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Shallow Incorporation of Lime and Gypsum has Limited Benefit over the Sole-surface Application of Lime for Improving Grain Yield and Water Use Efficiency in the Low Rainfall Region of Western Australia

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Abstract

Soil acidity is one of the major soil constraints for the grain-growing industry in Australia and around the globe. While surface liming is widely adopted, it has been proven ineffective for the timely amelioration of subsoil acidity. There is a growing interest in finding alternative approaches for the effective amelioration of subsoil acidity, especially for low-rainfall regions. In a controlled environment and a field experiment, we examined whether the combined application of lime and gypsum would be more effective than lime alone under no-till (NT) and shallow strategic tillage (ST) systems for reducing the impact of soil acidity and increasing grain yield.

The controlled environment experiment highlighted that lime increased soil pH and decreased the soil exchangeable aluminium concentration (EAC) which resulted in significantly better root growth. In the field experiment, we found that the lime plus gypsum treatment, in most cases, did not significantly affect grain yield, water use efficiency (WUE) or grain quality compared to the lime treatment alone. Lime incorporation with a shallow ST was more effective in increasing soil pH and decreasing EAC at 10–20 cm depth, compared to the surface application of lime without tillage. However, ST did not affect the grain yield and WUE of wheat in 2017 and 2018 and significantly decreased the grain yield and WUE of canola in 2019 and barley in 2020. We found that measurements of either soil pH or EAC were equivalent in their ability to explain and predict the root growth of major grain crops. The results indicate that soil pH is the simplest indicator for grain growers to measure the improvement of soil acidity with liming and its impact on root growth and crop productivity. We recommend the application of lime as the preferred amendment on acidic sands, while shallow ST should be avoided in the low rainfall region. Further studies involving deep ST are warranted.

Keywords: soil acidity, aluminium toxicity, soil compaction, yield potential, broadacre cropping, strategic tillage

1. Introduction

About one-third of global arable land is acidic and subsurface soil is becoming more acidic at depth (Rengel, 2003). Soil acidity is one of the most significant constraints for farming in Australia, particularly in Western Australia (WA) as 72% of topsoil has a pH less than 5.5 and 45% of subsoil has a pH less than 4.8 (Gazey, Andrew, & Griffin, 2013). With decreasing soil pH, the concentration of the toxic form of aluminium (Al^{3+}) increases exponentially which significantly limits root growth and crop yield (Conyers & Poile, 2018).

Lime ($CaCO_3$) is usually applied for managing acidic soils; however, conventional surface application of lime takes many years to increase subsurface soil pH and decrease Al toxicity (Azam & Gazey, 2020). Due to such delayed responses, growers did not realise the economic benefit of liming, so liming adoption was low which resulted in more soils acidifying at deeper depths (Gazey et al., 2013). Now that the penalty from subsoil acidification on crop production is recognised, growers are looking for more rapid methods, such as the use of strategic tillage or combined application of lime and gypsum, to fix subsoil acidity (Davies, Armstrong, Macdonald, Condon & Petersen, 2019).

Strategic tillage (ST) has been adopted for the management of multiple interacting soil constraints in southern Australia (Davies et al., 2019). Soil inversion or mixing ST is being used as a one-off or occasional practice to overcome soil water repellence, acidity, compaction and herbicide resistance. Strategic tillage has also been reported to increase grain yield in field research in southern Australia in the medium to high rainfall zones

(Davies et al., 2019; Liu et al., 2016). There has been low adoption of ST for the incorporation of lime for managing acidic soil in the low rainfall zone of southern Australia (Davies et al., 2019). Some recent research has included shallow ST to incorporate lime and showed no significant improvement in the subsoil acidity and grain yield, and the reasons for this are not well understood (Reynolds et al., 2021). In addition, the use of ST for lime incorporation in the low rainfall region needs further assessment involving multiple crops and use of other alternative soil ameliorants such as gypsum in short- and long-term field experiments.

Gypsum ($CaSO_4.2H_2O$) is thought to be an alternative ameliorant as gypsum has a greater solubility in water than lime and hence releases extra calcium faster for mitigating the Al toxicity (Whitten, 2002). When gypsum is applied to surface soil it rapidly moves into the subsoil, where it can reduce toxic aluminium concentration and supply calcium and sulphur nutrition (Sumner, 1995). The addition of extra calcium in itself might play a role in reducing aluminium toxicity to the plant root (Rengel, 1992). In contrast, Smith et al. (1994), reported that the application of gypsum on its own had inconsistent benefits in improving soil acidity, aluminium toxicity and crop yield in the medium rainfall zone of Australia. In contrast, the application of gypsum in combination with lime to a Red Yellow Latosol in Brazil and a grey massive earth in Australia showed improvement in crop yield compared to lime alone (Crusciol et al., 2016; Smith et al., 1994). The underlying mechanism of how gypsum improves soil pH, reduces aluminium toxicity or brings other beneficial chemical changes in soils has remained unclear (Zoca & Penn, 2017).

