INFLUENCE OF SOIL pH ON COTTON MORPHOLOGY, LINT YIELD AND LINT QUALITY

By

RAEDAN LANE SHARRY

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INFLUENCE OF SOIL pH ON COTTON MORPHOLOGY, LINT YIELD AND LINT QUALITY

Thesis Approved:

Dr. Brian Arnall

Thesis Adviser

Dr. Hailin Zhang

Dr. Rodney Jones

Dr. Seth Byrd

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I would like to express my appreciation to all my family and friends who have supported me throughout this process, including the numerous faculty, staff and students that have helped with my research over the past couple of years. I would also like to thank the professors that I have had throughout my collegiate career, without many of you I likely would never have made it this far, especially Dr. Brian Arnall. I also would like to express my gratitude to my mentor Kent Martin without whom I likely would have never began this journey. With this said I think it is fitting to close this chapter of my life with a quote from J.R.R Tolkien's The Hobbit: "There is nothing like looking, if you want to find something. You certainly usually find something, if you look, but it is not always quite the something you were after."

Name: RAEDAN SHARRY

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Abstract: The influence of commodity prices has led to an increase in cotton production in Oklahoma over the past decade. With this increase in production there has been growing interest in growing cotton in fields that have been traditionally managed for winter wheat production. The soils are sometimes found to be acidic, largely due to previous production practices, specifically, over application of nitrogen fertilizers. This study was conducted to evaluate the influence of soil acidity on cotton physiological growth and yield. The study took place at Perkins, OK and Stillwater, OK (EFAW Farm). Yield was evaluated using relative yield across a soil pH range of 4.0-8.0. Soil pH was altered utilizing aluminum sulfate and hydrated lime. Two cultivars, Nexgen 3930 and Deltapine 1612 were used at all locations. Soil acidity negatively affected cotton growth and yield. Relative yield was estimated to reach critical threshold at a soil pH of 5.4 while morphological measurements produced similar results. KCl extractable Al was also measured and relative yield was observed to be negatively correlated with Al. This study also conducted an evaluation of net present value of lime application as a function of soil pH, cost of lime application, lint value, lint yield goal, and location. Amelioration of soil acidity may be required to maximize profitability of cotton production in some conditions.

TABLE OF CONTENTS

Chapter Page

Chapter Page

LIST OF TABLES

Table Page

Table Page

LIST OF FIGURES

Figure Page

Figure Page

CHAPTER I

INTRODUCTION

The expansion of upland cotton acres grown in the state of Oklahoma over the last several years has come in response to a multitude of factors. This expansion of cotton production within Oklahoma has led to cotton being produced on soils that have historically been managed for hard red winter wheat, specifically those acres lying outside the southwest region of the state. Many of these acres traditionally managed for wheat production have been subject too high application rates of nitrogen fertilizers well above crop demand. The over-application of nitrogen fertilizers and the consequential removal of basic cations from the soil has led to a higher incidence of soil acidity across traditional wheat producing areas of Oklahoma (Zhang, 2017). This effect has been compounded by the widespread adoption of Al tolerant wheat varieties, and the practice of in-furrow banding of P fertilizers in wheat production on acidic soils (Zhang et al., 1998). Many of these wheat varieties are able to withstand soil pH as low as 5.5 (Zhang and Raun, 2006). With the aforementioned expansion of cotton production across the state, extensive amelioration of soil acidity may be required for cotton to perform as a viable crop on traditionally wheat producing soils.

Upland cotton (*Gossypium hirsutum L.*) is a field crop grown throughout Oklahoma with extensive production occurring in the southwest region. In 2018 Oklahoma planted 315 thousand hectares of cotton, just over a 32% increase in planted acres from 238 thousand hectares in 2017. The 2018 crop produced over 148 thousand tonnes yielding approximately 270 Kg/ha. (NASS., 2019).

This study will observe the impact of soil pH on relative yield to determine critical soil pH level. This study looks to quantify the impact of soil acidity on cotton quality measurements such as fiber length, strength and micronaire. This work aims to quantify the effects of soil acidity on cotton production as well as provide a framework for determining the economic ramification of production on acidic soils and their amelioration.

CHAPTER II

REVIEW OF LITERATURE

Soil Acidity

Soil acidity in the southern plains is a substantial problem for crop producers in the region. In Oklahoma, a study drawing on soil samples collected in both 1985 and 1996 observing the prevalence of wheat production on acidic soils indicated that 30% of the 17,560 samples tested had a soil pH of less than 5.5 (Zhang et al., 1998). Soil pH is the measurement of hydrogen (H^+) concentration in a soil solution, with pH being expressed as the negative logarithm of said concentration. Thus, as the H^+ concentration increases, soil pH decreases indicating an increase in soil acidity (NRCS, 1999). The prevalence of acidic soils in the region and the consequential increase in Al^{3+} concentrations have a negative impact on crop production (Zhang and Raun, 2006). The increase in Al concentration occurs as soils become more acidic releasing Al^{3+} affecting crop root growth (Kochian, 1995). This restriction of root growth leads to crop stressors such as nutrient deficiency and water stress (Kochian et al., 2004). A similar response occurs if a soil has a high concentration of manganese (Mn). As soil pH decreases, Mn becomes more soluble leading to the Mn toxicity and its resulting symptoms (Duncan et al., 1987).

Phosphorus deficiency symptoms are one of the most noted to occur in acidic conditions. The elevated levels of Aluminum accompany the adsorption of P causing a decrease inavailability to the crop and thus inhibiting crop performance further (Haynes and Mokolabate., 2001).

Drivers of Soil Acidity

Soil acidity can develop due to many reasons. Acidic soils occur naturally in high rainfall areas which experience greater leaching of basic cations, as well as locations where soils formed from acidic parent materials, while other soils may be acidic due to intensive agricultural production and the subsequent use of ammoniacal nitrogen fertilizers (Zhang., 2017). It should be noted that while nitrogen fertilizers themselves are not acidic in nature, some of the inputs to the soil during the processes occurring after application are acidic (Schroder et al., 2011), specifically the microbial oxidation of ammonium (NH_4^+) releasing H^+ into the soil (Barak et al., 1997). This oxidation is represented by the nitrification process described as:

$$\boldsymbol{2NH_4^+ \ + 3O_2 \rightarrow 2NO_2^- + 2H_2O + 4H^+}$$

The continued application of N fertilizers in intensive crop production systems has been shown to not only decrease soil pH but also increase exchangeable aluminum.

This was shown in work done at Oklahoma State University in the late 2000's observing interactions between exchangeable Al and the long-term application of different nitrogen fertilizers. In the experiment the amount of measured exchangeable Al was increased significantly over the control in the experiment (Schroder et al., 2011). This same experiment showed the soil pH also decreased over time with the application of nitrogen fertilizers showing a congruent observation to other work done by Wolcott et al., (1965), Rasmussen and Rohde. (1989), Darusman et al. (1991), Malhi et al. (1991, 2000), Bouman et al. (1995), Barak et al. (1997), Chien et al. (2008), and Shetty et al. (2019).

Amelioration of Soil Acidity

The amelioration of soil acidity can only be achieved through neutralizing the acid present in the soil (Zhang et al., 2017). This must be done by applying a basic material to the soil such as materials derived from limestone (calcium carbonate, $CaCO_3$). As these materials dissolve calcium attracts to the surface of soil particles replacing the hydrogen present. The hydrogen then reacts with carbonate to form carbon dioxide and water (Zhang et al., 2017). It is important to note that while calcium alone may replace the hydrogen on the soil particle surface it does not affect soil pH. Only a soil amendment containing a basic anion such as a carbonate can neutralize soil acidity (Anderson et al., 2013).

Soil Acidity and Cotton Production

While some work has been conducted with soil acidity and cotton production many of the studies such as Pearson et al. (1970) and Foy et al. (1967) have focused on the impact of sub soil acidity such as that found in some soils in the southeastern United States. Even though these studies do not focus on acidity in the upper portion of the soil profile which is prevalent in acidic the southern Great Plains, they still can provide insight into some of the difficulties of cotton production on acidic soils. The studies by both Pearson et al. (1970) and Foy et al. (1967) showed that soil acidity was a common factor among plants that appeared to be suffering from nutrient deficiency and draught stress. However, the presence of significant concentrations of Al^{3+} was shown to be likely the primary factor leading to these conditions. The study by Foy et al. (1967) also displayed varietal differences for dry weight measurements of both above and below ground biomass when soils were left un-limed (pH=4.53). The study also revealed what appeared to be a critical threshold for 8 of the 14 varieties observed at a subsoil pH level of 5.4, allowing for both adequate biomass and root growth in this particular study. Similar impacts on root development were found in the study by Pearson et al. (1970) showing that soil acidity became a detriment to root elongation at a soil pH of 5.5. A study by Adams and Lund. (1966) also observed that as Al^{3+} concentration increased, cotton root length was negatively impacted. These findings were also correlated with the impact of soil acidity and root length. It is also important to note that during this study, it was observed that the critical threshold of root length for soil Al^{3+} concentration varied between different soils (Adams and Lund, 1966).

Work from Georgia by Gascho and Parker (2001) showed that as soil pH was increased through lime application cotton yield, like other crops in the study were significantly increased. In another experiment placed in South Carolina evaluating the spatial variability of soil properties on cotton lint yield, Johnson et al. (2002) observed that soil pH was highly correlated with lint yield at an $R^2=0.46$. These two studies concur with early work done evaluating the impact of soil acidity on cotton production.

CHAPTER III

OBJECTIVE

The objective of this study was to evaluate the impact of surface soil acidity on cotton production. In-season morphological measurements were utilized to quantify possible stress during crop development across a range of soil pH values. Relative yield was used to quantify and discuss the potential for yield loss under acidic soil conditions. This study also evaluated the relationships between yield and in-season growth parameters, and KCl extractable Al (Al_{KCl}). In addition profitability of lime application under different scenarios for cotton production was reviewed utilizing the data obtained from this study.

CHAPTER IV

METHODOLOGY

This study was conducted over two growing seasons with three sites being selected to establish the pH conditions for the study. This experiment was established at the Cimarron Valley Research Station near Perkins, OK and the North Central Research Station near Lahoma, OK. Both of these sites utilized an 8 x 2 factorial design consisting of 8 target soil pH treatments ranging from a pH of 4.0 – 8.0 and two cultivars selected each season. Plot size was 6 m long x 3 m wide (4 rows) with 4.6 m alleys between each replication. Each cultivar was planted on opposite sides of the trial in blocks. The third site is located at the EFAW research farm, near Stillwater, OK. This site utilized an 8 x 2 factorial design like the other two locations (Lahoma & Perkins) using 1.5 m alleys with 6 m long x 3 m wide plots. However, this location was not planted on opposite sides of the trial in blocks like the other two locations. Instead the EFAW site will be planted with varieties side by side in an alternating pattern. Soil series descriptions for each location are listed in Table 1.

Table 1. Description of soil series at Perkins, Lahoma, and EFAW locations utilized for an experiment evaluating the influence of soil pH on cotton physiology and yield in 2019 and 2020.

Location	Soil Series
Perkins, OK	Teller series (Fine-loamy, mixed, active, thermic Udic Argiustolls) and Konawa series (Fine-loamy, mixed, active, thermic Mollic Albaqualfs)
Lahoma, OK	Grant series (Fine-silty, mixed, superactive, thermic Udic Argiustolls)
EFAW (Stillwater, OK)	Easpur series (Fine-loamy, mixed, superactive, thermic Fluventic Haplustolls)

Soil samples were taken from each plot prior to planting each growing season to determine actual soil pH. 2.54 cm diameter soil probes were used to take samples at a depth of approximately 15 cm. The samples were dried and ground to pass through a 2mm sieve. The samples were then analyzed for pH and buffer index using a 1:1 soil:water suspension and glass electrode (Sims,1996; Sikora, 2006).

Hydrated lime and aluminum sulfate application rates to reach target soil pH's were determined based upon a previous laboratory experiment. In the previous experiment composite samples were taken from each trial location. Five rates of aluminum sulfate and five rates of hydrated lime were then added to 0.5 kilogram subsamples from each of the locations to construct a response curve that could in turn be used to determine the appropriate rate of either aluminum sulfate or hydrated lime each plot should receive. These subsamples were then mixed and wetted, then measured for soil pH at increments of 2 weeks, 3 weeks and 4 weeks after the application (Butchee et al. 2012). The use of Aluminum sulfate has been shown to not impact soil Al^{3+} concentration significantly in work done by Kinraide and Parker. (1987) and Cameron et al. (1986). This is important to note given the impact of phytotoxic forms of Al on crops in previous studies.

Soil samples were again taken post-harvest to determine soil pH for that growing season as well as analyzed for extractable Al (Al_{KCl}) in the soil using the Bertsch and Bloom (1996) method. A 5.0 gram subsample from each plot was extracted using 25 ml of 1 M potassium chloride (KCl).After 5 minutes on a shaker Al extracted from the subsamples with 1 M KCl was then be quantified using inductively coupled plasma spectrometry (Soltanpour et al. 1996).

All locations were planted at approximately 86,419 seeds ha^{-1}. Field measurements taken included stand count, plant height, node count, NDVI, and end of season measurements. Stand counts were taken approximately two weeks after emergence with the plants from the harvest rows from each plot being counted. Plant height and node count was taken prior to first bloom as well as the end of season prior to the application of boll opener. Normalized difference vegetative index (NDVI) readings were collected using a Greenseeker™ sensor over the two harvest rows during the squaring stage as well as near the cutout stage. NDVI is defined as:

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

End of season measurements were taken prior to application of boll opener. These measurements included: nodes to first fruiting branch, nodes to uppermost cracked boll, nodes to uppermost harvestable boll, as well as total bolls and percent of bolls open.

Harvest was completed using a John Deere two row stripper harvester to harvest the middle two rows of each four-row plot. Bur cotton will be weighed and processed through a lint cleaner prior to ginning. After ginning lint and seed weights were taken for each plot. Lint samples were then sent to the Fiber and Biopolymer Research Institute in Lubbock, Texas for further lint quality analysis. Yields are reported in relative yield form to help remove bias associated with different locations for the study across multiple growing seasons. Relative Yield is expressed 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 similar research such as Butchee et al. (2012),Lollato et al. (2013) and Sutradhar. (2014). Relative yield is also used by Holhouser et al. (2018) in the Virginia OVT for soybeans to remove bias from multi-year averages when varieties are not tested at all locations. Presenting results in terms of relative yield will allow producers to determine levels at which soil acidity may lead to reduction in yield, as well as proper considerations for amelioration of soil acidity.

Table 2. 2. List of planting dates, locations and cultivars planted at approximately 86,419 seeds ha^{-1} for an experiment investigating the impact of soil pH on cotton physiology and lint yield conducted over the 2019 and 2020 growing seasons.

Planting Date	Location	Cultivars
May 17th, 2019	Perkins, OK	Nexgen 3930 and Deltapine 1612
May 31st, 2019 (Replant)	Lahoma, OK	Nexgen 3930 and Deltapine 1612
May 19th, 2020	Perkins, OK	Nexgen 3930 and Deltapine 1612
May 19th, 2020	EFAW (Stillwater, OK)	Nexgen 3930 and Deltapine 1612
May 20th, 2020	Lahoma, OK	Phytogen 400 and Phytogen 480

2019 Season

For the 2019 growing season, trials were initiated at both Perkins, Oklahoma and Lahoma, Oklahoma. Both locations experienced heavy rainfall from an event just after planting resulting in the Lahoma location being replanted. Early weed pressure had an impact on growth in some plots at the Perkins location. The Lahoma location was hit with off target auxin drift twice resulted in abandonment of the location for the 2019 season. The Perkins location was taken to harvest successfully.

2020 Season

For the 2020 growing season trials were placed at both Lahoma and Perkins Oklahoma once again with an additional location added at the Efaw farm near Stillwater, Oklahoma. In response to issues with auxin drift at the Lahoma location during the previous season varieties with a different herbicide tolerant trait were planted at this location. However, due to weather conditions emergence was severely limited due to soil surface crusting and the Lahoma location was again abandoned. Both the Stillwater and Perkins locations were successfully taken to harvest.

CHAPTER V

FINDINGS

Reaching Target Soil pH

The mean absolute deviation from the target soil pH on average at the Perkins location (Teller and Konawa Fine Sandy Loam) measured ± 0.36 for the 2019 growing season and ± 0.27 for the 2020 growing season. The 2020 EFAW (Stillwater) location (Easpur silt loam) on average deviated ± 0.57 from the target pH.

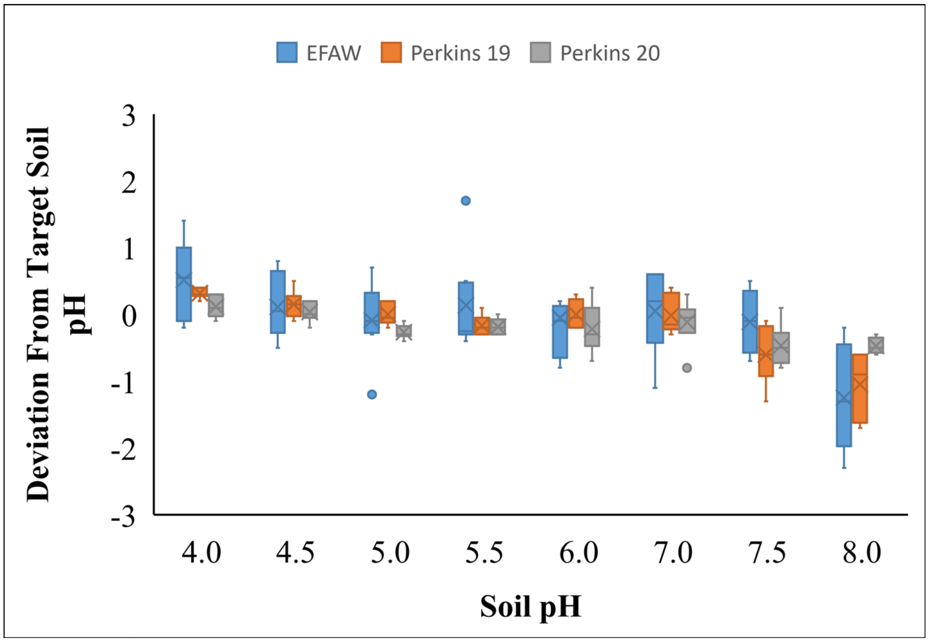

Figure 1. Box and Whisker chart displaying deviation of soil pH from target soil pH at Perkins, OK in 2019 and 2020 as well as EFAW farm in 2020 in an experiment evaluating the influence of soil pH on cotton morphology and yield.

Soil Aluminum Concentration

Aluminum toxicity is an important concern when considering the impacts of soil acidity on crop production. Soil pH and Al_{KCl} was correlated across all site years with R^2 values of 0.87, 0.78 and 0.73 at EFAW, Perkins 2019 and Perkins 2020 respectively in these soils as soil pH increased Al_{KCl} decreased linearly. The impact of Al concentration on yield will be discussed later in the results section.

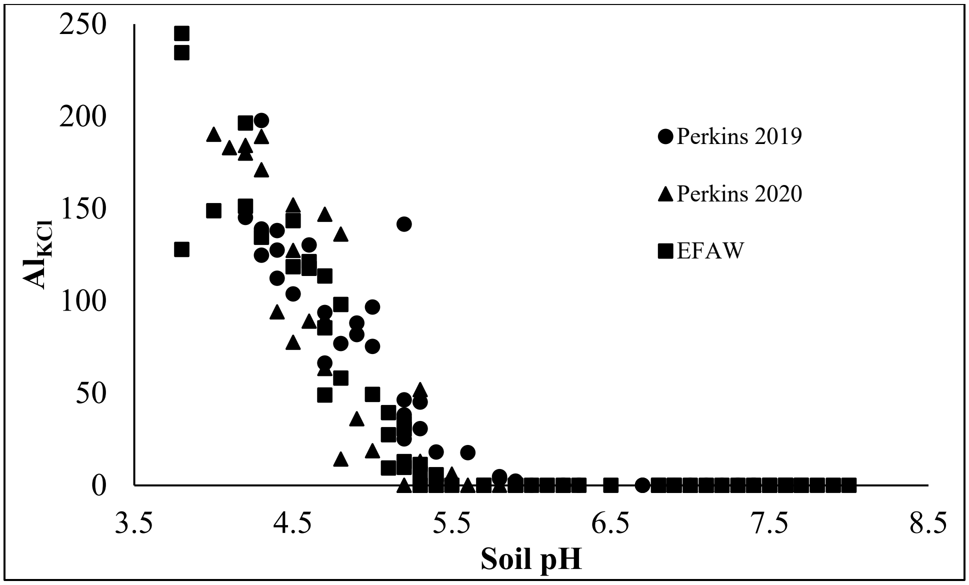

Figure 2. Relationship of Al_{KCl} concentration in the soil and soil pH across harvested sites at a sampling depth of 15 cm at Perkins and EFAW locations across all site years combined in an experiment evaluating the influence of soil pH on cotton morphology and yield

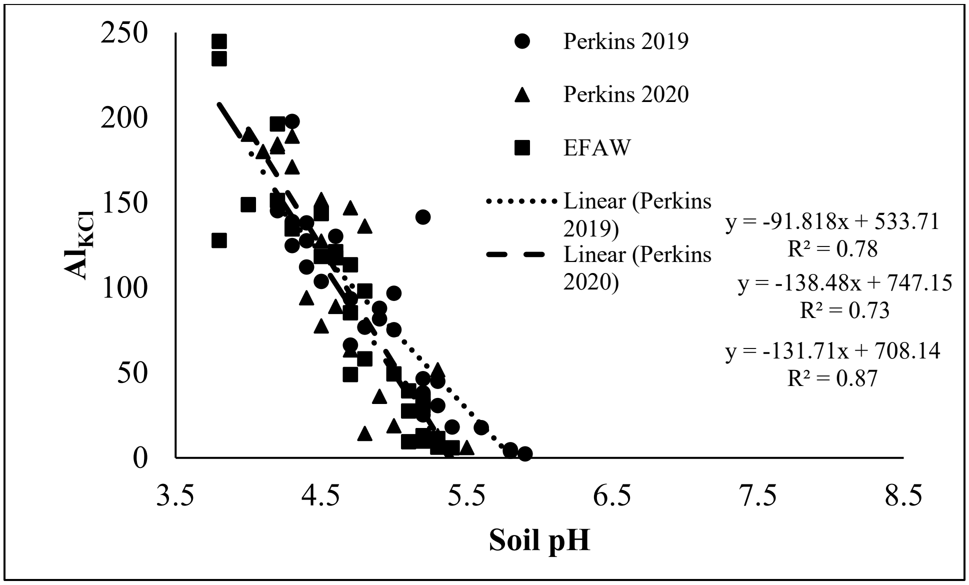

Figure 3. Linear relationship of soil pH and Al_{KCl} concentration mg kg^{-1} when Al > 0 at a sampling depth of 15 cm at Perkins and EFAW locations separated by site year in an experiment evaluating the influence of soil pH on cotton morphology and yield.

