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Impact of a New Deep Vertical Lime Placement Practice on Corn and Soybean Production in Conservation Tillage Systems

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Abstract: Agricultural soils utilized for corn (*Zea mays* L.) and soybean (*Glycine max* [L.] Merr.) production in the Midwestern U.S. are often managed to have adequate surface soil pH for crop growth, but the presence of acidic subsoils may limit crop production. Subsoil acidity may inhibit root growth, leading to decreased drought tolerance and grain yields. Application of aglime can increase soil pH, improve soil structure, and provide calcium and magnesium to the soil, but surface amendments that often occur in no-till systems rarely affect the subsoil, resulting in potential chemical and physical barriers to root growth. The objective of this study was to determine the effects of surface and a new deep vertical lime placement practice, at three application rates, on corn and soybean plant growth and yields in a conservation tillage system. Field trials were conducted from 2012 to 2016 in Northeast Missouri on a poorly-drained claypan soil with treatments of lime (0, 3.4, and 6.7 Mg ha^{-1}) broadcast on the soil surface or applied as a deep vertical band to a depth of 51 cm. When precipitation was below average, compared to control plots, deep vertical placed lime at 6.7 Mg ha^{-1} significantly raised corn yields by 1.3 Mg ha^{-1} four years after treatment. In years with adequate precipitation, no significant increases in corn yield were observed with deep lime placement treatments compared to the control. Lime treatments had a greater effect on corn yield than soybean. Deep vertical placement of lime resulted in no significant increase in soybean yield compared to the controls for all trials. Longer observation time may be needed to fully evaluate the effects of these lime placement treatments.

Keywords: subsoil acidity; lime; deep vertical placement; conservation tillage; grain yield

1. Introduction

Effects of subsoil acidity on agronomic production is of great concern in multiple regions around the world [1–6], with roughly 70% of the world's arable land having some level of soil acidity [7]. Acidic conditions in the subsoil horizons have been shown to affect nutrient availability and root growth of many agronomic crops [2,8,9]. Furthermore, soils under intense cropping systems may have substantial increases in subsoil acidity with depth [10,11].

Amendments of agriculture limestone have the ability to alleviate soil acidity [1–6,12,13]. Liming additions have been shown to increase grain yields of many crops through increased rooting systems, nutrient availability and uptake, drought resistance, and reduction of aluminum and manganese toxicities [1,4,5,14]. In the United States alone, it is estimated that roughly 73 million Mg of agricultural lime is required each year to neutralize acidity generated from crop removal [15]. However, it is estimated that under current management practices in the United States, only around 20 to 30 Mg of agriculture lime is applied each year, making up a fraction of the required recommendation [16].

Issues associated with surface and subsoil acidity are of increasing concern as rising global population pressures producers to cultivate more food on less land area, which increases the potential of soil acidity.

Conventional applications of lime have generally been restricted primarily to surface amendments, followed by shallow conventional tillage. Surface-applied lime is shown to effectively alleviate soil acidity, but is generally restricted to the plow layer [17–19]. Previous research has shown that soil acidity can be successfully reduced at lower depths by simply increasing the plowing depth. Doss et al. [20] found an increase in subsoil pH when incorporating treatments of lime through rotary tillage up to 45 cm. Treatments of lime increased rooting depth, plant height, and grain yield for corn [20]. Sumner et al. [1] found a 50% increase in alfalfa (*Medicago sativa* L.) yields when lime was incorporated with a moldboard plow to a 1 m depth over a 4-year period. However, effects from soil mixing alone significantly decreased yields.

Although conventional tillage has been a primary practice in agriculture for over 3000 years [21], recent developments in agricultural technology and concerns over soil erosion and degradation of soil structure caused by conventional tillage have begun to shift the average farmer in the United States towards no-till and conservation tillage practices. Soils maintained under no-till conditions have shown increases in soil aggregation and aggregate stability, as well as increases in soil organic carbon [22]. However, due to the slow downward movement of lime, the use of no-till or conservation tillage practices has caused difficulty in effectively reaching subsoil horizons with current liming practices [23].

A study to evaluate recently acidified soils under no-till production, applied limestone at amounts up to 10 Mg ha^{-1}, found little to no effects on subsoil pH 5 cm below the surface [24]. Furthermore, lime treatments generally did not have an effect on corn grain yield. However, plant calcium uptake increased significantly while manganese uptake decreased.

In order to effectively reduce subsoil acidity under no-till and conservation tillage practices, lime amendments must be directly applied to the subsoil. Farina and Channon [18] evaluated various methods of subsoil amelioration, which involved directly injecting lime into the subsoil at depths up to 70 cm. A long-term study of lime treatments [4,5] found beneficial effects of these treatments up to 10 years after application. However, the majority of research on deep placement of lime has occurred on highly weathered soils in tropical regions. There has been little research investigating the effects of deep lime placement on less weathered, but equally acidic soils. To our knowledge, no research has been conducted on the effects of deep lime vertical placement on yield response of corn and soybean for poorly-drained claypan soils, which have subsoil restrictions for root growth and downward movement of water.

The objective of this research was to evaluate the initial and residual impacts of a novel lime placement practice at differing application rates on corn and soybean plant growth and grain yields in a conservation tillage system.

2. Materials and Methods

2.1. Site Description and Experimental Design

Three field trials were established over the course of 2012 to 2014 at the Greenley Memorial Research Center (40°02′ N, 92°20′ W) near Novelty, MO (USA). Field Trials #1 and #3 were established in the spring of 2012 and the fall of 2013 on a Putnam silt loam (fine, smectitic, mesic Vertic Albaqualfs). Field Trial #2 was established in the fall of 2012 on a Kilwinning silt loam (fine, smectitic, mesic, Vertic Epiaqualfs). Initiating the lime application in different years allowed for a determination of the effects of differences in climate on crop response for the initial and residual years. All the field trials were conducted on separate field sites in close proximity to each other. Prior to the study, the experimental sites were under continuous no-till production for over 13 years. Sites with acidic surface and subsoil horizons were utilized for this experiment. Initial soil characteristics were taken at the establishment of each trial and are presented in Table 1.

Table 1. Initial average soil characteristics (±standard deviation) at different depths for the Trial #1, #2 and #3 established in 2012, 2013, and 2014, respectively.