In this study, we examined, in both controlled and field environments, the effect of lime and gypsum application (individual and combined) on soil pH, extractable aluminium concentration (EAC), crop biomass yield, grain yield, water use efficiency and grain quality parameters over four cropping years under a water-limited environment in a low rainfall region of WA. We tested whether the use of shallow ST for lime incorporation could be advantageous over the surface application of lime and gypsum for growing wheat, barley and canola crops. Finally, we also tested which measurement of soil acidity, ether pH or EAC is more accurate and reliable to explain the root growth response of major grain crops.

2. Materials and Methods

2.1 Incubation and Bioassay Experiment

2.1.1 Soil Sampling and Preparation

Bulk topsoil (0–10 cm) and subsoil (20–40 cm) were collected separately in April 2017 from Kalannie, Western Australia (35°42’S, 117°29’E). Soils were collected from the paddock where the field experiment was conducted during 2017–2020. This soil is classified as a Yellow-orthic Tenosol in the Australian Soil Classification (Isbell, 2016). The Tenosol of this region was naturally acidic before being cleared for use in agricultural cropping (McArthur, 2004). This soil type is found widely in the south-western region of WA and subsoil acidity is one of the major constraints for grain growers of the region (Gazey et al., 2013).

Table 1. Physical and chemical properties of topsoil, subsoil and mixed soil Kalannie, Western Australia, used in the experiments

Parameters	Topsoil	Subsoil	Mixed soil
Sampling depth (cm)	0-15	20-40	50:50 mixture of top and subsoil
Soil texture	Sandy loam	Sandy loam	Sandy loam
pH in 0.01M CaC_2	4.35	3.95	4.23
Extractable aluminium concentration (mg per kg)	2.47	22.2	6.32
Ammonium nitrogen (mg per kg)	7.33	2.33	8.45
Nitrate nitrogen (mg per kg)	11.00	6.33	15.30
Colwell phosphorus (mg per kg)	31.3	4.33	27.4
Phosphorus Buffering Index	24.2	63.1	43.5
Colwell potassium (mg per kg)	53.3	32.3	42.5
Organic carbon (%)	0.85	0.32	0.55
Sulphur (mg per kg)	7.4	28.6	22.7
Cation exchange capacity (meq per 100 g)	1.51	1.09	1.32

The soil was air-dried and sieved through a 2 mm mesh before sending for chemical analysis to a commercial laboratory, CSBP, Australia (Table 1). Both topsoil and subsoil had loamy-sand texture (Isbell, 2016) and had similar particle size distribution (87% sand, 3% silt and 10% clay). Physical and chemical properties of the topsoil and subsoil plus a 50–50 mixture (termed ‘mixed soil’) are presented in Table 1. Soil water retention for the saturated to near-saturated range (0–10 kPa) was determined for the subsoil and mixed soil using a hanging column (Dane & Hopmans, 2002). Soil volumetric water content at field capacity (10 kPa) was calculated from the soil water retention curves (van Genuchten, 1980) and this was used for watering the pots.

2.1.2 Experimental Setup and Measurements

The experiment was a complete factorial including four rates of lime and two rates of gypsum. Lime was sourced from Aglime of Australia in Lancelin, WA while gypsum was sourced from Gypsum Supplies in Kalannie, WA. The lime treatments were: 0 (L0), 0.25 (L1), 0.50 (L2), and 1.00 (L3) g lime per kg soil (94.9% equivalent weight of laboratory grade $CaCO_3$). The gypsum treatments were: 0 (G0) and 0.50 (G1) g gypsum per kg soil (96% equivalent weight of laboratory grade $CaSO_4$. $2H_2O$). A subsoil (to represent a seedbed following mouldboard ploughing) and a mixed soil (to represent a seedbed following rotary spading) were used. There were three replications for all treatments.

The lime treatments were applied first. For each treatment, lime was mixed with 15 kg of soil each time using a rotary mixer. Eight hundred grams of lime-treated soil was packed into a tapered pot (953 mL capacity, 10 cm high, 12 cm top diameter, 10 cm basal diameter). The gypsum treatments were then applied to the surface of the pots since it is a soluble salt that readily moves into deeper soil (Sumner, Shahandeh, Bouton & Hammel, 1986). Water was added to pots to reach field capacity (16% volumetric water content) and incubated for seven days in a growth room (26 ± 2 ℃ temperature, 60 ± 10% relative humidity) before planting with three widely cultivated crops in Western Australia: barley (*Hordeum vulgare* var. La Trobe), wheat (*Triticum aestivum* var. Mace) and canola (*Brassica napus* hybrid Hyola 559TT). Five seeds were sown in each pot. The initial soil solution pH and EC were measured on soil solution sample extracted from each pot using a rhizon sampler (MOM; porous tube, 5 cm long and 2.5 mm diameter; mean pore size of 0.15 µm; Rhizosphere Research Product, Wageningen, the Netherlands).

