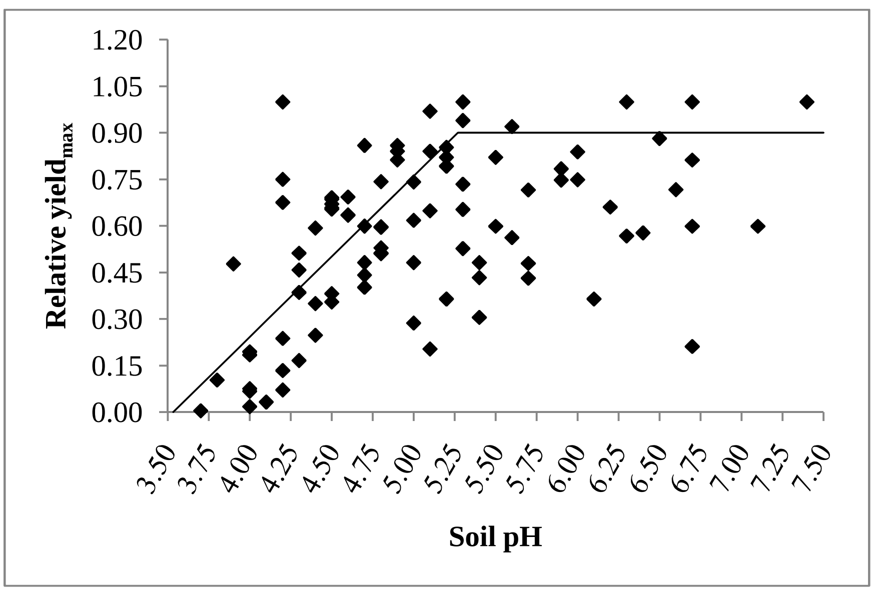

Figure 18. Relationship of sunflower relative yield$_{max}$ and soil pH at Lahoma, Perkins, and Haskell, OK with yield plateau occurring at 0.90 with critical soil pH 5.27 (2009 & 2010).

Al_{KCl} concentration in the soil was analyzed in 2010 and was found to be correlated with soil pH (r^2=0.88) and relative $yield_{max}$ (r^2=0.46). Cate and Nelson graphic methods (Cate and Nelson, 1965) determined the critical level of Al_{KCl} concentration in the soil for sunflower in this study was 29 mg kg^{-1} (Fig. 19).

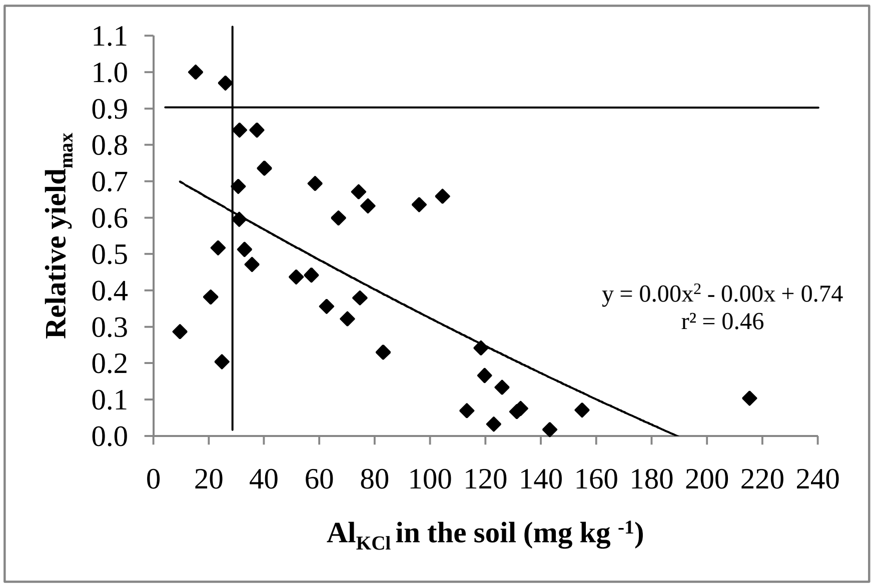

Figure 19. Quadratic relationship of Al_{KCl} concentration in the soil and sunflower relative $yield_{max}$ at Perkins, Lahoma, and Haskell, OK with Cate-Nelson critical point occurring at 29 mg kg^{-1} Al (2010).

According to the quadratic model of Al_{KCl} in the soil at relative $yield_{max}$ of 0.90, Al_{KCl} concentration in the soil was 29 mg kg^{-1} (Fig. 19). This indicates that yields were reduced by 10% at Al_{KCl} concentration of 29 mg kg^{-1} in this study. Al toxicity in sunflower was reached at soil pH of 5.23, 5.00, and 4.90 at Perkins, Lahoma, and Haskell, respectively.

Environmental Impacts

The environment played a significant role in the severity of soil acidity stresses observed in this study. Higher soil moisture in 2009 compared to 2010 could have masked the effect of soil pH and reduced the negative effects on yield. Damage incurred from birds was also an outside environmental impact that could not be controlled. Also in 2010 a compaction layer was observed at Perkins, OK that could have prevented roots from penetrating into more neutral subsoil, thereby emphasizing the effects of soil acidity in the top 15 cm seen at that location.

CHAPTER VI

CONCLUSIONS

The results from this study varied from location to location and year to year; however, a trend was detected that confirms soil acidity reduced yield in grain sorghum and sunflower. This study demonstrated that the environment played a significant role in the degree of soil acidity stresses observed in grain sorghum and sunflower production. The critical levels and relative yield models developed in this study will be helpful when making liming decisions. Depending on environmental factors, these estimated yield reductions may not hold true in all situations.

The yield reductions associated with soil acidity can be substantial; however, when producers consider liming, all factors should be taken into account. For example if commodity prices are down, land is rented, or potential yield levels are low, the cost of liming could outweigh the reward. The estimates developed in this study will provide producers with an additional tool to determine if liming a field is necessary and economical.

Al_{KCl} concentration in the soil, which is related to parent material and soil CEC, negatively affected crop response to soil acidity. Differences in Al_{KCl} concentration can cause soil acidity symptoms associated with Al toxicities to occur at higher or lower soil pH than expected. For this reason, it could be beneficial when developing liming recommendations to consider Al_{KCl} concentration in the soil in addition to soil pH and buffer index. In this study, at relative yield 0.90, the Al_{KCl} concentration in the soil was 18 mg kg^{-1} and 29 mg kg^{-1} for grain sorghum and sunflower, respectively. Interpreting the Al_{KCl} concentration to determine specific toxicity levels is useful; however, other soil factors likely play a role in the reliability of those toxicity levels across locations and scenarios. Soil pH is ultimately the soil factor that should be monitored to determine when liming is necessary and to avoid yield reductions.

In this study, at relative yield 0.90, the critical soil pH was 5.42 and 5.27 for grain sorghum and sunflower, respectively. The models developed in this study will provide producers with a tool to estimate yield reductions at a given soil pH (Fig.10 &18). As producers incorporate grain sorghum and sunflower into rotations, it is recommended that soil pH be tested to ensure significant yield reductions associated with soil acidity are avoided. Future research concerning crop response to soil pH may need to include additional locations and deep tillage so that soil pH is altered deeper than 15 cm.

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APPPENDICES

Table A1. Fertilizer rates applied at each location (2009 and 2010).

Location	**Year**	**N (kg ha^{-1})**	**P_2O_5 (kg ha^{-1})**	**K_2O (kg ha^{-1})**
Perkins, OK	2009	112	17	0
Lahoma, OK	2009	112	50	0
Haskell, OK	2009	112	50	67
Perkins, OK	2010	112	11	0
Lahoma, OK	2010	112	50	0
Haskell, OK	2010	112	45	77

Table A2. Target pH and rate of aluminum sulfate/hydrated lime used to initially alter soil pH (2009).

Perkins-2009 Initial pH 4.86			
Treatment	Target pH	Material	Rate (kg ha^{-1})
1 & 7	4	Alum	1,185
2 & 8	4.5	Alum	414
3 & 9	5	Lime	330
4 & 10	5.5	Lime	1,177
5 & 11	6	Lime	2,024
6 & 12	7	Lime	2,871
Lahoma-2009 Initial pH 5.50			
Treatment	Target pH	Material	Rate (kg ha^{-1})
1 & 7	4	Alum	7,669
2 & 8	4.5	Alum	6,276
3 & 9	5	Alum	4,883
4 & 10	5.5	Alum	3,490
5 & 11	6	Alum	2,097
6 & 12	7	Lime	223
Haskell-2009 Initial pH 5.22			
Treatment	Target pH	Material	Rate (kg ha^{-1})
1 & 7	4	Alum	4,572
2 & 8	4.5	Alum	2,504
3 & 9	5	Alum	436
4 & 10	5.5	Lime	641
5 & 11	6	Lime	1,280
6 & 12	7	Lime	2,558

Table A3. Target pH and mid-season measured pH at Lahoma, OK (2009).