	Soil Depth			
Soil Characteristics	**0–13 cm**	**13–25 cm**	**25–38 cm**	**38–51 cm**
Trial #1				
pH_s (0.01 *M* $CaCl_2$)	5.6 ± 0.2	5.6 ± 0.4	4.6 ± 0.2	4.6 ± 0.2
Neutralizable acidity ($cmol_c$ kg^{-1})	3.5 ± 2	2.9 ± 1	8.5 ± 1.6	6.8 ± 1.0
Organic matter (% w/w)	2.7 ± 0.3	2.3 ± 0.1	2.3 ± 0.3	2.2 ± 0.2
Bray 1P (kg ha^{-1})	17.4 ± 9.8	5.0 ± 1.4	3.9 ± 1.9	14.6 ± 4.5
Ca (kg ha^{-1})	4427 ± 347	5200 ± 661	5257 ± 706	4988 ± 673
Mg (kg ha^{-1})	494 ± 98	689 ± 189	981 ±138	996 ± 158
K (kg ha^{-1})	178 ± 12	173 ± 28	226 ± 32	231 ± 16
CEC ($cmol_c$ kg^{-1})	15.4 ± 2.3	17.3 ± 3.2	24.2 ± 3.2	22.0 ± 2.3
Trial #2				
pH_s (0.01 *M* $CaCl_2$)	5.0 ± 0.1	5.0 ± 0.5	4.9 ± 0.7	4.9 ± 0.8
Neutralizable acidity ($cmol_c$ kg^{-1})	5.1 ± 0.5	4.9 ± 1.9	6.9 ± 4.0	6.8 ± 3.8
Organic matter (% w/w)	3.0 ± 0.6	1.9 ± 0.4	1.8 ± 0.3	1.4 ± 0.4
Bray 1P (kg ha^{-1})	127.2 ± 46.2	19.1 ± 10.7	11.5 ± 4.0	30.8 ± 19.4
Ca (kg ha^{-1})	2841 ± 312	3263 ± 690	4138 ± 1828	4144 ± 1678
Mg (kg ha^{-1})	307 ± 91	415 ± 192	739 ± 452	848 ± 420
K (kg ha^{-1})	594 ± 240	159 ± 47	179 ± 77	233 ± 85
CEC ($cmol_c$ kg^{-1})	13.3 ± 1.4	13.9 ± 3.3	19.1 ± 6.4	19.4 ± 4.8
Trial #3				
pH_s (0.01 *M* $CaCl_2$)	6.1 ± 0.1	6.2 ± 0.1	5.0 ± 0.2	4.6 ± 0.1
Neutralizable acidity ($cmol_c$ kg^{-1})	1.8 ± 0.5	1.9 ± 0.3	7.1 ± 1.9	12.3 ± 1.9
Organic matter (% w/w)	2.3 ± 0.5	2.1 ± 0.2	2.3 ± 0.4	2.7 ± 0.3
Bray 1P (kg ha^{-1})	10.4 ± 4.7	5.6 ± 2.2	2.0 ± 0.6	1.1 ± 0
Ca (kg ha^{-1})	3954 ± 957	3646 ± 289	4497 ± 434	5223 ± 384
Mg (kg ha^{-1})	398 ± 158	377 ± 58	749 ± 142	1226 ± 80
K (kg ha^{-1})	154 ± 30	136 ± 12	220 ± 36	349 ± 28
CEC ($cmol_c$ kg^{-1})	12.2 ± 3.2	11.6 ± 0.8	20.2 ± 3.2	28.9 ± 2.7

A randomized complete block design was used for the three field trials with 12 treatments replicated four times. Plot sizes were 4.6 × 24.4 m for trials #1 and #3, and 4.6 × 22.9 m for trial #2. A factorial arrangement of treatments included two crops, two placement methods, and three lime application rates (0, 3.4, and 6.7 Mg ha^{-1}). The crops evaluated in this experiment were corn and soybean planted in rotation for subsequent years. Methods of placement included a surface broadcasted or a deep banding incorporation of calcitic pelletized lime at four depths (0–13, 13–25, 25–38, and 38–51 cm) simultaneously. Depths were selected to be similar to past literature [2,4,5]. For mechanical application purposes, pelletized lime was used instead of the fine powder form commonly utilized for agriculture lime applications.

Deep banding was accomplished using a conservation subsoiler (Case IH Ecolo-Til® 2500, Goodfield, IL, USA) with a newly developed custom built shank attachment (Nelson, K.A., Univ. of Missouri, Novelty, MO, USA) designed to deliver lime at desired depths (Figure 1). Lime application rates were selected based on the average subsoil recommendation (6.7 Mg ha^{-1}), and the average top 15 cm of soil recommendation (3.4 Mg ha^{-1}). The limestone source was comprised of pelletized lime (Kelly's Pelletized Lime, Kirksville, MO, USA) derived from quarried calcitic limestone containing 36.4% Ca and 1% Mg with a calcium carbonate equivalence (CCE) of 90.7%, and an effective neutralizing material (ENM) of 300 kg ENM Mg^{-1}. The concept and calculations for ENM are provided in Buchholz et al. [25]. Particle size distribution of the liming material before pelletizing consisted of 99.9% passing through a 2.36 mm mesh sieve, 97.0% passing through a 0.841 mm mesh sieve, 88.0% passing through a 0.420 mm mesh sieve, 63.0% passing through a 0.297 mm mesh sieve, and 61.0% passing through a 0.250 mm mesh sieve. A 2% lignosulfonate material was added as the binding agent for pelletization.

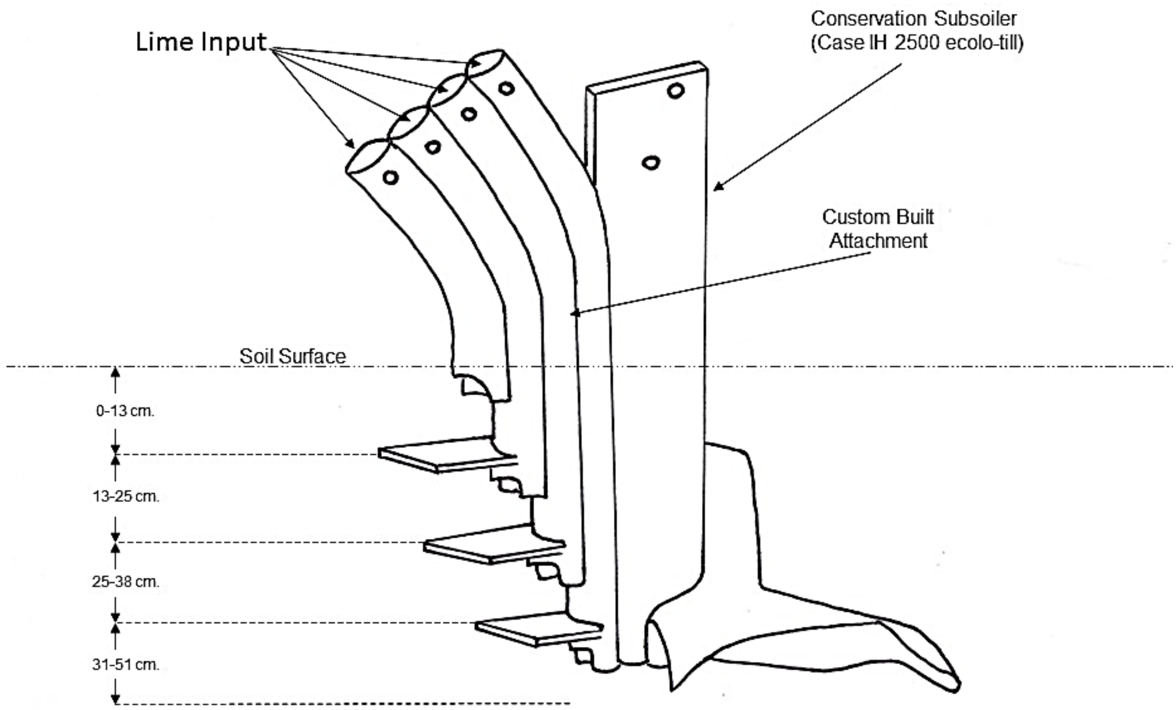

Figure 1. Custom built shank attachment schematics showing the depths at which lime was placed in the soil in relation to the soil surface.

Lime treatments were applied using a commercial Montag dry fertilizer air delivery system (Emmetsburg, IA, USA). Conservation zone tillage knives were spaced 76 cm apart, congruent with standard corn row spacing. Greater soil disturbance from vertical lime placement was observed compared to normal conservation vertical tillage. Surface tillage with a Tilloll 875 (Landoll Corp., Marysville, KS, USA) followed deep vertical placement treatments to smooth the soil surface prior to planting; however, no additional tillage was performed the following years after application of treatments. Uniform broadcast surface applications were achieved by running a conservation tiller with custom shank above the soil surface to ensure consistency. Strips of corn or soybean were randomly assigned at trial establishment, and rotated for subsequent years. Each crop strip was randomly divided into two additional strips of surface-applied and deep vertical placement lime. Deep vertical placement and surface-applied strips were then divided into plots of varying rates of lime, resulting in a split–split plot design.