In Season Growth Components

Soil pH impact on plant emergence was significant (α=0.05) at two of three site years when evaluated using quadratic least squares regression and non-linear regression. Two of three site years reached a plateau at pH levels of 4.6 and 5.4 for the Perkins 2020 and EFAW locations respectively as reported in Table 3. The relationship at the Perkins 2019 location was likely influenced by an intense rainfall event on May 20 and 21 of approximately 14.7 cm. The Perkins 2019 was also affected by early season weed pressure which may have negatively impacted stand in some plots.

Table 3. Results from quadratic least squares and non-linear regression when evaluating plant stand in an experiment evaluating the influence of soil pH on cotton morphology and yield Perkins and EFAW separated by site year (α=0.05).

Site	**DF**	**MSE**	**F**	**Prob F**	**r^2**
Perkins 19	2	13.6550	0.48	0.6224	0.02
Perkins 20	2	7.5111	15.78	<.0001	0.41
EFAW	2	4.8162	40.82	<.0001	0.57
Site	**Joint**	**Plateau**	**F**	**Prob F**	**r^2**
Perkins 19	-	-	-	-	-
Perkins 20	4.6	8.79	31.22	<.0001	0.58
EFAW	5.4	11.68	47.68	<.0001	0.61

The relationship between plant height and soil pH was significant across all site years when evaluated using quadratic least squares regression and non-linear regression (Table 4) at α=0.05. Node count at all three site years reached a plateau at a soil pH of 5.2, 5.1 and 5.4 as reported in Table 4.

Table 4. Results from quadratic least squares and non-linear regression when evaluating impact of soil pH on plant height in an experiment evaluating the influence of soil pH on cotton morphology and yield at Perkins and EFAW separated by site year (α=0.05).

Site	Analysis	DF	MSE	F	Prob F	r^2
Perkins 19	Quadratic	2	52.3168	51.51	<.0001	0.70
Perkins 20	Quadratic	2	93.3016	40.72	<.0001	0.64
EFAW	Quadratic	2	208.3045	39.82	<.0001	0.57
Site	**Analysis**	**Joint**	**Plateau**	**F**	**Prob F**	**r^2**
Perkins 19	Non-Linear	5.2	42.43	68.77	<.0001	0.75
Perkins 20	Non-Linear	5.1	46.99	53.05	<.0001	0.70
EFAW	Non-Linear	5.4	72.62	47.13	<.0001	0.60

Node count and soil pH were similarly significantly correlated (α=0.05) when evaluated using quadratic least squares regression and non-linear regression (Table 5). All three site years reached a plateau at soil pH levels of 4.8, 4.7 and 5.2 as shown in Table 5.

Table 5. Results from quadratic least squares and non-linear regression evaluating the impact of soil pH on plant node count in an experiment evaluating the influence of soil pH on cotton morphology and yield at Perkins and EFAW separated by site year (α=0.05).

Site	Analysis	DF	MSE	F	Prob F	r^2
Perkins 19	Quadratic	2	2.6906	22.25	<.0001	0.50
Perkins 20	Quadratic	2	6.9957	27.96	<.0001	0.55
EFAW	Quadratic	2	9.9321	19.31	<.0001	0.39
Site	**Analysis**	**Joint**	**Plateau**	**F**	**Prob F**	**r^2**
Perkins 19	Non-linear	4.8	8.18	37.02	<.0001	0.62
Perkins 20	Non-linear	4.7	11.26	66.46	<.0001	0.75
EFAW	Non-linear	5.2	13.51	25.56	<.0001	0.46

The relationship between NDVI during squaring and soil pH was significant across all site years when evaluated using quadratic least squares regression and non-linear regression (Table 6) (α=0.05). A plateau was observed for NDVI at soil pH levels of 5.3, 5.4 and 5.1 at all locations as displayed by Table 6.

Table 6. Results from quadratic least squares and non-linear regression evaluating the impact of soil pH on NDVI in an experiment evaluating the influence of soil pH on cotton morphology and yield at Perkins and EFAW separated by site year (α=0.05).

Site	**Analysis**	**DF**	**MSE**	**F**	**Prob F**	**r^2**
Perkins 19	Quadratic	2	0.0149	14.78	<.0001	0.40
Perkins 20	Quadratic	2	0.0122	43.09	<.0001	0.66
EFAW	Quadratic	2	0.0125	25.48	<.0001	0.46
Site	**Analysis**	**Joint**	**Plateau**	**F**	**Prob F**	**r^2**
Perkins 19	Non-linear	5.3	0.51	17.70	<.0001	0.44
Perkins 20	Non-linear	5.4	0.70	54.03	<.0001	0.71
EFAW	Non-linear	5.1	0.86	40.07	<.0001	0.57

Yield and Relative Yield

In this study lint yield ranged from 0-1439 kg ha^{-1}. The significant relationship between the in-season growth components and soil pH shown in Tables 4-6 was indicative of the impact of acidic soil conditions on plant health and biomass production. All in-season growth components exhibited a significant relationship with lint yield (α=0.05) when evaluated using linear regression. This indicates that there is a relationship between in-season stress induced by soil acidity and lint yield (Table 7). This relationship is also depicted by the significant relationship between relative yield and soil pH evaluated using quadratic least squares regression (Table 8) and non-linear regression (Table 9) at α=0.05.

Table 7. Results from linear regression evaluating the relationship between growth components and lint yield in an experiment evaluating the influence of soil pH on cotton physiology and yield at Perkins and EFAW across all locations combined (α=0.05).

Growth Component	**DF**	**MSE**	**F**	**Prob F**	**r^2**
Height	1	79786	23.91	<.0001	0.13
Node Count	1	77378	29.57	<.0001	0.16
NDVI	1	65955	45.83	<.0001	0.23

Table 8. Results from quadratic least squares regression evaluating the impact of soil pH on relative yield_{avg} in an experiment evaluating the influence of soil pH on cotton physiology and yield at Perkins and EFAW separated by site year and all locations combined (α=0.05). Relative yield_{avg} being compared to an average of 3 highest yields of site year

Site	**DF**	**MSE**	**F**	**Prob F**	**r^2**
Perkins 19	2	0.0362	17.48	<.0001	0.44
Perkins 20	2	0.0355	24.55	<.0001	0.52
EFAW	2	0.0495	15.37	<.0001	0.34
All Locations	2	0.0424	52.64	<.0001	0.40

Table 9. Results from non-linear regression evaluating the impact of soil pH on relative yield_{avg} in an experiment evaluating the influence of soil pH on cotton physiology and yield at Perkins and EFAW separated by site year and all locations combined (α=0.05). Relative yield_{avg} being compared to an average of 3 highest yields of site year.

Site	**Joint**	**Plateau**	**F**	**Prob F**	**r^2**
Perkins 19	6.9	0.84	13.1259	<.0001	0.37
Perkins 20	4.8	0.74	41.0032	<.0001	0.65
EFAW	5.7	0.68	17.1895	<.0001	0.36
All Locations	5.4	0.73	56.7478	<.0001	0.42

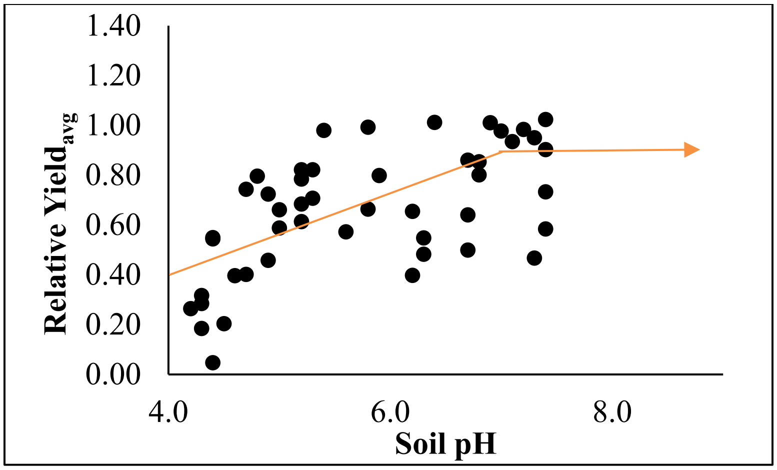

Figure 4. Non-linear relationship between relative yield$_{avg}$ and soil pH in an experiment evaluating the influence of soil pH on cotton physiology and yield at Perkins, OK in the 2019 growing season with two cotton cultivars combined in a soil pH range of 4.2 -7.4 in which critical threshold was observed at a soil pH of 6.9. Relative yield$_{avg}$ being compared to an average of 3 highest yields of site year.

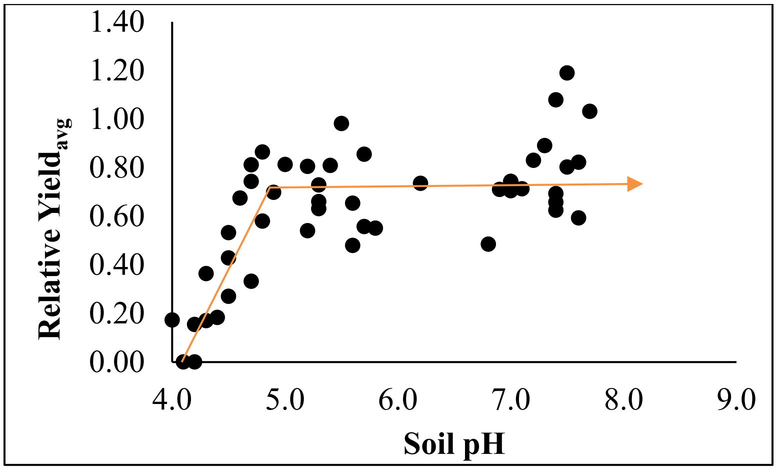

Figure 5. Non-linear relationship between relative yield$_{avg}$ and soil pH in an experiment evaluating the influence of soil pH on cotton physiology and yield at Perkins, OK in the 2020 growing season with two cotton cultivars combined in a soil pH range of 4.0 -7.7 in which critical threshold was observed at a soil pH of 4.8. Relative yield$_{avg}$ being compared to an average of 3 highest yields of site year

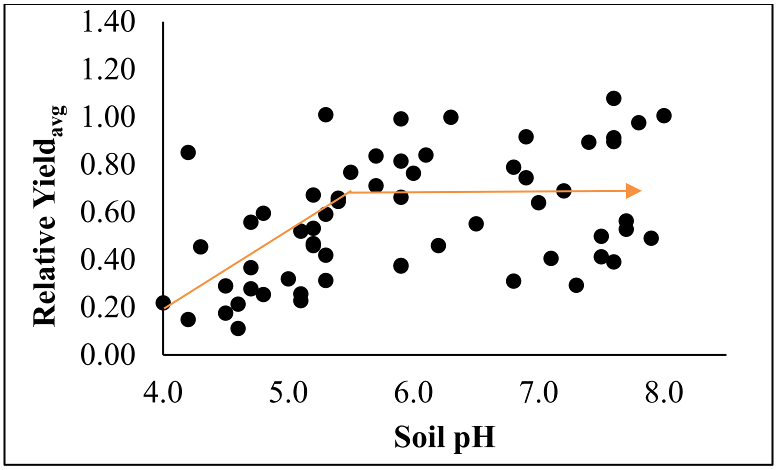

Figure 6. Non-linear relationship between relative yield$_{avg}$ and soil pH in an experiment evaluating the influence of soil pH on cotton physiology and yield at the EFAW farm in Stillwater, OK in the 2020 growing season with two cotton cultivars combined in a soil pH range of 4.3 -8.0 in which critical threshold was observed at a soil pH of 5.7. Relative yield$_{avg}$ being compared to an average of 3 highest yields of site year.

All three site years reached a plateau when evaluated using non-linear regression with critical soil pH levels shown at 6.9, 4.8 and 5.7 for Perkins 2019, Perkins 2020 and EFAW respectively. Non-linear analysis provided the highest coefficient of determination for 2 of the 3 site years. When all locations are combined, critical threshold was a soil pH level of 5.4, reaching a plateau at approximately 73% of relative lint yield. This relationship is depicted in Table 9 and is significant at α=0.05.

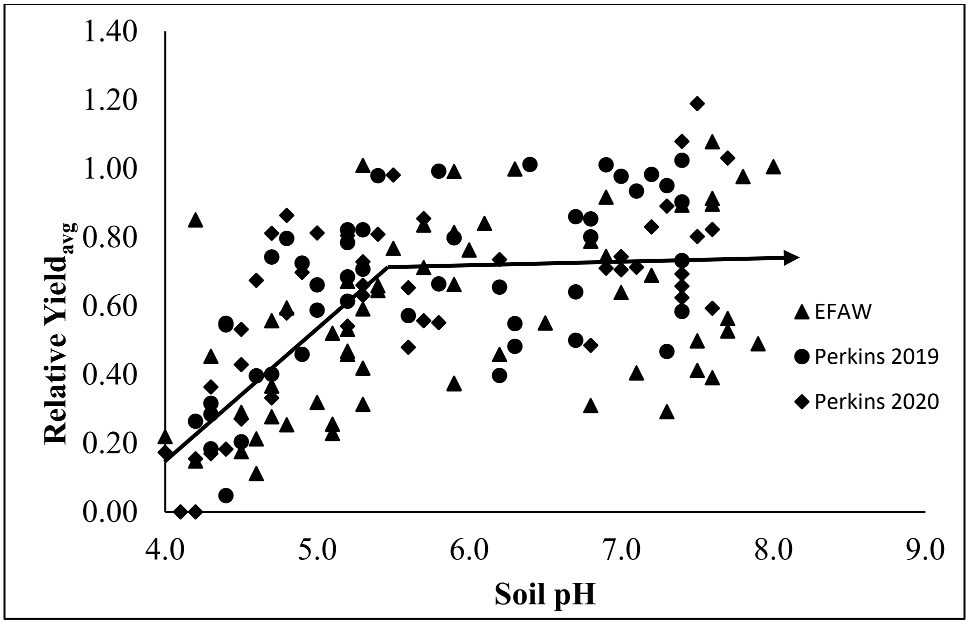

Figure 7. Non-linear relationship of relative yield$_{avg}$ and soil pH in an experiment evaluating the influence of soil pH on cotton physiology and yield. Perkins, OK and EFAW locations were combined across the 2019 and 2020 growing seasons with two cotton cultivars combined in a soil pH range of 4.0 -8.0 in which critical threshold was observed at a soil pH of 5.4. Relative yield$_{avg}$ being compared to an average of 3 highest yields of site year.

When all sites were combined and separated by cultivar, soil pH critical threshold was observed at 6.1 and 5.2 for Deltapine 1612 and NG 3930 respectively as depicted by Table 11. However, the two cultivars were not significantly different as the confidence intervals indicate at $\alpha=0.05$. This should be further evaluated though as the difference in the lower bound of the CI for DP 1612 and upper bound of NG 3930 only provide a difference of 0.08.

Table 10. Results from non-linear regression when evaluating the effect of soil pH on relative yield$_{avg}$ in an experiment evaluating the influence of soil pH on cotton physiology and yield at Perkins, OK and EFAW farm separated by cultivar (α=0.05). Relative yield$_{avg}$ being compared to an average of 3 highest yields of site year.

Cultivar	**Joint**	**Plateau**	**F**	**Prob F**	**r^2**	**CI**
DP 1612	6.1	0.76	25.43	<.0001	0.40	5.4947, 6.7370
NG 3930	5.2	0.72	17.77	<.0001	0.32	4.7466, 5.5795

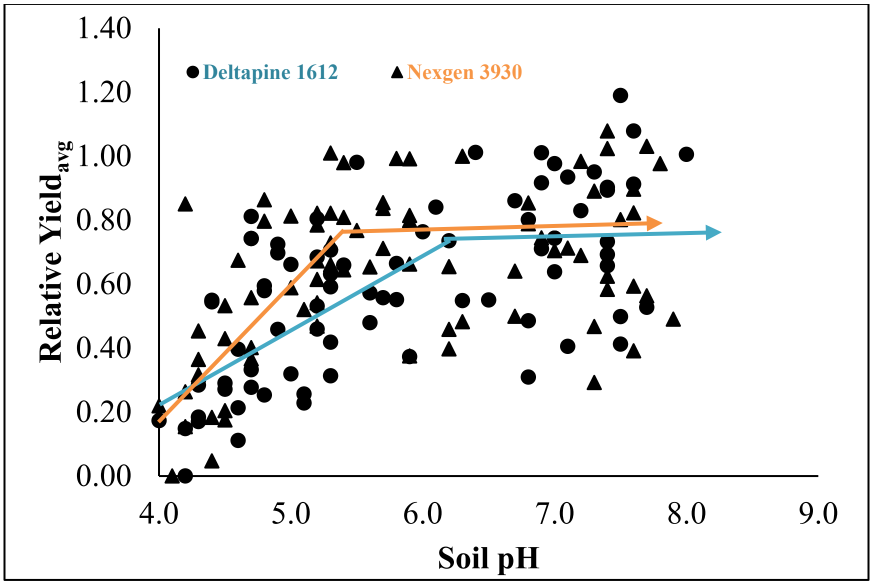

Figure 8. Non-linear relationship between relative yield$_{avg}$ and soil pH in and experiment evaluating the influence of soil pH on cotton physiology and yield. Perkins, OK and EFAW locations were combined across 2019 and 2020 growing seasons separated by cultivar across a soil pH range of 4.0 to 8.0 in which critical threshold was evaluated at 6.1 and 5.2 for Deltapine 1612 and Nexgen 3930 respectively. Relative yield$_{avg}$ being compared to an average of 3 highest yields of site year.

In addition to the evaluation of the relationship between relative yield and soil pH, the relationship between Al_{KCl} and relative yield was also examined. Relative yield$_{avg}$ was significant in relation to Al_{KCl} at α=0.05 across all sites as shown in Table 10. When all locations were combined the linear relationship was also significant with an r^2=0.30. This relationship is depicted in Figure 8.

Table 11. Results from linear regression evaluating the impact of Al_{KCl} on relative yield$_{avg}$ when Al>0 in an experiment evaluating the influence of soil pH on cotton physiology and yield at Perkins, OK and EFAW farm separated by site year and combined (α=0.05). Relative yieldavg being compared to an average of 3 highest yields of site year.

Site	DF	MSE	F	Prob F	r^2
Perkins 19	1	0.0318	25.02	<.0001	0.50
Perkins 20	1	0.0262	46.38	<.0001	0.68
EFAW	1	0.0311	19.48	0.0002	0.47
All Locations	1	0.0498	31.06	<.0001	0.30

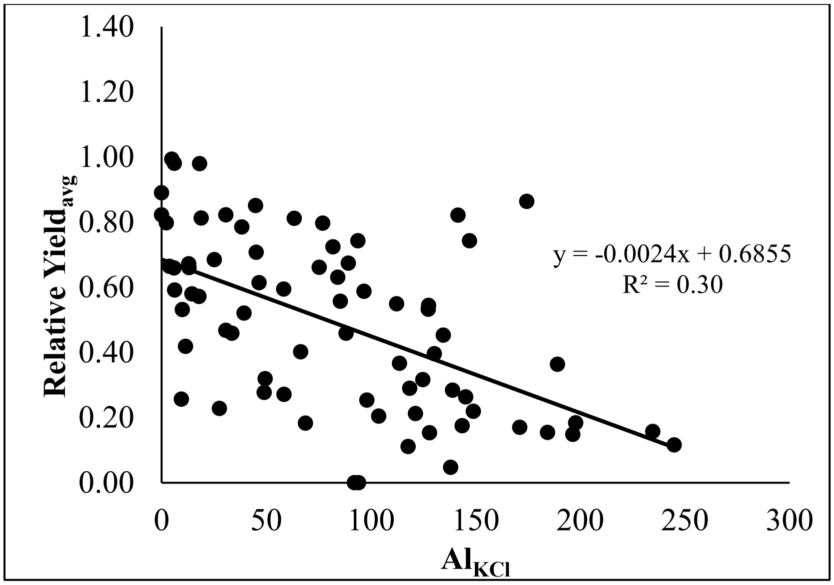

Figure 9. Linear relationship between relative yield$_{avg}$ and Al_{KCl} when Al>0 at Perkins, OK in 2019 and 2020 and the EFAW farm in 2020 with two cultivars combined in an experiment evaluating the influence of soil pH on cotton physiology and yield. Relative yield$_{avg}$ being compared to an average of 3 highest yields of site year.

Lint Quality

Some lint quality parameters exhibited a significant relationship with soil pH. No site showed a significant relationship between soil pH and all quality parameters analyzed at α=0.05, as shown in Table 12. Micronaire was significant in relation to soil pH at only the Perkins 2019 location. Length, uniformity and strength all were significant at the Perkins 2020 location. The EFAW 2020 location lacked a significant relationship with any lint quality parameter analyzed (α=0.05).

Table 12. Relationship between lint quality analysis and soil pH in an experiment evaluating the influence of soil pH on cotton physiology and yield at Perkins, OK and EFAW farm evaluated using quadratic least squares regression separated by site year (α=0.05).