Treatment	Crop	Target pH	Measured pH	+/-
101	Sorghum	4.0	4.2	-0.2
102	Sorghum	4.5	4.3	0.2
103	Sorghum	5.0	4.7	0.3
104	Sorghum	5.5	5.1	0.4
105	Sorghum	6.0	5.2	0.8
106	Sorghum	7.0	5.5	1.5
107	Sunflower	4.0	4.6	-0.6
108	Sunflower	4.5	5	-0.5
109	Sunflower	5.0	5	0
110	Sunflower	5.5	5.3	0.2
111	Sunflower	6.0	6.5	-0.5
112	Sunflower	7.0	7.4	-0.4
201	Sorghum	4.0	4.7	-0.7
202	Sorghum	4.5	4.9	-0.4
203	Sorghum	5.0	4.4	0.6
204	Sorghum	5.5	5.7	-0.2
205	Sorghum	6.0	4.4	1.6
206	Sorghum	7.0	4.9	2.1
207	Sunflower	4.0	4.2	-0.2
208	Sunflower	4.5	4.8	-0.3
209	Sunflower	5.0	5.2	-0.2
210	Sunflower	5.5	4.8	0.7
211	Sunflower	6.0	5.4	0.6
212	Sunflower	7.0	5.7	1.3
301	Sorghum	4.0	4.9	-0.9
302	Sorghum	4.5	4.4	0.1
303	Sorghum	5.0	4.3	0.7
304	Sorghum	5.5	4.6	0.9
305	Sorghum	6.0	5.4	0.6
306	Sorghum	7.0	6.6	0.4
307	Sunflower	4.0	4.9	-0.9
308	Sunflower	4.5	4.4	0.1
309	Sunflower	5.0	5.1	-0.1
310	Sunflower	5.5	4.7	0.8
311	Sunflower	6.0	5.3	0.7
312	Sunflower	7.0	5.6	1.4

Table A4. Target pH and mid-season measured pH at Perkins, OK (2009).

Treatment	Crop	Target pH	Measured pH	+/-
101	Sorghum	4.0	4.1	-0.1
102	Sorghum	4.5	4.3	0.2
103	Sorghum	5.0	4.3	0.7
104	Sorghum	5.5	4.7	0.8
105	Sorghum	6.0	5	1
106	Sorghum	7.0	5.9	1.1
107	Sunflower	4.0	4.7	-0.7
108	Sunflower	4.5	4.3	0.2
109	Sunflower	5.0	4.6	0.4
110	Sunflower	5.5	5.5	0
111	Sunflower	6.0	5.1	0.9
112	Sunflower	7.0	5.8	1.2
201	Sorghum	4.0	5.2	-1.2
202	Sorghum	4.5	4.6	-0.1
203	Sorghum	5.0	4.3	0.7
204	Sorghum	5.5	4.8	0.7
205	Sorghum	6.0	5.6	0.4
206	Sorghum	7.0	4.6	2.4
207	Sunflower	4.0	4.5	-0.5
208	Sunflower	4.5	4.4	0.1
209	Sunflower	5.0	4.7	0.3
210	Sunflower	5.5	5.5	0
211	Sunflower	6.0	5.3	0.7
212	Sunflower	7.0	5.2	1.8
301	Sorghum	4.0	4.5	-0.5
302	Sorghum	4.5	4.5	0
303	Sorghum	5.0	4.5	0.5
304	Sorghum	5.5	5.1	0.4
305	Sorghum	6.0	4.4	1.6
306	Sorghum	7.0	5.7	1.3
307	Sunflower	4.0	4.5	-0.5
308	Sunflower	4.5	4.7	-0.2
309	Sunflower	5.0	4.6	0.4
310	Sunflower	5.5	5	0.5
311	Sunflower	6.0	5.5	0.5
312	Sunflower	7.0	6	1

Table A5. Target pH and mid-season measured pH at Haskell, OK (2009).

Treatment	Crop	Target pH	Measured pH	+/-
101	Sorghum	4.0	4.2	-0.2
102	Sorghum	4.5	4.2	0.3
103	Sorghum	5.0	4.5	0.5
104	Sorghum	5.5	5.9	-0.4
105	Sorghum	6.0	6.3	-0.3
106	Sorghum	7.0	6.6	0.4
107	Sunflower	4.0	4.3	-0.3
108	Sunflower	4.5	4.7	-0.2
109	Sunflower	5.0	5	0
110	Sunflower	5.5	5.7	-0.2
111	Sunflower	6.0	6.7	-0.7
112	Sunflower	7.0	5.7	1.3
201	Sorghum	4.0	4.2	-0.2
202	Sorghum	4.5	4.1	0.4
203	Sorghum	5.0	4.6	0.4
204	Sorghum	5.5	5.3	0.2
205	Sorghum	6.0	5	1
206	Sorghum	7.0	5.6	1.4
207	Sunflower	4.0	4.2	-0.2
208	Sunflower	4.5	4.4	0.1
209	Sunflower	5.0	4.9	0.1
210	Sunflower	5.5	5.5	0
211	Sunflower	6.0	5.4	0.6
212	Sunflower	7.0	6.4	0.6
301	Sorghum	4.0	4.3	-0.3
302	Sorghum	4.5	5.4	-0.9
303	Sorghum	5.0	4.5	0.5
304	Sorghum	5.5	5.2	0.3
305	Sorghum	6.0	5.8	0.2
306	Sorghum	7.0	6	1
307	Sunflower	4.0	4.2	-0.2
308	Sunflower	4.5	4.7	-0.2
309	Sunflower	5.0	5.2	-0.2
310	Sunflower	5.5	5.4	0.1
311	Sunflower	6.0	6.1	-0.1
312	Sunflower	7.0	7.1	-0.1

Table A6. Target pH and mid-season measured pH at Lahoma, OK (2010).

Treatment	Crop	Target pH	Measured pH	+/-
101	Sorghum	4.0	4.1	-0.1
102	Sorghum	4.5	4.8	-0.3
103	Sorghum	5.0	4.7	0.3
104	Sorghum	5.5	4.8	0.7
105	Sorghum	6.0	6	0
106	Sorghum	7.0	7.2	-0.2
107	Sunflower	4.0	4.3	-0.3
108	Sunflower	4.5	4.5	0
109	Sunflower	5.0	4.8	0.2
110	Sunflower	5.5	6.2	-0.7
111	Sunflower	6.0	6.3	-0.3
112	Sunflower	7.0	6.7	0.3
201	Sorghum	4.0	4.4	-0.4
202	Sorghum	4.5	4.5	0
203	Sorghum	5.0	5	0
204	Sorghum	5.5	5.1	0.4
205	Sorghum	6.0	5.9	0.1
206	Sorghum	7.0	7.3	-0.3
207	Sunflower	4.0	4.5	-0.5
208	Sunflower	4.5	4.6	-0.1
209	Sunflower	5.0	4.8	0.2
210	Sunflower	5.5	5	0.5
211	Sunflower	6.0	5.3	0.7
212	Sunflower	7.0	6	1
301	Sorghum	4.0	4.3	-0.3
302	Sorghum	4.5	4.4	0.1
303	Sorghum	5.0	4.9	0.1
304	Sorghum	5.5	5.3	0.2
305	Sorghum	6.0	5.8	0.2
306	Sorghum	7.0	6.1	0.9
307	Sunflower	4.0	4.5	-0.5
308	Sunflower	4.5	4.5	0
309	Sunflower	5.0	5.1	-0.1
310	Sunflower	5.5	5.3	0.2
311	Sunflower	6.0	5.9	0.1
312	Sunflower	7.0	6	1

Table A7. Target pH and mid-season measured pH at Perkins, OK (2010).