2.2. Field Management

In the spring of 2012, lime treatments were applied to Trial #1 followed by planting of corn and soybean. In the fall 2012, lime treatments were applied to Trial #2 with planting of corn and soybean the following spring of 2013 for Trials #1 and #2. In the fall of 2013, lime treatments for Trial #3 were applied with corn and soybean planted the following spring of 2014 for Trials #1, #2, and #3. Corn was planted in each trial in 76 cm wide rows at 72,140 seeds ha^{-1}. Plot size for corn was 4.6 by 22.9 to 24.4 m. All corn trials from 2012 to 2016 received recommended N fertilizer rates for corn production in Missouri of 135 to 235 kg N ha^{-1} as either broadcast urea or polymer-coated urea (ESN, Agrium, Loveland, CO, USA), or injected anhydrous ammonia [25]. For soybean trials, the row spacing was 19 to 38 cm and seeding rate was 440,000 seeds ha^{-1}. Plot size for soybean trials was 4.6 by 22.9 to 24.4 m. Additional fertilizer was added in the form of 20–80–140–20–2 kg ha^{-1}

N–P–K–S–Zn (MicroEssentials SZ, Mosaic, Plymouth, MN, USA) or 15–73–129 kg ha^{-1} N–P–K as monoammonium phosphate to corn and soybean trials when required based on soil test results. All plots were maintained weed-free using burndown, preemergence, and postemergence herbicides.

2.3. Plant Data

The center two rows of corn plots were harvested using a plot combine (Wintersteiger Delta, Salt Lake City, UT, USA) and grain yields were adjusted to 150 g kg^{-1} moisture. For plots planted to soybean, the center 1.5 m of the soybean plot was harvested using a plot combine (Wintersteiger Delta, Salt Lake City, UT, USA), and yields adjusted to 130 g kg^{-1} moisture. Plant populations were calculated based on middle row stand counts for corn, and a middle of plot stand count for a 1.2 m length of row for soybean. Yield percent differences were calculated by comparing the means of treatment plots within each replication of a trial with the non-treated control means of the same replications within the trial. Percent differences from control plots were grouped into years after application, and averaged for each treatment.

Data were analyzed using analysis of variance (ANOVA), and comparisons among treatment means were made using Fisher's protected least significant difference (LSD) at $p < 0.10$. Statistical procedures were carried out with SAS statistical software [26].

3. Results and Discussion

3.1. Climatic and Environmental Conditions

Climatic conditions at the field sites varied among growing seasons. Rainfall over the growing seasons (Figure 2) for 2012, 2013, and 2016 were 275, 26, and 188 mm below the 10-year average of 699 mm, respectively. Although 2013 rainfall over the growing season was only slightly below average, the majority of the precipitation occurred over the course of a few events, and an extended dry period persisted from early July to September. Rainfall for 2014 and 2015 was 48 and 212 mm above the 10-year average, respectively. These seasonal differences in rainfall may account for some of the observed differences in grain yields for both corn and soybean over the cropping years.

Additionally, Trials #1 and #3 were conducted on a Putnam silt loam, whereas Trial #2 was on a Kilwinning silt loam, which had very acidic surface soil pH. Furthermore, variation in surface and subsoil acidity may explain inconsistent variations in plant growth and yields between treatments. Even within a specific soil series, surface and subsoil acidity can vary greatly in a field [27].

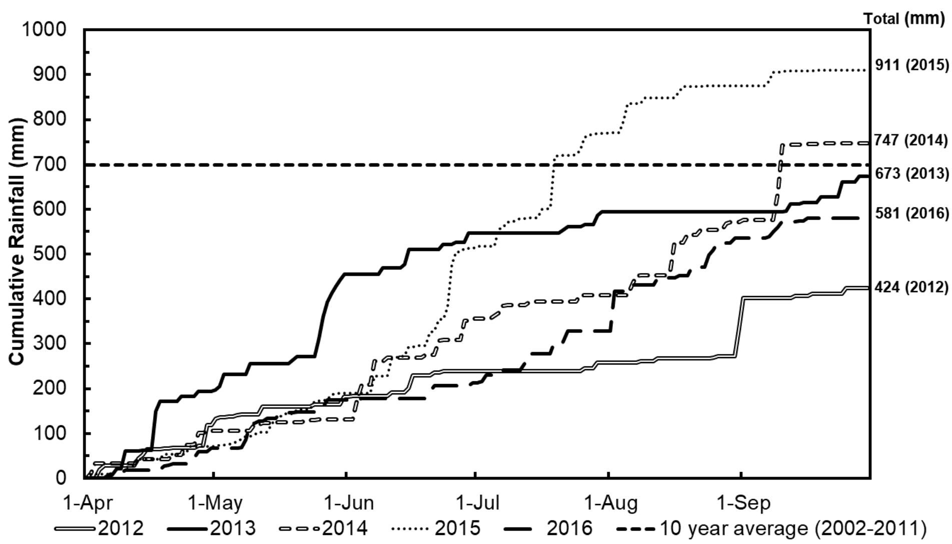

Figure 2. Cumulative precipitation during the 2012 to 2016 growing seasons and the 10 (2002 to 2011)-year average (699 mm) at the Greenley Memorial Research Center near Novelty, Missouri (USA).

3.2. Crop Response to Lime

3.2.1. Corn

The effects of lime placement on corn heights taken at or later than VT (tassling growth stage) for all three field trials for 2012 to 2014 are shown in Table 2. In Trial #1, plant heights were significantly taller by 5 to 21 cm over the control for all deep vertical placement methods in 2012 and 2014. In 2012, a surface application at 6.7 Mg ha^{-1} had 5 cm shorter plants in Trial #1. However, a surface application at 6.7 Mg ha^{-1} significantly increased heights in 2013 and 2014 over the control by 6 and 16 cm, respectively. For Trial #2, no treatments increased corn stand heights compared to the control in 2013. However, deep tillage effects alone significantly increased plant height 8 cm in 2014. Plant height for Trial #3 significantly increased by 13 cm compared to the control with a surface application of 3.4 Mg ha^{-1} in 2014.

Table 2. VT (tassling) growth stage or later corn plant heights for lime treatments for all field trials from 2012 to 2014.

		Cropping Season		
Trial #	**Treatment** ††	**2012**	**2013**	**2014**
			cm	
Trial #1	CTRL	164	202	224
	S-LO	163	206	231
	S-HI	159	208	240
	D-NO	171	204	238
	D-LO	172	202	235
	D-HI	170	201	245
	$LSD_{(p \leq 0.10)}$	5	5	10
Trial #2	CTRL	— †	246	266
	S-LO	—	252	271
	S-HI	—	243	270
	D-NO	—	248	274
	D-LO	—	246	266
	D-HI	—	239	268
	$LSD_{(p \leq 0.10)}$	—	10	5
Trial #3	CTRL	—	—	251
	S-LO	—	—	264
	S-HI	—	—	251
	D-NO	—	—	253
	D-LO	—	—	250
	D-HI	—	—	259
	$LSD_{(p \leq 0.10)}$	—	—	10

† Field site was not established and no data were collected. †† Abbreviations: CTRL, control; S-LO, surface 3.4 Mg ha^{-1}; S-HI, surface 6.7 Mg ha^{-1}; D-NO, deep tillage no lime; D-LO, deep placement 3.4 Mg ha^{-1}; D-HI, deep placement 6.7 Mg ha^{-1}.

Corn plant populations for all trials from 2012 to 2016 are reported in Table 3. Deep tillage alone and lime at 3.4 Mg ha^{-1} decreased plant populations by 2000 to 17,300 plants ha^{-1} in 2012, 2014 and 2016 for Trial #1. In 2016, deep vertical placement treatments at 6.7 Mg ha^{-1} decreased plant populations by 9800 plants ha^{-1} for Trial #1. Treatments of deep vertical placement with no lime decreased plant populations in 2014 by 3100 plants ha^{-1} for Trial #2. No other differences in corn plant populations were observed among lime treatments in Trials #2 and #3.