The pots were moved to a controlled glasshouse 5 days after sowing. Two days after the last seedling germinated, a 5 mm layer of polyethylene beads (Alkathene^{TM}) was applied to the surface of each pot to minimise evaporation. Pots were weighed and watered every 2–3 days to maintain soil water content at field capacity. No drainage from the pots was observed. At the end of the experiment (33 days after emergence), plant shoots were cut 1 cm above the soil surface, dried at 60 ℃ for 48 hours and weighed.

A subsample of soil (100 g) was also collected from the centre of each pot at the end of the experiment. The subsamples were dried at 40°C in a forced-draught oven and passed through a 2 mm sieve before measuring soil pH in 1:5 soil: 0.01 M calcium chloride ($CaCl_2$) extract (Method 4B1, Rayment & Lyons, 2011) and $CaCl_2$-extractable total aluminium (Bromfield, 1987). Plant roots were separated from the soil using a gentle jet of water over a 0.5 mm sieve. All roots from each pot were then scanned using a high-resolution (600 dpi) scanner. Root lengths were measured using WinRhizo software (v. 2005c; Régent Instruments Inc., Quebec, Canada).

2.2 Field Experiment

2.2.1 Experimental Design

The field experiment was established in March 2017 and monitored for four years until December 2020. In the beginning, the whole site was deep ripped to 500 mm depth using a straight tine deep ripper (Agroplow®, Molong, New South Wales), to remove soil compaction as a factor in the analysis. The experimental plots, of 1.8 x 20 m, were set at 15° angle to the ripping line. The experiment had a complete factorial design replicated three times in complete blocks. There were three factors: tillage, lime rate and gypsum rate. Four lime rates were used: 0 (L0), 2 (L1), 4 (L2) and 6 (L3) t/ha (94.9% equivalent weight of laboratory grade $CaCO_3$). Four gypsum rates were also used: 0(G0), 1(G1), 2(G2) and 3(G3) t/ha (96% equivalent weight of laboratory grade $CaSO_4.2H_2O$). In the field experiment, both lime and gypsum (sourced from the same suppliers as mentioned earlier) were applied to the surface of the soil before tillage treatments were applied as blocks. The two tillage treatments were (i) no-till and (ii) tilled, which involved shallow incorporation to 20 cm depth using a one-way disc plough.

3.2.2 Data Collection

In the field experiment, wheat (*Triticum aestivum* var. Mace) was sown in 2017 and 2018, canola (*Brassica napus* var Bonito) in 2019 and barley (*Hordeum vulgare* var. La Trobe) in 2020. Seasonal weather data, cropping and agronomic management details are presented in Table 2. Crop emergence was counted three weeks after the sowing in each season at three replicated quadrants of 0.44 m^2 area from each experimental plot. Plant biomass was estimated by hand harvesting mature crops from three replicated quadrants of 0.44 m^2 area from each experimental plot. Grain yield was estimated by harvesting the whole experimental plot using a combine plot harvester (ZÜRN 150). Water use efficiency was estimated using French & Schultz (1984). Grain quality parameters such as thousand-grain weight, hectolitre weight, grain protein and oil content (for canola) were also determined. A composite soil profile sample (four profiles per plot) was collected from 0–5, 5–10, 10–15, 15–20, 20–30, 30–40, 40–50 and 50–60 cm depths from each plot in July 2018 and 2020 to measure soil pH (Method 4B1, Rayment and Lyons, 2011) and extractable aluminium concentration (EAC, Bromfield, 1987).

Table 2. Seasonal weather data, cropping and agronomic management details during 2017-2020

Parameters	2017	2018	2019	2020
Weather data				
Annual rainfall (mm)	256	317	204	237
GSR (mm)	143	211	180	155
Effective ASW (mm)	58	128	81	65
Crop management				
Crops	Wheat	Wheat	Canola	Barley
Seeding date	23/05/2017	10/05/2018	02/05/2019	01/05/2019
Seeding rate	60	60	2.2	84
Fertilisation – N, P, K and S	MAP 37 kg/ha, SOP 100 kg/ha; Urea 57 kg	MAP 37 kg/ha, Urea 57 kg	MAP 37 kg/ha, Urea 57 kg	MAP 37 kg/ha, Urea 57 kg
Herbicides, Insecticides and Fungicides	Pre-sowing: Triflurex 2 L/ha, Sprayseed 250 2 L/ha, Sakura 118 g/ha; Post-sowing: Velocity 670 ml/ha, methylated seed oil 1%	Pre-sowing: Triflurex 2 L/ha, Sprayseed 250 2 L/ha, Sakura 118 g/ha; Post-sowing: Velocity 670 ml/ha, methylated seed oil 1%	Pre-sowing: Atrazine 1.1 kg/ha, Triflurex 1.5 L/ha, Chlorpyrifos 200 ml/ha and Alfa Scud 200 ml/ha; Post-sowing: Atrazine 1.1 kg/ha, methylated seed oil 1%	Pre-sowing: Triflurex 2 L/ha, Sprayseed 250 2 L/ha, Sakura 118 g/ha; Post-sowing: Velocity 670 ml/ha, methylated seed oil 1%