Treatment	Crop	Target pH	Measured pH	+/-
101	Sorghum	4	4	0
102	Sorghum	4.1	4.5	0.4
103	Sorghum	4.6	5	0.4
104	Sorghum	5.3	5.5	0.2
105	Sorghum	5.8	6	0.2
106	Sorghum	6.1	7	0.9
107	Sunflower	4	4	0
108	Sunflower	4	4.5	0.5
109	Sunflower	4.7	5	0.3
110	Sunflower	4.9	5.5	0.6
111	Sunflower	5.6	6	0.4
112	Sunflower	6.7	7	0.3
201	Sorghum	3.9	4	0.1
202	Sorghum	4	4.5	0.5
203	Sorghum	4.4	5	0.6
204	Sorghum	5.1	5.5	0.4
205	Sorghum	5.3	6	0.7
206	Sorghum	6.6	7	0.4
207	Sunflower	4.2	4	-0.2
208	Sunflower	4.2	4.5	0.3
209	Sunflower	4.6	5	0.4
210	Sunflower	5.1	5.5	0.4
211	Sunflower	5.3	6	0.7
212	Sunflower	5.9	7	1.1
301	Sorghum	4.2	4	-0.2
302	Sorghum	4.1	4.5	0.4
303	Sorghum	4.2	5	0.8
304	Sorghum	5.2	5.5	0.3
305	Sorghum	5.7	6	0.3
306	Sorghum	6.9	7	0.1
307	Sunflower	4.1	4	-0.1
308	Sunflower	4	4.5	0.5
309	Sunflower	4.7	5	0.3
310	Sunflower	5.1	5.5	0.4
311	Sunflower	5.5	6	0.5
312	Sunflower	4	4	0

Table A8. Target pH and mid-season measured pH at Haskell, OK (2010).

Treatment	Crop	Target pH	Measured pH	+/-
101	Sorghum	4	4	0
102	Sorghum	4.2	4.5	0.3
103	Sorghum	4.3	5	0.7
104	Sorghum	4.3	5.5	1.2
105	Sorghum	4.7	6	1.3
106	Sorghum	6.6	7	0.4
107	Sunflower	3.7	4	0.3
108	Sunflower	3.9	4.5	0.6
109	Sunflower	4.8	5	0.2
110	Sunflower	4.5	5.5	1
111	Sunflower	4.2	6	1.8
112	Sunflower	6.3	7	0.7
201	Sorghum	4	4	0
202	Sorghum	4.4	4.5	0.1
203	Sorghum	4.2	5	0.8
204	Sorghum	4.5	5.5	1
205	Sorghum	4.3	6	1.7
206	Sorghum	6.2	7	0.8
207	Sunflower	3.8	4	0.2
208	Sunflower	4	4.5	0.5
209	Sunflower	4.3	5	0.7
210	Sunflower	4.5	5.5	1
211	Sunflower	5.2	6	0.8
212	Sunflower	6.6	7	0.4
301	Sorghum	4.2	4	-0.2
302	Sorghum	4.3	4.5	0.2
303	Sorghum	4.2	5	0.8
304	Sorghum	4.6	5.5	0.9
305	Sorghum	4.3	6	1.7
306	Sorghum	4.5	7	2.5
307	Sunflower	4	4	0
308	Sunflower	4.3	4.5	0.2
309	Sunflower	4.5	5	0.5
310	Sunflower	4.4	5.5	1.1
311	Sunflower	4.8	6	1.2
312	Sunflower	5.2	7	1.8

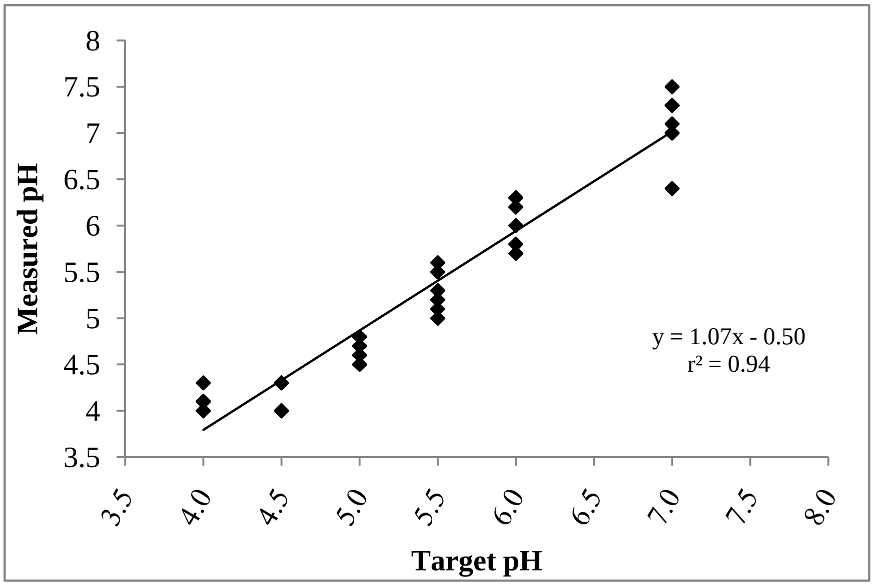

Figure A1. Target pH and final measured pH at Perkins, OK (2010).

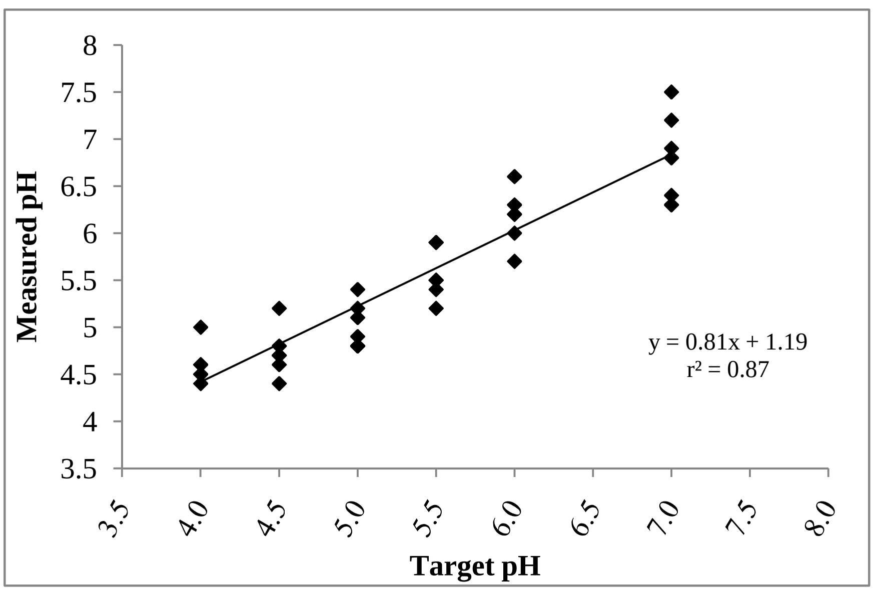

Figure A2. Target pH and final measured pH at Lahoma, OK (2010).

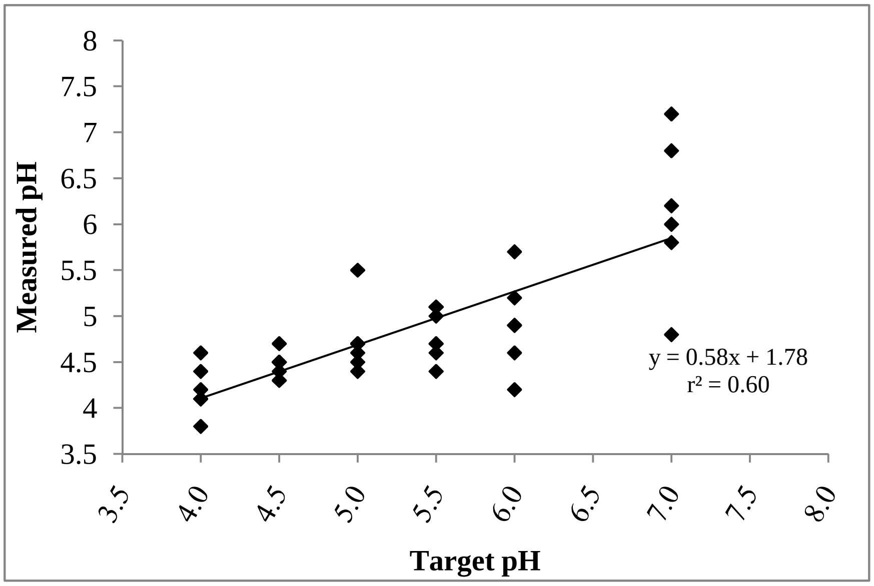

Figure A3. Target pH and final measured pH at Haskell, OK (2010).