Perkins 19	**DF**	**MSE**	**F**	**Prob F**	**r^2**
Micronaire	2	0.1157	4.55	0.0159	0.17
Length	2	0.0010	1.80	0.1764	0.07
Uniformity	2	0.7968	0.16	0.8488	0.01
Strength	2	1.6127	0.26	0.7703	0.01
Perkins 20	**DF**	**MSE**	**F**	**Prob F**	**r^2**
Micronaire	2	0.1108	2.09	0.1359	0.09
Length	2	0.0008	4.32	0.0193	0.16
Uniformity	2	1.1704	6.74	0.0028	0.23
Strength	2	2.011	4.63	0.0150	0.17
EFAW	**DF**	**MSE**	**F**	**Prob F**	**r^2**
Micronaire	2	0.0357	2.09	0.1320	0.06
Length	2	0.0011	0.79	0.4566	0.03
Uniformity	2	1.6637	0.90	0.4116	0.03
Strength	2	3.433	1.15	0.3246	0.04

All locations that showed a significant relationship between soil pH and a lint quality parameter were analyzed separately by cultivar as shown in Table 13. When separated by cultivar, the micronaire measurement from the Perkins 2019 location showed only the Deltapine 1612 cultivar to be linearly significant in relation to soil pH displayed by Figure 7. The Deltapine cultivar was also the only cultivar showed a significant relationship between length and soil pH at the Perkins 2020 location when evaluated using quadratic least squares regression as shown by figure 8. Strength was significant for both cultivars at the Perkins 2020 location when analyzed using quadratic least squares regression shown by Figures 9 and 10.

Table 13. Relationships between lint quality parameters and soil pH in an experiment evaluating the influence of soil pH on cotton physiology and yield. Measurements not listed were insignificant (NS) by site year (α=0.05).

Site/ Measure / Cultivar	**Relationship**	**DF**	**MSE**	**F**	**Prob F**	**r^2**
Perkins 19						
Micronaire						
DP 1612	Linear	1	0.0766	12.56	0.0018	0.36
NG 3930	NS	-	-	-	-	-
Perkins 20						
Length						
DP 1612	Quadratic	2	.0004	5.44	0.0125	0.34
NG 3930	NS	-	-	-	-	-
Uniformity						
DP 1612	NS	-	-	-	-	-
NG 3930	Quadratic	2	0.9761	6.37	0.0072	0.39
Strength						
DP 1612	Quadratic	2	1.4891	3.90	0.0364	0.27
NG 3930	Quadratic	2	1.1615	4.44	0.0254	0.31

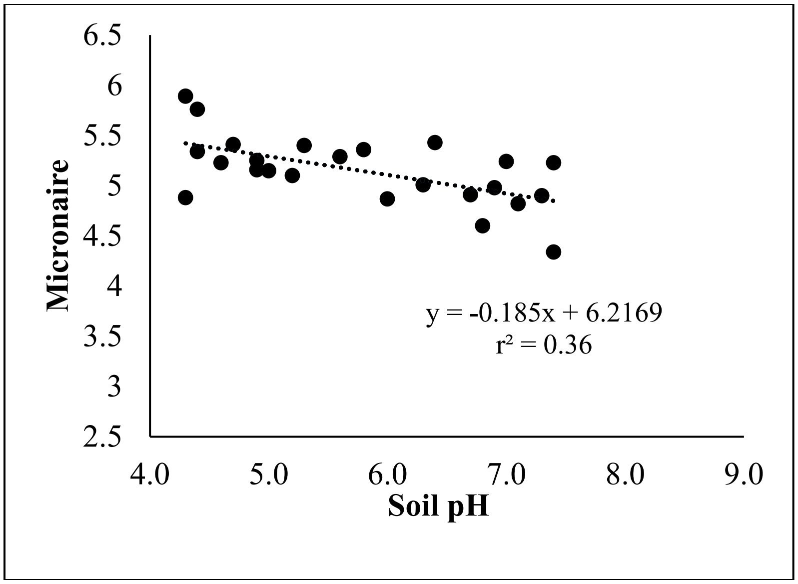

Figure 10. Linear relationship between soil pH and micronaire for Deltapine 1612 in an experiment evaluating the influence of soil pH on cotton physiology and yield at Perkins, OK in 2019.

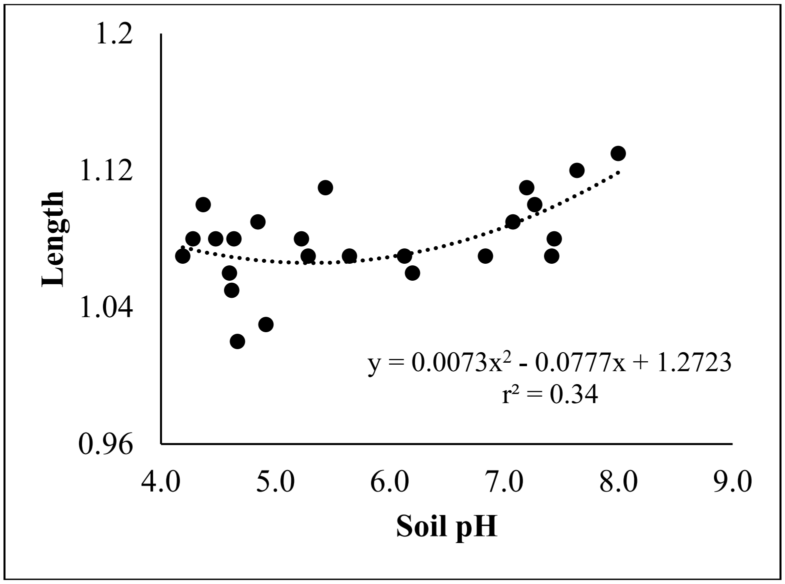

Figure 11. Quadratic relationship between lint length and soil pH for Deltapine 1612 in an experiment evaluating the influence of soil pH on cotton physiology and yield at Perkins, OK in 2020.

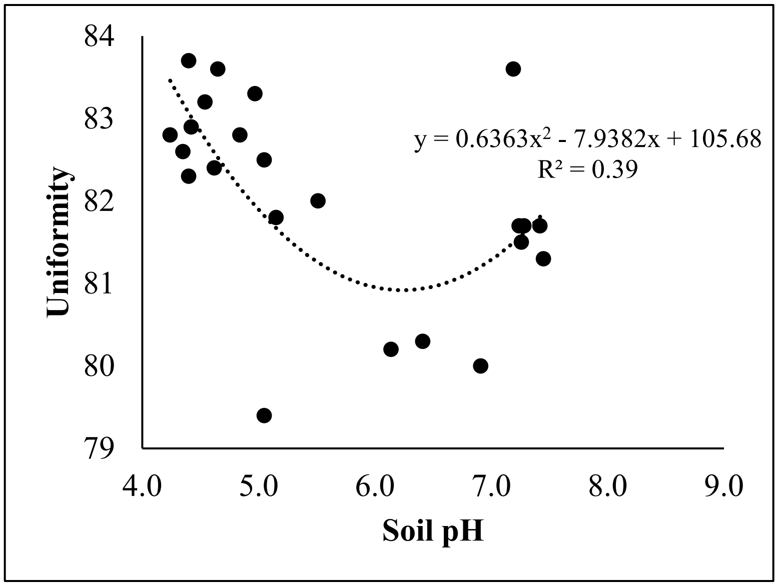

Figure 12. Quadratic relationship between uniformity and soil pH for Nexgen 3930 in an experiment evaluating the influence of soil pH on cotton physiology and yield at Perkins, OK in 2020

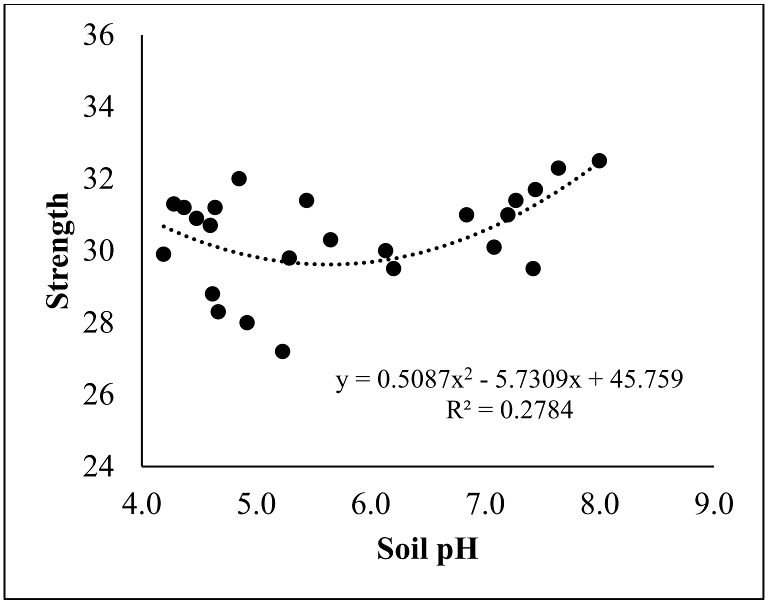

Figure 13. Quadratic relationship between lint strength and soil pH for Deltapine 1612 in an experiment evaluating the influence of soil pH on cotton physiology and yield at Perkins, OK in 2020

Discussion

When analyzing the relationship between soil pH and relative yield the non-linear analysis was observed to provide a greater coefficient of determination while also allowing for the identification of a clear critical threshold at which yield begins to decrease. The determination of a critical threshold is imperative to this study as it allows recommendation for amelioration of soil acidity at a specific soil pH level. For the rest of this discussion and conclusion yield will only be discussed as it pertains to the non-linear relationship with soil pH.

At all three locations a critical threshold soil pH for lint yield was identified. However, critical thresholds differed across locations, ranging from 6.9 at the Perkins 2019 site to 4.8 at the Perkins 2020 location. This variability in critical threshold suggests that environment during the growing season impacts crop response to soil pH level. This variance in response maybe tied to the ability of the cotton root system to penetrate below the acidic zone in the upper portion of the soil profile in to more basic subsurface soil.

A similar response was described in work with grain sorghum and sunflower by Butchee et al. (2012) and Sutradhar et al. (2014) respectively. This theory is supported by the increased mean fractional water index in June and July at the Perkins 2019 site as compared to other locations as shown in Table 14 as well as the EFAW site when compared to the Perkins 2020 site (Brock et al. 1995; McPherson et al. 2007). This may explain the much higher critical threshold for the Perkins 2019 location observed at a soil pH of 6.9 as well as the EFAW site at a critical threshold observed at a soil pH of 5.7. However, weed pressure at the Perkins 19 location was significant enough to impact crop growth in specific plots with above neutral soil pH values, note in Figure 4 the points at a pH above 6.0 have abnormally low yields compared to the grouping of points from other plots in the experiment. When all sites were combined a critical threshold of 5.4 was observed for the relationship between soil pH and relative yield. This is similar to the critical threshold reported for other crops such as wheat (Zhang and Raun.,2006).

Table 14. Mean fractional water index for June and July at Perkins, OK in 2019 and 2020 as well as the EFAW farm in 2020.

Site	**June**	**July**
Perkins 2019	0.97	0.51
Perkins 2020	0.67	0.36
EFAW	0.61	0.48

When considering cultivar response to soil pH this study found there to be no significant difference in critical soil pH at α=0.05. However, as stated previously the investigation of cultivar response to soil pH across a wider range of genetic background may likely yield significant results. This also indicates there may be scientific and applicable value to the pursuit of germplasm selection for acidic tolerant cultivars when considering the wide range of soil pH values in which cotton maybe produced.

The variability of critical soil pH was not as great when considering critical thresholds for the in-season growth parameters measured. All in-season growth parameters with significant relationships with soil pH were shown to be within a critical soil pH range of 4.6 to 5.4, except for the Perkins 2019 emergence measurement which was insignificant likely due to excessive weed pressure in some plots early in the growing season. The relationship shown by the in-season growth parameters measured are indicative of crop stress even when yield loss may not have been observed at a given soil pH level, for example, the difference in critical pH for relative yield and NDVI as seen at the Perkins 2020 site. As such producers may be interested in ameliorating soil pH in expectation of possible yield loss in the future even when not present in the previous crop.

Similar to the analysis of soil pH, all sites showed a significant relationship between lint yield and Al_{KCl}. This reinforces the information found in the literature that toxic elements such as Al^{3+} decrease crop production potential as they become more readily available in solution in acidic soil conditions. This may further exasperate other problems that may become present, for example, the reduced availability of some nutrients such as P. While Al_{KCl}^{3+} was linearly correlated with relative yield with an r^2 value of 0.30, soil pH was a better predictor of a decline in relative lint yield with an r^2 value of 0.42. These results suggest that soil pH should continue to be used as the main parameter in predicting a reduction of crop productivity to soil acidity in many soils of Oklahoma.

CHAPTER VI

EXPECTED ECONOMIC RETURN TO LIME APPLICATION

As presented in the previous sections of this work cotton lint yield is expected to be negatively impacted by soil acidification when pH is below a level of 5.4. However, cotton producers may be reluctant to ameliorate soil pH due to the high initial cost of lime. This may be especially true for those producers who have utilized other methods to mitigate the effects of soil acidity when producing a lower value crop such as wheat. This chapter is dedicated to the analysis of value associated with the liming operation across multiple economic and yield scenarios for cotton production.

Methodology

Using the pH value of 5.4 that was shown to be the critical threshold across all sites combined in the field experiment described previously and its correlated relative yield plateau level of approximately 0.73 an analysis of the net present value (NPV) of lime application as a function of initial pH, lint value and distance from quarry was completed for both the EFAW and Perkins, OK locations individually based on Sikora buffer pH values from each location. All lime recommendation rates were adjusted to

100% ECCE lime for analysis and based of a pH goal of 6.4 as recommended in Oklahoma by Zhang. (2017).

Lime recommendations for both locations differed as expected likely due to soil texture. The recommendation curves based off Sikora buffer values for the 2020 soil analysis data (Figures 11 and 12) display this difference as the relationship between initial soil pH and the lime recommendation function. The Perkins location is shown to have a higher expected rate of pH change to lime application than the EFAW location.

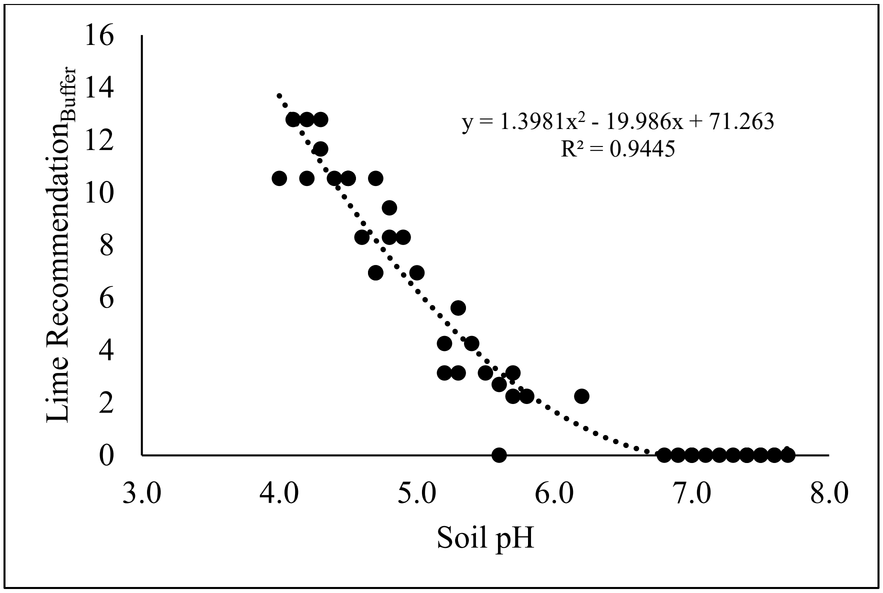

Figure 14. Relationship between ECCE lime recommendation (Mg ha^{-1}) and soil pH as a function of buffer pH at Perkins, OK (Fine sandy loam soil) in 2020.

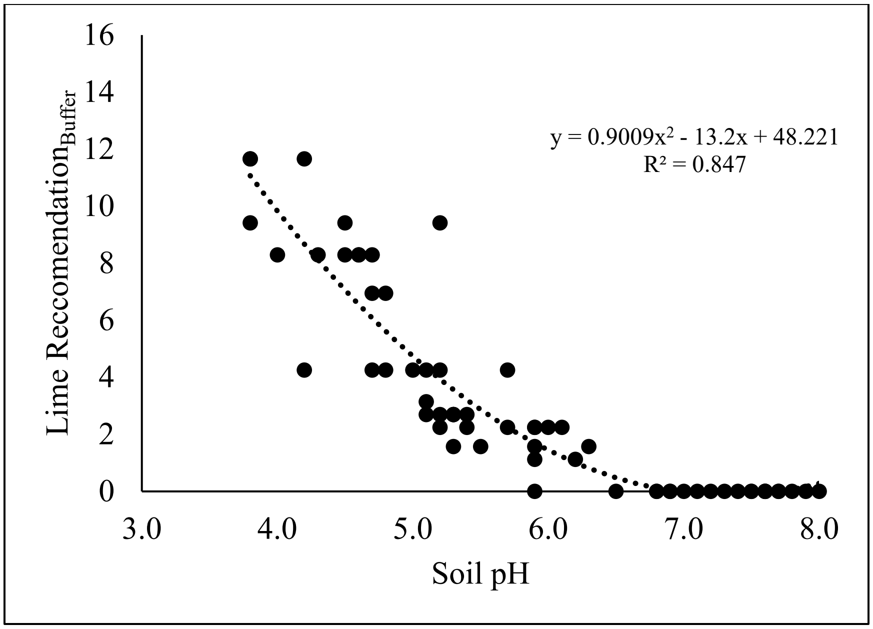

Figure 15. Relationship between ECCE lime recommendation (Mg ha^{-1}) and soil pH as a function of buffer pH at the EFAW farm near Stillwater, OK (Loam soil) in 2020.

The analysis of NPV was completed following a similar framework to that which was utilized by Cho et al. (2020). NPV was evaluated as a function of location, initial soil pH, expected yield level, cotton lint value, and all costs associated with lime application. For this analysis all other variables were considered equal and not evaluated. The NPV function used is stated as:

$$NPV = \sum_{t=0}^{T} \frac{V \times Y_g}{(1+r)^t} - L$$

where NPV is the per hectare net present value in US$ of returns to lime application to a target pH of 6.4. T is the planning horizon of 5 years and V is the value of cotton lint in US$ at three levels \$1.10 kg^{-1}, \$1.54 kg^{-1} and \$1.99 kg^{-1}. L is the total costs associated with the lime application including transportation based on distance from quarry, close being a distance of approximately 32 km and far 193 km respectively. These values were retrieved by Cho et al, (2020) from Farmers Grain Company located in Pond Creek, OK. The r variable is the discount rate of 3.25% which is the interest rate reported for the farm ownership loan program from the USDA Farm Service Agency (USDA FSA, 2020), Y_g is the estimated difference in yield above the initial pH and is defined as the relative yield of the initial pH level subtracted from the relative yield at pH=6.4. This value is then multiplied by a yield goal value of 1600, 1076, or 538 kg ha^{-1}. For this analysis yields were treated as stable across the 5 year planning horizon to simplify the analysis. All yield goal levels were analyzed.

Findings

Tables 15 through 23 depict the sensitivity analysis of the NPV of lime application based on initial soil pH assuming a target pH of 6.4. When NPV was evaluated at a yield goal level of 1600 kg ha^{-1} the analysis returned positive NPV values until the plateau at a pH value of 5.4 was reached, regardless of location, distance from quarry or lint value. When NPV was analyzed utilizing a yield goal of 1076 kg ha^{-1} NPV was negative for three scenarios, all of which included the 193 km distance from quarry. However, when yield goal levels were lowered to a level of 538 kg ha^{-1} levels in which positive NPV values decreased in some instances. When NPV was calculated at a lint value of $1.10 kg^{-1} at the 538 kg ha^{-1} yield goal using the Perkins lime recommendation curve, lime application was shown to provide a positive NPV only when initial soil pH was below 4.8 even while relative yield level is only 45% at this pH level. However, this does not apply across all scenarios at the 538 kg ha^{-1} yield goal level. When analysis was completed using the EFAW lime recommendation curve at a lint value of \$1.10 kg^{-1} with a 538 kg ha^{-1} yield goal, lime application provided positive NPV values when liming a soil with an initial pH of 5.0 or lower while this threshold increased as lint value increased.

Discussion

This analysis suggests that profitability of liming agricultural fields for cotton production should be considered under specific circumstances such as but not limited to soil type, cost of lime and application, lint value, and yield goal. This analysis highlights the fact that amelioration efforts when soil pH values are greater than the critical threshold as expected always return a negative value as there is no expectation of a positive response to lime application above a soil pH of 5.4 based on the field experiment described previously.

Lime application was shown to be unprofitable at soil pH levels lower than the critical threshold of 5.4 under 3 scenarios when yield goal was 1076 kg ha^{-1} and 8 scenarios when yield goal was 538 kg ha^{-1}, while lime application was always expected to be profitable at the 1600 kg ha^{-1} yield goal. This indicates that while total cost of lime and lint value are important factors to consider, yield goal may be the most influential on the profitability of lime application.

This economic analysis of liming acidic soils for cotton production was simplified to provide a rough understanding of the potential impact that variables such as yield expectation, lime cost, and lint value may have on profitability. However, it does not address the many other impacts that production under acidic condition may have on profitability. For example the loss in yield potential likely would have a negative impact on nitrogen use efficiency driving up the per-unit cost of production assuming that nitrogen application rate was held constant across all soil pH levels. Soil pH has the potential to influence the profitability of cotton production in more than one way. It is imperative to understand the specific scenario in which production may occur, and consider the appropriate strategy to maximize profitability, this often may require the amelioration of soil acidity. All graphs depicting the relationship between soil pH and NPV of lime application may be found in the appendices section of this work.

Table 15. Estimated net present value (NPV) of ECCE lime application as a function of initial pH and distance from quarry at a lint value of US\$1.10 kg^{-1} utilizing a 1600 kg ha^{-1} yield goal.

