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Research Article

Determining Critical Soil pH for Grain Sorghum Production

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Grain sorghum (*Sorghum bicolor* L.) has become a popular rotation crop in the Great Plains. The transition from conventional tillage to no-tillage production systems has led to an increase in the need for crop rotations. Some of the soils of the Great Plains are acidic, and there is concern that grain sorghum production may be limited when grown on acidic soils. The objective of this study was to evaluate the effect of soil pH for grain sorghum production. Potassium chloride-exchangeable aluminum was also analyzed to determine grain sorghum's sensitivity to soil aluminum (Al) concentration. The relationship between relative yield and soil pH was investigated at Lahoma, Perkins, and Haskell, Oklahoma, USA with soil pH treatments ranging from 4.0–7.0. Soil pH was altered using aluminum sulfate or hydrated lime. Soil acidity reduced grain sorghum yield, resulting in a 10% reduction in yield at soil pH 5.42. Potassium chloride-exchangeable aluminum levels above 18 $mg\,kg^{-1}$ resulted in yield reductions of 10% or greater. Liming should be considered to increase soil pH if it is below these critical levels where grain sorghum will be produced.

1. Introduction

Producers throughout the Great Plains are converting areas of conventional tillage to no-tillage systems [1]. A key component of successful no-tillage production systems is the integration of crop rotations, which help break weed, disease, and insect cycles [1]. Due to its ability to tolerate warm and relatively dry climates, grain sorghum (*Sorghum bicolor* L.) is well suited for crop rotations in the Central Great Plains.

Grain sorghum has traditionally been grown on soils with a pH of >6.5 [2]; however, a review of soil test results in 2005 by the Potash and Phosphate Institute [3] observed that 46% of the tested samples in Oklahoma had a soil pH of <6.0. 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. With the integration of grain sorghum as a rotation crop, acidic soils may need to be limed; whereas, this may not have been necessary when continuous winter wheat was produced.

This study focused on evaluating relative yields of grain sorghum with respect to soil pH, which are useful for determining if there is a yield reduction associated with soil acidity. This information will be helpful for producers when determining if liming an acidic soil where grain sorghum will be produced is economical and necessary.

The exact quantitative effect of soil pH on grain sorghum 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 [4, 5]. Determining the behavior of grain sorghum grown on soil varying in pH will be a useful tool for educating producers and agronomists about the importance of liming acidic soils.

Previous research concerning grain sorghum and soil pH determined that as reactive Al concentration increased, the symptoms of Al toxicity also increased [6]. 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 tissue matter.

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

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)

Duncan et al. [7] observed different grain sorghum genotypes to determine their acid tolerance. Grain yields dropped from 2069 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 4279 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 did not 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.

Tan and Keltjens [8] determined that Al toxicity was evident as damage to the roots and through the reduction of magnesium (Mg) availability. 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. Liming a soil with pH of 4.3 and raising it to pH 4.7 alleviated the Al toxicity.

Flores et al. [9] 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. [9] concluded that all sorghum genotypes grown at Al saturation above 70% performed poorly.

2. Materials and Methods

The field experiment was established in 2009 at the Cimarron Valley Research Station near Perkins (Teller series), Oklahoma, the North Central Research Station near Lahoma (Grant Series), Oklahoma, and the Eastern Research Station near Haskell (Taloka series), Oklahoma (Table 1).

The experimental design was Randomized Complete Block (RCBD) with four replications. Plot size was 6 m long × 3 m wide with 4.6 m alleys between each replication at Lahoma and Perkins and 3 m alleys between each replication at Haskell. Soil was amended in each location to obtain six target soil pH ranging from 4.0 to 7.0.