Significant decreases in corn plant populations from deep vertical placement were observed only in alternate years (2012, 2014, 2016) for Trial #1 (Table 3). The small populations every other year of Trial #1 may suggest either notable variation in soil properties of individual plots or possibly mechanical differences during initial applications. Furthermore, the higher corn plant heights observed in 2012 and 2014 of Trial #1 could be due to smaller populations during those years, as there would be less competition for sunlight among the individual plants.

Table 3. Corn plant populations of lime treatments for all trials from 2012 to 2016.

		Cropping Season				
Trial #	**Treatment** †††	**2012**	**2013**	**2014**	**2015**	**2016**
				No. ha^{-1}		
Trial #1	CTRL	74,400	66,000	70,200	62,800	74,000
	S-LO	74,200	66,900	70,500	61,600	73,400
	S-HI	72,200	67,800	68,400	61,100	74,900
	D-NO	64,400	66,400	67,600	61,600	67,600
	D-LO	57,100	68,400	68,200	61,600	58,800
	D-HI	69,000	70,200	66,900	62,000	64,200
	LSD$_{(p \leq 0.10)}$	5400	NS †	2000	NS	4900
Trial #2	CTRL	— ††	66,600	65,500	62,100	66,100
	S-LO	—	63,000	63,300	64,900	65,000
	S-HI	—	66,100	65,200	63,000	70,300
	D-NO	—	65,900	62,400	61,300	68,300
	D-LO	—	67,700	64,600	64,100	72,300
	D-HI	—	66,800	64,400	61,900	69,300
	LSD$_{(p \leq 0.10)}$	—	4200	2500	NS	NS
Trial #3	CTRL	—	—	61,400	75,900	74,500
	S-LO	—	—	60,300	73,000	72,700
	S-HI	—	—	58,800	73,700	75,300
	D-NO	—	—	62,200	74,200	77,000
	D-LO	—	—	56,000	73,700	74,600
	D-HI	—	—	60,000	74,000	71,200
	LSD$_{(p \leq 0.10)}$	—	—	NS	NS	NS

† NS denotes no significance difference at $p \leq 0.10$. †† Field site was not established and no data were collected. ††† Abbreviations: CTRL, control; S-LO, surface 3.4 Mg ha^{-1}; S-HI, surface 6.7 Mg ha^{-1}; D-NO, deep tillage no lime; D-LO, deep placement 3.4 Mg ha^{-1}; D-HI, deep placement 6.7 Mg ha^{-1}.

Grain yield varied greatly among years, and appeared to be heavily influenced by rainfall. Corn grain yields for Trial #1, #2, and #3 are presented in Figure 3A, Figure 4A, and Figure 5A, respectively. In 2012, a drought year, the effects of the deep vertical placement implement alone without lime increased corn yield by 0.3 Mg ha^{-1} compared to control plots for Trial #1 (Figure 3A). However, no differences were observed when compared with other lime treatments. Subsequently, the effects of deep vertical placement, in the following wetter years, decreased corn grain yields compared to control plots by 0.8 and 1.2 Mg ha^{-1} in 2013 and 2014, respectively (Figure 3A).

Research by Tupper et al. [2] suggested that deep tillage fracturing of hardpans resulted in greater exposure to soil acidity, causing greater Al and manganese (Mn) toxicity. Likewise, adverse effects of deep vertical placement with no lime observed in 2013 and 2014 may indicate a greater exposure to soil acidity when tillage was not accompanied by a lime treatment. Additionally, under no-tillage, surface applications of lime at 3.4 Mg ha^{-1} increased corn yield 1.2 Mg ha^{-1} in 2014 for Field Trial #1 (Figure 3A), indicating a possible limitation due to surface acidity. Lack of significant yield increases in wetter years, from deep vertical placed lime, signifies that under adequate soil moisture subsoil, acidity may not be a substantial limiting factor for these soils. Likewise, similar research on correction of soil acidity found less yield responses to lime treatments under non-drought conditions compared to crops under drought stress [9]. One possible explanation for the different response to deep liming in wetter versus drier years is that in wetter years, plant roots may not explore the lower soil profile, due to adequate moisture in the upper soil layers [28]. No differences from non-treated plots were observed in 2015 for Field Trial #1; however, deep vertical placement of lime at 3.4 Mg ha^{-1} in 2016 reduced corn yield by 1.4 Mg ha^{-1} compared to the control (Figure 3A).