Location/Initial pH Level	**Close to Quarry NPV US\$ ha^{-1}**	**Far from Quarry NPV US\$ ha^{-1}**
Perkins		
4.0	3685	3128
4.5	2373	1981
5.0	1027	772
5.5	(169)	(317)
EFAW		
4.0	3864	3464
4.5	2492	2205
5.0	1099	906
5.5	(134)	(250)

Table 16. Estimated net present value (NPV) of ECCE lime application as a function of initial pH and distance from quarry at a lint value of US$1.54 ha^{-1} utilizing a 1600 kg ha^{-1} yield goal.

Location/Initial pH Level	Close to Quarry NPV US$ ha^{-1}	Far from Quarry NPV US$ ha^{-1}
Perkins		
4.0	5415	4858
4.5	3501	3109
5.0	1556	1300
5.5	(169)	(317)
EFAW		
4.0	5594	5194
4.5	3621	3334
5.0	1627	1434
5.5	(134)	(250)

Table 17. Estimated net present value (NPV) of ECCE lime application 9as a function of initial pH and distance from quarry at a lint value of US$1.99 ha^{-1} utilizing a 1600 kg ha^{-1} yield goal.

Location/Initial pH Level	Close to Quarry NPV US$ ha^{-1}	Far from Quarry NPV US$ ha^{-1}
Perkins		
4.0	7146	6589
4.5	4631	4239
5.0	2084	1829
5.5	(169)	(317)
EFAW		
4.0	7325	6925
4.5	4751	4464
5.0	2156	1963
5.5	(134)	(250)

Table 18. Estimated net present value (NPV) of ECCE lime application as a function of initial pH and distance from quarry at a lint value of US\$1.10 ha^{-1} utilizing a 1076 kg ha^{-1} yield goal.

Location/Initial pH Level	**Close to Quarry NPV US\$ ha^{-1}**	**Far from Quarry NPV US\$ ha^{-1}**
Perkins		
4.0	2270	1713
4.5	1449	1057
5.0	595	340
5.5	(169)	(317)
EFAW		
4.0	2449	2049
4.5	1568	1281
5.0	667	474
5.5	(134)	(250)

Table 19. Estimated net present value (NPV) of ECCE lime application as a function of initial pH and distance from quarry at a lint value of US\$1.54 ha^{-1} utilizing a 1076 kg ha^{-1} yield goal.

Location/Initial pH Level	**Close to Quarry NPV US\$ ha^{-1}**	**Far from Quarry NPV US\$ ha^{-1}**
Perkins		
4.0	3433	2876
4.5	2208	1816
5.0	950	695
5.5	(169)	(317)
EFAW		
4.0	3612	3212
4.5	2328	2040
5.0	1022	829
5.5	(134)	(250)

Table 20. Estimated net present value (NPV) of ECCE lime application as a function of initial pH and distance from quarry at a lint value of US\$1.99 ha^{-1} utilizing a 1076 kg ha^{-1} yield goal.

Location/Initial pH Level	**Close to Quarry NPV US\$ ha^{-1}**	**Far from Quarry NPV US\$ ha^{-1}**
Perkins		
4.0	4597	4040
4.5	2968	2576
5.0	1306	1050
5.5	(169)	(317)
EFAW		
4.0	4776	4376
4.5	3087	2800
5.0	1378	1185
5.5	(134)	(250)

Table 21. Estimated net present value (NPV) of ECCE lime application as a function of initial pH and distance from quarry at a lint value of US\$1.10 ha^{-1} utilizing a 538 kg ha^{-1} yield goal.

Location/Initial pH Level	**Close to Quarry NPV US\$ ha^{-1}**	**Far from Quarry NPV US\$ ha^{-1}**
Perkins		
4.0	817	260
4.5	500	108
5.0	152	(57)
5.5	(169)	(317)
EFAW		
4.0	996	596
4.5	620	333
5.0	223	30
5.5	(134)	(250)

Table 22. Estimated net present value (NPV) of ECCE lime application as a function of initial pH and distance from quarry at a lint value of US\$1.54 ha^{-1} utilizing a 538 kg ha^{-1} yield goal.

Location/Initial pH Level	**Close to Quarry NPV US\$ ha^{-1}**	**Far from Quarry NPV US\$ ha^{-1}**
Perkins		
4.0	1398	841
4.5	880	488
5.0	329	73
5.5	(169)	(317)
EFAW		
4.0	1577	1177
4.5	1000	712
5.0	401	208
5.5	(134)	(250)

Table 23. Estimated net present value (NPV) of ECCE lime application as a function of initial pH and distance from quarry at a lint value of US\$1.99 ha^{-1} utilizing a 538 kg ha^{-1} yield goal.

Location/Initial pH Level	**Close to Quarry NPV US\$ ha^{-1}**	**Far from Quarry NPV US\$ ha^{-1}**
Perkins		
4.0	1980	1424
4.5	1260	868
5.0	507	251
5.5	(169)	(317)
EFAW		
4.0	2160	1759
4.5	1380	1092
5.0	579	386
5.5	(134)	(250)

CHAPTER VII

CONCLUSIONS

Soil acidity is a prevalent problem in Oklahoma as 16.3 % of all agricultural soil samples tested in the 2014-2017 period at the Soil, Water, and Forage Analytical Laboratory (SWAFL) at Oklahoma State University were found to have a soil pH <5.5 (Zhang and McCray, 2018). When considering this finding combined with the increase in cotton planted in the state of Oklahoma since 2013 (NASS USDA, 2021) it is likely that cotton is being produced on acidic soils in areas that have traditionally focused on producing other crops such as wheat. This leads to the conclusion that it is important to understand the impact that soil acidity may have on cotton growth and yield as producers make decisions for their operation.

This study provided meaningful results as it demonstrated that soil acidity can significantly impact cotton performance based on both physiological measurements and lint yield. Soil pH was found to negatively affect cotton yield when reaching levels below 5.4. This study also exhibited the likelihood of soil pH requiring a management strategy that takes into account both site and environment. The critical thresholds shown while examining yield and in-season growth measurements will impart impactful guidance when considering amelioration of soil acidity for cotton production. However, it is important to still consider the distinct environment in which production is occurring and the impact on liming decisions. As producers consider introducing cotton into their production systems it should be recommended to utilize soil testing to ensure an adequate soil pH to avoid possible reductions in cotton growth and yield and an ensuing decrease in profitability.

Al_{KCl} concentration in the soil negatively impacts crop performance as exhibited by this study. However, the presence of exchangeable Al^{3+} or similar toxic elements can vary across soils largely based on variables, in particular, parent material of a soil. As such Al_{KCl} concentration may be a useful measurement when considering lime applications. However, the information obtained by this study show soil pH to be a preferable method of determination for deciding to pursue soil acidity amelioration.

Loss of yield due to soil acidity may be substantial and is further demonstrated by the overview of the profitability of lime application on some fields for cotton production. The influence of lint value, yield goal level, and cost of lime and application on the profitability of lime application cannot be overstated. As such producers should take all variables into account when making a decision to ameliorate acidic soils.

Moving forward as cotton continues to be produced on potentially acidic soils, it will be important for producers take into consideration the impact that soil pH will likely have on cotton performance under these conditions. Future research may benefit from additional locations with varying growing environments as well as investigating the possibility of differing response of different cotton cultivars under acidic soil conditions.

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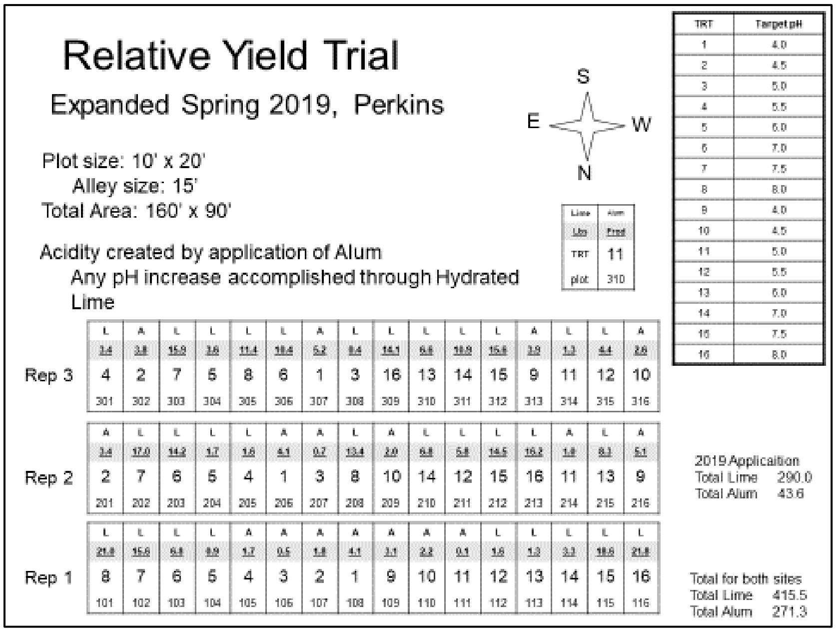
APPENDICES



Relative Yield Trial

Expanded Spring 2019, Perkins

Plot size: 10' x 20'
Alley size: 15'
Total Area: 160' x 90'

Acidity created by application of Alum
Any pH increase accomplished through Hydrated Lime

Lime	Alum
Lbs	Pred
TRT	11
plot	310

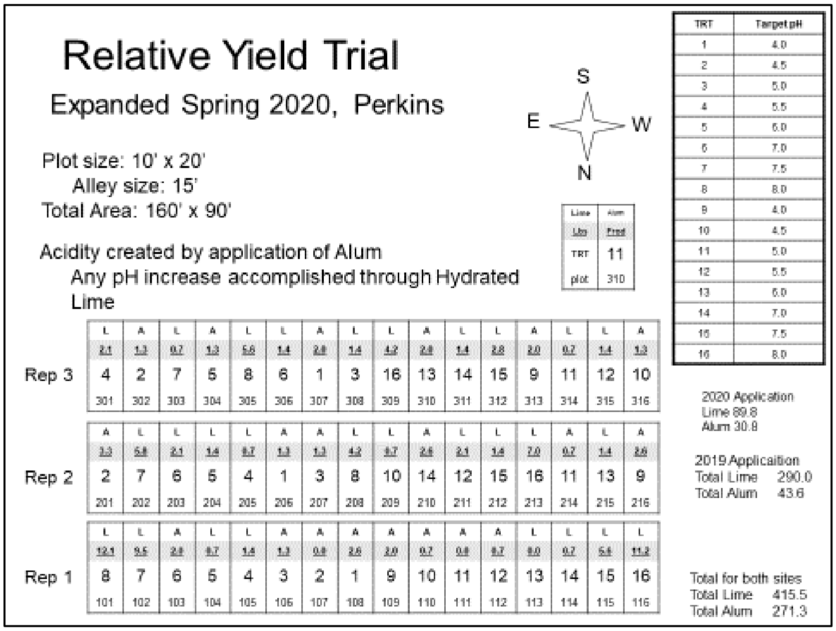
TRT	Target pH
1	4.0
2	4.5
3	5.0
4	5.5
5	6.0
6	7.0
7	7.5
8	8.0
9	4.0
10	4.5
11	5.0
12	5.5
13	6.0
14	7.0
15	7.5
16	8.0

	L	A	L	L	L	L	A	L	L	L	L	L	A	L	L	A
	3.4	3.8	15.9	3.6	11.4	10.4	5.2	8.4	14.1	6.6	10.9	15.6	3.9	1.3	4.4	2.6
Rep 3	4	2	7	5	8	6	1	3	16	13	14	15	9	11	12	10
	301	302	303	304	305	306	307	308	309	310	311	312	313	314	315	316
	A	L	L	L	L	A	A	L	A	L	L	L	L	A	L	A
	3.4	17.0	14.2	1.7	1.6	4.1	0.7	13.4	2.0	6.8	5.8	14.5	16.2	1.8	8.1	5.1
Rep 2	2	7	6	5	4	1	3	8	10	14	12	15	16	11	13	9
	201	202	203	204	205	206	207	208	209	210	211	212	213	214	215	216
	L	L	L	L	A	A	A	A	A	A	A	L	L	L	L	L
	21.8	15.6	6.8	8.9	1.7	0.5	1.8	4.1	3.1	2.2	0.1	1.6	1.3	3.3	18.6	21.8
Rep 1	8	7	6	5	4	3	2	1	9	10	11	12	13	14	15	16
	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116

2019 Applicaition
Total Lime 290.0
Total Alum 43.6

Total for both sites
Total Lime 415.5
Total Alum 271.3

Figure 16. Treatment Structure at Perkins, OK (2019).



Relative Yield Trial

Expanded Spring 2020, Perkins

Plot size: 10' x 20'
Alley size: 15'
Total Area: 160' x 90'

Acidity created by application of Alum
Any pH increase accomplished through Hydrated Lime

Lime	Alum
Lbs	Pred
TRT	11
plot	310

TRT	Target pH
1	4.0
2	4.5
3	5.0
4	5.5
5	6.0
6	7.0
7	7.5
8	8.0
9	4.0
10	4.5
11	5.0
12	5.5
13	6.0
14	7.0
15	7.5
16	8.0

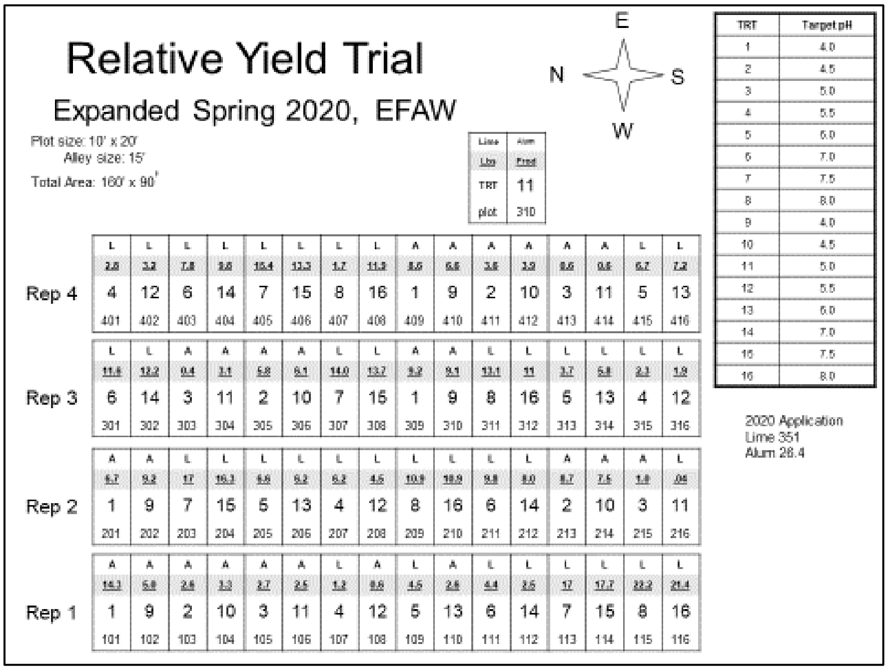
	L	A	L	A	L	L	A	L	L	A	L	L	A	L	L	A
	2.1	1.3	0.7	1.3	5.6	1.4	2.0	1.4	4.2	2.0	1.4	2.8	2.0	0.7	1.4	1.3
Rep 3	4	2	7	5	8	6	1	3	16	13	14	15	9	11	12	10
	301	302	303	304	305	306	307	308	309	310	311	312	313	314	315	316
	A	L	L	L	L	A	A	L	L	A	L	L	L	A	L	A
	3.3	5.8	2.1	1.4	0.7	1.3	1.3	4.2	0.7	2.6	2.1	1.4	7.0	0.7	1.4	2.6
Rep 2	2	7	6	5	4	1	3	8	10	14	12	15	16	11	13	9
	201	202	203	204	205	206	207	208	209	210	211	212	213	214	215	216
	L	L	A	L	L	A	A	A	A	A	A	A	L	L	L	L
	12.1	9.5	2.0	0.7	1.4	1.3	0.0	2.6	2.0	0.7	0.0	0.7	8.0	0.7	5.6	11.2
Rep 1	8	7	6	5	4	3	2	1	9	10	11	12	13	14	15	16
	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116

2020 Application
Lime 89.8
Alum 30.8

2019 Applicaition
Total Lime 290.0
Total Alum 43.6

Total for both sites
Total Lime 415.5
Total Alum 271.3

Figure 17. Treatment structure at Perkins, OK (2020).



Relative Yield Trial

Expanded Spring 2020, EFAW

Plot size: 10' x 20'
Alley size: 15'
Total Area: 160' x 90'

Lime	Alum
Lbs	Prod
TRT	11
plot	310

	L	L	L	L	L	L	L	L	A	A	A	A	A	A	L	L
	2.8	3.2	7.8	9.8	15.4	13.3	1.7	11.8	8.6	6.6	3.6	3.9	8.6	0.6	6.7	7.2
Rep 4	4	12	6	14	7	15	8	16	1	9	2	10	3	11	5	13
	401	402	403	404	405	406	407	408	409	410	411	412	413	414	415	416
	L	L	A	A	A	A	L	L	A	A	L	L	L	L	L	L
	11.6	12.2	0.4	3.1	5.8	6.1	14.0	13.7	9.2	9.1	13.1	11	3.7	5.8	2.1	1.8
Rep 3	6	14	3	11	2	10	7	15	1	9	8	16	5	13	4	12
	301	302	303	304	305	306	307	308	309	310	311	312	313	314	315	316
	A	A	L	L	L	L	L	L	L	L	L	L	A	A	A	L
	6.7	9.2	17	16.3	6.6	6.2	6.2	4.5	10.9	18.9	9.8	8.0	8.7	7.5	1.8	.06
Rep 2	1	9	7	15	5	13	4	12	8	16	6	14	2	10	3	11
	201	202	203	204	205	206	207	208	209	210	211	212	213	214	215	216
	A	A	A	A	A	A	L	A	L	A	L	L	L	L	L	L
	14.3	5.8	2.8	3.3	2.7	2.5	1.2	8.6	4.5	2.8	4.4	2.5	17	17.7	22.2	21.4
Rep 1	1	9	2	10	3	11	4	12	5	13	6	14	7	15	8	16
	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116

TRT	Target pH
1	4.0
2	4.5
3	5.0
4	5.5
5	6.0
6	7.0
7	7.5
8	8.0
9	4.0
10	4.5
11	5.0
12	5.5
13	6.0
14	7.0
15	7.5
16	8.0

2020 Application
Lime 351
Alum 28.4

Figure 18. Treatment structure at EFAW (Stillwater, OK, 2020).

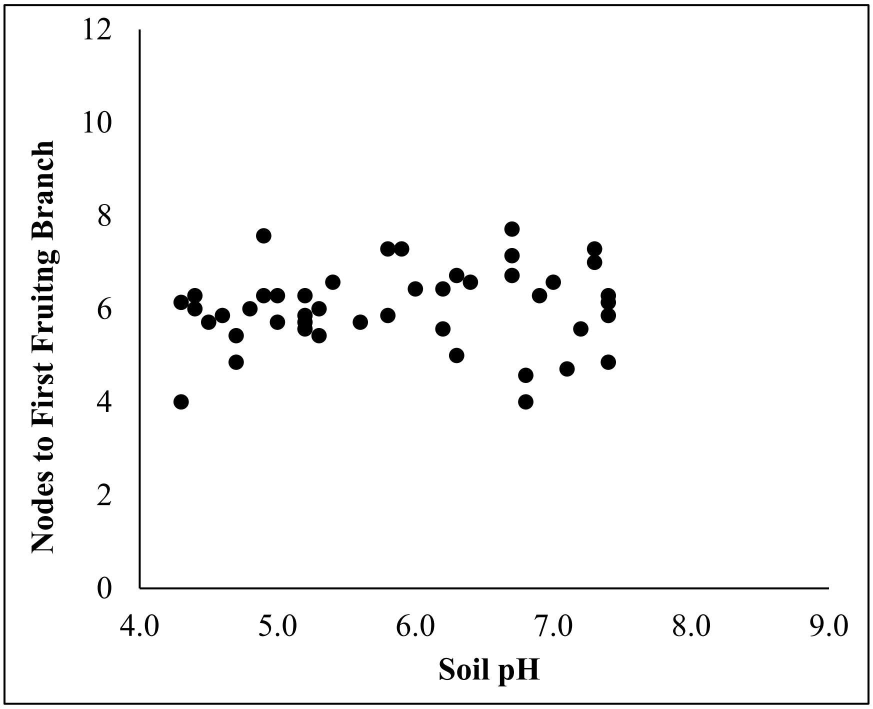


Figure 19. Relationship between soil pH and nodes to first fruiting branch at Perkins 2019.

