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Research Article

Determining Critical Soil pH for Sunflower Production

Apurba Sutradhar,[1] Romulo P. Lollato,[1] Katy Butchee,[2] and Daryl B. Arnall[1]

[1] *Department of Plant and Soil Sciences, Oklahoma State University, Stillwater, OK 74078, USA*
[2] *Western Oklahoma State College, 2801 N. Main, Altus, OK 73521, USA*

Correspondence should be addressed to Daryl B. Arnall; b.arnall@okstate.edu

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Soil acidity has become a major yield-limiting factor in cropping systems of the Southern Great Plains, in which winter wheat (*Triticum aestivum* L.) is the predominant crop. Sunflower (*Helianthus annuus* L.) is a strong rotational crop with winter wheat due to its draught and heat tolerance. However, the effects of low soil pH on sunflower productivity have not been explored. The objective of this study was to determine the critical soil pH and aluminum concentration (Al_{KCl}) for sunflower. Sunflower was grown in a randomized complete block design with three replications of a pH gradient ranging from 4.0 to 7.0 at three locations with varying soil types. Soil pH was altered using aluminum sulfate ($Al_2(SO_4)_3$) and hydrated lime ($Ca(OH)_2$). Plant height, vigor, and survivability were all negatively affected by soil acidity. Sunflower yield was reduced by 10% at or below soil pH 4.7 to 5.3 dependent upon location and soil type. Levels of Al_{KCl} above 6.35 mg kg^{-1} reduced seed yield by 10% or greater. We concluded that sunflower may serve as a better rotational crop with winter wheat under acidic conditions when compared to other adaptable crops.

1. Introduction

The southern Great Plains of the United States is one of the most intensive winter wheat (*Triticum aestivum* L.) production regions in the world. However, the increasing adoption of no-tillage practices in recent years led to greater crop diversification and, consequently, alternative summer crops are being grown as part of crop rotation systems [1]. Sunflower (*Helianthus annuus* L.) arises as a valuable option as rotational crop with no-till winter wheat for its ability to tolerate warm and relatively dry climates, which are typical characteristics of summer periods in the region. Summer periods in Oklahoma are characterized by high evaporative demand and low precipitation; thus the crops are often subjected to drought stress [2]. Thus, strategies to mitigate the effects of water deficit such as choosing a drought tolerant crop are warranted for summer crops in the region.

Although acidity is not a natural problem for most agricultural soils in Oklahoma, intensive monocropping wheat production led to soil acidification in many Oklahoma fields. A review of soil test results in 1997 by the Potash and Phosphate institute concluded that 37% of the tested samples in Oklahoma had soil pH of less than 6.0 [3]. Furthermore, Zhang and McCray [4] reported that 23.6% of 68,000 soil samples received by the Oklahoma State University Soil, Water, and Forage Analytical Laboratory had soil pH of less than 5.5 during the period of 2004 to 2008. The observed lower soil pH values resulted from heavy use of ammonia/ammonium based nitrogen (N) fertilizers, which led to acidic conditions by the net positive balance of hydrogen ions in the soil [5, 6]. Oxidation of NH_4^+ to NO_3^- generates H^+ which results in lower soil pH [7, 8]. This acidification is further worsened by the removal of basic cations through the harvesting of forage and grain [9].

Decreased soil pH has the aggravating consequence of increased solubility of aluminum (Al). Toxic Al is associated with soil pH and as soil pH decreases, solubility of Al increases. In extreme acidic soils in Oklahoma, Al toxicity is one of the major causes of crop failure [10], as micromolar concentrations of Al can be toxic for many plants [11]. Increased Al concentration primarily inhibits root elongation and decreases plants' ability to explore soil for moisture and nutrients [12]. Decreased root elongation is then followed by an inhibition of DNA synthesis that might result in reduced seedling emergence and shoot growth [13–15]. Therefore, Al toxicity significantly affects growth and yield of many crops.

Winter wheat can tolerate soil pH 5.5 and lower [16, 17], depending on soil and weather characteristics. Also, use of Al tolerant winter wheat varieties and banding of phosphorus fertilizers has allowed producers to grow winter wheat in unfavorable low pH conditions [17, 18]. As winter wheat accounts for approximately 75% of Oklahoma's cropland [10], many producers do not consider liming in their management practices when soil pH is below the critical threshold levels for winter wheat. However, sunflower has traditionally been produced on soils with nearly neutral pH (6.5 to 7.5) [19]. Thus, with the integration of sunflower into the rotation system, liming acidic soils may now need to be considered within the farmer's management practices.

The exact quantitative effect of soil pH on sunflower growth and productivity has not previously been evaluated. Most 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 crops [13, 20]. Determining the effects of a wide range of soil pH and extractable Al on sunflower growth and seed yield will be a useful tool for educating producers and agronomists about the importance of liming acid soils. Therefore, the objective of this study was to determine the critical soil pH and Al tolerance for sunflower production in Oklahoma.

2. Materials and Methods

2.1. Sites. Three field experiments were conducted for the growing seasons of 2009 and 2010, one in a Teller sandy loam (fine-loamy, mixed, active, thermic Udic Argiustolls) at the Cimarron Valley Research Station near Perkins (35°59′23″N, 97°2′48″W) and another in a Taloka silt loam (fine, mixed, active, thermic Mollic Albaqualfs) at the Eastern Research Station near Haskell (35°49′1″N, 95°39′24″W); and the third was in a Grant silt loam (fine-silty, mixed, superactive, thermic Udic Argiustolls) at the North Central Research Station near Lahoma (36°23′4″N, 98°6′27″W), Oklahoma. Initial soil fertility conditions for all three locations are presented in Table 1.

2.2. Treatments and Experimental Design. Treatments were arranged in a randomized complete block design with 6 m long and 3 m wide plots. Treatments were six target soil pH values ranging from 4.0 to 7.0 (i.e., 4.0, 4.5, 5.0, 5.5, 6.0, and 7.0). All experimental treatments were replicated three times with 4.6 m alleys at Perkins and Lahoma and 3 m alleys at Haskell. One composite sample consisting of 15 to 20 soil cores to a depth of 15 cm was collected from each plot prior to planting. These samples were used to determine the initial soil pH and plant-available nitrogen (N), phosphorus (P), and potassium (K) concentrations. 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 pH meter were used to measure soil pH and buffer index [21, 22]. Soil nitrate-nitrogen (NO_3-N) and ammonium-nitrogen (NH_4-N) were extracted using 1 M potassium chloride (KCl) quantified by a flow injection autoanalyzer (Lachat Instrument, Milwaukee, Wis, USA). Mehlich 3 solution was used to extract plant-available P and K, and the amounts of P and K were quantified using a Spectro Ciros inductively coupled plasma (ICP) spectrophotometer [23, 24]. Initial soil test results were used to calculate N, P, and K fertilizer rates and were broadcasted over each trial in 2009 and 2010.