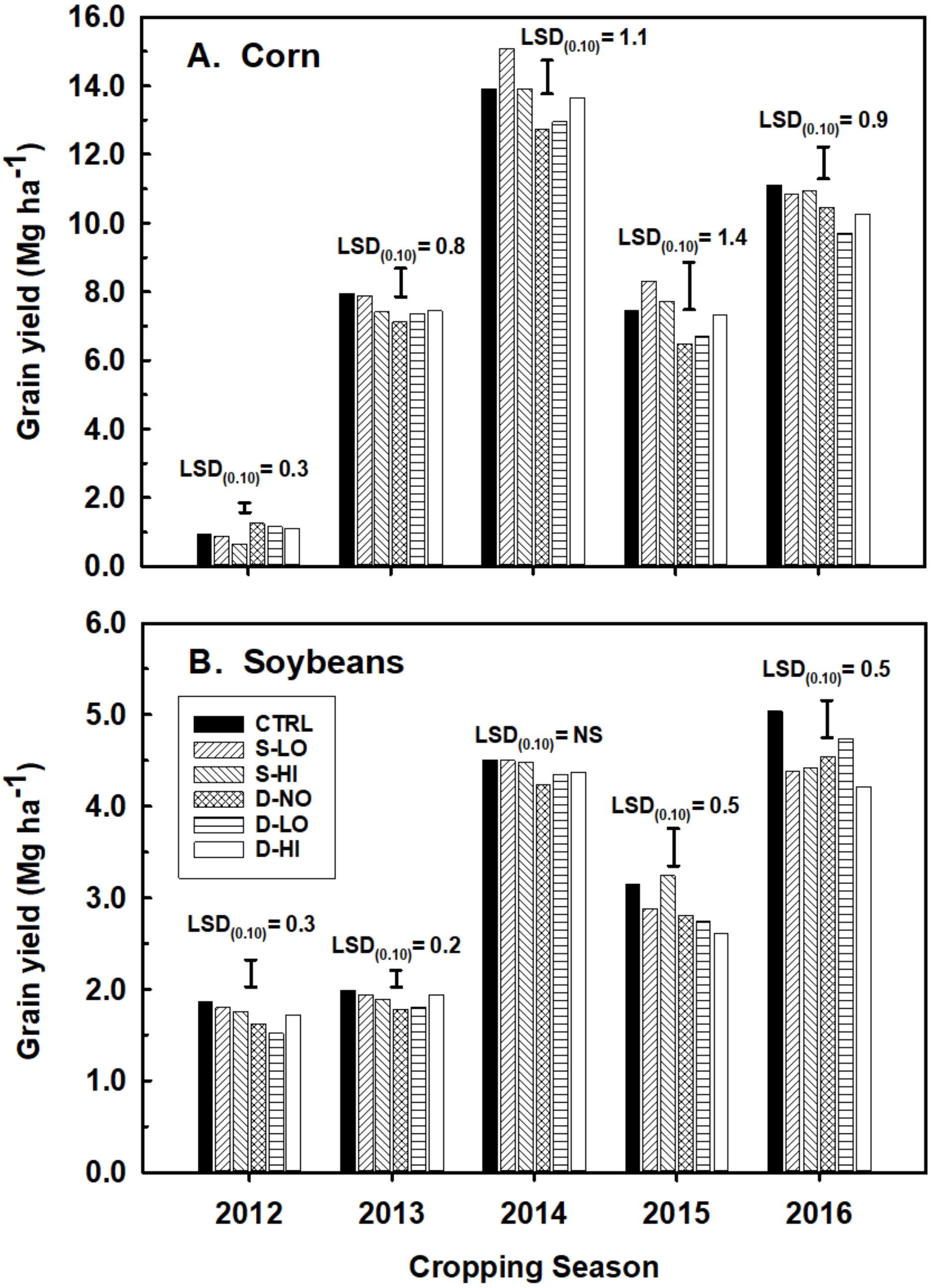

Figure 3. (**A**,**B**) Trial #1 grain yields (Mg ha^{-1}) for (**A**) corn and (**B**) soybean, due to lime treatments from the 2012 to 2016 cropping seasons. $LSD_{(0.10)}$ is least significant differences at $p \leq 0.10$. (Abbreviations: CTRL, control; S-LO, surface 3.4 Mg ha^{-1}; S-HI, surface 6.7 Mg ha^{-1}; D-NO, deep tillage no lime; D-LO, deep placement 3.4 Mg ha^{-1}; D-HI, deep placement 6.7 Mg ha^{-1}; NS, not significant).

For Trial #2, no differences between treatments were observed for the first two years of the experiment (Figure 4A). Slower solubility and reaction time of lime may be a possible cause for no response to the lime treatments for the early years of experimental plots. By the third year of treatment, corn grain yields were 1.8 Mg ha^{-1} less with deep vertical placed lime treatment at 6.7 Mg ha^{-1} for Trial #2 in 2015 (Figure 4A). However, this large observed reduction in yield may be mainly a result of climatic conditions and environmental variability. Lack of significant reductions in previous years, along with heavy precipitation for that year, is a possible indication that yield loss was likely affected by environmental factors rather than treatment factors. Nevertheless, deep tillage with no lime, and deep vertical placed lime at 6.7 Mg ha^{-1} in 2016, increased corn yield 1.4 and 1.3 Mg ha^{-1}, respectively (Figure 4A). Increased grain yields in Trial #2 from deep vertical placement with no lime, and lime placement treatments, were observed in 2016 when precipitation was below average, which may indicate a beneficial effect of lime on drought tolerance in low moisture environments.

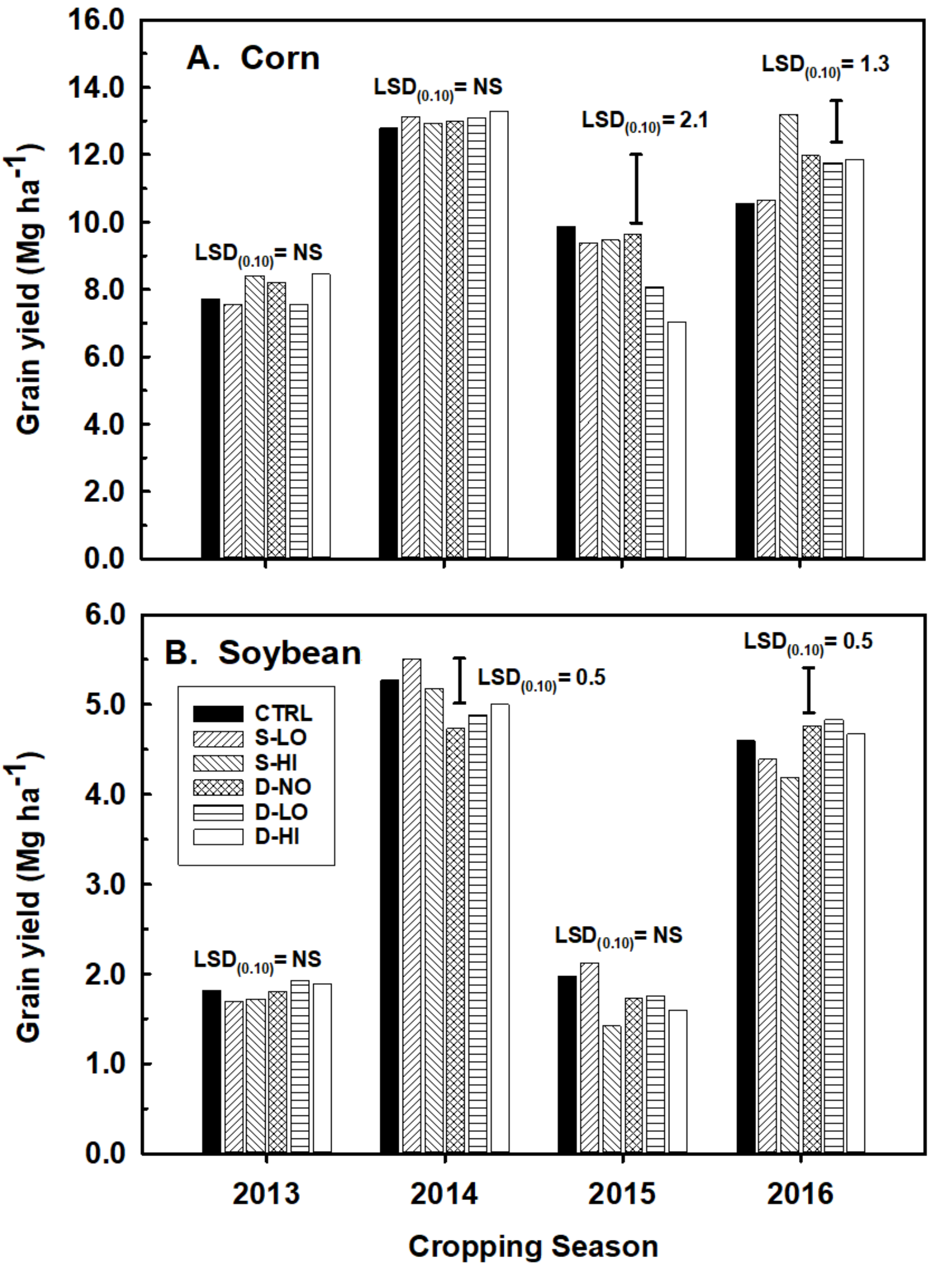

Figure 4. (**A**,**B**) Trial #2 grain yields (Mg ha^{-1}) for (**A**) corn and (**B**) soybean due to lime treatments from the 2012 to 2016 cropping seasons. $LSD_{(0.10)}$ is least significant differences at $p \leq 0.10$. (Abbreviations: CTRL, control; S-LO, surface 3.4 Mg ha^{-1}; S-HI, surface 6.7 Mg ha^{-1}; D-NO, deep tillage no lime; D-LO, deep placement 3.4 Mg ha^{-1}; D-HI, deep placement 6.7 Mg ha^{-1}; NS, not significant).

As past research has demonstrated, lime treatments can effectively decrease soil acidity, resulting in greater root development and decreased drought sensitivity of a crop [9,14,29]. Furthermore, in wetter years (2014 and 2015), corn yields following deep vertical placed lime were either insignificant or significantly less than the controls. This result suggests a decreased effect of subsoil acidity or deep lime placement on plant growth under adequate soil moisture environments.

Under excessive soil moisture conditions, partly due to the poor drainage characteristics of the soils in this study, rooting depth could have been reduced, limiting the effects of the deep vertical placed lime.

No treatment raised corn yields compared to the control in the first year of Trial #3 (Figure 5A). Consequently, two years after treatment, surface applied lime at 3.4 Mg ha^{-1} and deep vertical placed lime at 6.7 Mg ha^{-1} had decreased corn yields by 1.8 and 1.6 Mg ha^{-1} in 2015 (extremely wet year), respectively (Figure 5A).