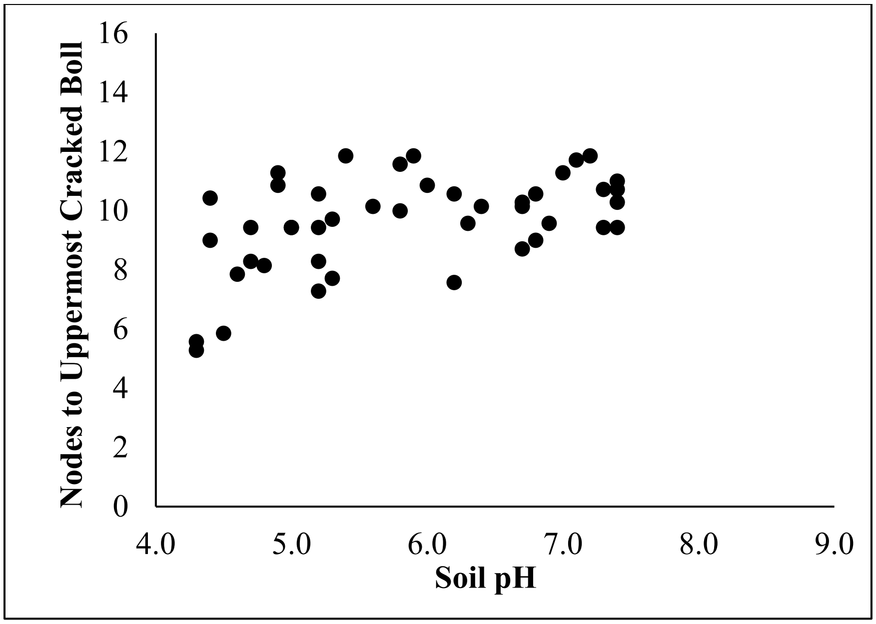


Figure 20. Relationship between soil pH and nodes to uppermost cracked boll at Perkins 2019

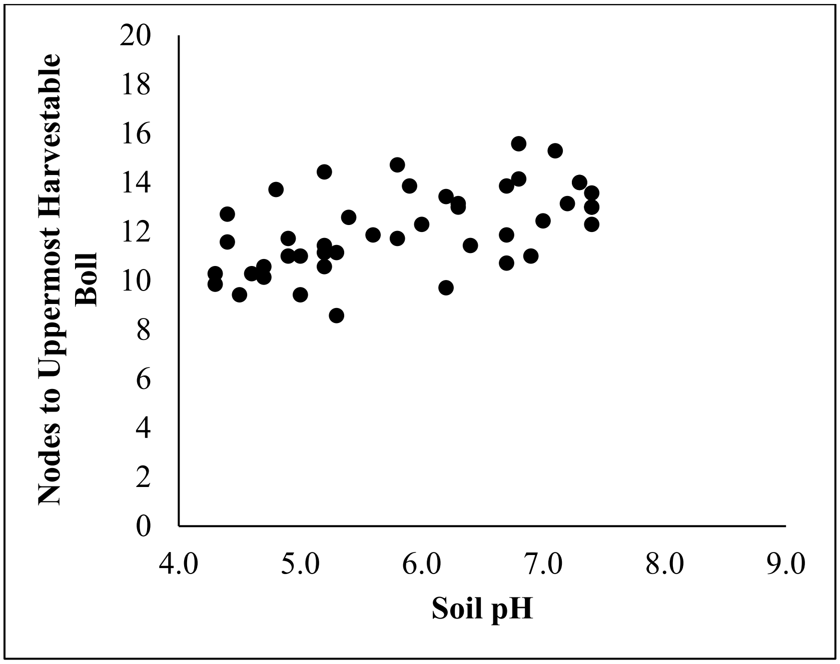


Figure 21. Relationship between soil pH and nodes to uppermost harvestable boll at Perkins 2019.

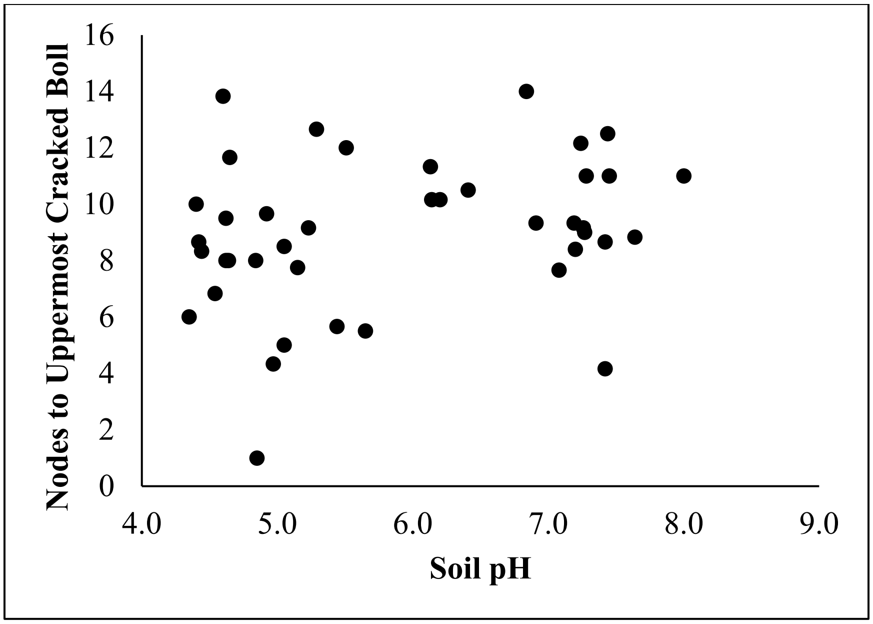


Figure 22. Relationship between soil pH and nodes to first fruiting branch at Perkins 2020.

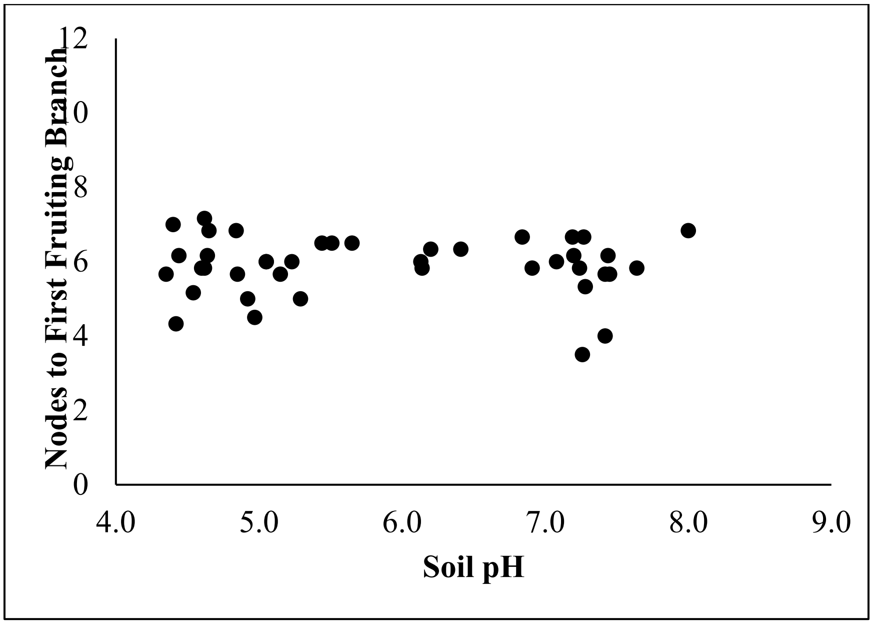


Figure 23. Relationship between soil pH and nodes to uppermost cracked boll Perkins 2020.

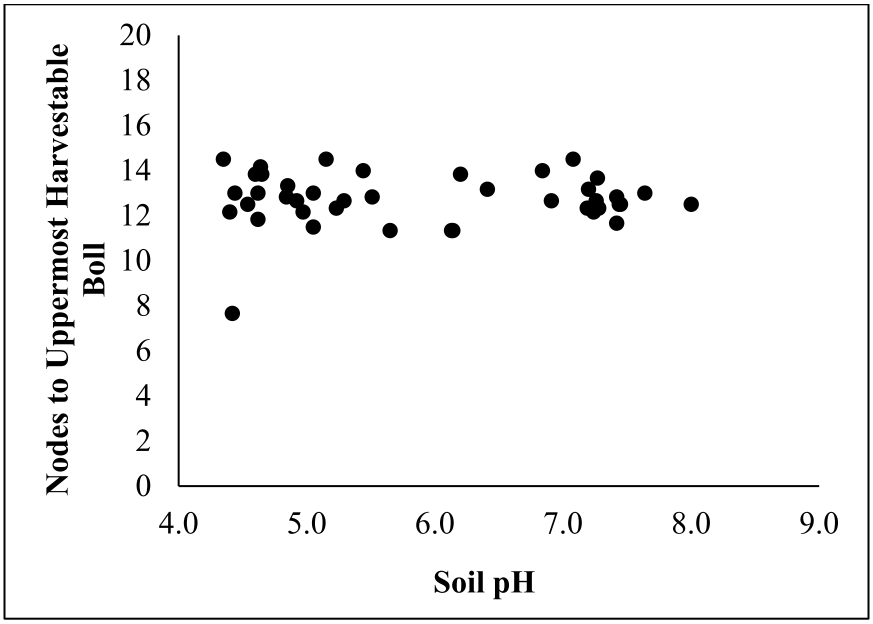


Figure 24. Relationship between soil pH and nodes to uppermost harvestable boll at Perkins 2020.

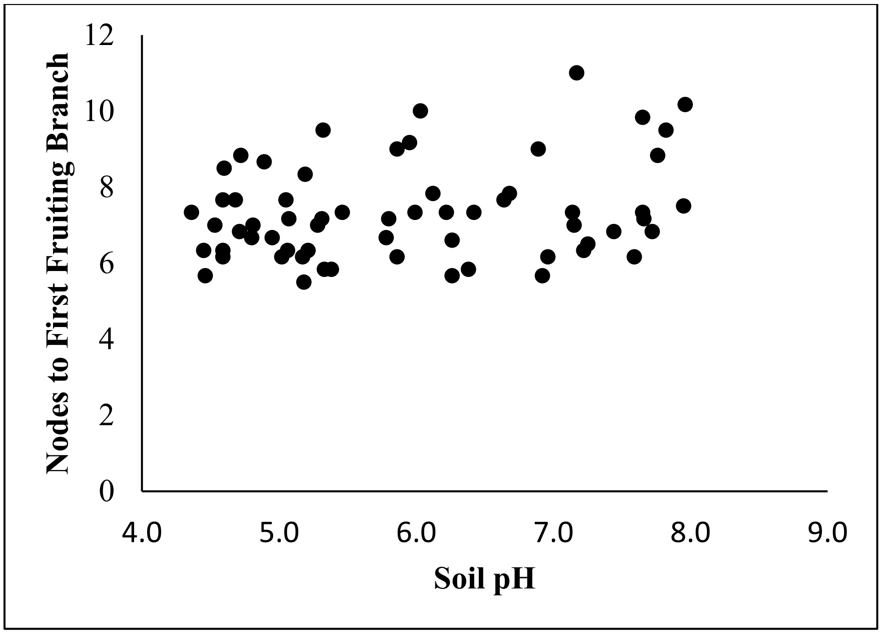


Figure 25. Relationship between soil pH and nodes to first fruiting branch at Efaw.

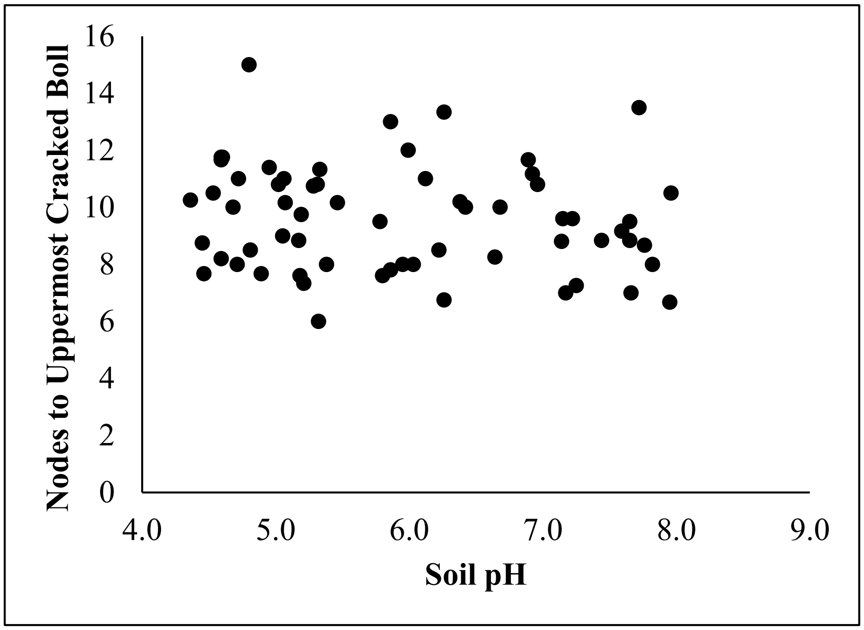


Figure 26. Relationship between soil pH and nodes to uppermost cracked boll at Efaw.

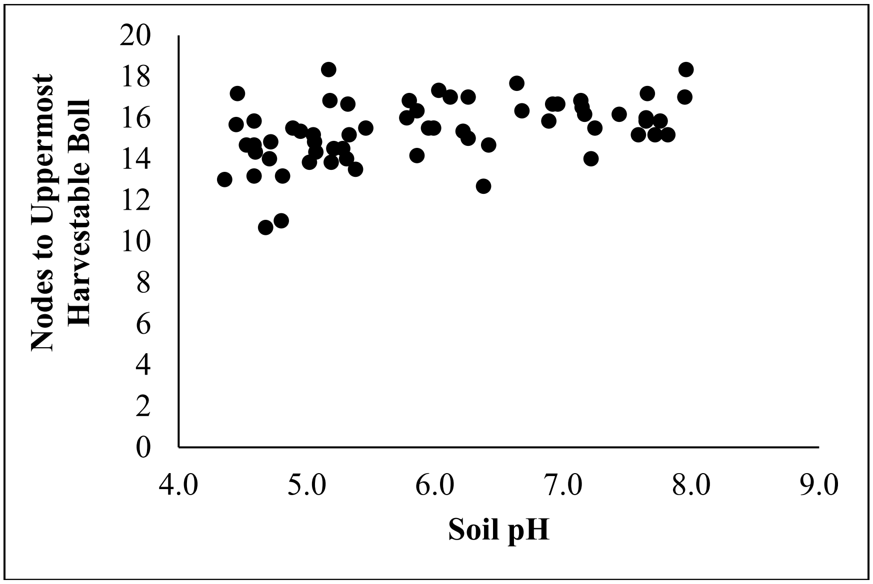


Figure 27. Relationship between soil pH and nodes to uppermost harvestable boll at Efaw.

Perkins 20	**DF**	**MSE**	**F**	**Prob F**	**r^2**
NFFB	2	0.6681	0.12	0.8837	0.01
NUCB	2	7.2645	1.27	0.2938	0.06
NUHB	2	1.4847	0.15	0.8627	0.01
Perkins 19	**DF**	**MSE**	**F**	**Prob F**	**r^2**
NFFB	2	0.7288	1.27	0.2908	0.06
NUCB	2	1.8647	10.23	0.0002	0.33
NUHB	2	2.0440	9.69	0.0003	0.32
EFAW	**DF**	**MSE**	**F**	**Prob F**	**r^2**
NFFB	2	1.5362	2.46	0.0938	0.08
NUCB	2	3.5227	0.77	0.4654	0.03
NUHB	2	1.9118	8.13	0.0008	0.22

Table 24. Evaluation of end of season measurements by location using quadratic least squares regression.

Site/Cultivar	**Relationship**	**MSE**	**F**	**Prob F**	**r^2**
Perkins 2019	NS	-	-	-	-
DP 1612	NS	-	-	-	-
NG 3930	NS	-	-	-	-
Perkins 2020	Quadratic	0.0416	11.18	0.0001	0.36
DP 1612	NS	-	-	-	-
NG 3930	Quadratic	0.0390	11.23	0.0006	0.54
EFAW	NS	-	-	-	-
DP 1612	NS	-	-	-	-
NG 3930	NS	-	-	-	-

Table 25. Relationships between soil pH and percentage of open bolls prior to harvest aid application.

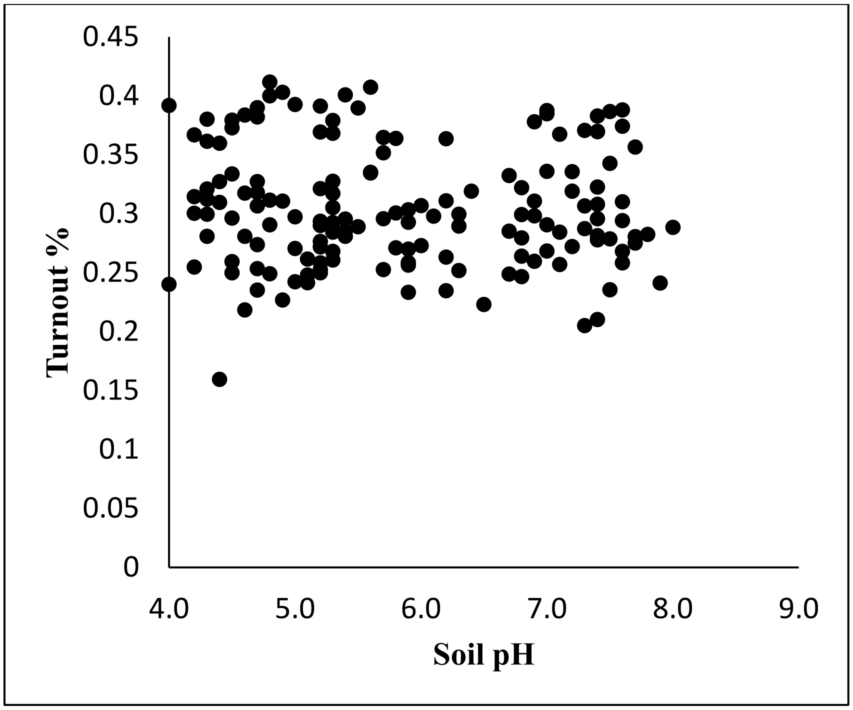


Figure 28. Relationship between lint turnout and soil pH across all sites.

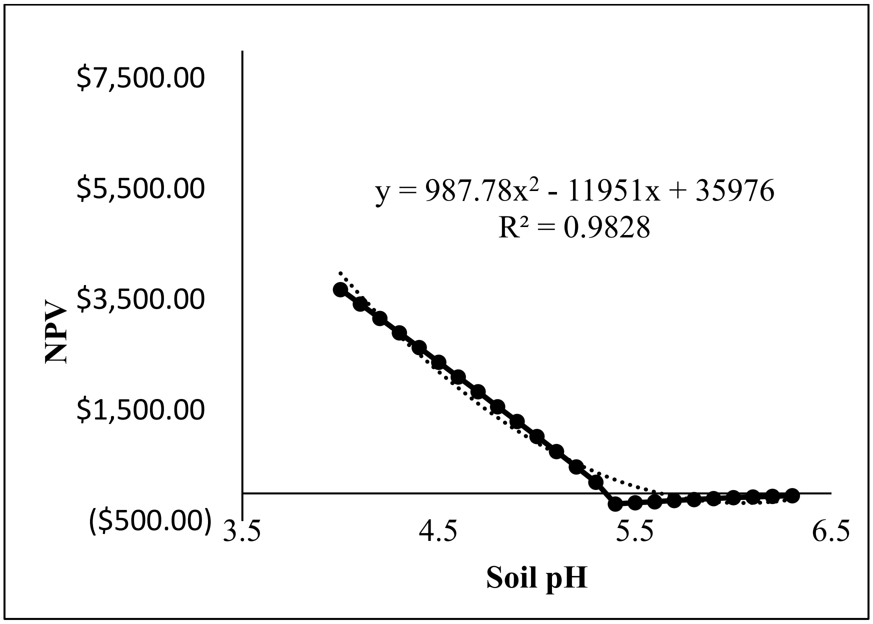


Figure 29. Relationship between soil pH and net present value at Perkins assuming 32 km from quarry at a lint value of \$1.10 kg^{-1} when yield goal is 1600 kg ha^{-1}.

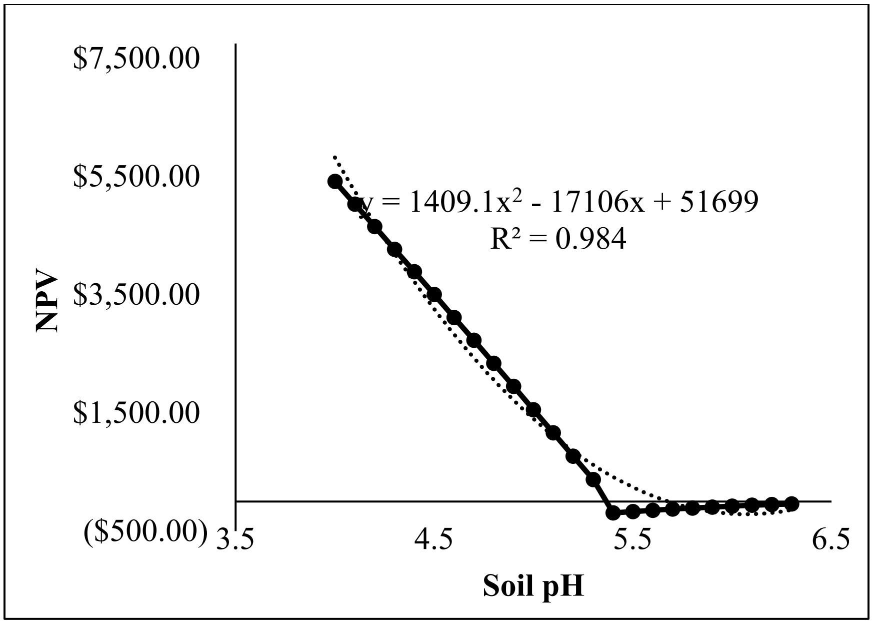


Figure 30. Relationship between soil pH and net present value a Perkins assuming 32 km from quarry at a lint value of \$1.54 km^{-1} when yield goal is 1600 kg ha^{-1}.

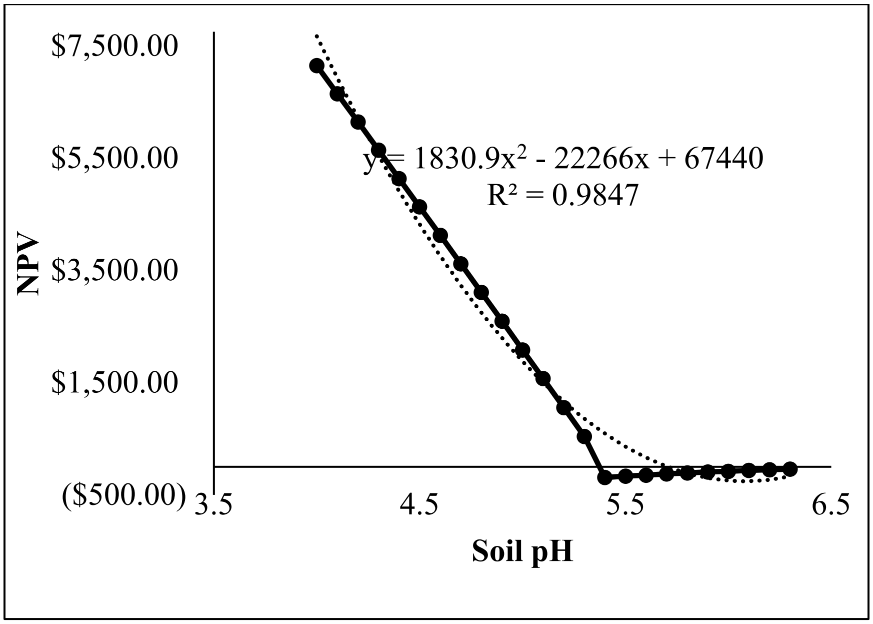


Figure 31. Relationship between soil pH and net present value a Perkins assuming 32 km from quarry at a lint value of \$1.99 kg^{-1} when yield goal is 1600 kg ha^{-1}.