Notes: GSR = growing season rain (rainfall during April-October in each year); ASW = available soil moisture (25% of the non-growing season rainfall plus 100% of the growing season rainfall minus potential evaporation of 100 mm per year); MAP = mono ammonium phosphate; SOP = potassium sulphate.

2.3 Statistical Analyses

A linear model was fitted to each of the soil properties, crop growth and grain yield parameters using the ANOVA procedure in GenStat (Version 18.1, VSN International, Oxford, UK) to compare the factorial treatments of lime by gypsum with polynomial contrasts. For non-normal data, a log transformation (log10) was performed to stabilise the variance. For detecting any statistically significant differences between treatment means, Fisher's protected least significant difference (LSD) was applied at the 0.05 significance level. When reporting treatment effects, they were ordered by the relative (%) change between the lowest and the highest.

3. Results

3.1 Incubation and Bioassay Experiment

3.1.1 Soil pH and Extractable Aluminium Concentration (EAC)

The addition of gypsum with lime did not have any significant benefit compared to the addition of lime alone on increasing soil pH (Figures 1a and 1d) and decreasing soil EAC (Figures 1b and 1e). Lime (both alone and with gypsum) linearly increased soil pH with increasing application rates and decreased EAC exponentially. Higher lime rates were more effective at increasing the pH of the subsoil compared to the mixed soil. Subsoil pH increased to a greater extent (2.26 pH units) with the incorporation of 1 g lime per kg of soil compared to the mixed soil (1.67 pH units) from the same lime rate (Figures 1a and 1d). A 0.25 g lime per kg soil decreased the EAC by 80%, and EAC was below the detection limit with 0.50 and 1 g lime per kg subsoil (Figure 1b). Mixing only (without lime) decreased the EAC to less than 10 mg per kg from an initial EAC of 22.2 mg per kg in the subsoil (Figure 1e). The change of soil EAC showed a strong correlation (R^2 ranged from 0.95 to 0.98) with the change of soil pH for both subsoil and mixed soil under both lime or lime plus gypsum treatments (Figure 1c and 1f).