To better compare the early residual effects of lime treatments on corn grain yields, percent differences from the control plots were averaged and combined for all three field trials (Figure 6A). During the first year, deep vertical placement with no lime and vertical lime placement treatments increased grain yields by 6.5 to 15.2%. However, only the effects from deep vertical placement with no lime were significant, with a grain yield increase of 15.2%. No significant changes in corn yield were observed two years after application (Figure 6A). Three years after treatment, deep vertical placement at 3.4 and 6.7 Mg ha^{-1} significantly decreased grain yields by 8.4 and 12.3%, respectively (Figure 6A). Reductions in corn yield three years after treatment could be explained by greater amounts of precipitation observed during the 2014 and 2015 growing season (Figure 2) leading to adequate levels of soil moisture during the third residual year of treatment for Trials #1 and #2. Therefore, tillage effects, in combination with the success of control plots, may have resulted in the observed decreases in yield. No significant differences among treatments were observed for the fourth year after application. Lack of differences in yield response to treatments observed may be attributed to higher levels of soil moisture over the 2015 and 2016 seasons.

Soil variability between and within the trial sites was indicated by variations in corn yields of lime-treated plots. For example, deep vertical placement of lime treatments appeared to have a greater response in Trial #2 compared to Trials #1 and #3. As indicated in the initial soil characteristics table (Table 1), Trial #2 had greater surface soil acidity, as well as overall more acidic subsoil pH. Previous research suggests that benefits from deep placed lime only become apparent when subsoil pH is a large enough limiting factor to plant growth and development [27]. This can be observed by the increased yield response seen in Trial #2, a site with greater surface soil acidity compared to Trials #1 and #3. Yet, significant increases in grain yield from deep applications of lime similar to those observed in the highly weathered soils of the tropics (4, 5, 8) were not detected in this study. This may be attributed to the greater soil base cation concentrations, especially with exchangeable Ca, and lower levels of soil neutralizable acidity in the top 15 cm of the soil profile for these claypan soils (Table 1). This suggests that the initial effects on plant growth of deep vertical placement on these soils may be reduced compared to more acidic soils. Additional measurements of the spatial effects of this deep vertical placement on soil acidity in the soil profile also showed that the effects of the lime placement were generally limited to the application zone, and due to the limited interaction with soil, may have also reduced the rate of reaction with the soil volume [30]. In addition, an examination of the effects of lime placement often requires long-term evaluation, as lime applications may take years to fully react and have a beneficial effect on plant growth many years after application [4,5,18].

3.2.2. Soybean

Soybean heights were recorded late August to early September each year from 2012 to 2015 (Table 4). Deep vertical placement with no lime application for Trial #1 significantly increased soybean height by 2 cm in 2012. Significant differences in soybean heights among treatments were observed in 2014 and 2015 for Trial #1. However, no treatments were significantly different from control plots.

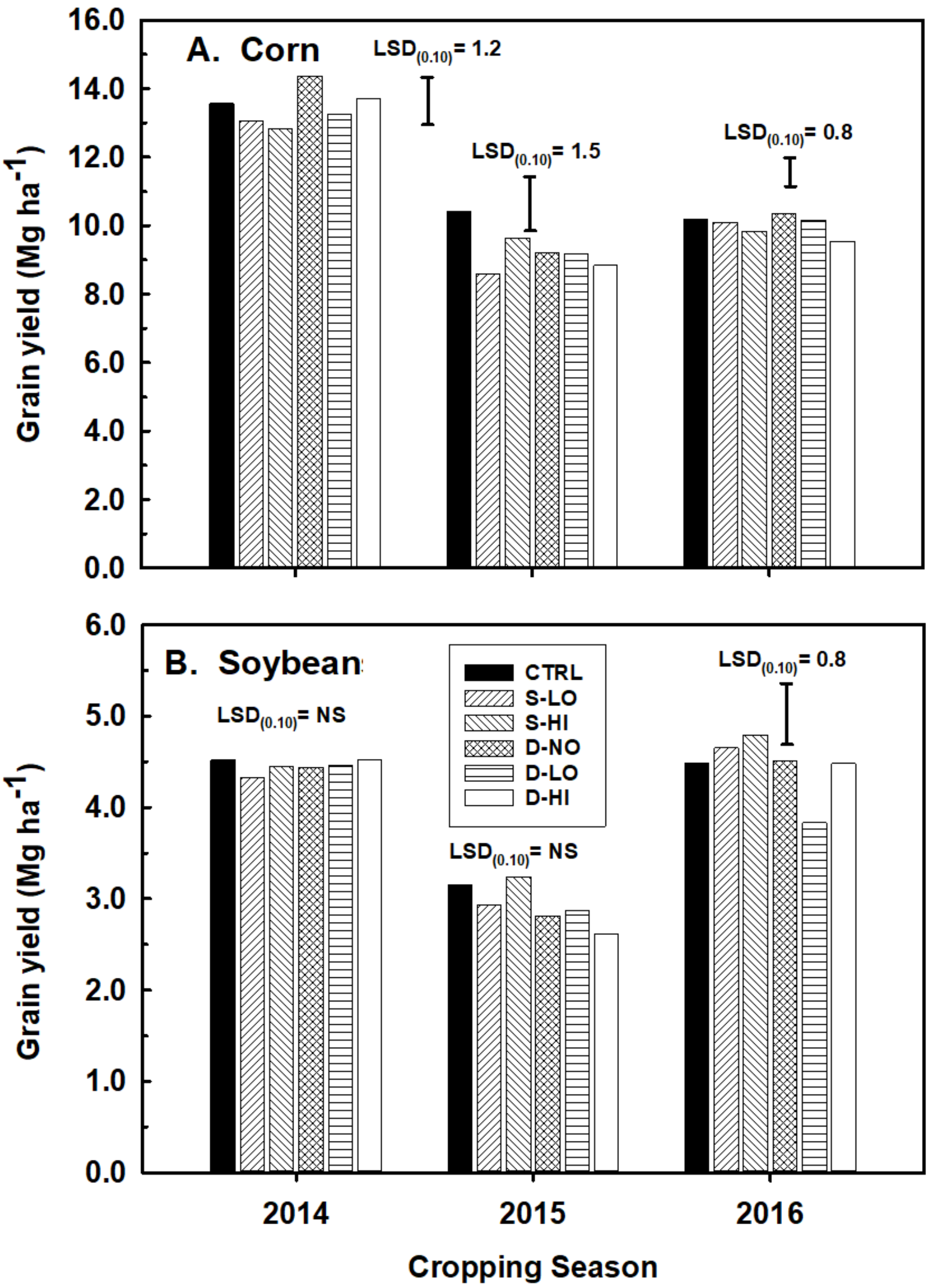

Figure 5. (**A**,**B**) Trial #2 grain yields (Mg ha^{-1}) for (**A**) corn and (**B**) soybeans due to lime treatments from the 2012 to 2016 cropping seasons. $LSD_{(0.10)}$ is least significant differences at $p \leq 0.10$. (Abbreviations: CTRL, control; S-LO, surface 3.4 Mg ha^{-1}; S-HI, surface 6.7 Mg ha^{-1}; D-NO, deep tillage no lime; D-LO, deep placement 3.4 Mg ha^{-1}; D-HI, deep placement 6.7 Mg ha^{-1}; NS, not significant).