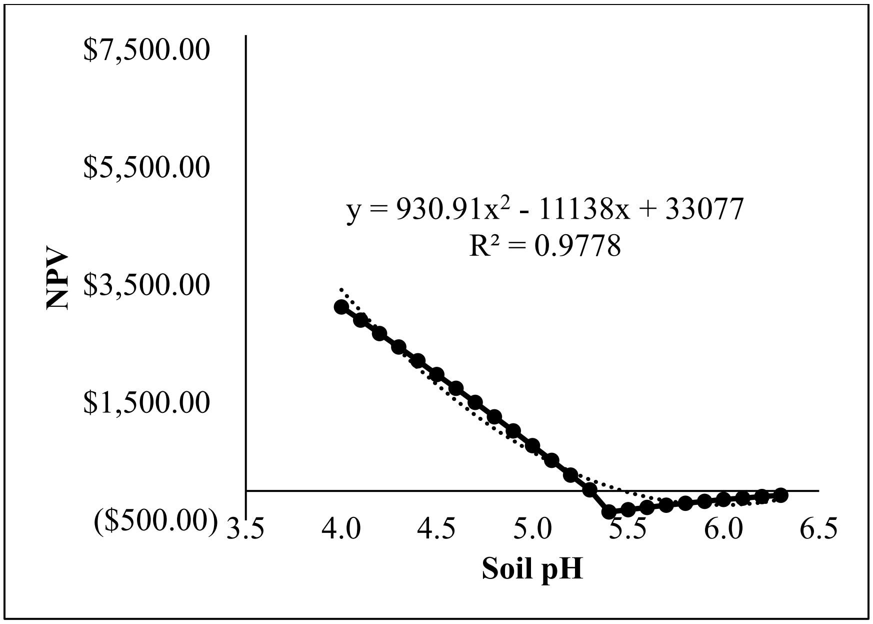


Figure 32. Relationship between soil pH and net present value a Perkins assuming 193 km from quarry at a lint value of \$1.10 kg^{-1} when yield goal is 1600 kg ha^{-1}.

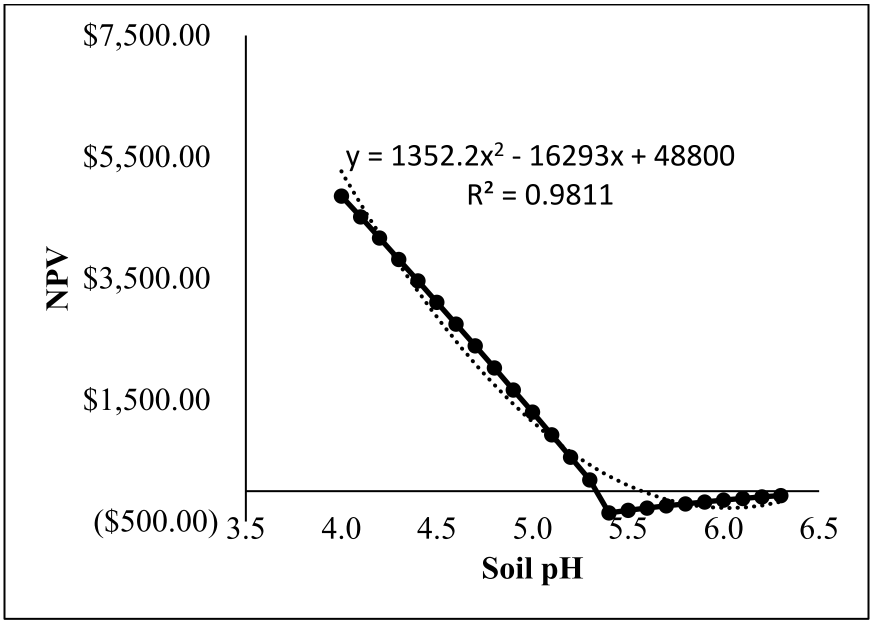


Figure 33. Relationship between soil pH and net present value at Perkins assuming 193 km from quarry at a lint value of \$1.54 kg^{-1} when yield goal is 1600 kg ha^{-1}.

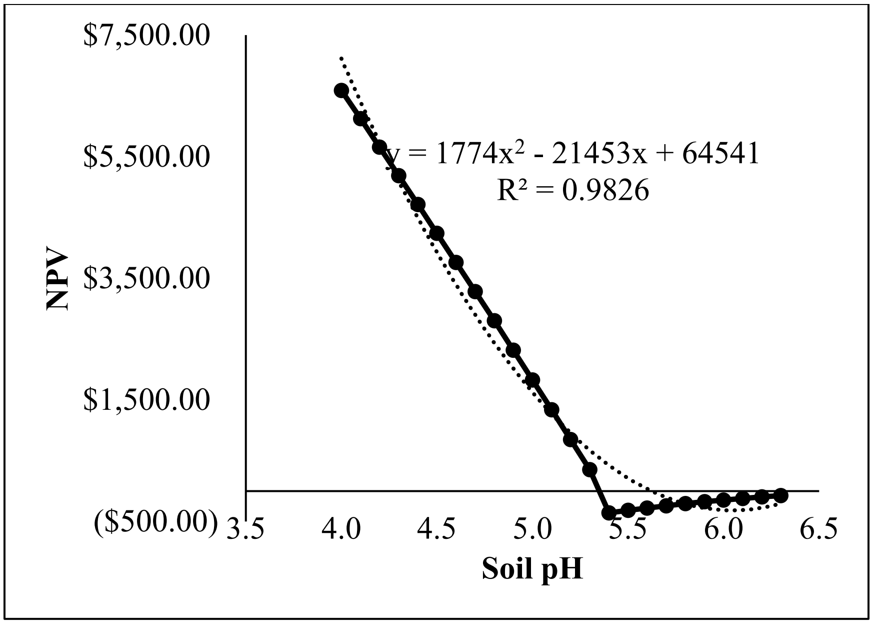


Figure 34. Relationship between soil pH and net present value at Perkins assuming 193 km from quarry at a lint value of \$1.99 kg^{-1} when yield goal is 1600 kg ha^{-1}.

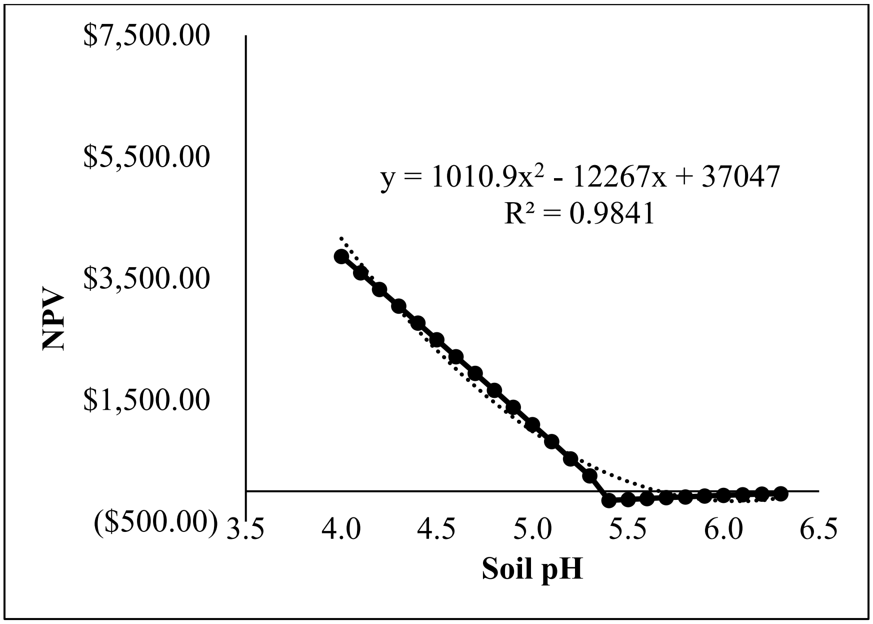


Figure 35. Relationship between soil pH and net present value at EFAW assuming 32 km from quarry at a lint value of \$1.10 kg^{-1} when yield goal is 1600 kg ha^{-1}.

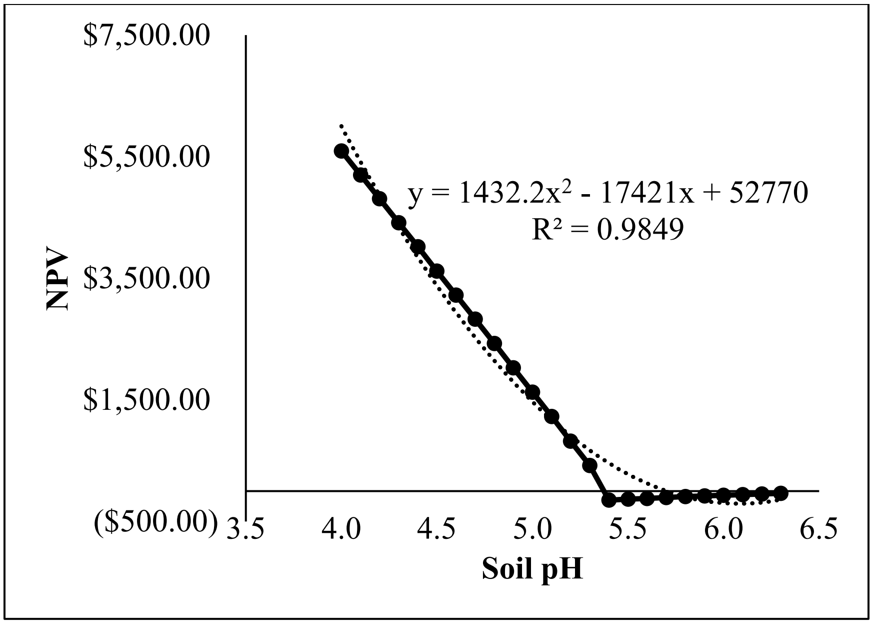


Figure 36. Relationship between soil pH and net present value at EFAW assuming 32 km from quarry at a lint value of \$1.52 kg^{-1} when yield goal is 1600 kg ha^{-1}.

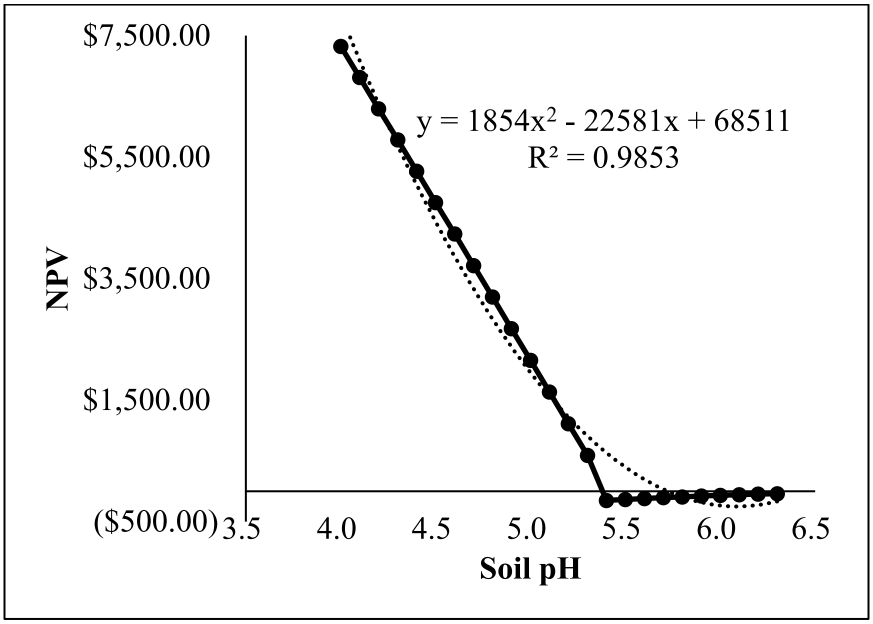


Figure 37. Relationship between soil pH and net present value at EFAW assuming 32 km from quarry at a lint value of \$1.99 kg^{-1} when yield goal is 1600 kg ha^{-1}.

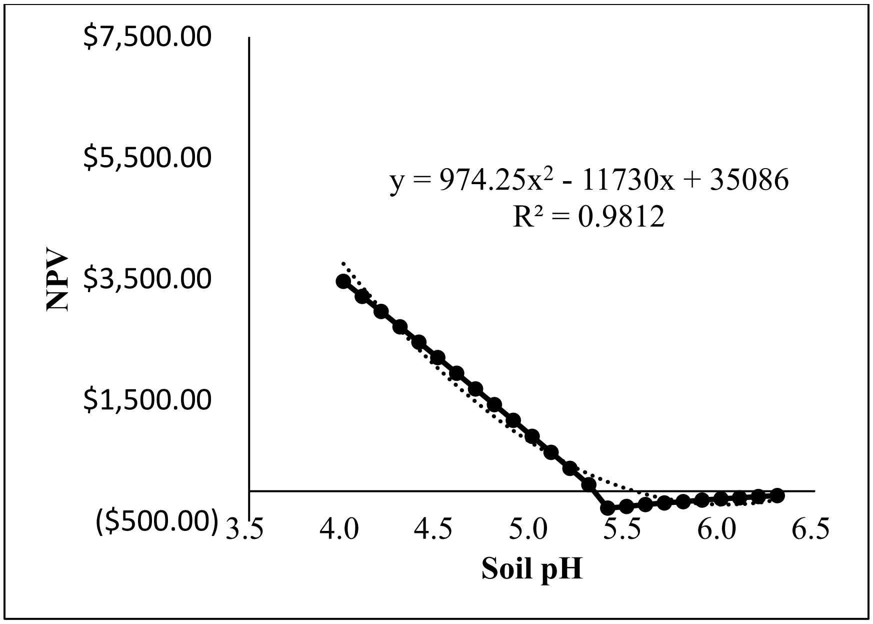


Figure 38. Relationship between soil pH and net present value at EFAW assuming 193 km from quarry at a lint value of \$1.10 kg^{-1} when yield goal is 1600 kg ha^{-1}.

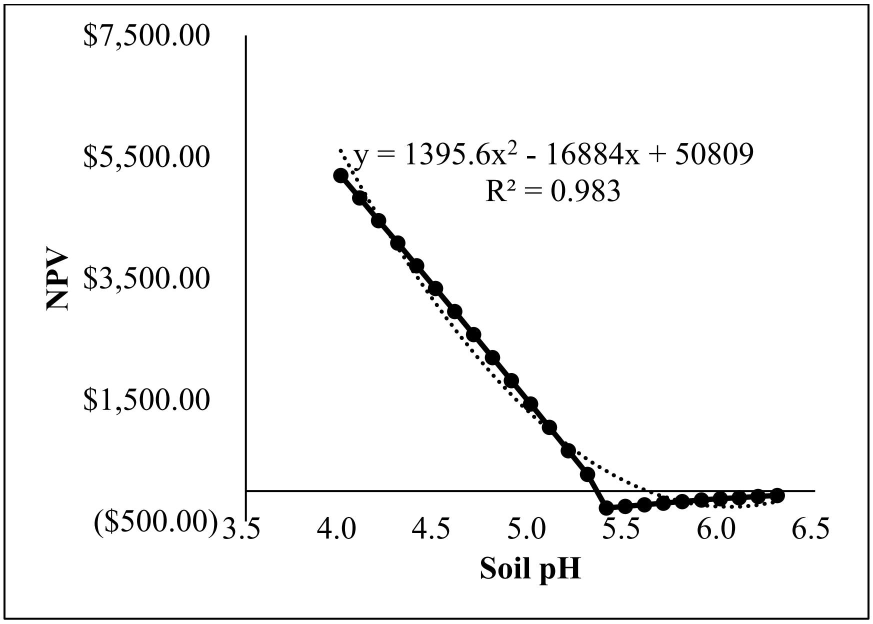


Figure 39. Relationship between soil pH and net present value at EFAW assuming 193 km from quarry at a lint value of \$1.54 kg^{-1} when yield goal is 1600 kg ha^{-1}.

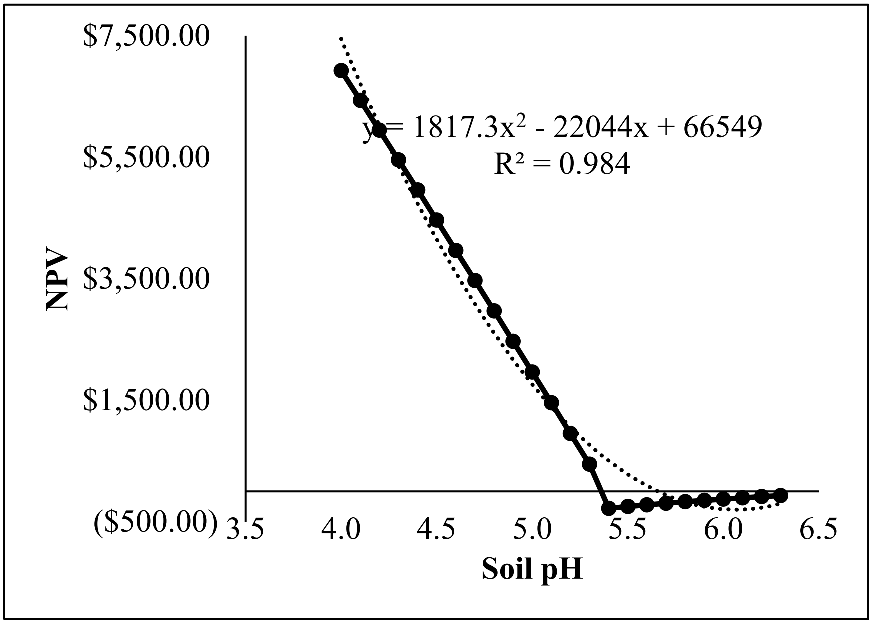


Figure 40. Relationship between soil pH and net present value at EFAW assuming 193 km from quarry at a lint value of \$1.99 kg^{-1} when yield goal is 1600 kg ha^{-1}.

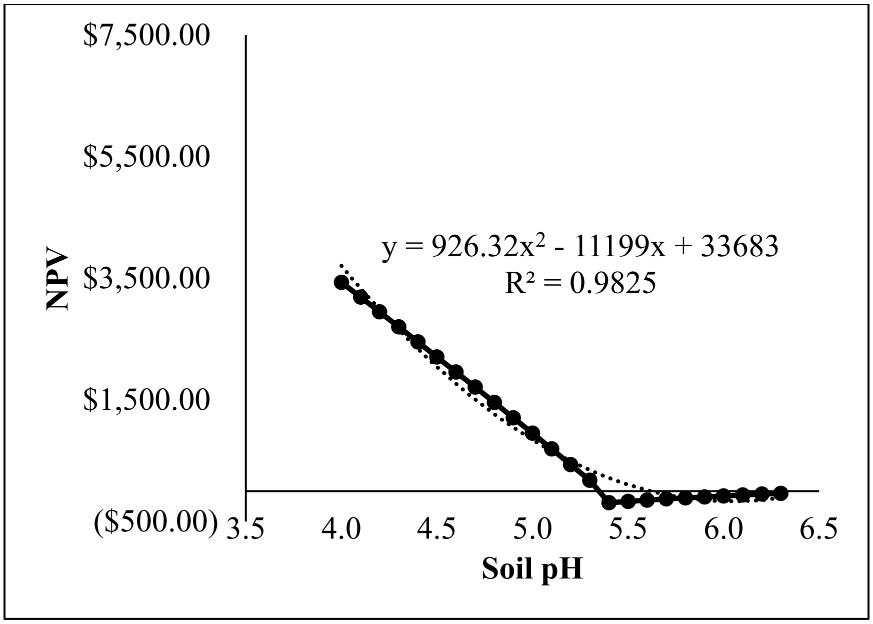


Figure 41. Relationship between soil pH and net present value at Perkins assuming 32 km from quarry at a lint value of \$1.10 kg^{-1} when yield goal is 1076 kg ha^{-1}.

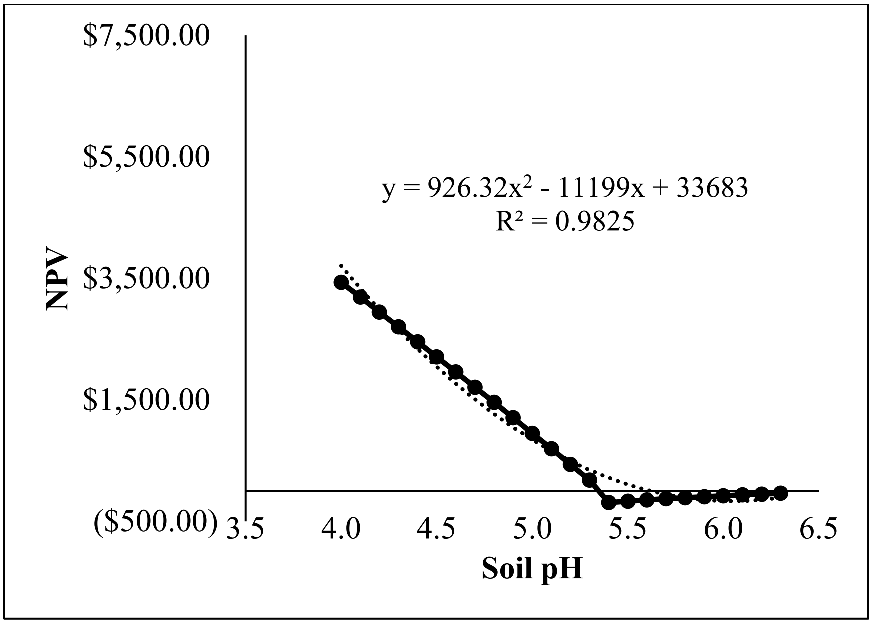


Figure 42. Relationship between soil pH and net present value at Perkins assuming 32 km from quarry at a lint value of \$1.54 kg^{-1} when yield goal is 1076 kg ha^{-1}.