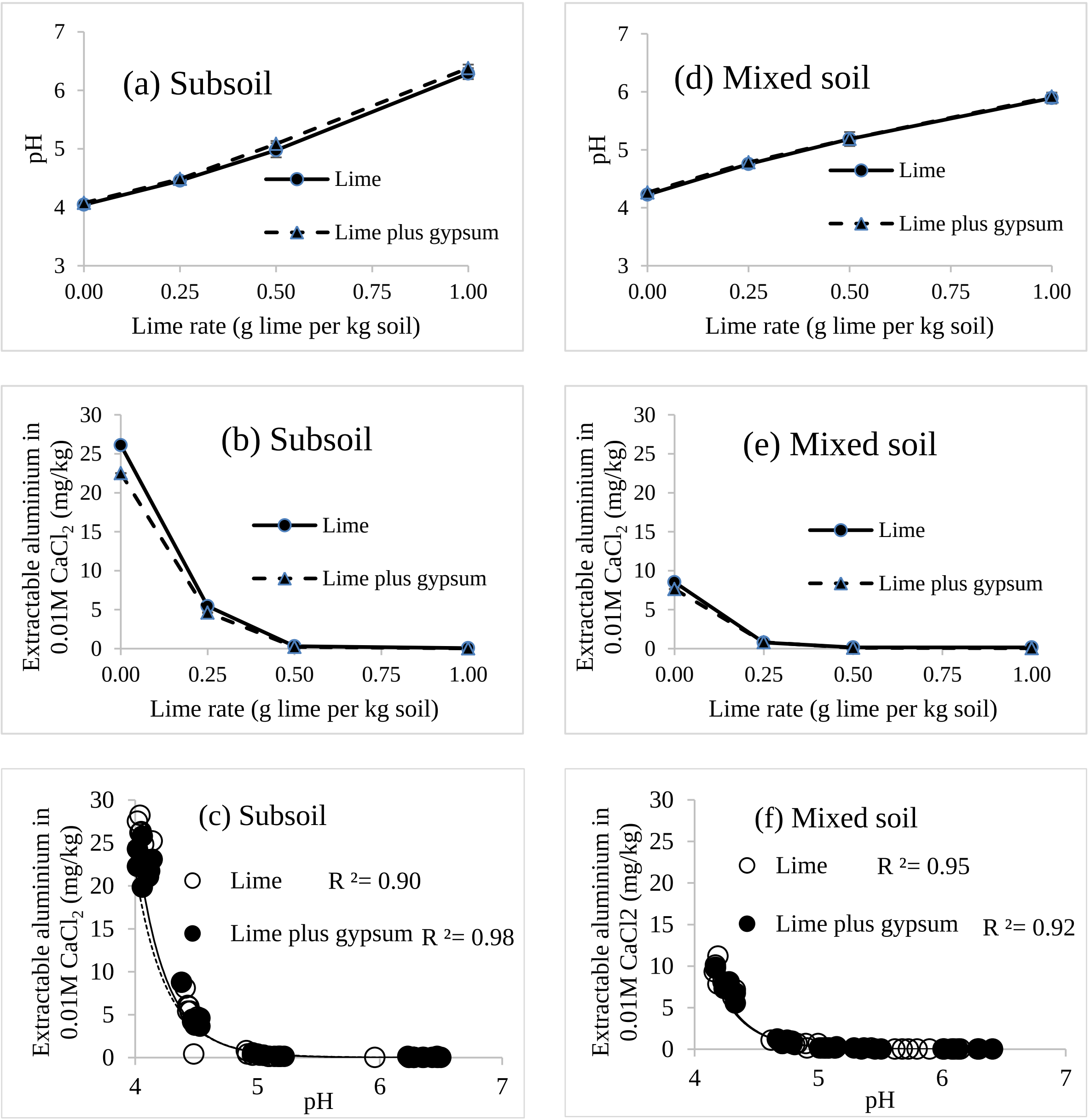

Figure 1. Interactive effect of lime and gypsum on pH (a and d), extractable aluminium (b and e) and the relationship between pH and extractable aluminium (c and f) of subsoil (a, b and c) and mixed soil (d, e and f). Vertical error bars represent the standard error of the mean values

3.1.2 Root Growth

Increasing the rate of lime addition increases the root length of barley with a greater relative increase in the subsoil than in the mixed soil (Figures 2a and 2d). In the subsoil, the root length increased by more than 4 fold for the L3 compared to L0 (ranging from 0.59 to 2.49 m per plant) rates. By comparison, in the mixed soil, the root length ranged from 1.85 m per plant for L0 to 2.52 m per plant with L2 rate. The addition of gypsum had variable impacts on barley root length. In the subsoil, the addition of gypsum alone decreased barley root length (Figure 2a) but barley root length was increased with the addition of gypsum to the L2 lime rate in both the subsoil (Figure 2a) and mixed soil (Figure 2d). The interaction between lime and gypsum was not significant compared to the sole application of lime.