Hydrated lime ($Ca(OH)_2$) and aluminum sulfate ($Al_2(SO_4)_3$) were applied to obtain target soil pH. To determine the amount of material needed to reach a given target soil pH, a laboratory experiment was conducted in 2009 to develop a response curve, as previously described by Butchee et al. [25]. To perform this laboratory experiment, composite soil samples were collected from all experimental sites to characterize initial site conditions. Subsamples weighing 500 g were taken from each composite sample and mixed with five incremental rates of $Al_2(SO_4)_3$ and $Ca(OH)_2$. The samples were then wetted and, after two, three, and four weeks, soil pH of each subsample was measured. These pH values were plotted as a function of $Ca(OH)_2$ and $Al_2(SO_4)_3$ to produce different response curves for the three studied locations. Equations obtained from the response curves were then solved to determine the amount of $Ca(OH)_2$ and $Al_2(SO_4)_3$ needed to achieve a specific soil pH for each soil. Depending on the initial values, $Ca(OH)_2$ was applied to raise or $Al_2(SO_4)_3$ was used to lower actual pH to the target pH assuming treatments of 15 cm soil depth. Table 2 lists the initial soil pH for each location and the amount of $Ca(OH)_2$ and $Al_2(SO_4)_3$ needed to change soil pH by 1.0 unit. The plots were cultivated to incorporate $Ca(OH)_2$ and $Al_2(SO_4)_3$ down to 20 cm several months prior to planting.

2.3. Sunflower Management and Relative Yield. Sunflower variety "Triumph S671" was planted in May for all locations for the growing seasons of 2009 and 2010 except for Perkins 2009, where sunflower was planted on June 3rd. A 6200 Monosem vacuum planter was used with a planting rate of 49,400 seeds ha^{-1}. Weeds, insects, and diseases were controlled using commercially available pesticides as needed throughout the growing seasons to ensure these were not limiting factors for crop growth and yield.

2.4. Measurement of Growth Components. Sunflower growth components were measured in 2010 for all three locations. To determine soil pH effects on crop stand, plant counts were taken from two middle rows of each treatment one to three weeks after emergence. At 7th leaf stage, plant height measurements were taken from five random plants within the two middle rows of each treatment at Perkins and Lahoma. Plant height measurements were taken at 8th leaf stage at Haskell. Normalized Difference Vegetative Index (NDVI) readings were taken from the two middle rows of each treatment when two to five leaves were visible at Perkins and Lahoma with a GreenSeeker (Model 505, NTech Industries, Ukiah, CA). At Haskell, NDVI readings were collected at 8th leaf stage.

The wavelengths of near-infrared (NIR) and red light are 780 nm and 671 nm, respectively. Healthier plants have higher amount of chlorophyll, thus absorbing more red light and

Table 1: Initial soil fertility conditions at Perkins, Haskell, and Lahoma, Oklahoma. Soil fertility is characterized by extractable sodium (Na), potassium (K), calcium (Ca), magnesium (Mg), aluminum (Al_{KCl}), effective cation exchange capacity (ECEC), and aluminum saturation (Al_{sat}).

Location	Na	K	Ca	Mg	Al_{KCl}	ECEC	Al_{sat}
			mg kg^{-1}			cmolc kg^{-1}	%
Perkins	11	37	17	5	0.9	0.28	1.3
Haskell	25	9	26	4	29.4	0.62	31.5
Lahoma	20	13	62	29	0.1	0.67	0.1

Table 2: Initial soil pH values of each trial-location and amount of hydrated lime and aluminum sulfate required to change soil pH by 1.0 unit.

Location	Initial soil pH	Hydrated lime [Mg ha^{-1}]	Aluminum sulfate [Mg ha^{-1}]
Perkins	4.8	1.69	1.52
Haskell	5.2	4.10	2.17
Lahoma	5.5	1.31	2.78

reflecting more NIR [26]. Both reflected lights are received by the sensor; and NDVI is calculated as

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

Therefore, healthier plants have higher NDVI values. These values provide a very strong correlation with biomass, plant health, and plant vigor [27].

Number of sunflower heads in the middle two rows of each plot was counted prior to harvest and was then used to calculate percent reduction in number of plants as

$$\begin{aligned}&\text{Percent reduction of number of heads}\\&\quad = \left[\frac{(\text{Emergence} - \text{number of heads})}{\text{Emergence}}\right] \times 100.\end{aligned} \tag{2}$$

2.5. Sunflower Harvest and Relative Yield. Sunflower was hand-harvested on 3 September 2009 at Lahoma and Haskell. Sunflower was not harvested at Perkins in 2009 due to bird pressure. In 2010, sunflower was hand-harvested at all three locations during the second week of August. Sunflower heads were dried to 13% moisture level and threshed using a Massey Ferguson experimental plot combine and a Kincaid thresher.

In this study, relative yield was used to avoid bias associated with multiple locations and varying growing conditions. Relative yield was expressed as percentage of maximum yield potential for a particular location for a particular year. Relative yield was calculated as

$$\begin{aligned}&\text{Relative yield}\\&\quad = \left[\frac{\text{Actual yield}}{\text{highest yield for that location for a particular year}}\right].\end{aligned} \tag{3}$$

2.6. Soil Sampling and Analyses. Mid-season soil samples were collected yearly to determine actual soil pH. These pH values were plotted with sunflower yield and growth factors to create linear plateaus for determining critical level. Soil samples were also collected following the 2009 harvest to evaluate soil nutrient status and soil pH. After harvest in 2010, a final set of composite soil samples was collected to determine potassium-chloride-extractable aluminum (Al_{KCl}) and saturated Al (Al_{sat}) present in the soil. Soil sample management and measuring cations were followed using the procedures as described previously. To determine Al concentration, a 2.0 g subsample was taken from each composite sample and was extracted with 20 mL 1 M KCl. Samples were placed on a shaker for 30 minutes and filtered, and the amount of Al extracted with 1 M KCl was quantified using inductively coupled plasma spectrometry (ICP) [24]. Effective cation exchange capacity (ECEC) and saturated Al (Al_{sat}) were determined using formula (4) and (5), respectively, suggested by Sumner and Miller (1996) [28]:

$$\begin{aligned}&\text{ECEC}\left(\text{cmol}_c\ \text{kg}^{-1}\right)\\&\quad = [\text{K}] + [\text{Ca}] + [\text{Mg}] + [\text{Na}] + [\text{Al}_{\text{KCl}}],\end{aligned} \tag{4}$$

$$\%\text{Al}_{\text{sat}} = \left(\frac{\text{Al}_{\text{KCl}}}{\text{ECEC}}\right) \times 100. \tag{5}$$

Additional 91 cm deep soil cores were taken from three plots with target soil pH of 4.0, 6.0, and 7.0 using a Giddings probe to determine the variation in soil pH within the profile. Deep soil cores were not collected at Haskell.

2.7. Statistical Analyses. Data were analyzed using SAS 9.3 software of SAS system (Copyright© SAS Institute Inc.). PROC LOESS procedure was used to get smoothed nonparametric fit of data. Using this procedure, breakpoints were estimated visually. Piecewise models for the critical points were developed using nonlinear procedure (PROC NLIN). Two linear regression models using PROC REG for an estimated breakpoint were used on the data to generate starting parameters for PROC NLIN procedure. General linear model (PROC GLM) was used for linear least square regression.