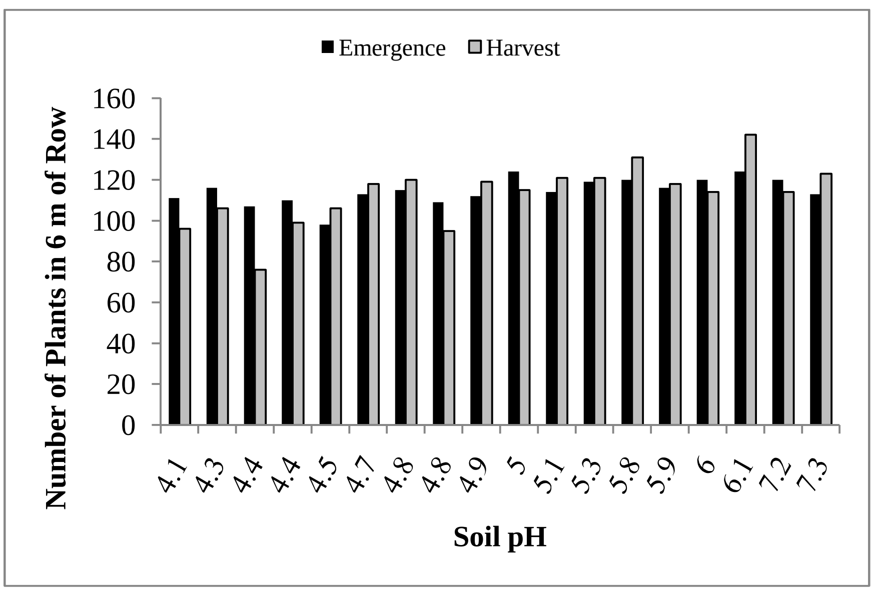

Figure A4. Grain Sorghum plant counts at emergence and number of heads at harvest at Lahoma, OK (2010).

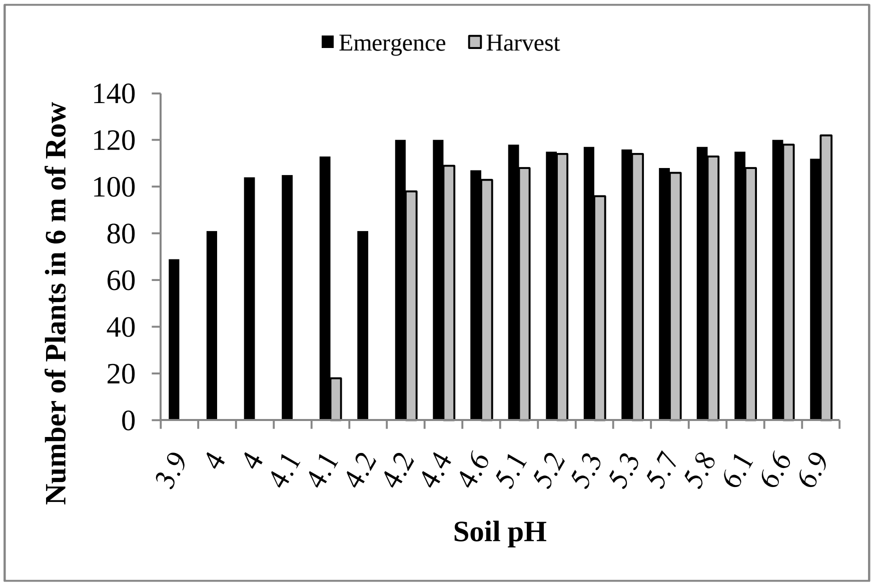

Figure A5. Grain Sorghum plant counts at emergence and number of heads at harvest at Perkins, OK (2010).

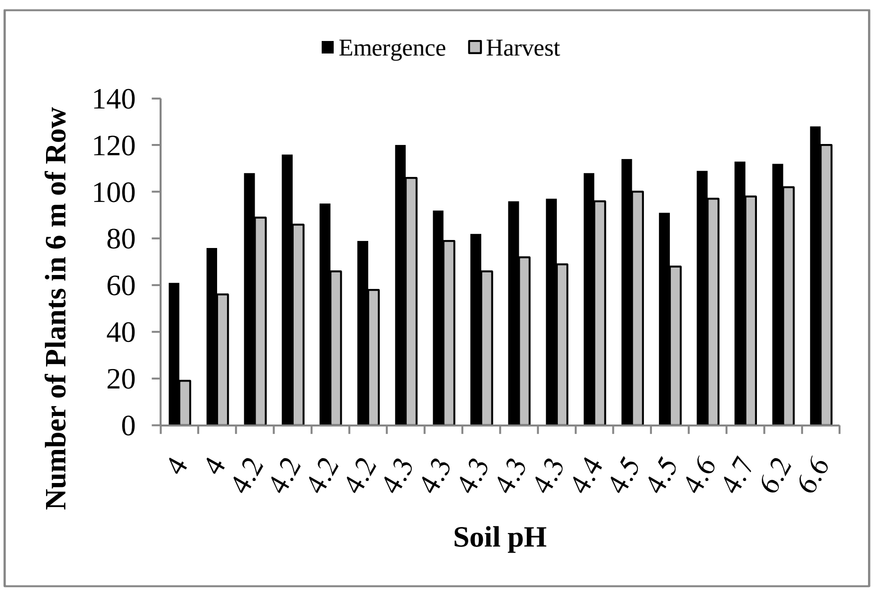

Figure A6. Grain Sorghum plant counts at emergence and number of heads at harvest at Haskell, OK (2010).

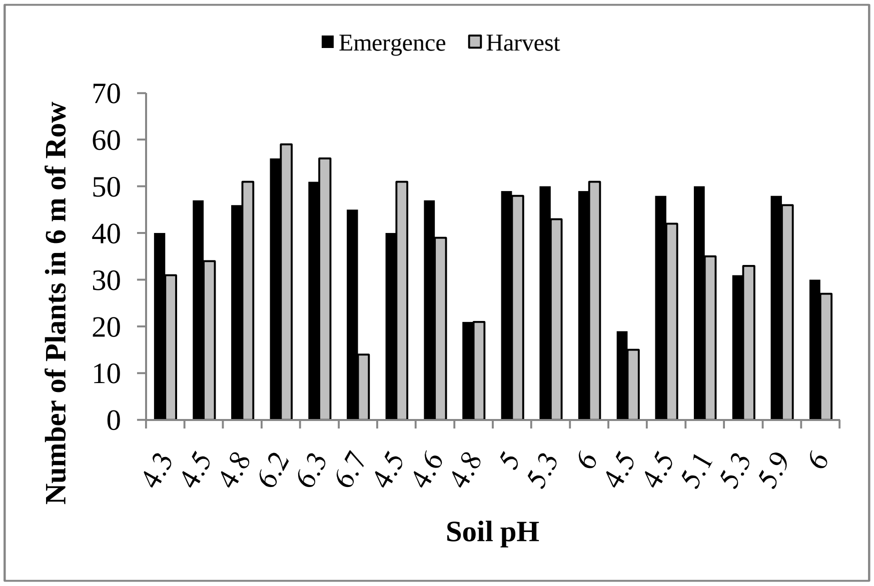

Figure A7. Sunflower plant counts at emergence and number of heads at harvest at Lahoma, OK (2010).