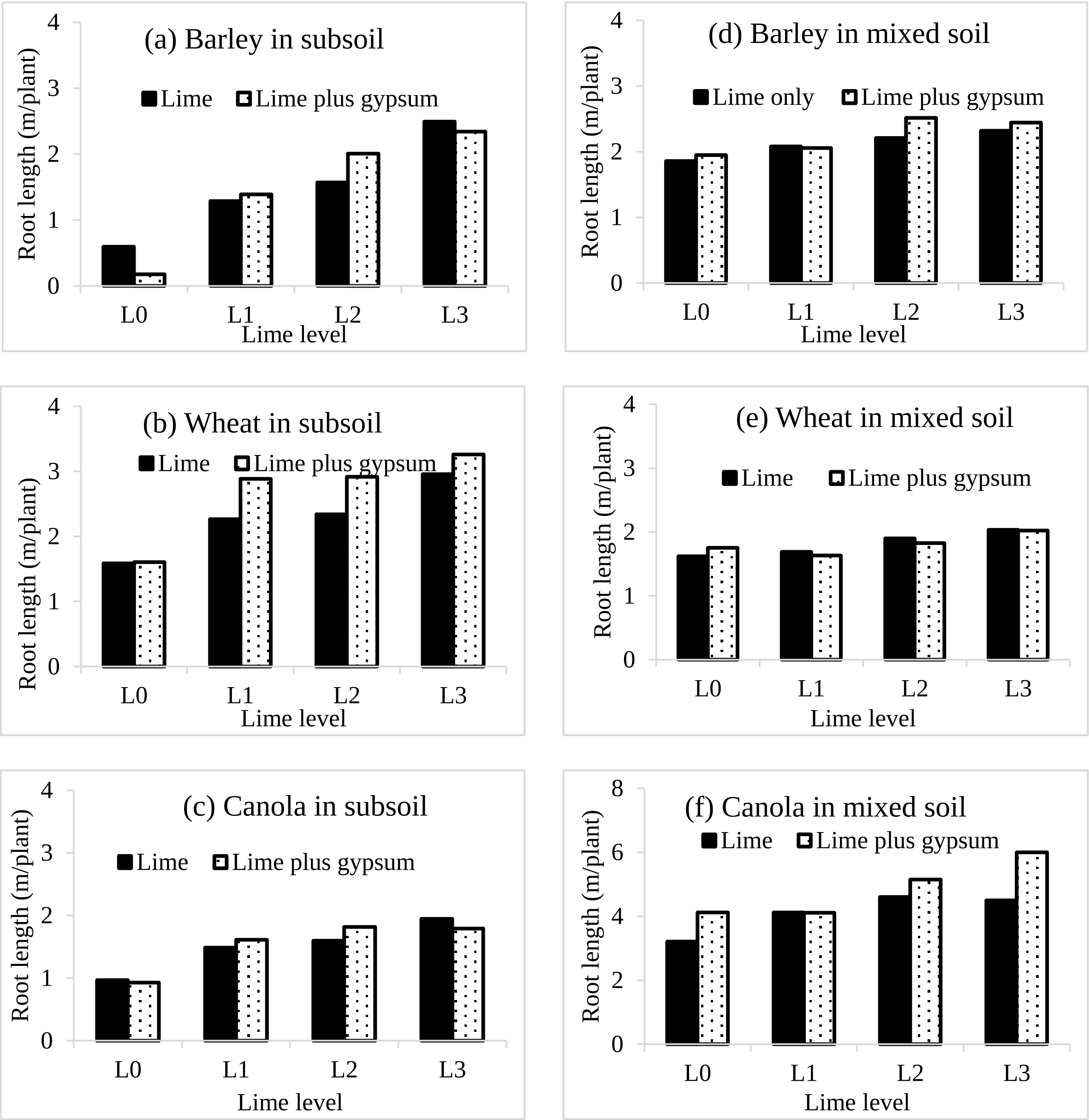

Figure 2. Effect of lime and gypsum application on root length of barley (a and d), wheat (b and e) and canola (c and f) grown in a subsoil and mixed acidic in aluminium toxic loamy sand. Statistics: LSD for soil type x lime rate x gypsum rate ($P < 0.05$) of means root length of barley = 0.30, wheat = 0.27 and canola = 0.84. Values on Y-axes vary due to different levels of response by different crops

Similarly, the root length of wheat significantly increased as the rate of lime application increased with a greater relative benefit on subsoil than mixed soil (Figures 2b and 2e). In the subsoil, the root length increased nearly 2 fold with 1.58 m per plant for L0 compared to 3.26 m per plant for L3. In the mixed soil, the root length ranged from 1.62 m per plant in the L0 to 2.03 m per plant in the L3. In the absence of lime, the addition of gypsum alone had no impact on wheat root length in either the subsoil or mixed soil (Figures 2b and 2e). The addition of gypsum in combination with the L1 and L2 rates showed an additional increase in wheat root length in the subsoil but gypsum addition had no significant impact on wheat root length in mixed soil relative to the addition of lime alone (L1, L2 and L3).

Canola root length also increased as the rate of lime addition increased (Figures 2c and 2f). In the subsoil, the canola root length ranged from 0.97 m per plant in the L0 to 1.95 m per plant in the L3. In the mixed soil, the root length increased to 4.60 m per plant in the L2 from 3.21 m per plant in the L0. The addition of gypsum in the absence of lime (L0) showed no significant difference in canola root length in either the subsoil or the mixed soil (2c and 2f). The addition of gypsum to the lime did not show any significant difference in the canola root length compared to sole lime addition (L1, L2 and L3) in both subsoil and mixed soil except for L3G1 in the mixed soil where canola root growth did increase with the addition of gypsum.

3.2 Field Experiment

3.2.1 Crop Establishment, Yield, Water Use Efficiency and Grain Quality

The interaction of lime, gypsum and tillage was not significant to influence (i) plant emergence counts after three weeks of seeding, (ii) the number of ears per unit area, and (iii) biomass yield, in any of the seasons (Table 3). The single-factor effects of gypsum were also not significant on any of the above-mentioned parameters (Table 3 and Appendix 1). Tillage treatment significantly affected plant emergence counts (Table 3 and Appendix 2). In 2017, wheat emergence was significantly slowed by the tillage treatment and therefore plant counts after three weeks of seeding were significantly smaller (2 plants per m^2) compared to the no-tilled treatment (13 plants per m^2). Due to slow emergence, plants were recounted after eight weeks of seeding and tillage treatment (36 plants per m^2) surpassed the no-tilled treatment in plant counts (29 plants per m^2). As wheat plants emerged later in the tilled plots, the shoot biomass yield (1.93 t/ha) was lower than in the no-till plots (2.16 t/ha). The wheat emergence counts (59 plants per m^2) in 2018, and the canola emergence counts (52 plants per m^2) in 2019 were improved by tillage treatment compared to the no-till control (2018 wheat 55 plants per m^2; 2019 canola 30 plants per m^2). The effect of tillage treatment was no longer significant on plant emergence counts in the 2020 season. Wheat biomass yield in 2018 and barley biomass yield in 2020 were unaffected by tillage treatment (Appendix 2).