3. Results and Discussion

3.1. Amendment Effects on Soil pH. A wide range of final soil pH values was achieved with the application of amendment strategies. In 2010, soil pH ranged from 4.1 to 7.3 at Perkins

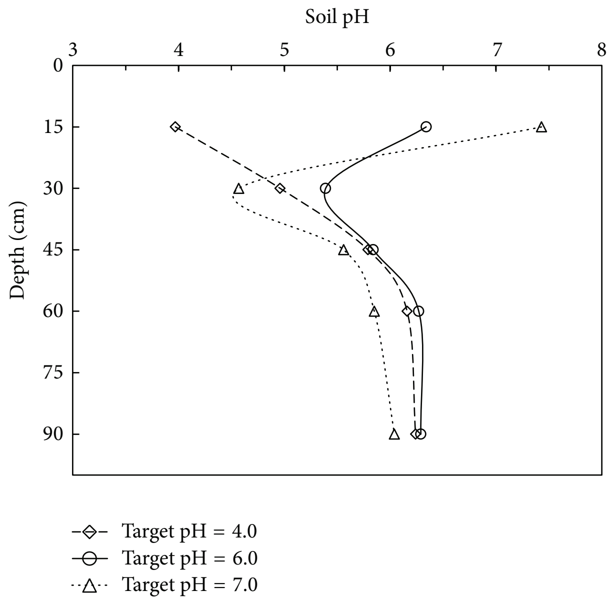

Figure 1: Effect of soil amendments on soil profile pH at Perkins, Oklahoma, in 2010 for target pH of 4.0, 6.0, and 7.0. Initial soil pH on the top 15 cm soil in 2009 prior to soil amendments application was 4.8.

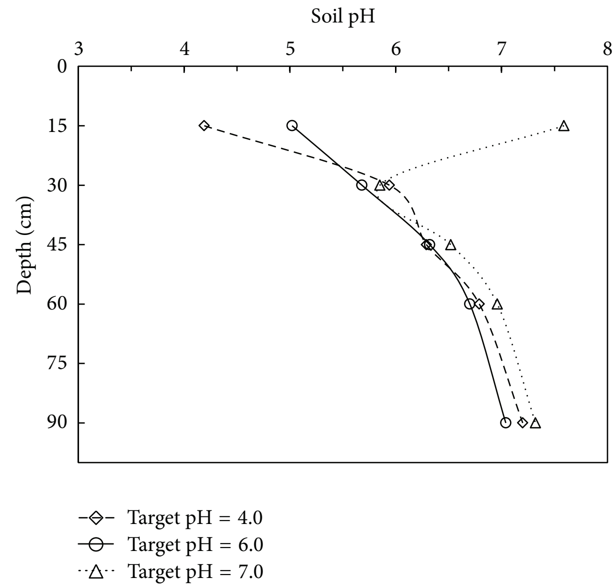

Figure 2: Effect of soil amendments on soil profile pH at Lahoma, Oklahoma, in 2010 for target pH of 4.0, 6.0, and 7.0. Initial soil pH on the top 15 cm soil in 2009 prior to soil amendments application was 6.8.

(Figure 1), 4.3 to 6.7 at Lahoma (Figure 2), and 3.8 to 6.8 at Haskell that provided a valuable dataset for the analysis of sunflower growth and development on three different soil pH gradients. The differences between actual and target pH values varied. In the fine sandy loam at Perkins, soil pH deviated by −0.1, +0.3, and +0.4 from the target soil pH of 4.0, 6.0, and 7.0 at the 15 cm depth (Figure 1). Soil pH differed down to a depth of 31 cm, indicating a leaching of amendment materials to deeper profile. In the Grant silt loam at Lahoma, pH deviated by +0.2, −1.0, and +0.6 in the 15 cm depth from target pH (Figure 2). However, deeper soil profile analysis indicated that amendment materials did not alter soil pH at 31 cm. The sandier soil at Perkins allowed leaching of the amendment materials down to approximately 31 cm depth, whereas, the finer silt loam soil at Lahoma did not. By restricting soil acidity to the upper profile, effects of low pH on sunflower have been masked by deep root penetration in the Lahoma soil that is typical for sunflower. Nevertheless, this scenario is similar to many Oklahoma acidic soils that are only acidic in the top 15 cm [29] due to subsequent application of N fertilizer for wheat production [16, 30], which makes the results of this research more practical and applicable in the region.

3.2. Extractable Aluminum Concentration and Aluminum Saturation. Potassium-chloride-extractable Al ranged from 1.19 mg kg^{-1} to 154 mg kg^{-1} at Perkins; from 1.0 mg kg^{-1} to 119 mg kg^{-1} at Lahoma; and from 1.44 mg kg^{-1} to 254 mg kg^{-1} at Haskell (Figure 3(a)). Differences in Al concentrations among locations could have been caused by variation in soil pH and also by inherent soil chemical characteristics. At similar soil pH, the three different soils contained different Al_{KCl} concentrations, with the sandy loam at Perkins generally presenting the highest Al_{KCl} concentration at a given soil pH. For example, at pH 4.6, the Al concentration at Haskell was 35.6 mg kg^{-1}, whereas, at Lahoma it was 58.4 mg kg^{-1}. At similar pH level, the soil at Perkins resulted in an Al concentration of 96.0 mg kg^{-1}, which indicates that pH threshold may differ among locations due to the inherent differences among soil types. A significant inverse exponential relationship existed between soil pH and Al_{KCl} at all sites, with r^2 of 0.93, 0.84, and 0.94 at Perkins, Lahoma, and Haskell, respectively (Figure 3(a)). Potassium-chloride-extractable Al concentrations increased exponentially as soil pH decreased. For example, at Perkins, a pH increase from 4.3 to 6.3 decreased Al_{KCl} concentration from 131 mg kg^{-1} to 1.32 mg kg^{-1}. Similar decrease in Al concentration was observed at Lahoma, where an increase in soil pH from 4.3 to 6 decreased Al concentration from 119 mg kg^{-1} to 1.33 mg kg^{-1}, and at Haskell, where an increase from a pH of 4.1 to 6.0 decreased Al concentration from 118 mg kg^{-1} to 1.44 mg kg^{-1}.

Likewise, Al_{sat} decreased exponentially with the increase of soil pH (Figure 3(b)). Results at Haskell and at Perkins were similar to an extent, with Al_{sat} ranging from 2.38 to 77% at Haskell and from 1.67 to 67% at Perkins. Average Al_{sat} across all plots at both sites was near 37%. At Lahoma, however, Al_{sat} values were lower and ranged from 0.85 to 49%, with an average of near 15% across all plots. As Al_{sat} was calculated based on the concentrations of extractable base cations, the higher base cation concentrations at Lahoma (Table 1) most likely led to lower Al_{sat} values at this site as compared to both Perkins and Haskell.