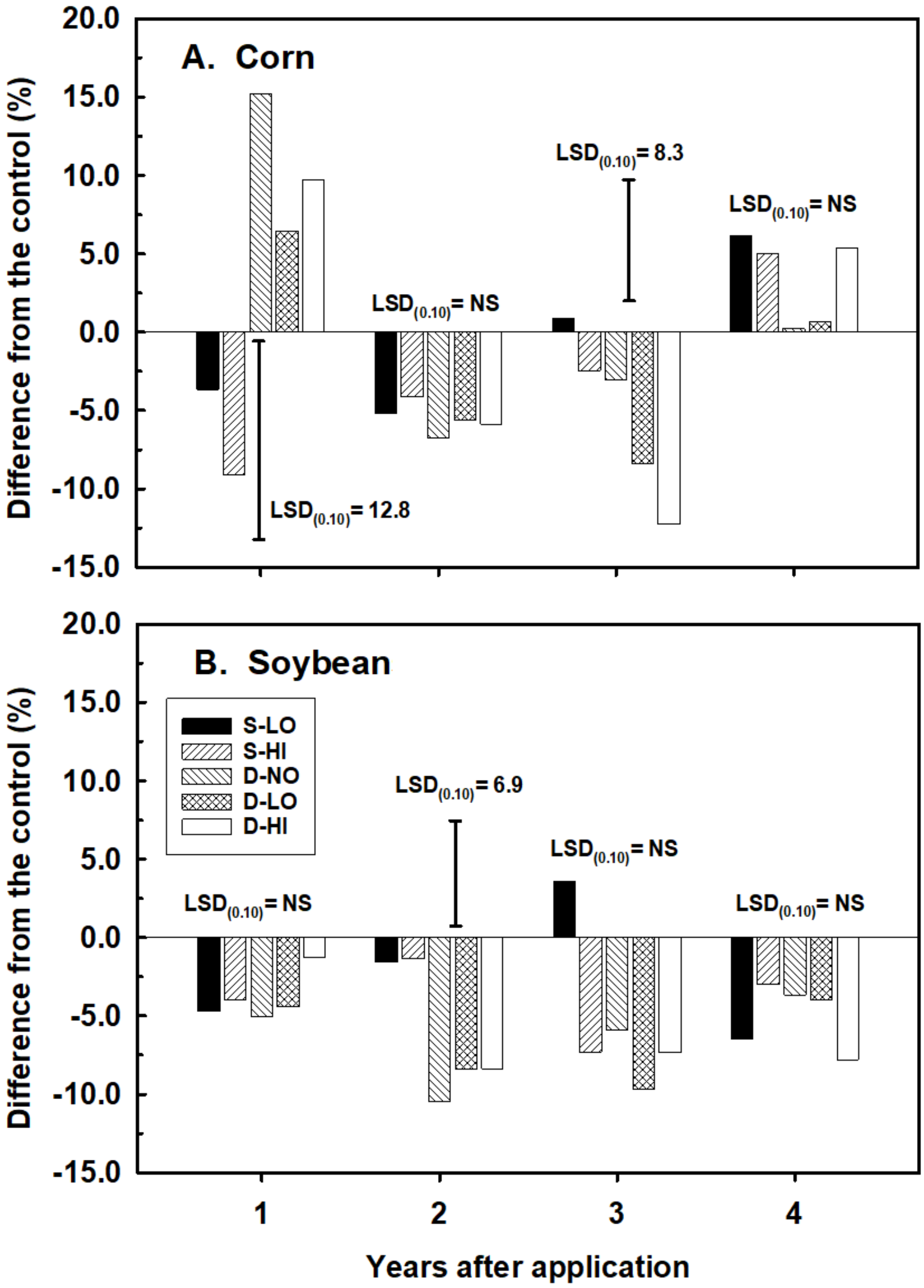

Figure 6. (**A**,**B**) Grain yield differences from the control plots for (**A**) corn and (**B**) soybean in response to lime treatments for all trials 1 to 4 years after treatments were initially applied. $LSD_{(0.10)}$ is least significant differences at $p \leq 0.10$. (Abbreviations: CTRL, control; S-LO, surface 3.4 Mg ha^{-1}; S-HI, surface 6.7 Mg ha^{-1}; D-NO, deep tillage no lime; D-LO, deep placement 3.4 Mg ha^{-1}; D-HI, deep placement 6.7 Mg ha^{-1}; NS, not significant).

Table 4. Late season soybean plant top heights of lime treated plots for all field trials 2012 to 2015.

		Cropping Season			
Trial #	**Treatment** †††	**2012**	**2013**	**2014**	**2015**
		cm			
Trial #1	CTRL	53	70	99	83
	S-LO	54	70	104	74
	S-HI	53	66	105	84
	D-NO	55	68	98	79
	D-LO	53	67	98	86
	D-HI	54	66	108	72
	$LSD_{(p \leq 0.10)}$	1	NS †	10	12
Trial #2	CTRL	— ††	75	99	61
	S-LO	—	74	94	63
	S-HI	—	74	92	58
	D-NO	—	72	91	57
	D-LO	—	77	96	60
	D-HI	—	73	94	58
	$LSD_{(p \leq 0.10)}$	—	NS	6	NS
Trial #3	CTRL	—	—	98	84
	S-LO	—	—	97	74
	S-HI	—	—	102	70
	D-NO	—	—	100	72
	D-LO	—	—	104	79
	D-HI	—	—	103	74
	$LSD_{(p \leq 0.10)}$	—	—	6	10

† NS denotes no significance difference at $p \leq 0.10$. †† Field site was not established and no data were collected. ††† Abbreviations: CTRL, control; S-LO, surface 3.4 Mg ha^{-1}; S-HI, surface 6.7 Mg ha^{-1}; D-NO, deep tillage no lime; D-LO, deep placement 3.4 Mg ha^{-1}; D-HI, deep placement 6.7 Mg ha^{-1}.

For Trial #2, surface application at 6.7 Mg ha^{-1} and deep vertical placement with no lime significantly lowered plant height compared to the control in 2014 by 7 and 8 cm, respectively (Table 4). No significant differences in soybean heights were observed between treatments in 2013 and 2014 for Trial #2.

Significant differences in soybean plant height among treatments were observed in 2014 for Trial #3. However, all of the treatments were similar to the control. In 2015, deep vertical placement with no lime, placement at 6.7 Mg ha^{-1}, and surface application of 6.7 Mg ha^{-1} shortened soybean heights by 8, 10, and 14 cm, respectively, in Trial #3.

Significant differences in soybean plant populations between treatments were observed for all experimental years of Trial #1 (Table 5). However, only 2012 and 2014 had treatments with populations greater than the control. For example, surface lime applications at 3.4 Mg ha^{-1} had greater soybean plant populations by 118,500 plants ha^{-1} in 2012, compared to the control. In 2014, deep vertical placement at 3.4 Mg ha^{-1} had plant populations that were 64,600 plants ha^{-1} greater than the control in Trial #1.

No significant differences in soybean plant populations were observed among treatments in Trial #2 for all crop years, with the exception of 2014 (Table 5). Compared to the control plots, soybean populations decreased by 32,300 and 37,700 plants ha^{-1}, from surface treatment at 6.7 Mg ha^{-1} and a deep vertical placement treatment at 3.4 Mg ha^{-1}, respectively, in 2014. Surface-applied lime at 6.7 Mg ha^{-1} in Trial #3 reduced plant populations by 64,600 plant ha^{-1} compared to control treatments, whereas no differences between treatments were observed in 2014 and 2016.

Table 5. Soybean plant populations of lime treated plots for all trials 2012 to 2016.