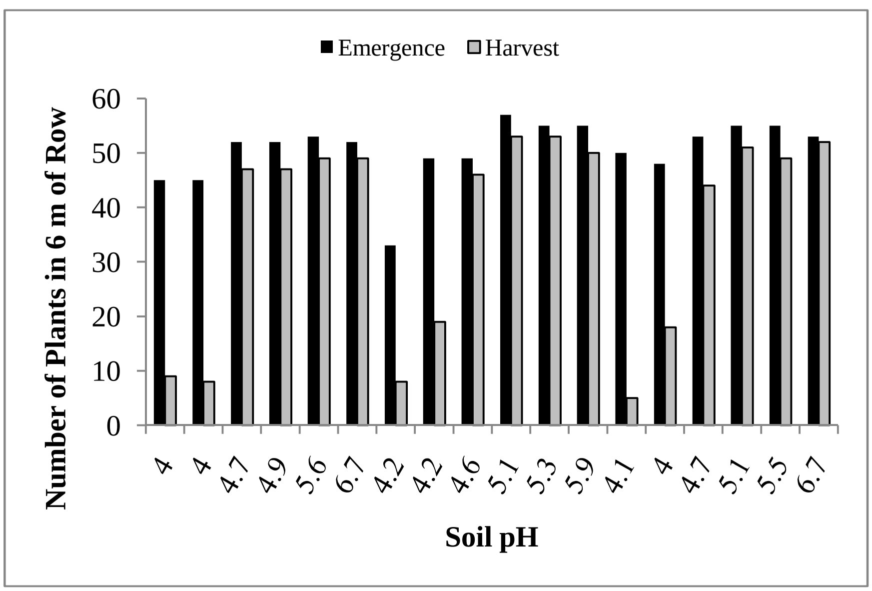

Figure A8. Sunflower plant counts at emergence and number of heads at harvest at Perkins, OK (2010).

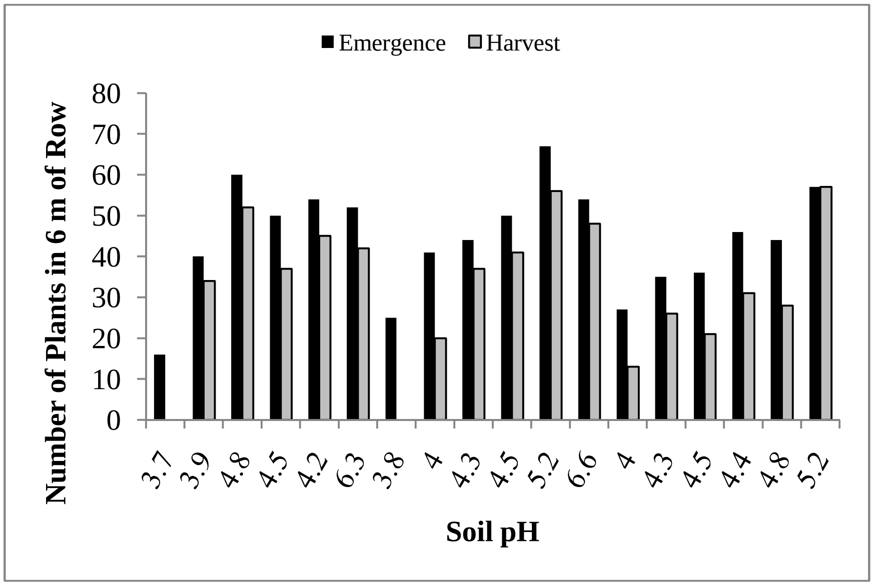

Figure A9. Sunflower plant counts at emergence and number of heads at harvest at Haskell, OK (2010).

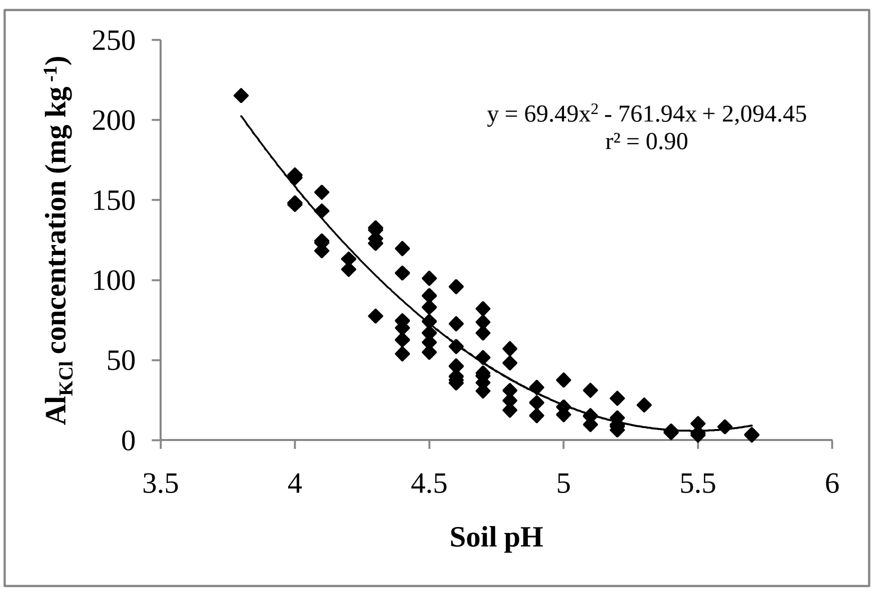

Figure A10. 1 *M* KCl extractable Aluminum concentration in the soil and soil pH at Perkins, Lahoma, and Haskell, OK (2010).

Table A9. Regression results of Al_{KCl} concentration in the soil and soil pH of all treatments at Lahoma, Perkins, and Haskell, OK

2010	**DF**	**Mean Square**	**F**	**Prob F**	**R^2**
Grain Sorghum	1	77150	69.90	<0.0001	0.57
Sunflower	1	92605	90.86	<0.0001	0.64

Table A10. Regression results of grain sorghum and sunflower relative yield and Al_{KCl} concentration in the soil at Lahoma, Perkins, and Haskell, OK (2010).

2010	**DF**	**Mean Square**	**F**	**Prob F**	**R^2**
Grain Sorghum	1	2.63533	97.02	<0.0001	0.65
Sunflower	1	2.24748	52.23	<0.0001	0.50

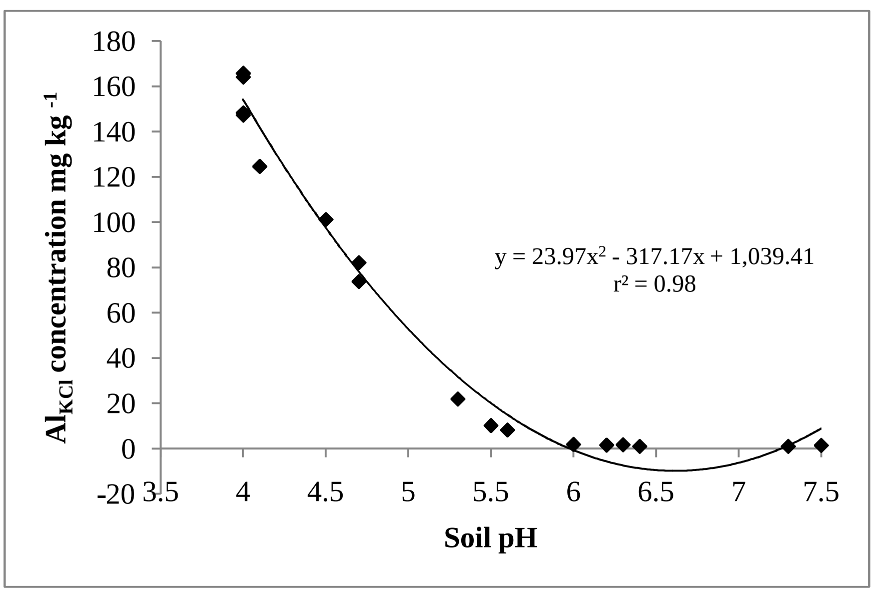

Figure A11. 1 *M* KCl extractable aluminum concentration and soil pH in grain sorghum treatments, used to determine the soil pH where Al toxicity (45 mg kg^{-1}) occurred at Perkins, OK

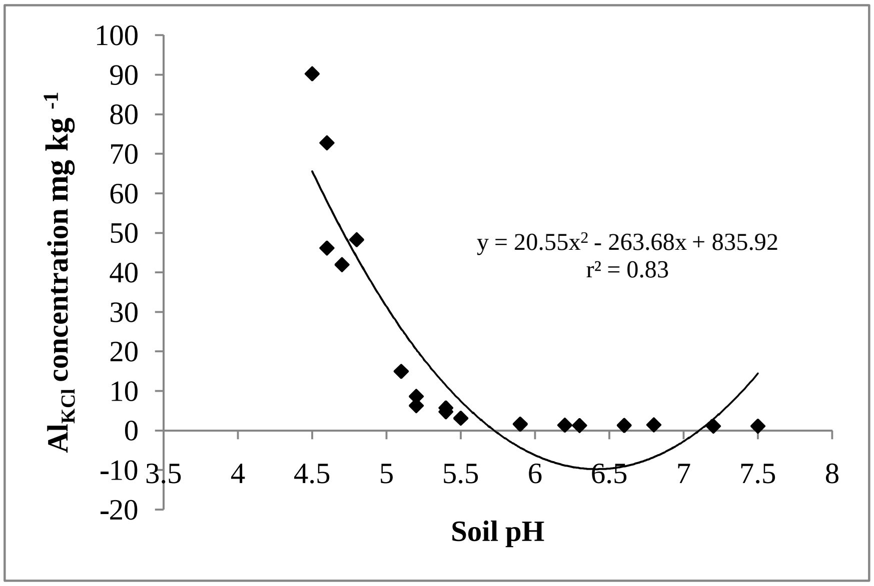

Figure A12. 1 *M* KCl extractable aluminum concentration and soil pH in grain sorghum treatments, used to determine the soil pH where Al toxicity (45 mg kg^{-1}) occurred at Lahoma, OK