Table 3. Summary of ANOVA tests on emergence count, ear count, biomass yield, grain yield, protein, oil content and grain size of wheat, barley and canola

Year and crop	Interactions	Emergence count (plant per m^2)	No. of ear per m^2	Biomass yield (t/ha)	Grain yield (t/ha)	WUE (kg/mm)	Grain size (g per 1000-grain)	Protein (%)
2017 Wheat	L x G x T	NS	NS	NS	NS	NS	NS	NS
	L x T	NS	NS	NS	NS	NS	NS	NS
	L	NS	***	**	***	***	***	NS
	G	NS	NS	NS	NS	NS	NS	NS
	T	***	NS	**	NS	NS	***	***
2018 Wheat	L x G x T	NS	NS	NS	NS	NS	NS	NS
	L x T	NS	NS	NS	NS	NS	NS	NS
	L	NS	NS	NS	***	***	***	NS
	G	NS	NS	NS	NS	NS	NS	NS
	T	**	NS	NS	NS	NS	***	***
2019 Canola	L x G x T	NS	N/A	NS	NS	NS	NS	NS
	L x T	NS	N/A	NS	NS	NS	NS	NS
	L	NS	N/A	NS	***	***	***	NS
	G	NS	N/A	NS	***	***	*	NS
	T	***	N/A	NS	NS	NS	NS	*
2020 Barley	L x G x T	NS	NS	NS	NS	NS	NS	NS
	L x T	NS	NS	NS	NS	NS	NS	***
	L	NS	NS	**	***	***	**	***
	G	NS	NS	NS	NS	NS	NS	NS
	T	NS	NS	NS	***	***	NS	***

Notes: L = lime; G = gypsum; T = tillage; NS = non-significant, N/A = not assessed, WUE = water use efficiency; * = significant at P≤0.05; ** = significant at P≤0.01; *** = significant at P≤0.001

Lime treatments did not have any significant effect on the plant emergence counts in any of the seasons (data not presented), however, it significantly improved the number of wheat ears per unit area (lime treatments had 113 ears per m^2 compared to 100 ears per m^2 in the unlimed control, LSD 5% = 8 ears per m^2) in 2017 (data not presented). Lime treatments also significantly increased wheat shoot biomass yield compared to the unlimed control (LSD 5% = 0.19 t/ha) in 2017 but there was no difference observed between the 2, 4, or 6 t/ha lime rates

(Figure 3a). Lime treatments did not improve wheat shoot biomass yield in 2018, and canola shoot biomass yield was not measured in 2019. Barley shoot biomass yield in 2020 increased with all lime rates compared to the unlimed control (Figure 3a).