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 60°C overnight and ground to pass through a 2 mm sieve. A 1 : 1 soil : water suspension and glass electrode were used to measure soil pH and buffer index [10, 11]. 1 M KCl solution was used to extract soil NO_3–N and NH_4–N and quantified using a Flow Injection Autoanalyzer (Lachat Instruments, Milwaukee, WI, USA). Mehlich III solution was used to extract plant-available P and K [12], and the amount of P and K were quantified using a Spectro Ciros inductively coupled plasma (ICP) spectrophotometer [13]. 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 1/2 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 subsamples 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 $Ca(OH)_2$ was 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. Based on the average total soil Al concentrations for this soil (~12,000 mg kg^{-1}), the highest alum amendment only added Al at 2.3% of the total background soil Al concentration. Table 2 lists the initial pH of each location and the amount of $Ca(OH)_2$ and $Al_2(SO_4)_3$ needed to change soil ph by 1.0. The plots were cultivated to incorporate the $Ca(OH)_2$ and $Al_2(SO_4)_3$ several months prior to planting. Grain sorghum was planted at a seeding rate of 123,500 seeds ha^{-1}. The middle two rows of each plot were harvested by hand or with a small plot combine. Grain was dried and weighed. Grain yield was corrected to 14% moisture content.

Additional soil samples were taken midseason and postharvest 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) [13].

Table 2: Initial soil pH values of each trial location and the amount of hydrated lime and alum (Mg ha^{-1}) required to change soil pH by 1.0 unit.

Location	Initial soil pH	Mg ha^{-1} hydrated lime 1.0 pH change	Mg ha^{-1} alum 1.0 pH change
Perkins, OK	4.86	1.69	1.52
Lahoma, OK	5.5	1.31	2.78
Haskell, OK	5.2	4.1	2.17

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, USA. These samples were analyzed for soil pH to determine the variation in soil pH within the profile. Samples were not taken at Haskell, OK, USA due to equipment and travel constraints.

Plant counts were taken from the two middle rows of each treatment 1–3 weeks after emergence in 2009 and 2010. Plant height measurements were taken from 5 random plants within the two middle rows of each treatment at the 7 leaf stage at Lahoma and Perkins and at the 8-leaf stage at Haskell in 2010. Also in 2010, the Greenseeker was used to collect Normalized Difference Vegetative Index (NDVI) readings from the middle two rows of each treatment at the 2–5 leaf stage at Lahoma and Perkins and at the 8 leaf stage at Haskell. NDVI is calculated as:

$$\mathrm{NDVI} = \left[\frac{(\mathrm{NIR} - \mathrm{Red})}{(\mathrm{NIR} + \mathrm{Red})}\right]. \quad (1)$$

NIR and Red are near-infrared (780 nm) wavelengths, and red (671 nm) wavelengths respectively [14]. These readings provide a measurement of biomass, plant health, and plant vigor. The red light emitted from the Greenseeker is absorbed by plant chlorophyll. Healthier plants have a higher NDVI value because they absorb more red light and reflect more near-infrared light [15]. 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. Grain was collected and weighed to calculate yield.

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 was expressed as a percentage of maximum yield potential for that location. Relative yield was calculated as:

$$\text{Relative yield}_{\text{avg}} = \left[\frac{(\text{Actual yield})}{(\text{Average of 3 highest yields for that site})}\right]. \quad (2)$$

Data analysis was generated using SAS software, Version 9.2 of the SAS system (Copyright 2008) SAS Institute Inc. Data was analyzed using quadratic least squares regression (PROC GLM) and nonlinear regression (PROC NLIN).