The increase in both Al_{KCl} and Al_{sat} is most likely due to solubilization of soil minerals at the decreased soil pH and not due to added Al in the plots that were treated with $Al_2(SO_4)_3$. In a study, Moore and Edwards [31] reported that soil exchangeable Al was increased due to soil acidification

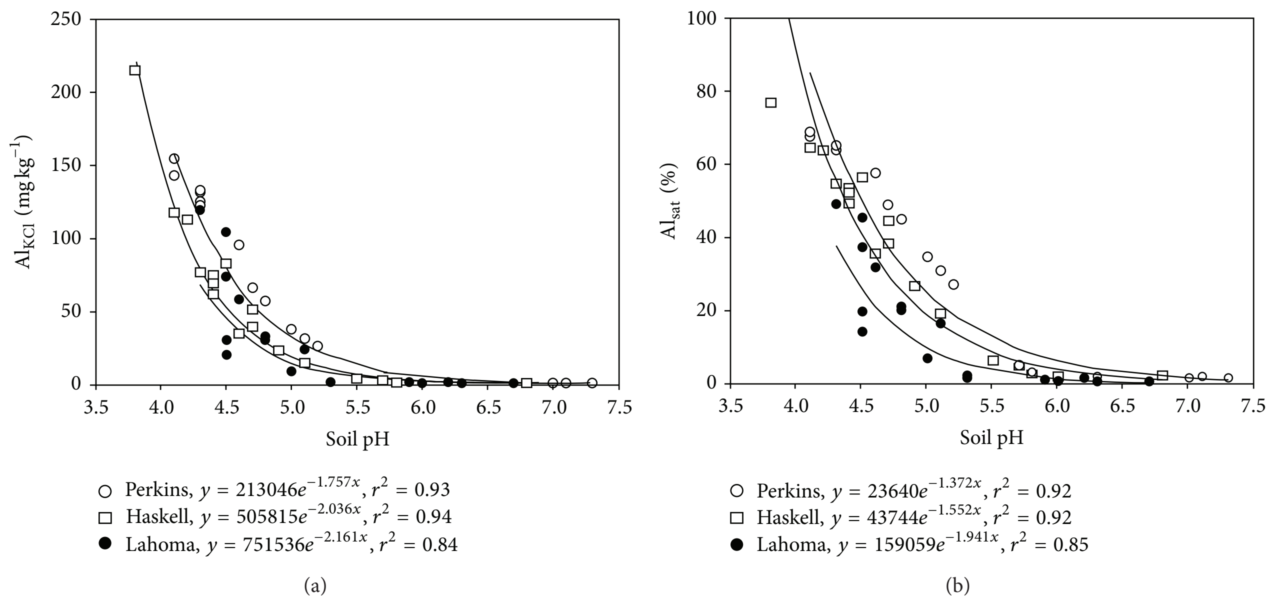

Figure 3: Potassium-chloride-extractable aluminum concentration (mg kg^{-1}) and aluminum saturation (%) in the soil as the functions of soil pH from a 15 cm composite soil sample for each treatment at Perkins, Haskell, and Lahoma, Oklahoma (2010).

resulted from ammonium nitrate application. In the same study poultry litter with added Al treatments did not affect soil exchangeable Al. Similar results were found by Warren et al. [32] when comparing Al treated poultry litter and non-Al treated poultry litter applied to two different types of soils; the relationships between soil pH and extractable Al concentration were not affected by litter application.

3.3. Growth Components. Number of sunflower heads per plot at harvest was reduced in low pH treatments when compared to the plant counts at emergence at all locations in 2010 (Figure 4). This suggested that soil acidity had strong negative impact on sunflower vegetative growth and yield. Percent reduction in number of plants differed among soil types and pH ranges. Distinct breakpoints appeared for each location when percent reduction in plants was plotted as a function of soil pH. Breakpoints are the pH values where two fitted functions intersected. These pH values are considered the transition points (critical values) where high and low reductions in number of plants were differentiated.

Breakpoints generated from nonlinear regression analysis showed that critical pH for sunflower establishment ranged from 4.0 to 4.8 among all locations. At Perkins, plant mortality was high when soil pH was less than 4.7, although, at this pH, stand reduction was approximately only 10%. A further decrease in soil pH to 4.2 increased percent reduction in number of plants as high as 90%. At Haskell, breakpoint occurred at pH 4.0 where approximately 26% plant reduction was observed. Below this pH level, plant mortality was very high, reaching 100%. A 10% plant loss was calculated when the soil pH was 6.8 or higher at Haskell. Percent plant reduction was 9% at pH 4.8 at Lahoma, and decreasing the pH below that threshold level only resulted in plant mortality near 30%. No sunflower heads were harvested from those plots where pH was 3.8 or lower. Differences in critical pH values in terms of plant mortality among all locations may be functions of the different soil properties such as Al concentrations. At similar pH level, Al concentrations were different in different soil types. Therefore, it was necessary to evaluate the same response also as a function of Al concentration.

Linear plateau occurred in terms of sunflower establishment when Al_{KCl} concentration was 85.4 mg kg^{-1} at Perkins in 2010, which resulted in plant mortality around 14% (Figure 4). Using 10% mortality limit, a threshold point for extractable Al was calculated as 41.0 mg kg^{-1} for Perkins, using the regression equation derived from PROC NLIN. Plant mortality was linearly correlated to soil Al_{KCl} concentration at Haskell, and a 10% plant reduction was calculated at Al_{KCl} concentration of 2.20 mg kg^{-1}, which is a much lower threshold than the one found for Perkins. These results are consistent with the result that a micromolar concentration of Al can be toxic for plants, as reported by Delhaize and Ryan [11]. It is important to notice that the soil at Haskell originally had greater Al_{KCl} concentration than the soil at Perkins (29.4 mg kg^{-1} versus 0.90 mg kg^{-1}, Table 1) which may have resulted in higher Al saturation (percent of exchange sites occupied by Al over the total exchange sites occupied by base cations) and therefore greater plant reduction across the whole experiment. Reduction of number of plants was not strongly related to soil Al_{KCl} at Lahoma, with percent reduction in number of plants rarely surpassing 20%. The very high effective cation exchange capacity (ECEC) of the Grant silt loam at Lahoma probably reduced the Al saturation; therefore, even when Al concentration was high, its effects probably were amended by the high base cation concentration in the soil. Thus, the contrasting results in Al_{KCl} breakpoint threshold between locations may be a function of the different inherent soil chemical properties. Even soils with high