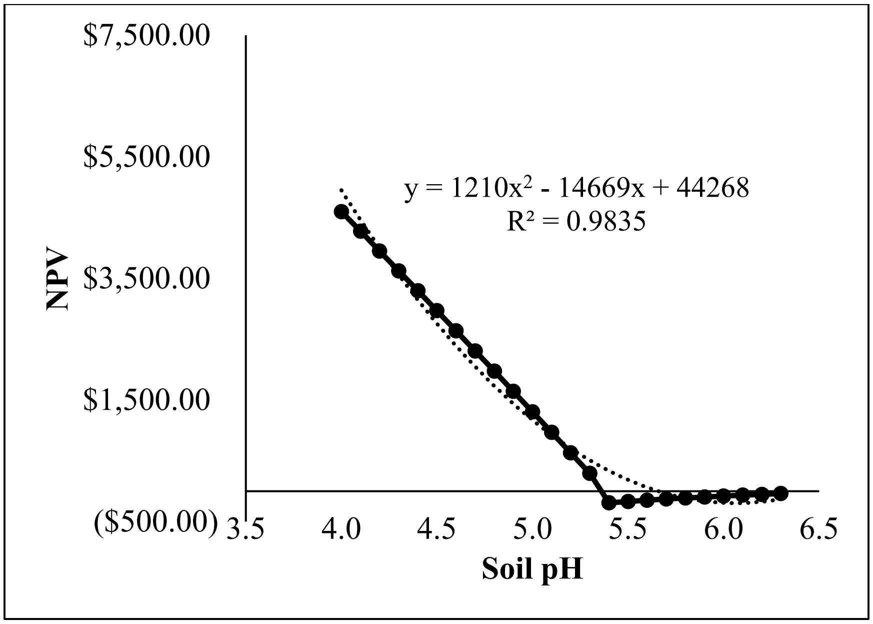


Figure 43. Relationship between soil pH and net present value at Perkins assuming 32 km from quarry at a lint value of \$1.99 kg^{-1} when yield goal is 1076 kg ha^{-1}.

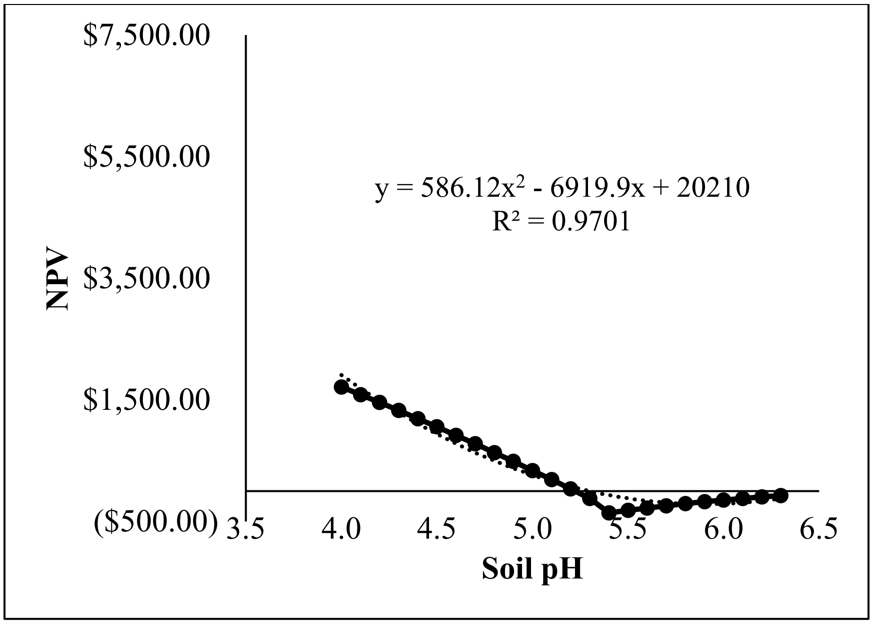


Figure 44. Relationship between soil pH and net present value at Perkins assuming 193 km from quarry at a lint value of \$1.10 kg^{-1} when yield goal is 1076 kg ha^{-1}.

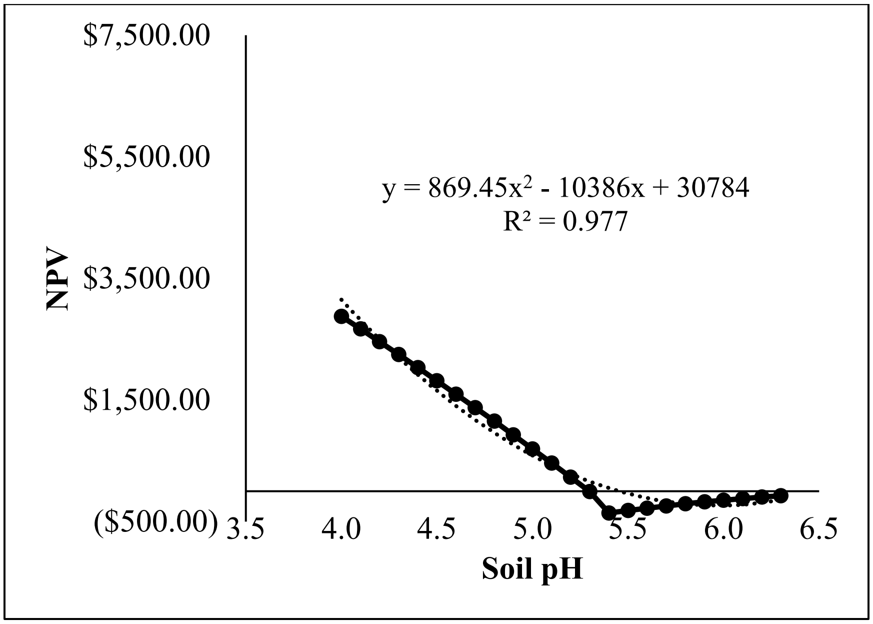


Figure 45. Relationship between soil pH and net present value at Perkins assuming 193 km from quarry at a lint value of \$1.54 kg^{-1} when yield goal is 1076 kg ha^{-1}.

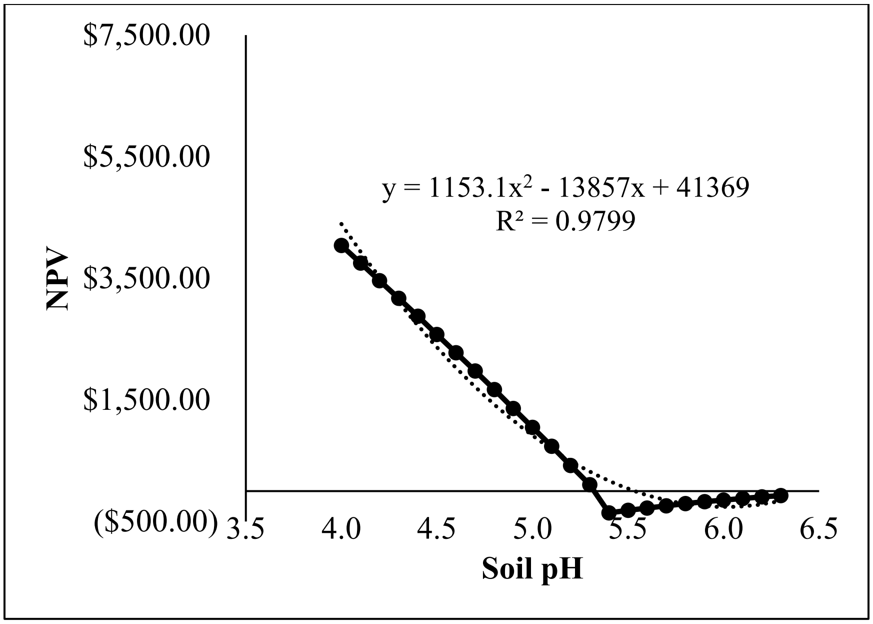


Figure 46. Relationship between soil pH and net present value at Perkins assuming 193 km from quarry at a lint value of $1.99 kg^{-1} when yield goal is 1076 kg ha^{-1}.

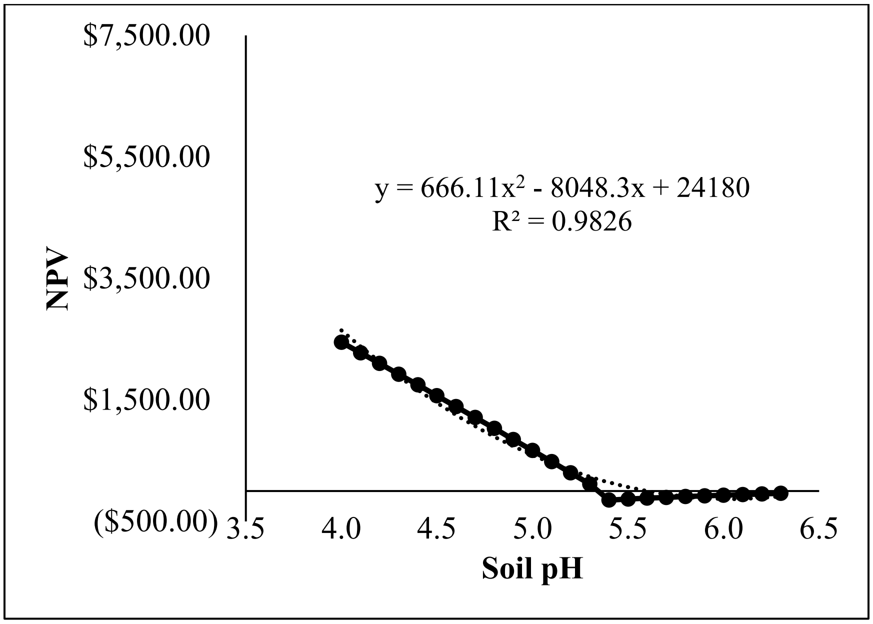


Figure 47. Relationship between soil pH and net present value at EFAW assuming 32 km from quarry at a lint value of $1.10 kg^{-1} when yield goal is 1076 kg ha^{-1}.

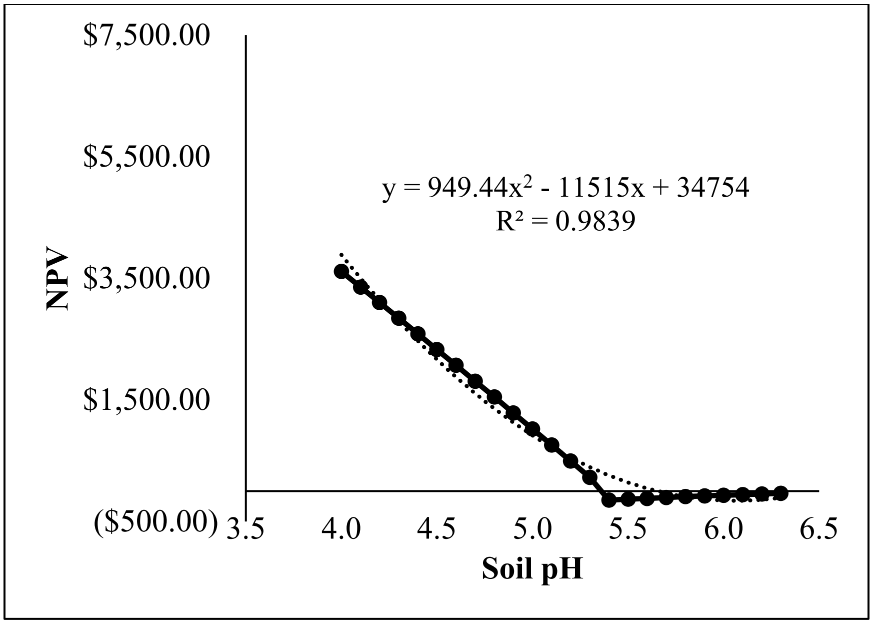


Figure 48. Relationship between soil pH and net present value at EFAW assuming 32 km from quarry at a lint value of \$1.54 kg^{-1} when yield goal is 1076 kg ha^{-1}.

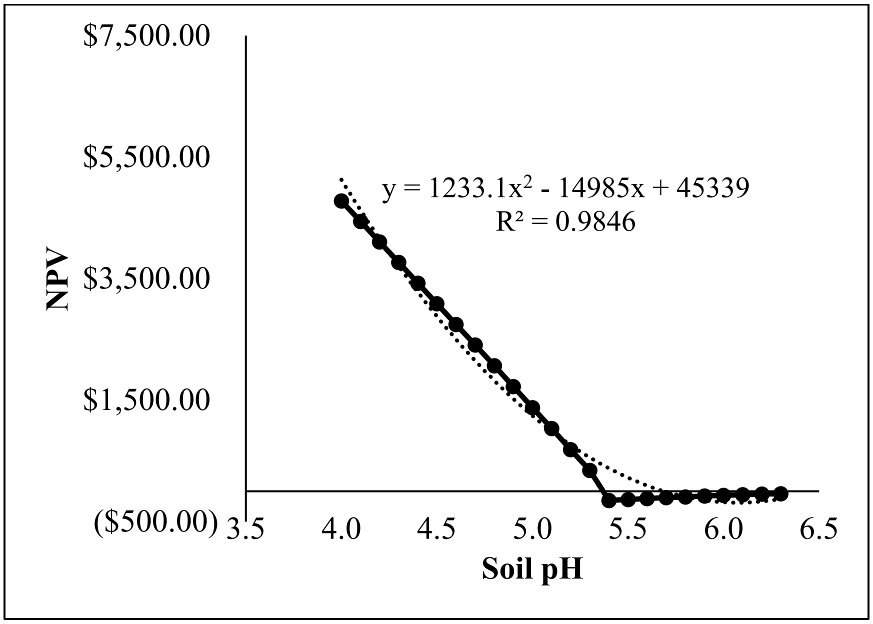


Figure 49. Relationship between soil pH and net present value at EFAW assuming 32 km from quarry at a lint value of \$1.99 kg^{-1} when yield goal is 1076 kg ha^{-1}.

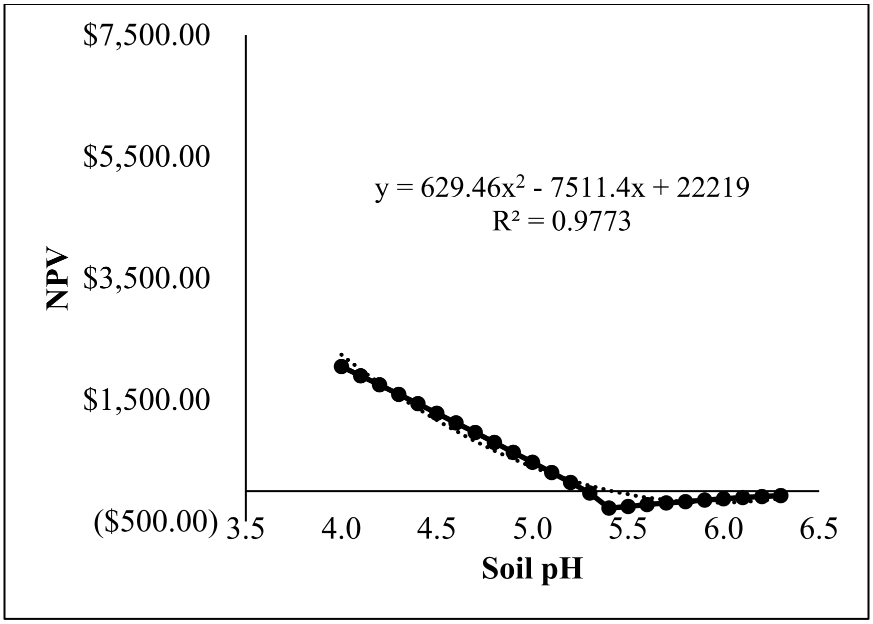


Figure 50. Relationship between soil pH and net present value at EFAW assuming 193 km from quarry at a lint value of $\$1.10$ kg^{-1} when yield goal is 1076 kg ha^{-1}.

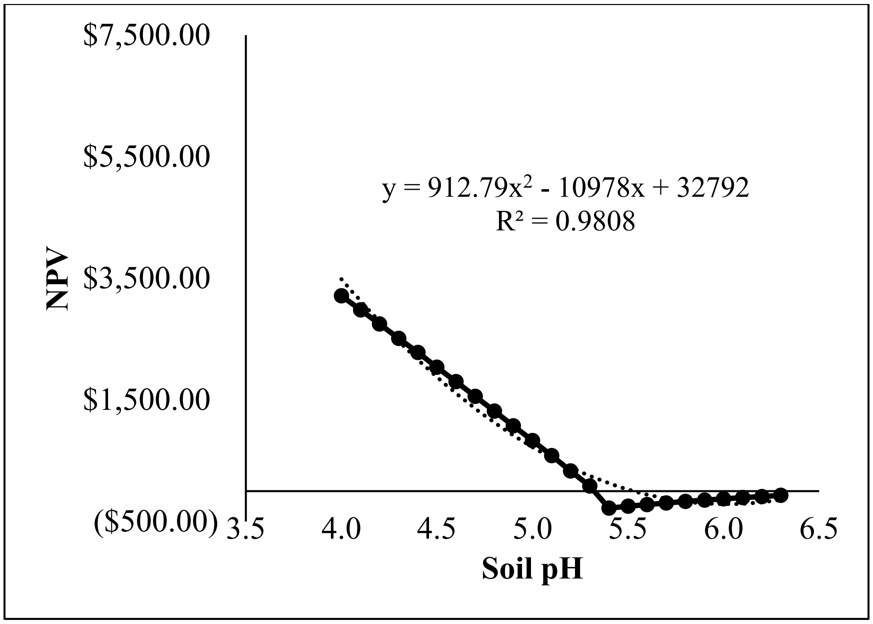


Figure 51. Relationship between soil pH and net present value at EFAW assuming 193 km from quarry at a lint value of $\$1.54$ kg^{-1} when yield goal is 1076 kg ha^{-1}.

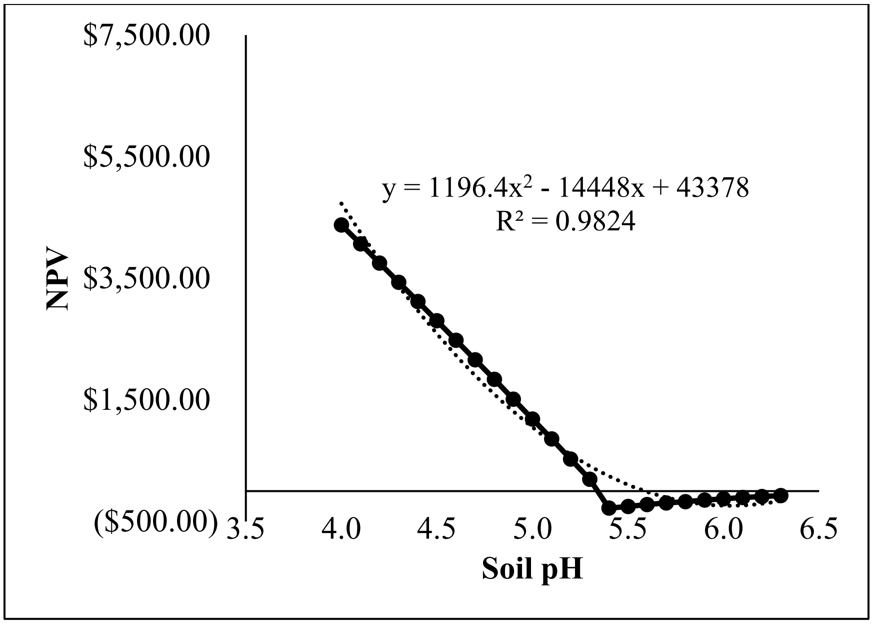


Figure 52. Relationship between soil pH and net present value at EFAW assuming 193 km from quarry at a lint value of \$1.99 kg^{-1} when yield goal is 1076 kg ha^{-1}.

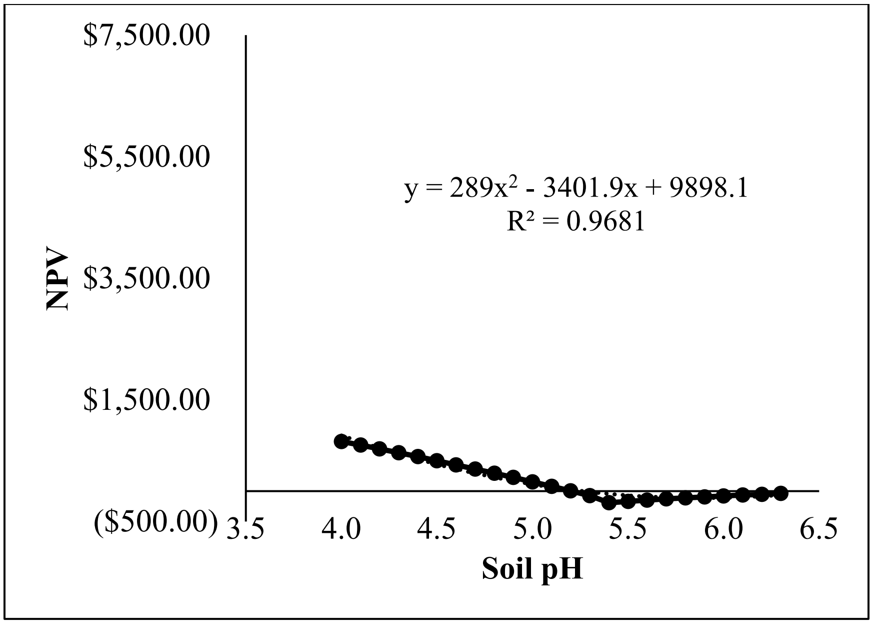


Figure 53. Relationship between soil pH and net present value at Perkins assuming 32 km from quarry at a lint value of \$1.10 kg^{-1} when yield goal is 538 kg ha^{-1}.