3. Results and Discussion

3.1. Soil Profile pH. Soil profile pH results indicate that soil pH was altered to a depth of approximately 31 cm at Perkins and Lahoma (Figures 1 and 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 [16]. The Lahoma location has a slight slope, and sheet erosion likely caused the treatment with target pH of

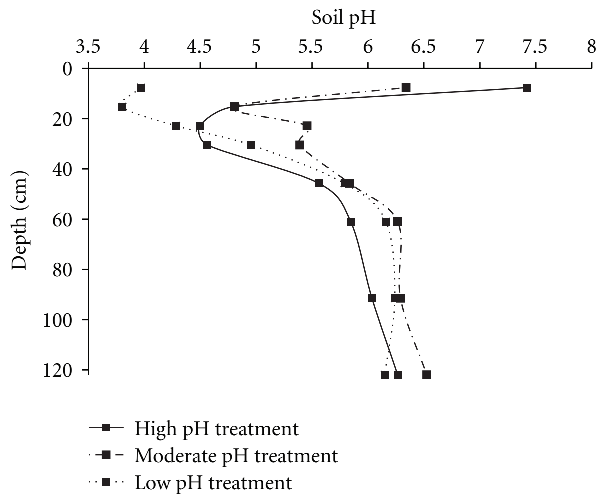

Figure 1: Postharvest soil profile pH at Perkins, Oklahoma for target pH treatments of 4.0, 6.0, and 7.0 (2010).

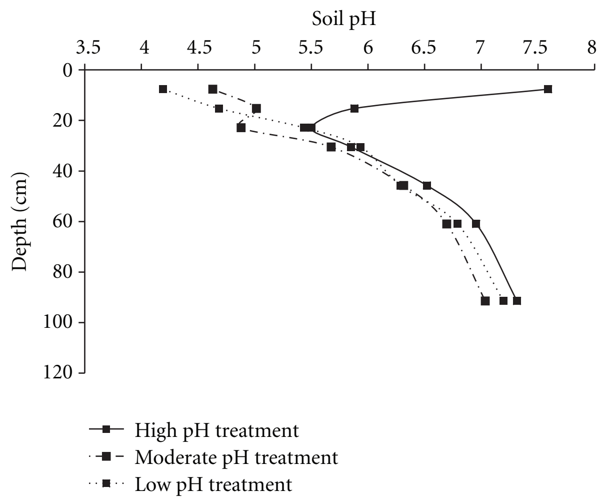

Figure 2: Postharvest soil profile pH at Lahoma, OK, USA for target pH treatments of 4.0, 6.0, and 7.0 (2010).

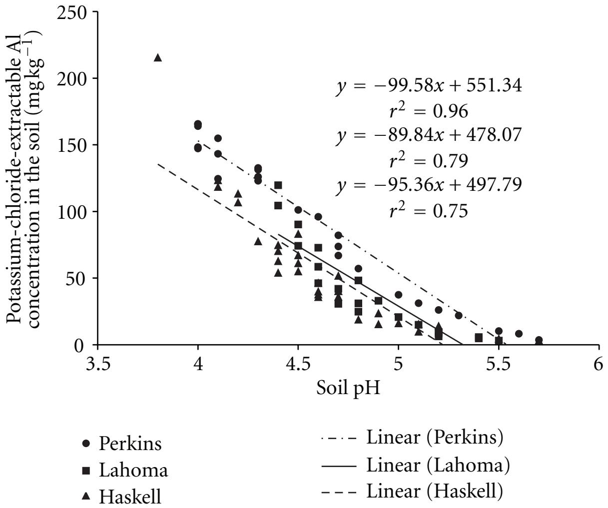

Figure 3: Relationship between potassium-chloride-extractable Al concentration in the soil and soil pH from a 15 cm composite soil sample for each treatment at Perkins, Lahoma, and Haskell, Oklahoma (2010).

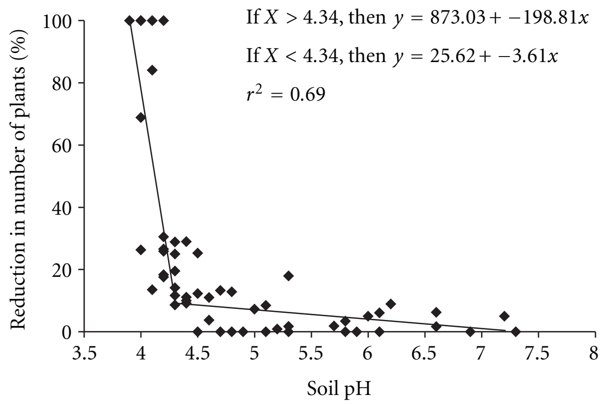

Figure 4: Percent reduction in number of grain sorghum plants from emergence to immediately prior to harvest at Perkins, Lahoma, and Haskell, Oklahoma (2010).