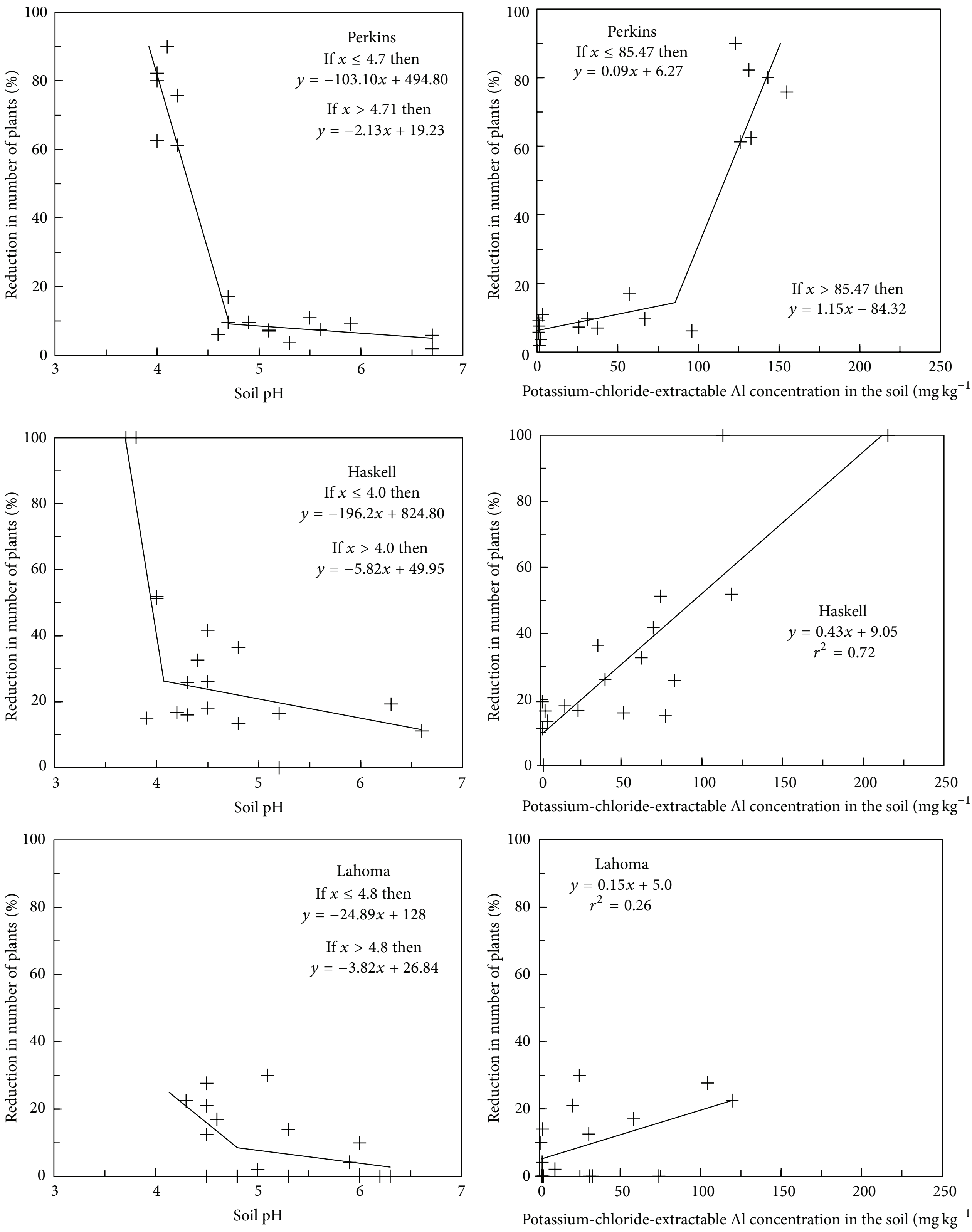

FIGURE 4: Percent reduction in number of sunflower plants from emergence to harvest as a function of soil pH and potassium-chloride-extractable aluminum concentration ($mg\,kg^{-1}$) in the soil at Perkins, Haskell, and Lahoma, Oklahoma, in 2010.

extractable Al level may not induce Al toxicity symptoms in crops if the soil has adequate levels of exchangeable base cations [17, 33].

Sunflower growth, as measured by plant height and NDVI, was adversely affected by soil acidity and Al_{KCl} concentration in the soil (Figures 5 and 6). The effects of soil pH in plant height and in NDVI followed very similar patterns. However, plant height was more sensitive to soil pH and to extractable Al than NDVI, with a broad range of plant height values across locations.

Plant height was significantly affected by soil pH at Perkins, resulting in low plant height values and steep response curve of plant height to soil pH, ranging from approximately 5 cm to 25 cm (Figure 5). Plant height increased linearly with soil pH until pH 4.9, where a plateau occurred. At Haskell, plant height ranged from 28 cm to 99 cm, and although the values were not affected as they were at Perkins, a steep response curve of plant height to soil pH was also observed. Plant height increased linearly with the increase in soil pH until approximately a pH of 4.6, where it reached a similar plateau observed at Perkins. At Lahoma, plant height ranged from 34 cm to 61 cm, and, despite absolute values lower than the ones achieved at Haskell, the response curve of plant height as affected by soil pH was not as accentuated. A plateau was reached at approximately pH 5.7. Considering all sites, plant height plateaus were attained at soil pH of 4.6 or greater. The response of plant height to Al concentration followed a negative linear response, with greater Al_{KCl} resulting in greater reduction in plant height (Figure 5).

Similar to the plant height, NDVI response to soil pH was well modeled by linear plateau functions, with a linear increase in NDVI as pH increased until approximately 5, followed by a plateau with nearly constant NDVI (Figure 6). The breakpoints for NDVI, however, differed from those found for plant height, probably because NDVI is a function of whole plant health and growth status, correlated with several plant variables other than plant height (i.e., plant biomass, nitrogen concentration, and yield) [34]. The breakpoints resulting from the analysis of NDVI versus soil pH were generally lower than that resultant from plant height versus pH, indicating that NDVI had reached stable (maximum) values at lower soil pH than did plant height. At Perkins, plateau occurred at a pH of 4.9; however, at Lahoma, the plateau was decreased from 5.7 to 5.2 and at Haskell from 4.6 to 4.2. The lower breakpoints found for NDVI as compared to plant height are probably function of other factors driving NDVI readings, such as biomass, fractional canopy cover, or nitrogen concentration, which were not measured in this study. Nonetheless, the NDVI data demonstrate the reduction in biomass and plant vigor of plants in the plots with low pH treatments as compared to the high pH plots. As low pH caused Al to be soluble in the soil solution, NDVI reading significantly decreased as the Al concentration increased, following a linear trend as did plant height. The decreasing trend of plant biomass and plant vigor in response to Al concentrations was more accentuated in Perkins and Haskell as compared to Lahoma, as relationships between NDVI and soil Al concentrations were not significant at the later site.

3.4. Relative Yield. The relationships between relative sunflower seed yield and soil pH are presented in Figure 7. Yield data from Haskell 2009 could not be analyzed due to intense bird damage and nonrepresentative sunflower seed yields and therefore data are not shown. Also, yield data were not presented for Perkins 2009 because germination was severely affected by flooding. Relative yield exhibited a positive response to increasing soil pH at different magnitudes based on locations and years, and nonlinear regression analysis generated yield plateaus for the four site-years analyzed for yields as function of soil pH.