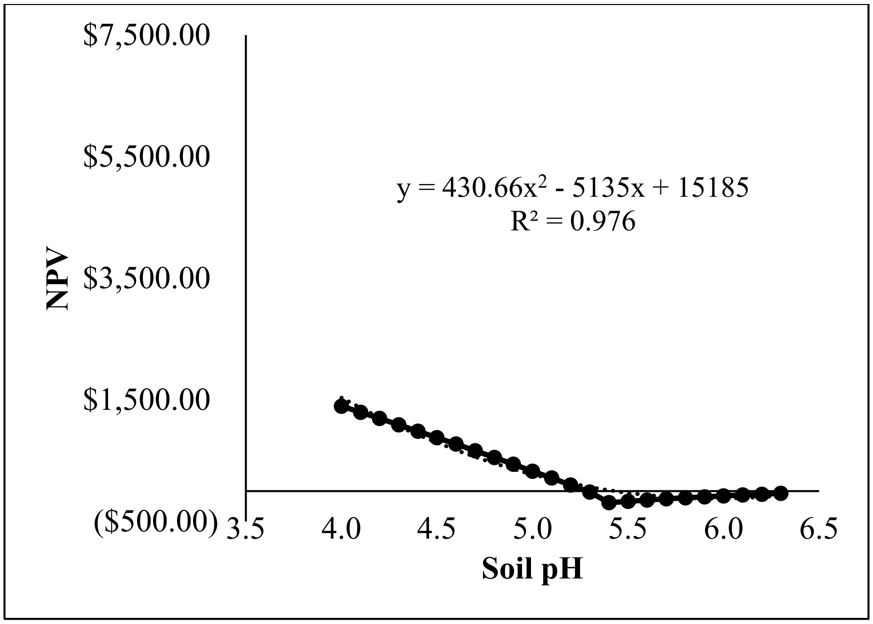


Figure 54. Relationship between soil pH and net present value at Perkins assuming 32 km from quarry at a lint value of \$1.54 kg^{-1} when yield goal is 538 kg ha^{-1}.

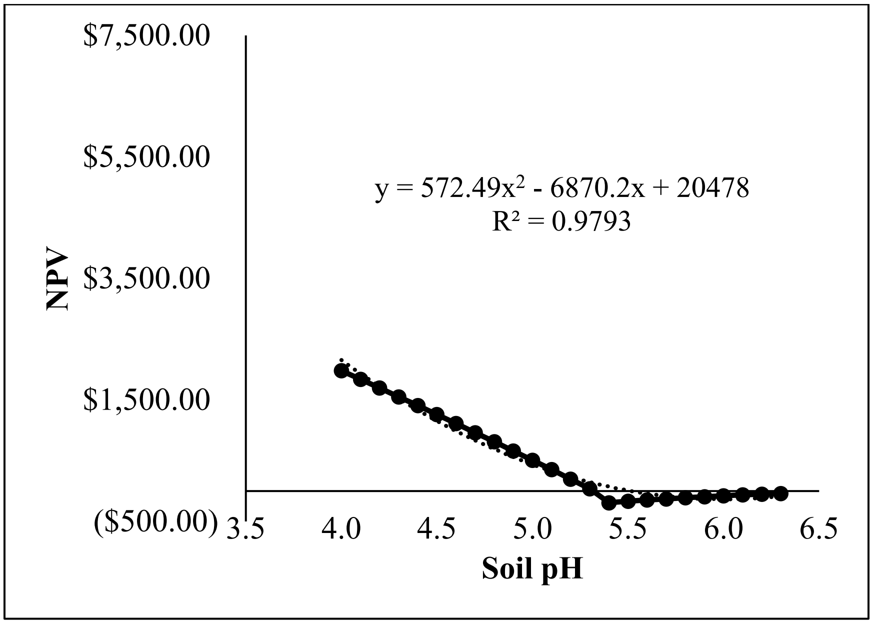


Figure 55. Relationship between soil pH and net present value at Perkins assuming 32 km from quarry at a lint value of \$1.99 kg^{-1} when yield goal is 538 kg ha^{-1}.

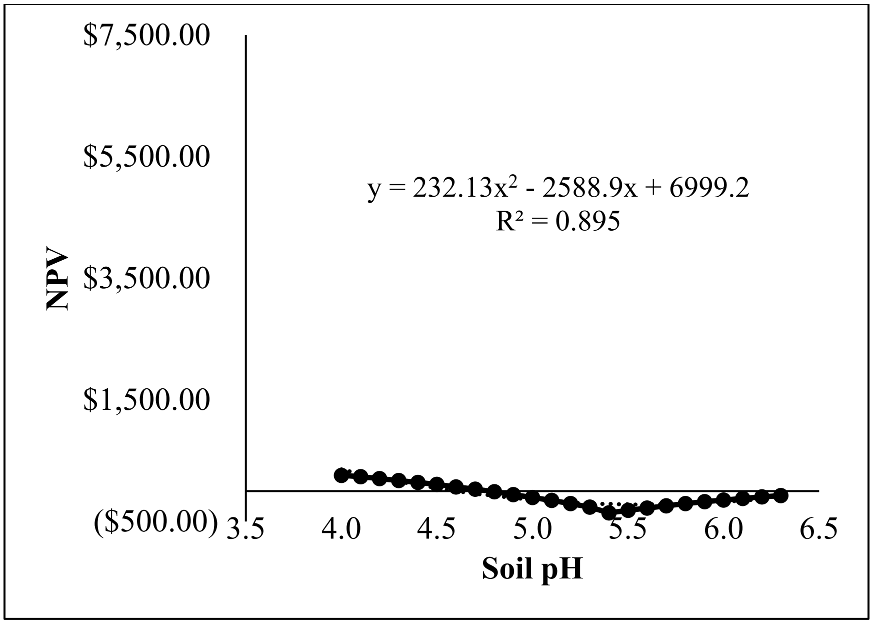


Figure 56. Relationship between soil pH and net present value at Perkins assuming 193 km from quarry at a lint value of \$1.10 kg^{-1} when yield goal is 538 kg ha^{-1}.

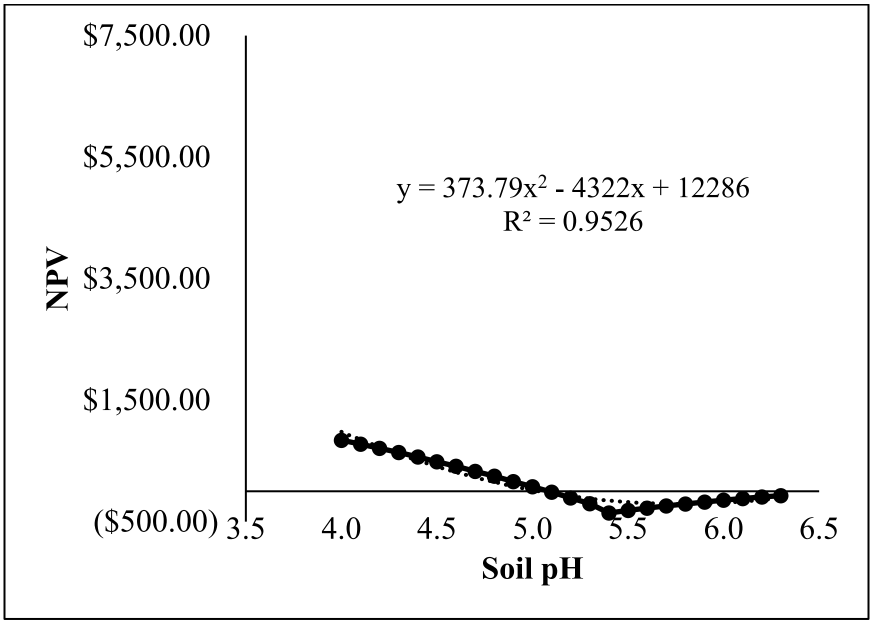


Figure 57. Relationship between soil pH and net present value at Perkins assuming 193 km from quarry at a lint value of \$1.54 kg^{-1} when yield goal is 538 kg ha^{-1}.

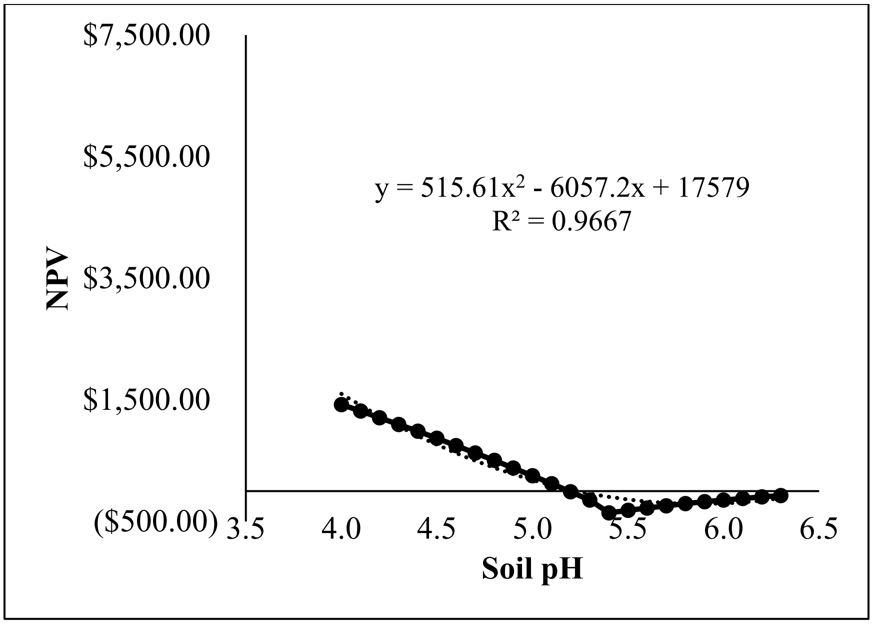


Figure 58. Relationship between soil pH and net present value at Perkins assuming 193 km from quarry at a lint value of \$1.99 kg^{-1} when yield goal is 538 kg ha^{-1}.

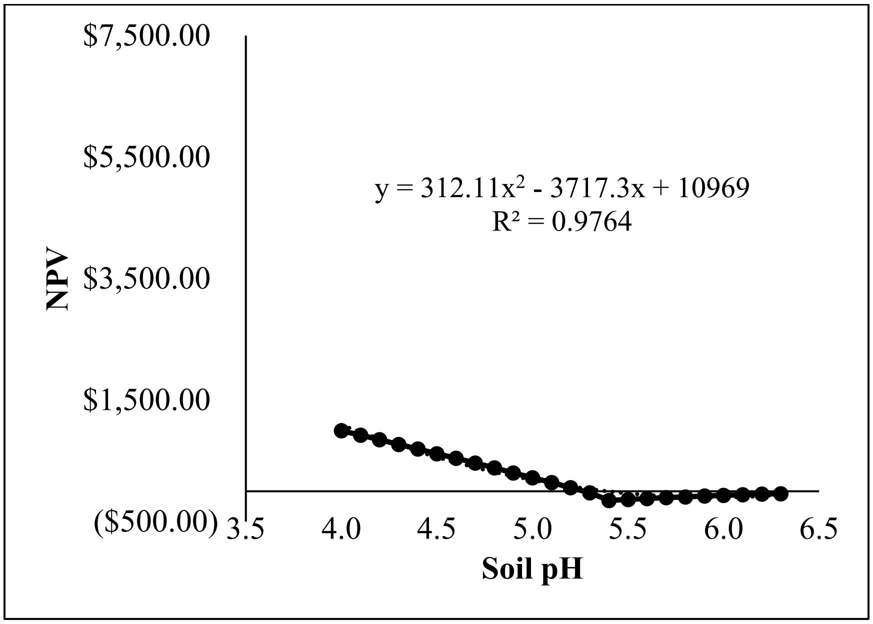


Figure 59. Relationship between soil pH and net present value at EFAW assuming 32 km from quarry at a lint value of \$1.10 kg^{-1} when yield goal is 538 kg ha^{-1}.

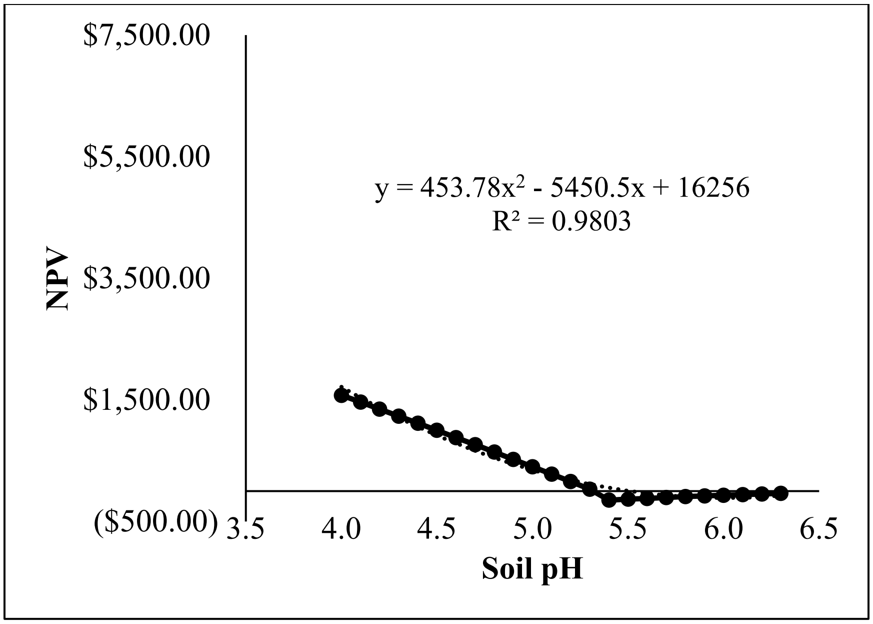


Figure 60. Relationship between soil pH and net present value at EFAW assuming 32 km from quarry at a lint value of $1.54 kg^{-1} when yield goal is 538 kg ha^{-1}.

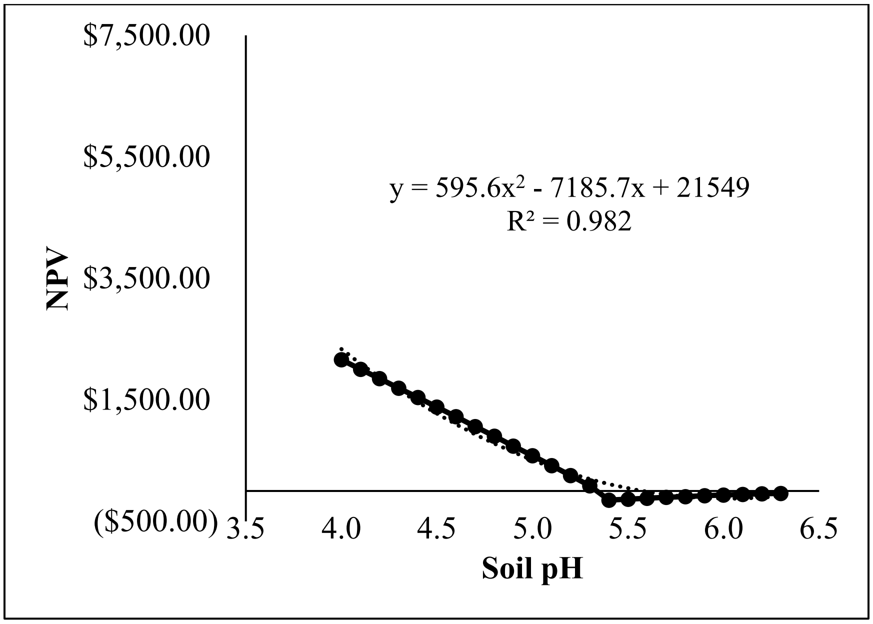


Figure 61. Relationship between soil pH and net present value at EFAW assuming 32 km from quarry at a lint value of $1.99 kg^{-1} when yield goal is 538 kg ha^{-1}.

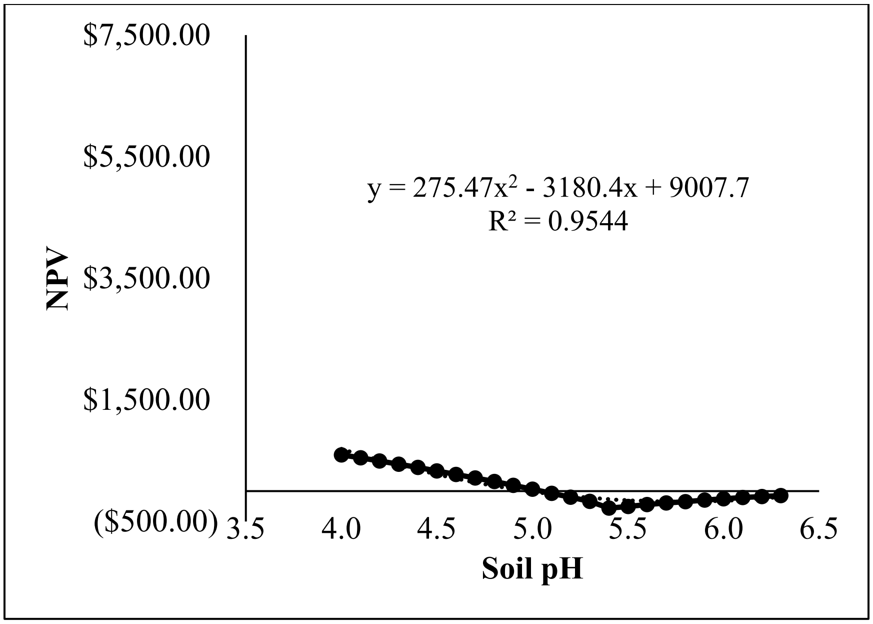


Figure 62. Relationship between soil pH and net present value at EFAW assuming 193 km from quarry at a lint value of \$1.10 kg^{-1} when yield goal is 538 kg ha^{-1}.

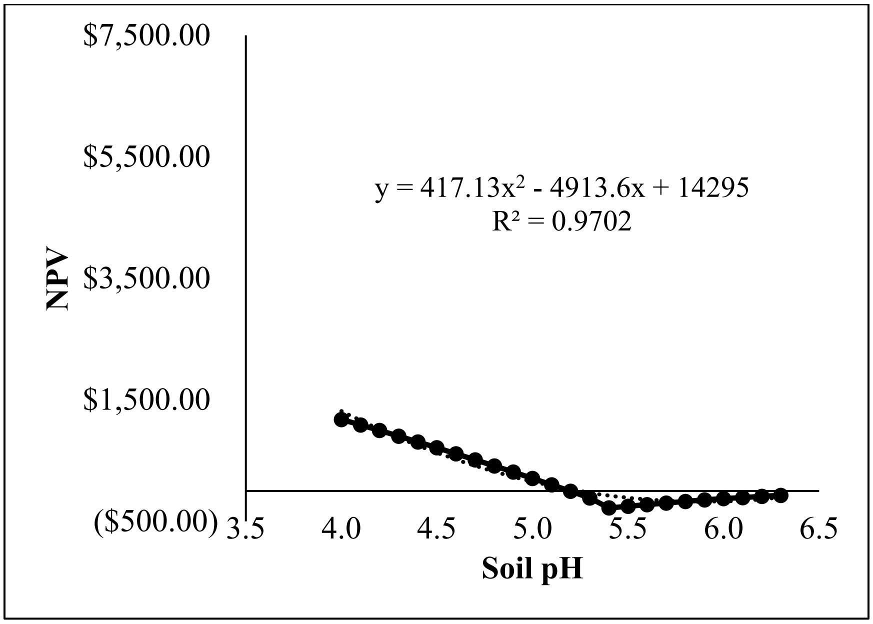


Figure 63. Relationship between soil pH and net present value at EFAW assuming 193 km from quarry at a lint value of \$1.54 kg^{-1} when yield goal is 538 kg ha^{-1}.

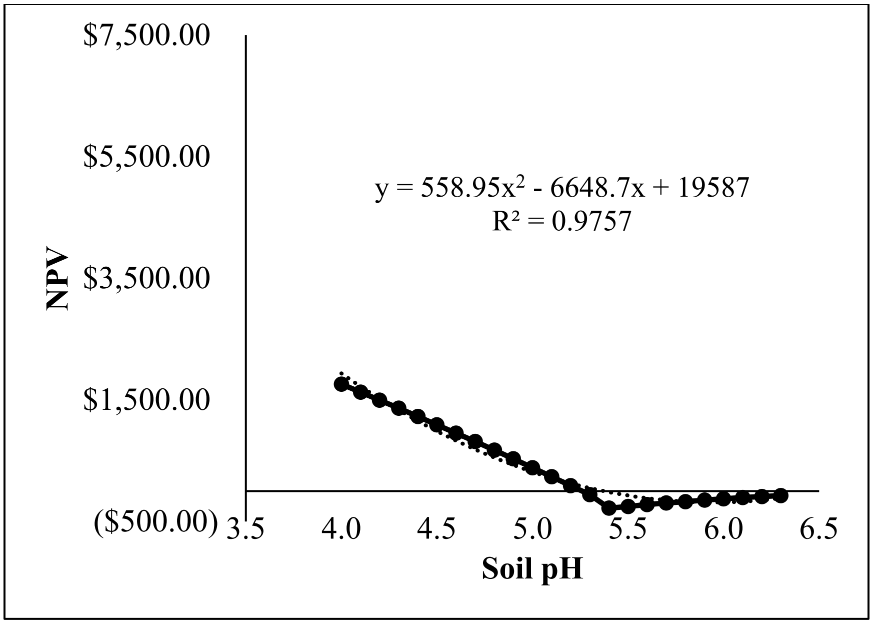


Figure 64. Relationship between soil pH and net present value at EFAW assuming 193 km from quarry at a lint value of \$1.99 kg^{-1} when yield goal is 538 kg ha^{-1}.

VITA

Raedan Lane Sharry

Candidate for the Degree of

Master of Science

Thesis: INFLUENCE OF SOIL pH ON COTTON MORPHOLOGY, LINT YIELD AND LINT QUALITY

Major Field: Plant and Soil Science

Biographical:

Education:

Completed the requirements for the Master of Science in Plant and Soil Science at Oklahoma State University, Stillwater, Oklahoma in July, 2021.

Completed the requirements for the Bachelor of Science in Agricultural Economics at Oklahoma State University, Stillwater, Oklahoma in 2019.

Experience:

Undergraduate Research Assistant
Graduate Research Assistant

Professional Memberships:

American Society of Agronomy
Soil Science Society of America
Crop Science Society of America