6 being much lower in the top 15 cm (Figure 2) as the target pH of the plot upslope was 4.0. After emergence a heavy rain drove sediment down slope into the plot.

3.2. Extractable Aluminum Concentration in Soil. Aluminum toxicity is one of the primary concerns when addressing soil acidity; therefore, potassium-chloride-extractable Al was analyzed in all plots in 2010. Soil pH and potassium-chloride-extractable Al concentrations 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. Potassium-chloride-extractable Al concentrations increased as soil pH decreased (Figure 3). Regardless of the Al added with the alum, the increase in extractable Al is due to the decrease in pH. Soil soluble Al is controlled by pH conditions, not by total soil Al concentrations. For example, Warren et al. [17] applied normal and alum-treated poultry litter to two different Virginia soils. Even though the alum-treated litter added more Al to the soil compared to normal litter, the relationship between soil exchangeable Al and pH was unaffected by litter type (i.e., amount of Al added). Similarly, Moore and Edwards [18] found that application of N in the form of ammonium nitrate increased soil exchangeable Al due to decreasing pH, while the addition of Al from alum-treated litter had no impact on soil exchangeable Al. Soil Al mostly resides in the octahedral sheets of 1 : 1 and 2 : 1 clay minerals and also amorphous and crystalline Al oxides/hydroxides. Any Al added to the soil will immediately precipitate into an amorphous Al hydroxide mineral as a function of the soil pH. Similarly, the solubility of Al in soil minerals containing Al will be mostly controlled by pH; as pH decreases below 7, Al solubility increases.

3.3. Growth Factors. Plant emergence and plant height exhibited a negative response ($\alpha = 0.05$) to soil acidity when analyzed across all locations in 2009 and 2010 (Table 3). A negative response to soil acidity was also observed in NDVI measurements ($\alpha = 0.05$) at all locations, which demonstrates the reduction in biomass and plant vigor of plants in acidic treatments (Table 3). The number of heads plot^{-1} at harvest was reduced in low pH treatments at all locations in 2009 and 2010 suggesting that plant mortality increased with decreasing soil pH. 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 was correlated with soil pH (Figure 4). Plant mortality was not reduced when soil pH > 5.5, but the number of plants significantly decreased when soil pH < 4.43 (Figure 4). The plants located in treatments with lower soil pH likely had increased root pruning as a result of soil acidity, which 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.

3.4. Relative Yield. Relative yield exhibited a negative response to soil acidity and was significant ($\alpha = 0.05$) when evaluated in quadratic least squares regression at two of the five grain sorghum site years (Table 4). Nonlinear regression generated a yield plateau at 0.71 relative yield and soil pH 4.54. Assuming that most producers would not be willing to sustain yield losses of greater than 10%, relative yield 0.90 was chosen as the yield plateau level. The regression equation generated from PROC NLIN ($y = 0.3513 \times -1.0051$) was used to determine that the soil pH at relative yield 0.90 was 5.42 (Figure 5).

There was a considerable amount of variation in the yield response to soil pH among locations and years, which was likely due to environmental impacts other than soil pH. For example, results from the 2009 season show less

Table 3: Results from quadratic least squares regression when evaluating the effect of soil pH on grain sorghum emergence, plant height, NDVI, and mortality (2009 and 2010).