Relative yield and soil pH were highly correlated at Perkins ($r^2 = 0.94$) and Haskell ($r^2 = 0.70$) in the 2010 growing season, while yield response to soil acidity was not as strongly correlated at Lahoma in either of the years (Figure 7). At Perkins, nonlinear regression analysis generated a yield plateau at relative yield 0.88 and soil pH 5.0. This means that at pH 5.0 yield losses were approximately 12%. The regression equation obtained from the nonlinear regression analysis was solved to determine the soil pH at relative yield of 0.90 considering 10% yield loss. At 10% yield loss, the critical pH at Perkins was calculated as 5.1. Similar procedure was used to calculate critical soil pH for all locations, resulting in critical soil pH of 4.9 at Haskell. The slightly lower soil pH resulting in the 0.90 relative yields at Haskell as compared to Perkins may be a function of the higher Al_{KCl} concentration at Perkins at similar soil pH levels (Figure 3). At Haskell Al_{KCl} concentration was approximately 23.4 mg kg^{-1}, and at Perkins Al_{KCl} was 31.1 mg kg^{-1} in terms of corresponding critical soil pH. Using information from Table 1, the approximate Al saturation of Haskell at pH 5.1 is 27%, whereas at Perkins, the Al saturation at pH 4.9 is 31%. Aluminum saturation may be the major cause of lower relative yields of 0.90 when compared to maximum yields. The presence of Al_{KCl} per se may not induce crop Al toxicity in acid soils of Oklahoma [17, 18]. The weaker relationship between relative sunflower seed yield and soil pH at Lahoma is also likely function of low Al saturation at this site. Due to the high base cation concentration in the Grant silt loam at Lahoma (Table 1), average Al saturation across the experiment was approximately 19%, which did not significantly reduce yields to levels lower than 0.9 in the remaining sites of this study. At Lahoma, only four plots resulted in Al saturation greater than 20%, indicating that the low Al saturation at this site was not enough to decrease yields significantly.

Relative seed yield as a function of Al_{KCl} and Al saturation was significant in two out of three locations in 2010 (Figure 8). At Perkins, Al_{KCl} concentration was calculated as 6.35 mg kg^{-1} when 10% yield loss was accounted. The same yield loss was calculated for Al saturation at 2%. Negative linear relationship between relative yield and Al_{KCl} and Al saturation was also found at Haskell, indicating that yield loss was associated with greater Al concentrations in the soil at both locations. For both the Teller fine-loamy at Perkins and the Taloka fine soil at Haskell, yield loss was greater than 60% when Al_{KCl} in the soil was over 100 mg kg^{-1}. Relative yield was significantly correlated neither to Al_{KCl} nor to Al saturation at Lahoma, probably due to a greater effective

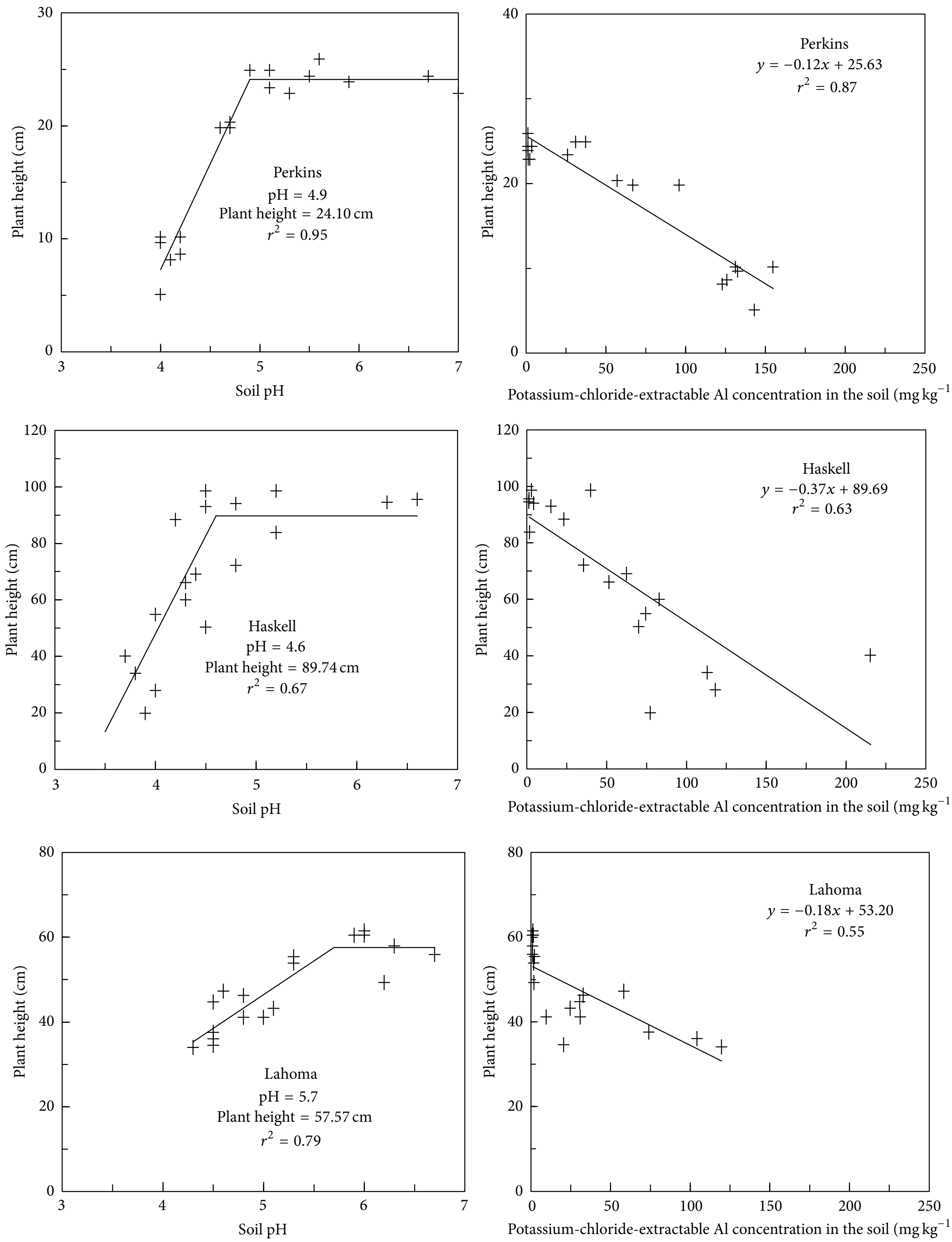

FIGURE 5: Sunflower plant height as a function of soil pH and potassium-chloride-extractable aluminum concentration (mg kg^{-1}) in the soil at Perkins, Haskell, and Lahoma, Oklahoma, in 2010.