		Cropping Season				
Trial #	**Treatment †††**	**2012**	**2013**	**2014**	**2015**	**2016**
				No ha^{-1}		
Trial #1	CTRL	462,800	376,700	226,000	269,100	592,000
	S-LO	581,300	387,500	258,300	290,600	505,900
	S-HI	398,300	409,000	269,100	312,200	581,300
	D-NO	484,400	355,200	236,800	269,100	742,700
	D-LO	452,100	312,200	290,600	290,600	721,200
	D-HI	570,500	366,000	279,900	226,000	710,400
	$LSD_{(p \leq 0.10)}$	116,100	86,400	56,000	59,000	19,7900
Trial #2	CTRL	— ††	452,100	215,300	193,800	656,600
	S-LO	—	430,600	199,100	204,500	721,200
	S-HI	—	366,000	183,000	226,000	699,700
	D-NO	—	344,400	188,400	215,300	688,900
	D-LO	—	376,700	177,600	204,500	753,500
	D-HI	—	409,000	199,100	215,300	581,300
	$LSD_{(p \leq 0.10)}$	—	NS †	31,700	NS	NS
Trial #3	CTRL	—	—	269,100	290,600	839,600
	S-LO	—	—	269,100	290,600	914,900
	S-HI	—	—	258,300	226,000	1,065,600
	D-NO	—	—	247,600	279,900	882,600
	D-LO	—	—	258,300	269,100	1,097,900
	D-HI	—	—	279,900	279,900	1,108,700
	$LSD_{(p \leq 0.10)}$	—	—	NS	54,200	NS

† NS denotes no significance difference at $p \leq 0.10$. †† Field site was not established and no data were collected. ††† Abbreviations: CTRL, control; S-LO, surface 3.4 Mg ha^{-1}; S-HI, surface 6.7 Mg ha^{-1}; D-NO, deep tillage no lime; D-LO, deep placement 3.4 Mg ha^{-1}; D-HI, deep placement 6.7 Mg ha^{-1}.

Similar to corn yields, soybean yields varied among years, and were largely affected by rainfall (Figures 3B, 4B and 5B). During the first and second years after treatment (2012 and 2013), Trial #1 soybean yields decreased 0.3 and 0.2 Mg ha^{-1}, respectively, with deep vertically placed lime at 3.4 Mg ha^{-1} (Figure 3B). Likewise, the effects of just deep tillage decreased soybean yield 0.2 Mg ha^{-1} when compared to the control in 2013. There were no observed differences in yield amongst treatments three years after site establishment of Trial #1. Compared to the control plots, deep vertical placed lime at 6.7 Mg ha^{-1} resulted in significant decreases in soybean yield of 0.5 and 0.8 Mg ha^{-1} in 2015 and 2016, respectively (Figure 3B). Additionally, in 2016, the control had greater yields than all other treatments, except deep vertical placed lime at 3.4 Mg ha^{-1}.

Little significance in soybean yield between treatments was observed for Trial #2 for the four years after establishment (Figure 4B). Deep vertical placement with no lime in 2014 was the only treatment significantly different from control plots, where treatment effects decreased soybean yield by 0.5 Mg ha^{-1}. Significant differences in yield were observed between treatments for Trial #2 in 2016; however, all treatments were similar to the control plots. Similarly, no significance in soybean yields was observed in the first two years for Trial #3. Moreover, treatments failed to significantly increase soybean yield compared to control plots in 2016 (Figure 5B).

Due to large variations in precipitation, percent differences of treatments from non-treated controls were used to evaluate the residual effects of treatments. Differences from control plots for each trial were combined into residual years after treatment and averaged (Figure 6B). During the first year of treatment, no significant differences in soybean yields were observed. Two years after application, deep lime placement treatments decreased soybean yields compared to the control by 10.5, 8.4, and 8.4% for 0, 3.4, and 6.7 Mg ha^{-1}, respectively. In the third and fourth years after treatment, no significant changes in soybean yield were observed compared to the control.

When comparing soybean yield with corn yield, the shallow rooting nature of soybeans compared to that of corn may have affected the response to the deep placed lime. In all three field trials, the only significant effects of deep vertical placement methods were negative. This may be attributed to the lack of lime amendment added to 13 cm of the surface soil in deep vertical placement treatments, where the majority of the roots may be found. Furthermore, in addition to adverse effects from tillage on soybean, greater acidity found in the unamended portion of deep vertical placement treatments may hinder early plant development in both corn and soybean, leading to an early stunting of the plant. Nevertheless, surface amendments of lime displayed no significant yield increase over control plots in these trials. This could be a result of the slow reaction time of lime within the surface horizon. Various other studies indicated a lack of yield response of both corn and soybean during the first few years after application, and suggested that lime could require over a decade to fully react [5,20,28,31]. Additionally, the cation exchange capacity of soybean roots (CECR) is much greater than that of corn [32]. With a greater CECR, soybean plants are far more effective at extracting soil nutrients, and may experience less beneficial effects from lime amendments. Lack of increases in soybean yields may also be attributed to herbicide applications from previous years. For example, in a study conducted by Scharf et al. [33], the authors observed a decrease in soybean yield of 0.4 Mg ha^{-1} under a 1:1 corn/soybean rotation when the herbicide atrazine was applied to corn the previous year. As atrazine is an active ingredient of many of the herbicides used in management of trials, residual effects from previous application may have resulted in decreases in soybean production that were related to soil pH levels.

Based on observed changes in soil acidity in the soil profile [30], the chemical effects of lime were generally restricted to the zone of application, which is a similar result compared to past research [5,31]. Furthermore, pelletized lime was used as the lime amendment, instead of the more traditional powder form. Past research has shown that pelletized lime behaves the same as conventional non-pelletized lime when surface applied [6]. However, pelletized lime may not react as fast as the non-pelletized counterpart once it was incorporated into the soil. Additionally, past research on in-furrow placement of dolomitic pelletized lime found little changes in soil properties less than 2 cm from placement [13]. Furthermore, the spherical structure of dolomitic lime pellets was maintained 220 days after application. This physical form of pelletized lime observed in this study may have contributed to delaying the soil chemical reactions that took place after deep vertical placement of the amendments.

4. Conclusions

Ameliorating subsoil acidity impediments to root growth in conservation tillage systems using a novel deep vertical lime placement practice was assessed for corn and soybean production in a less weathered poorly-drained soil. The results of this research indicate that the deep vertical placement practice was more effective for corn production as compared to soybean production, possibly due to the more shallow-rooted growth habit of soybean compared to that of corn, and the limited spatial distribution of lime with this practice. Corn yield improvement with deep vertical lime placement was also more likely to occur in lower rainfall years, possibly due to its effects on deeper root growth.

The impact of deep vertical lime placement on crop production may require many years to fully assess due to the possible delay in lime reaction with the subsoil from the localized placement and the interactive effects of climate. Results from this research indicate that there are variable, but long-term residual effects from deep vertical lime placement on corn production. Continued long-term analysis of field sites with deep vertical lime placement may be needed to determine the extent of the residual effect on corn production, its interaction with climatic variation, and corn response when deep vertical lime placement is used in claypan landscapes common to this region. These claypan soils are characterized by variable depth to the more acidic claypan at different landscape positions.

Alterations to the design of the custom built shank for deep banded placement may be needed to incorporate the lime into a larger soil volume in the plow layer and subsoil, and to reduce the physical disturbance to the surface soil which may have caused initial decreases in plant populations. A possible combination of simultaneous shallow and deep lime placement could be explored, which would also allow for greater flexibility in the placement and amounts of lime applied based on the location and quantity of acidity in the soil. If prior information is available on the spatial location and quantity of subsoil acidity (e.g., a map of the variation in depth to the acidic claypan across a field) then the tool may be adapted for variable rate lime applications by depth.

Use of pelletized lime facilitated the deep vertical placement and reduced possible plugging of delivery lines, but it also may have delayed reaction time with the soil, and is more expensive compared to the regular form of lime. An additional alteration to the design may need to be explored to develop a system to allow for use of regular agricultural lime and for application of higher rates of lime for soils that have higher levels of subsoil acidity.

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