	DF	Mean square	F	Prob F	r^2	R
			2009			
Emergence	2	0.21	5.37	0.0077	0.17	0.48
			2010			
Emergence	2	0.19	19.60	<0.0001	0.44	0.54
Plant height	2	1.01	43.08	<0.0001	0.63	0.62
NDVI	2	0.92	122.18	<0.0001	0.83	0.78
Mortality	2	20351.59	35.42	<0.0001	0.59	0.53

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

	DF	Mean square	F	Prob F	r^2
			2009		
Lahoma	2	0.06	2.31	0.133	0.24
Perkins	2	0.04	0.35	0.7082	0.04
All locations	2	0.18	3.23	0.0542	0.18
			2010		
Lahoma	2	0.06	1.59	0.2371	0.17
Perkins	2	1.24	37.67	<0.0001	0.83
Haskell	2	0.25	15.65	0.0002	0.68
All locations	2	1.12	22.82	<0.0001	0.47

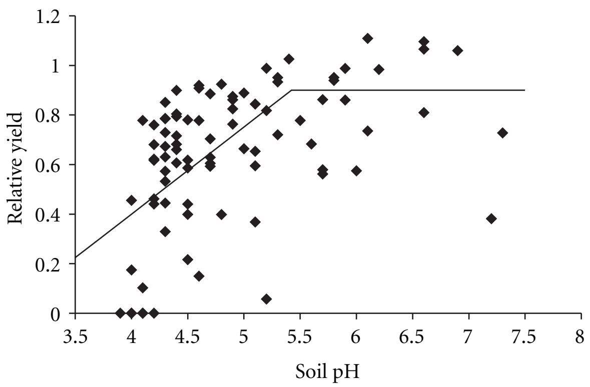

Figure 5: Relationship of grain sorghum relative yield and soil pH at Lahoma, Perkins, and Haskell, Oklahoma with yield plateau occurring at 0.90 with critical soil pH 5.42 (2009 and 2010).

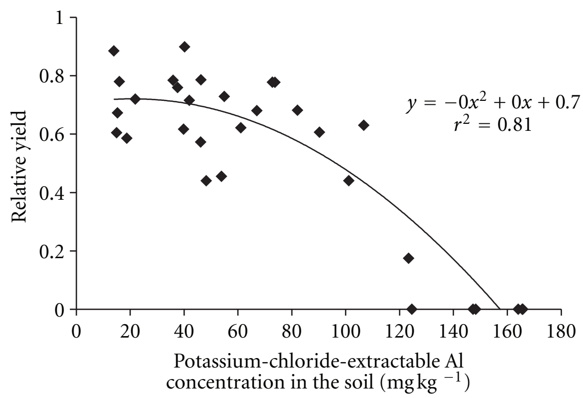

Figure 6: Quadratic relationship of potassium-chloride-extractable Al concentration in soil and grain sorghum relative yield at Perkins, Lahoma, and Haskell, Oklahoma (2010).

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. The concentration of extractable Al in the soil was analyzed in 2010 and was found to be highly correlated with soil pH ($r^2 = 0.90$) and relative yield ($r^2 = 0.81$) (Figures 3 and 6).

3.5. 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 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.

4. Conclusions

The results from this study varied from location to location and year to year; however, a trend was detected that confirms that soil acidity reduced grain sorghum yield. This study demonstrated that the environment played a significant role in the degree of soil acidity stresses observed in grain sorghum 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 low, land is rented, or there is not high yield potential, 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.

Potassium-chloride-extractable Al concentration in the soil, which is related to parent material and soil CEC, negatively affected crop response to soil acidity. Differences in potassium-chloride-extractable Al 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 concentration in the soil in addition to soil pH and buffer index.

In this study, at grain sorghum relative yield 0.90, the critical soil pH was 5.42. The models developed in this study will provide producers with a tool to estimate yield reductions at a given soil pH (Figure 5). As producers incorporate grain sorghum into rotations, it is recommended that soil pH be tested and limed if soil pH is 5.42 or below to ensure that 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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