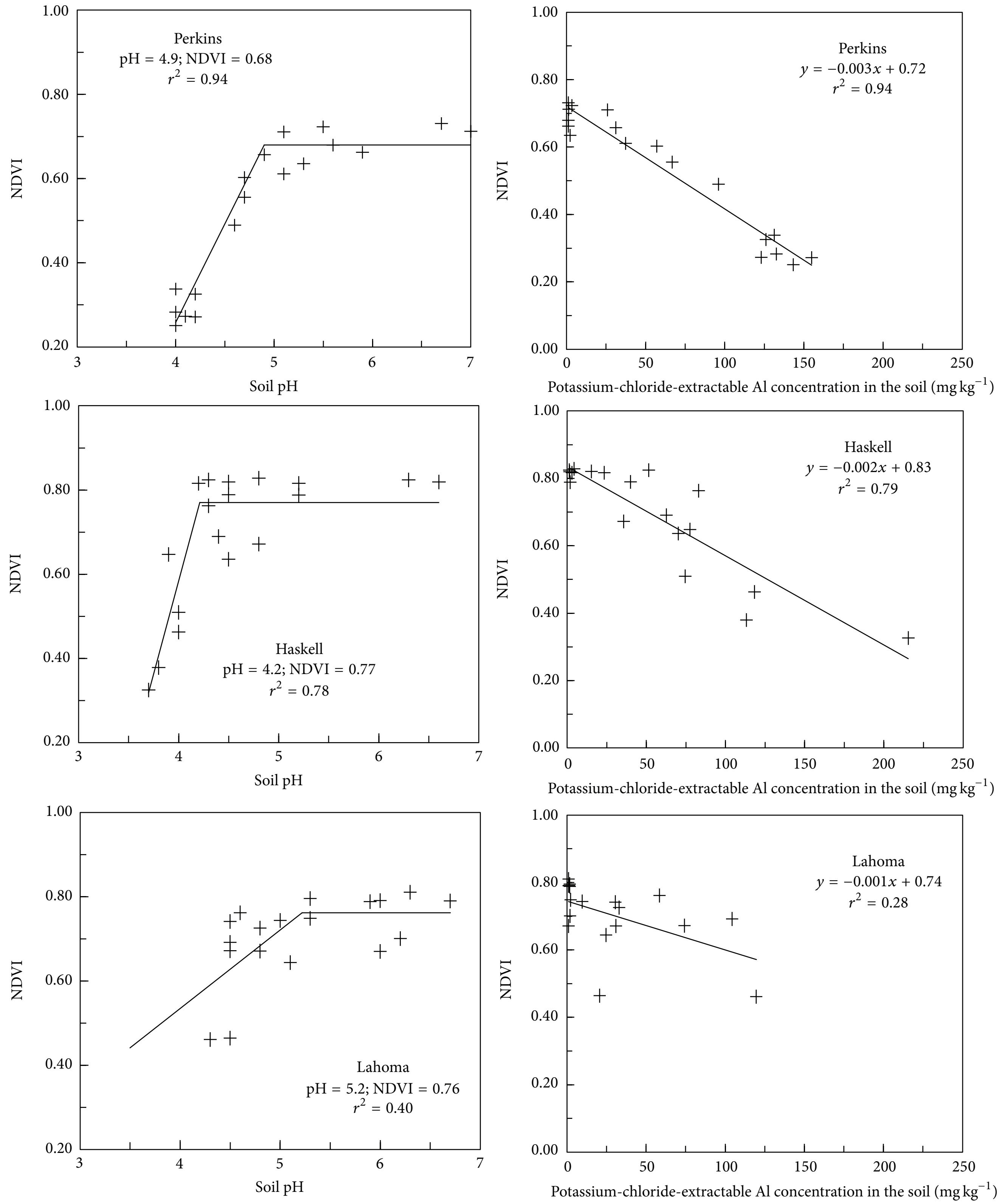

Figure 6: Normalized Difference Vegetative Index (NDVI) as a function of soil pH and potassium-chloride-extractable aluminum concentration (mg kg^{-1}) in the soil at Perkins, Haskell, and Lahoma, Oklahoma, in 2010.

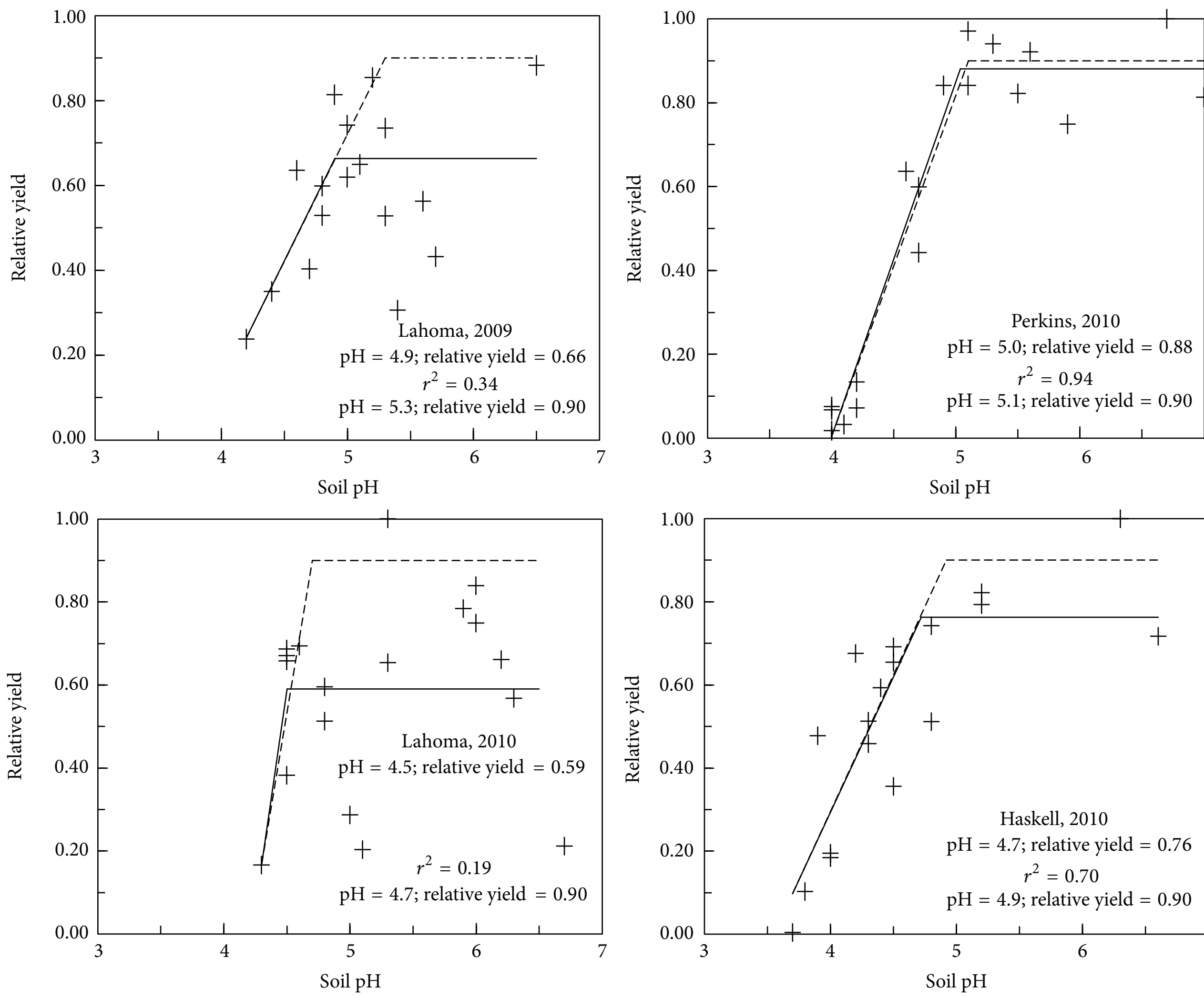

Figure 7: Relative seed yield of sunflower as a function of soil pH at Lahoma, Perkins, and Haskell, OK. Solid lines show where the yield plateau occurred. Broken lines mean yield plateau occurring at 0.90 with critical soil pH (2009 and 2010).

cation exchange capacity of the studied Grant Silt Loam, alleviating the consequences of the presence of Al_{KCl}.