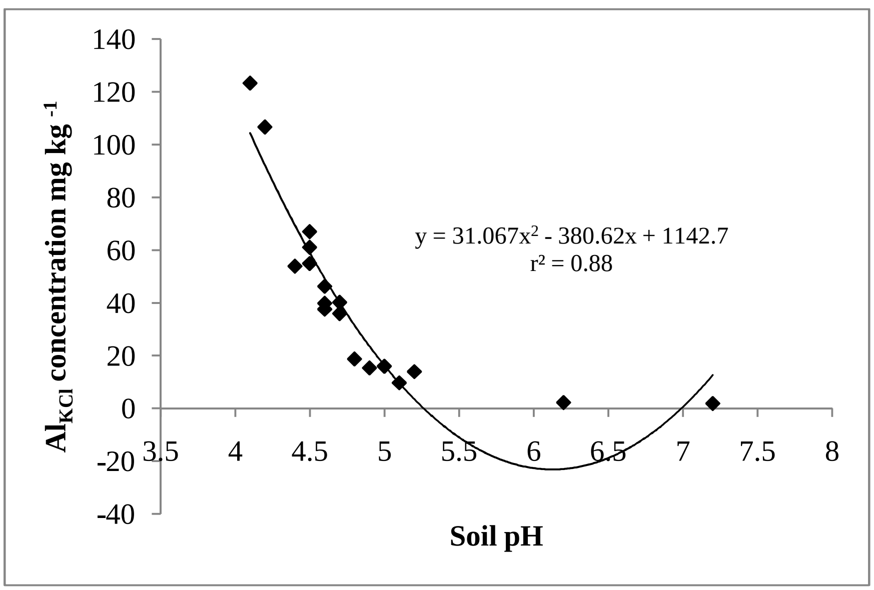

Figure A13. 1 *M* KCl extractable aluminum concentration and soil pH in grain sorghum treatments, used to determine the soil pH where Al toxicity (45 mg kg^{-1}) occurred at Haskell, OK

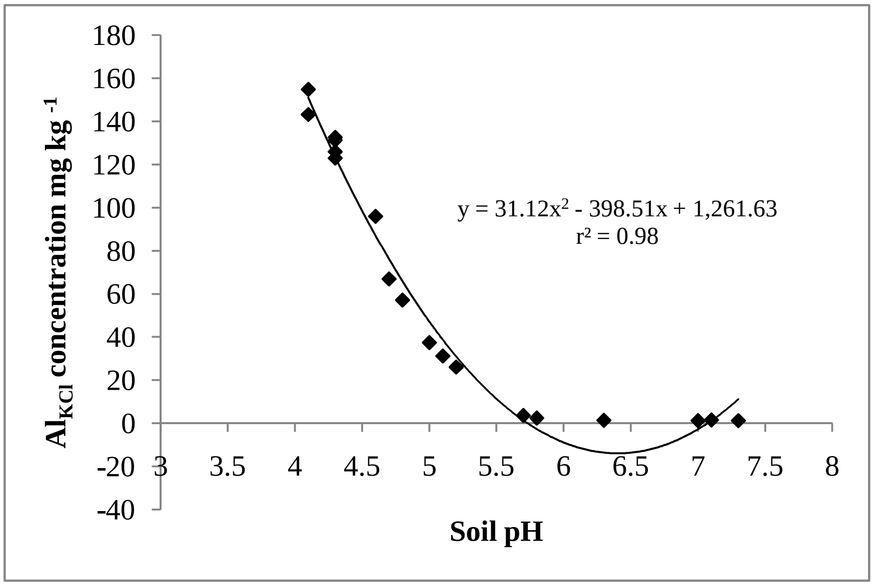

Figure A14. 1 *M* KCl extractable aluminum concentration and soil pH in sunflower treatments, used to determine the soil pH where Al toxicity (40 mg kg^{-1}) occurred at Perkins, OK (2010).

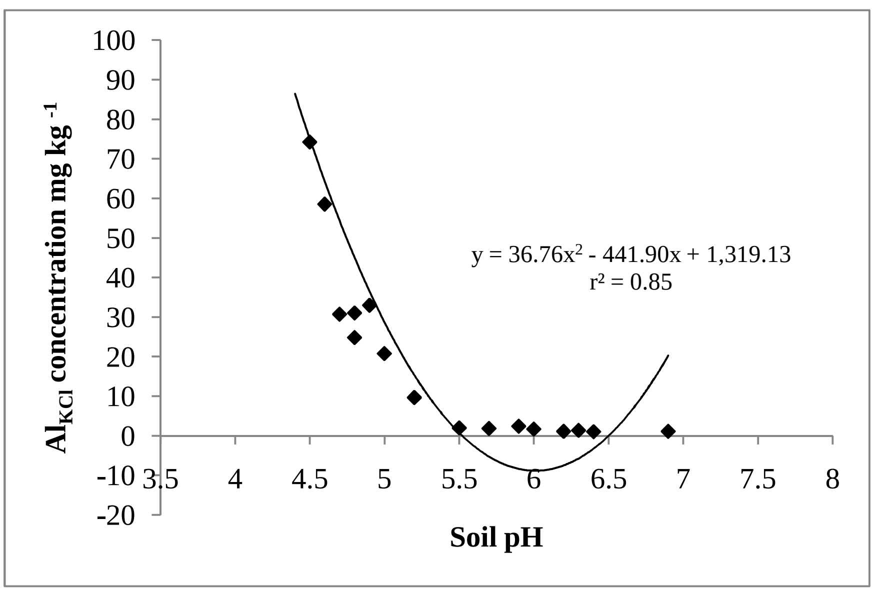

Figure A15. 1 *M* KCl extractable aluminum concentration and soil pH in sunflower treatments, used to determine the soil pH where Al toxicity (40 mg kg^{-1}) occurred at Lahoma, OK (2010).

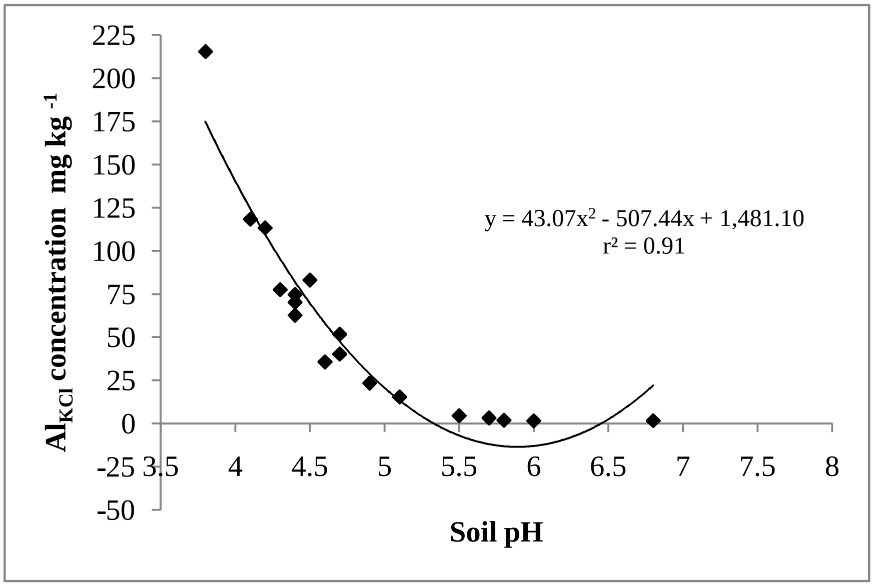

Figure A16. 1 *M* KCl extractable aluminum concentration and soil pH in sunflower treatments, used to determine the soil pH where Al toxicity (40 mg kg $^{-1}$) occurred at Haskell, OK (2010).