4. Conclusions

Results from this research demonstrate that low soil pH and high concentration of Al_{KCl} resulted in a significant reduction in sunflower growth and yield. Plant mortality, height, NDVI, and relative seed yield with potassium-chloride-extractable Al also showed significant negative relationships in most site-years. Critical soil pH and Al_{KCl} differed by soil types and years for all growth and yield parameters evaluated. At the Perkins site, Teller sandy loam, a plant loss of greater than 10% occurred at a pH of 4.7 and corresponding Al_{KCl} level of 41 mg kg^{-1}. Both plant height and NDVI were maximized at a soil pH of 4.9. At Perkins the relative yields values fell below the point of 90% at a soil pH of 5.1. At the Haskell location, Taloka silt loam, plant stand was significantly impacted at a pH of 4.0 and negatively linearly correlated with Al_{KCl} level with no critical point being found. A soil pH of 4.6 and 4.2 was found for plant height and NDVI, respectively. The linear plateau model of seed yield identified a 4.7 soil pH as the critical level. At the final location, Lahoma a Grant silt loam, 10% plant loss occurred at a soil pH of 4.8. Analysis of plant vigor measurements, plant height, and NDVI resulted in critical levels of 5.7 and 5.2, respectively. Yield, however, plateaued at a soil pH of 4.9 and 4.5 in 2009 and 2010, respectively. Based on the findings of this research the agronomic optimum level of soil pH for sunflower production is at a level of 5.0 and above. Given the relative low pH in which sunflower yield resulted in 10% losses (4.7 to 5.3), the crop is a very promising summer rotation to winter wheat in fields where the remediation of soil acidity via application of lime is not economically feasible. Comparing critical soil pH for some other rotational crops in Oklahoma, such as grain sorghum (pH 5.4) [25], canola (pH 5.8) [13], and soybean (pH 5.5 to 7.0) [16], sunflower is a better choice in acidic conditions as rotational crop with winter wheat as the critical pH values are less than the above mentioned crops.

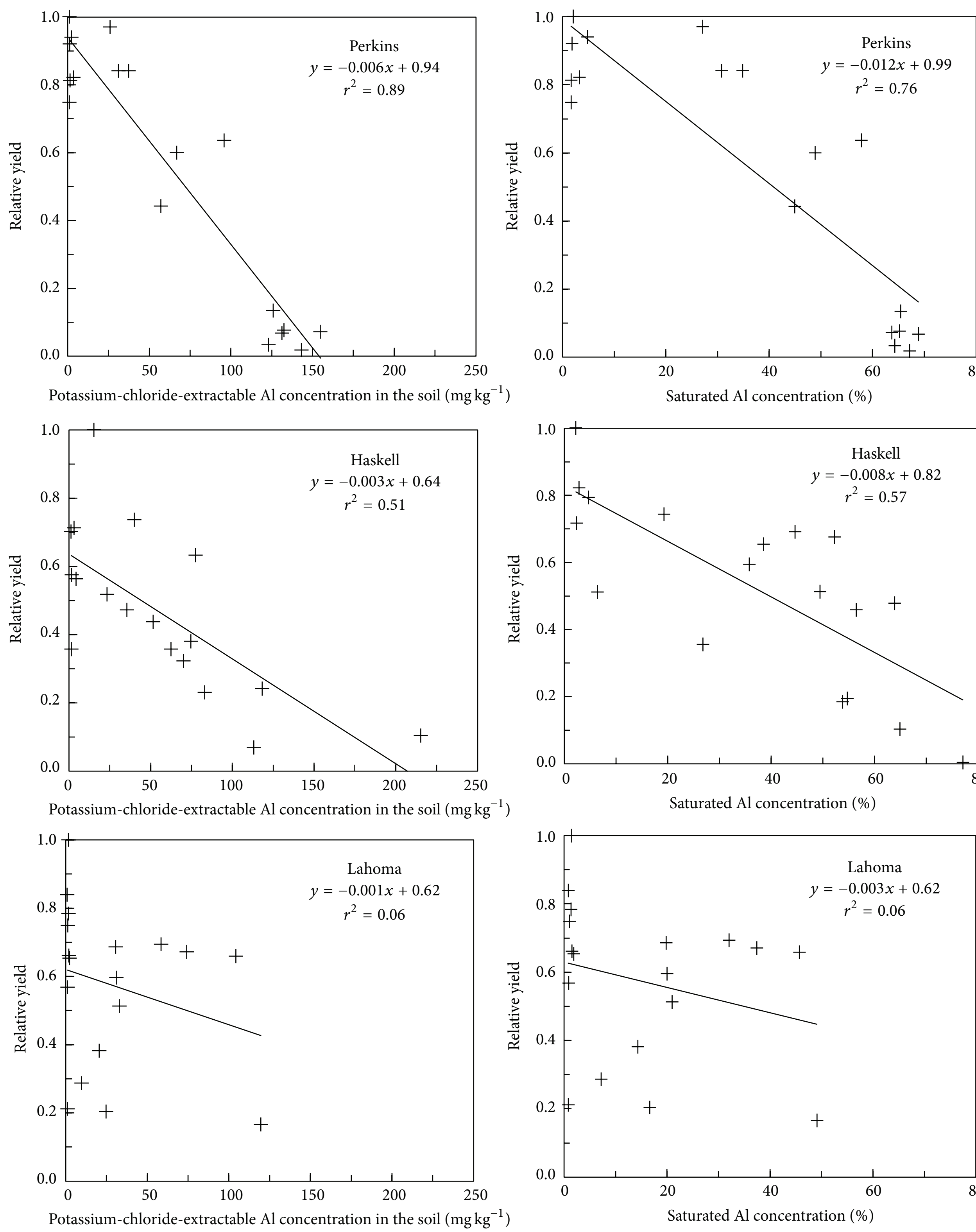

Figure 8: Relative sunflower seed yield as a function of potassium-chloride-extractable aluminum concentration (mg kg^{-1}) and aluminum saturation (%) in the soil at Perkins, Haskell, and Lahoma, Oklahoma, in 2010.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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