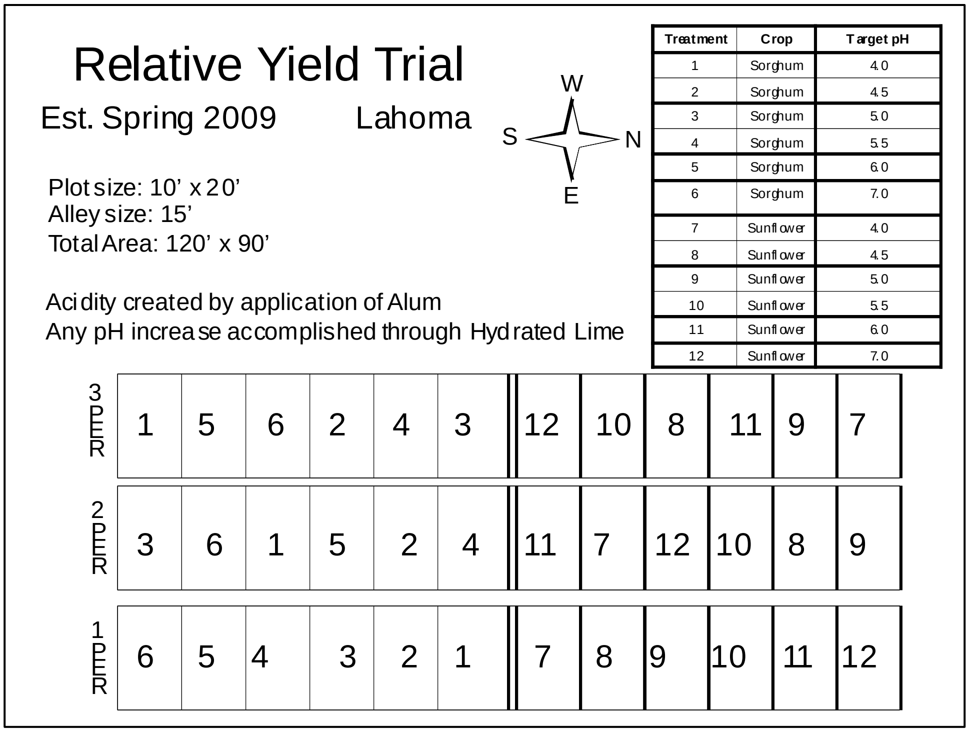

Figure A17. Treatment structure at Lahoma, OK (2009).

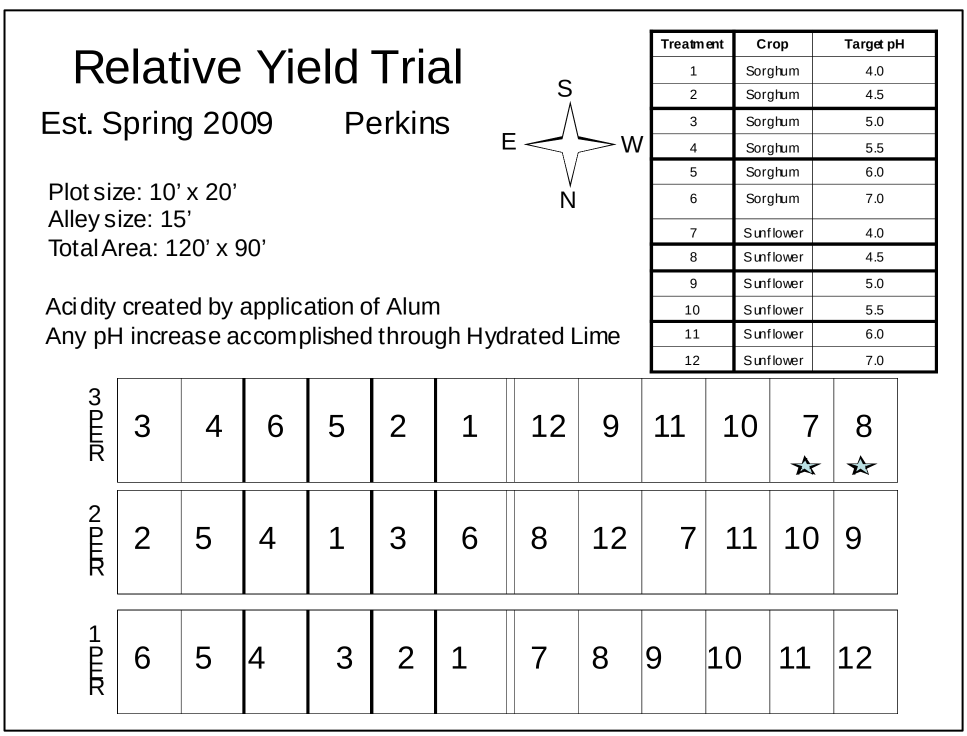

Figure A18. Treatment structure at Perkins, OK (2009).

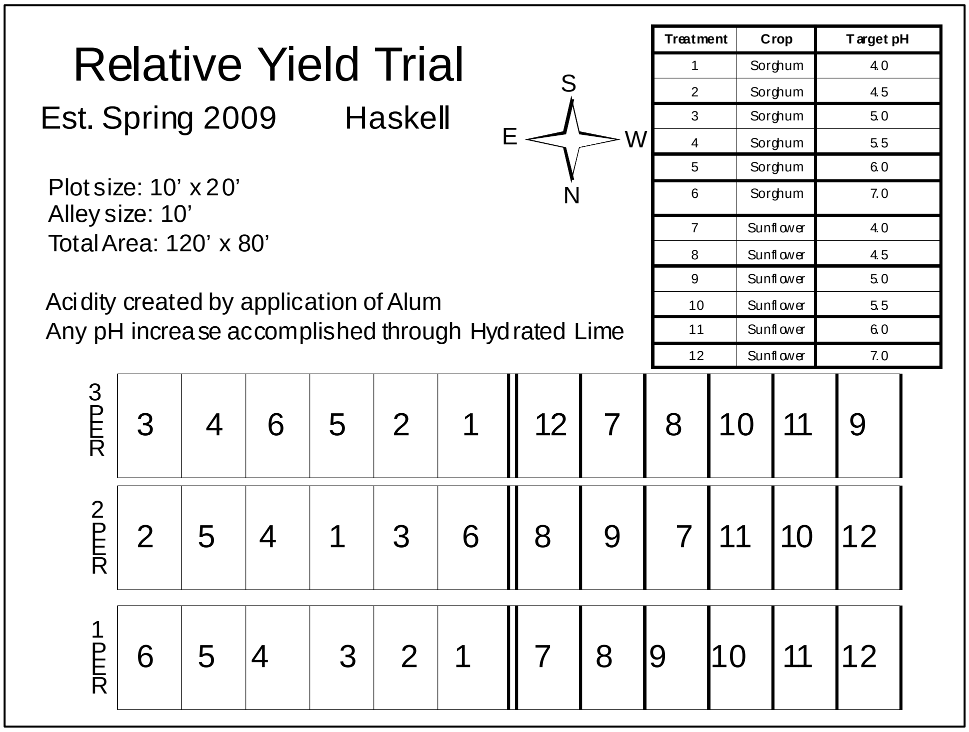

Figure A19. Treatment structure at Haskell, OK (2009).

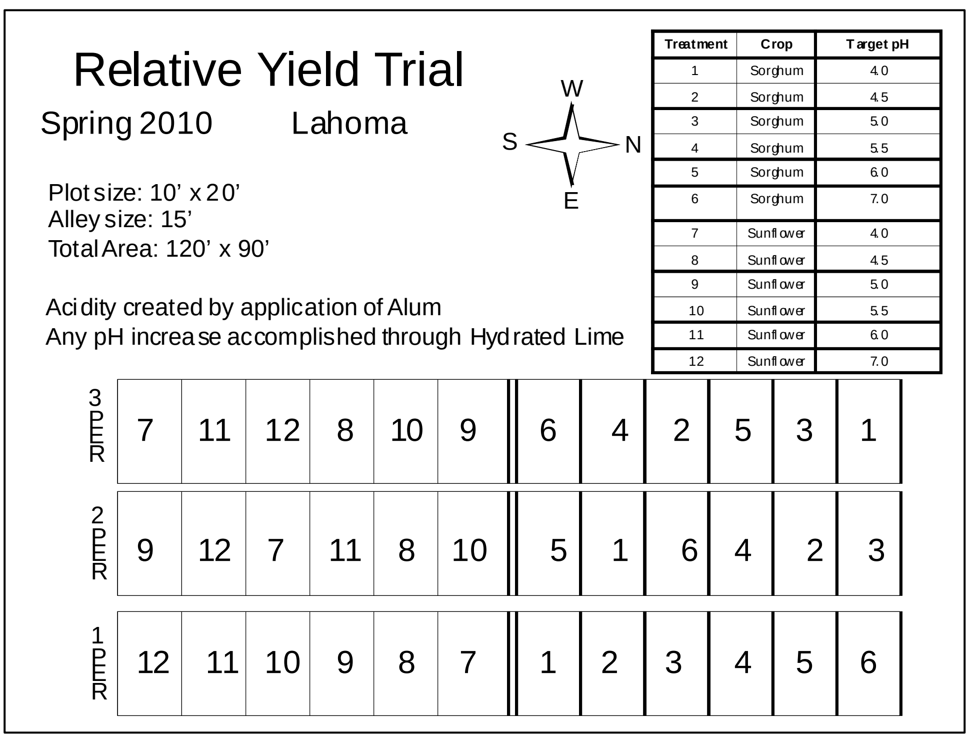

Figure A20. Treatment structure at Lahoma, OK (2010).

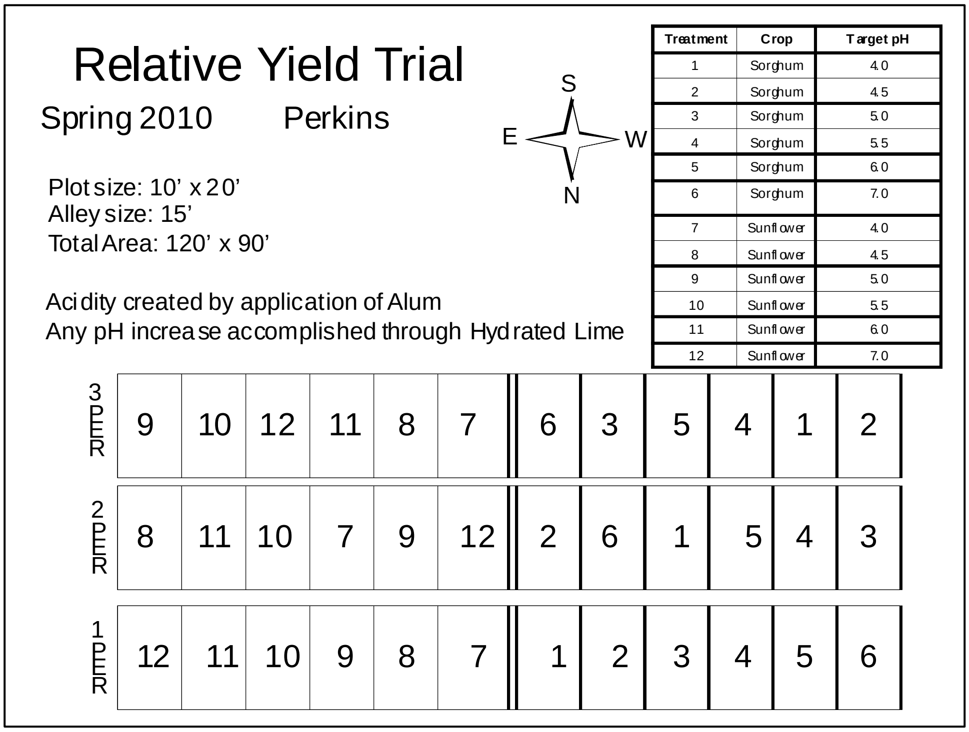

Figure A21. Treatment structure at Perkins, OK (2010).

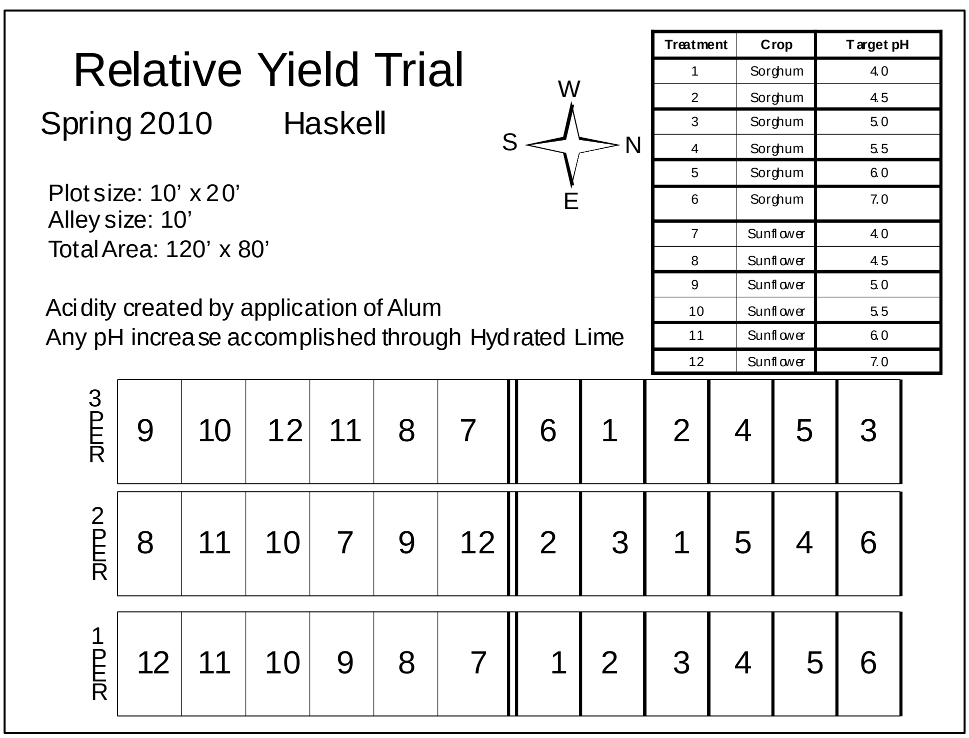

Figure A22. Treatment structure at Haskell, OK (2010).

VITA

Katy Shayne Butchee

Candidate for the Degree of

Master of Science

Thesis: EVALUATING THE EFFECTS OF SOIL PH ON GRAIN SORGHUM *(SORGHUM BICOLOR)* AND SUNFLOWER *(HELIANTHUS ANNUUS* L.*)* PRODUCTION

Major Field: Plant and Soil Sciences

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Graduated from Hollis High School, Hollis, OK in May 2005.

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Employed by Oklahoma State University as an office assistant (2007-2009).

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Professional Memberships:

American Society of Agronomy 2010-Present
Crop Science Society of America 2010-Present
Soil Science Society of America 2010-Present

Name: Katy Shayne Butchee Date of Degree: May, 2011

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: EVALUATING THE EFFECTS OF SOIL PH ON GRAIN SORGHUM *(SORGHUM BICOLOR)* AND SUNFLOWER *(HELIANTHUS ANNUUS* L.*)* PRODUCTION

Pages in Study: 68 Candidate for the Degree of Master of Science

Major Field: Plant and Soil Sciences

Scope and Method of Study:

The transition from conventional tillage winter wheat production systems to no-tillage production systems has led to the incorporation of grain sorghum and sunflower as rotation crops; however, these crops may not perform well when grown on acidic soils. This study was conducted to determine the quantitative effect of soil pH on grain sorghum and sunflower production. The relationship of relative yield and soil pH was investigated at Lahoma, Perkins, and Haskell, OK with soil pH treatments ranging from 4.0 – 7.0. Soil pH was altered using aluminum sulfate or hydrated lime. In season measurements (plant counts, plant height, and NDVI), yield and 1 *M* KCl extractable Al concentration in the soil were analyzed.

Findings and Conclusions:

Soil acidity negatively affected yield in both grain sorghum and sunflower. Yield reductions of 10% were observed at soil pH 5.42 and 5.27 in grain sorghum and sunflower, respectively. When soil pH was at or below 5.14 and 5.08, yield reductions of >20% were observed in grain sorghum and sunflower, respectively. Liming should be considered to increase soil pH if it is below these critical levels where grain sorghum or sunflower will be produced.

ADVISER'S APPROVAL: Dr. Brian Arnall