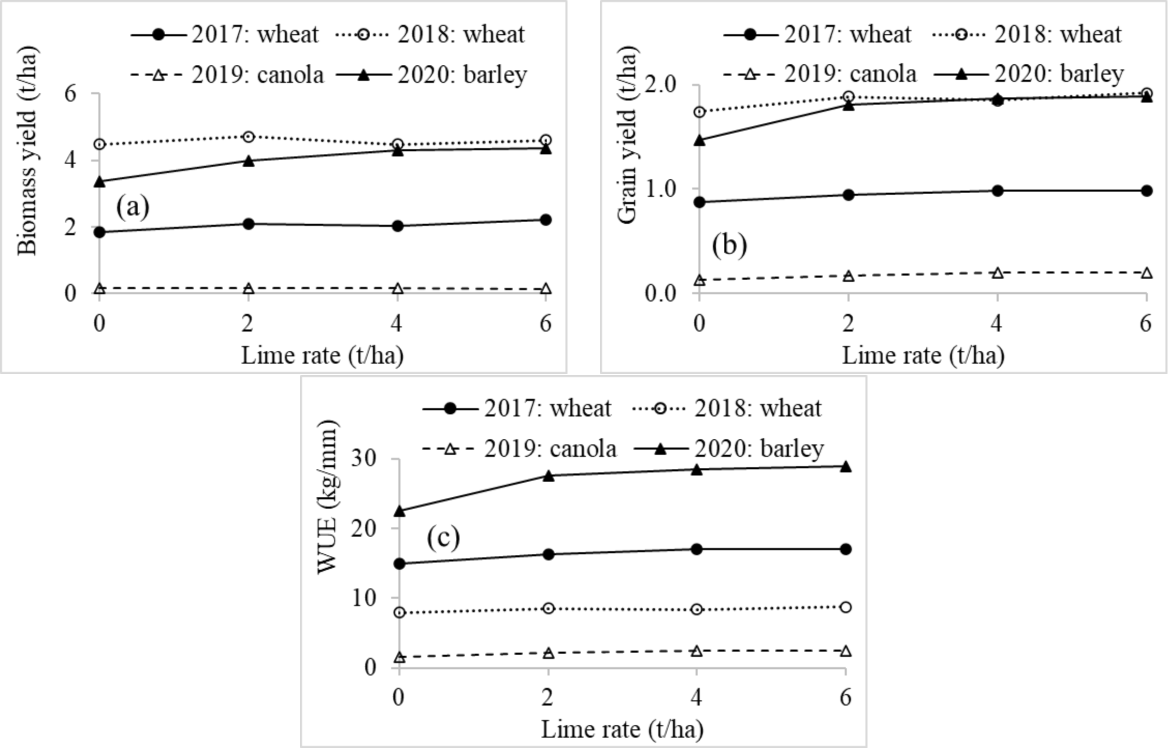

Figure 3. Effect of lime treatments on (a) biomass, (b) grain yield, and (c) water use efficiency (WUE) of wheat, barley and canola crop. Y-axis values are different for different variables

None of the interactions between lime, gypsum and tillage treatments significantly influenced grain yield and grain size, in any of the seasons (Table 3). Gypsum treatments did not affect the grain yield and grain size of wheat (in 2017 and 2018) and barley (in 2020), but significantly increased both grain yield and grain size of canola in 2019 compared to the zero gypsum treatment, with higher rates of gypsum having a greater impact (Table 3 and Appendix 1). Tillage treatments had no significant effect on wheat grain yield in 2017 and 2018 but significantly decreased barley grain yield in 2020 (Appendix 2). Tillage had no significant effect on canola grain yield in 2019. Tillage treatments significantly increased the grain protein content of all four crops over the study period (Table 4). Tillage treatment increased the 1000-grain weight of wheat in 2017 and 2018, but no such effect was observed on the 1000-grain weight of canola in 2019 and barley in 2020 (Appendix 2).

Table 4. Effects of lime and tillage on the grain protein contents (%) of wheat, barley and canola

Lime rates (t/ha)	2017 (wheat)		2018 (wheat)		2019 (canola)		2020 (barley)	
	No tilled	Tilled	No tilled	Tilled	No tilled	Tilled	No tilled	Tilled
0	10.91^{a}	12.37^{b}	9.48^{a}	9.63^{a}	21.39^{a}	21.28^{a}	14.85^{b}	15.26^{b}
2	11.00^{a}	12.33^{b}	9.34^{a}	9.68^{a}	21.18^{a}	22.25^{a}	13.53^{a}	15.19^{b}
4	10.92^{a}	12.51^{b}	9.35^{a}	9.69^{a}	21.58^{a}	21.71^{a}	13.35^{a}	14.88^{b}
6	10.91^{a}	12.56^{b}	9.25^{a}	9.71^{a}	21.62^{a}	22.07^{a}	13.06^{a}	14.80^{b}
LSD 5% (L x T)	0.40		0.29		0.69		0.51	

Notes: L = lime rates; T = tillage; LSD = least significant difference; mean value of the protein contents accompanying different letters is significant (within the same season) at $P \leq 0.05$.

Lime treatments increased the grain yield and water use efficiency (WUE) of wheat, canola, and barley crops (Table 3, Figures 3b and 3c). In 2017, 2018 and 2020 lime treatment increased cereal (wheat and barley) grain yield by 8–26% compared to unlimed control but there was no difference among 2, 4, and 6 t/ha lime rates (Figure 3b). The barley yield increase in response to lime was greater than that for wheat. In 2019 canola, the effect of lime rates was significant where higher lime rates (4 and 6 t/ha) had greater yield increase compared to 0 and 2 t/ha lime rates (Figure 3b). In the 2017 season, lime increased the WUE of wheat from 15.0 kg/mm in the control to 17.0 kg/mm in the limed plot (Figure 3c). In the 2018 season, lime increased the WUE of wheat from 7.9 kg/mm in the control to 8.7 kg/mm in the limed plot. And in the 2020 season, lime increased the WUE of barley from 22.6 kg/mm in the control to 29.0 kg/mm in the limed plot. Lime treatment also increased the average kernel/seed size of wheat, canola and barley (data not presented).

3.2.2 Improvement in Soil Acidity

Soil pH and extractable aluminium concentration (EAC) were measured in July 2018 and 2020 from eight different depths. In both years, the interaction of lime rate x depth, tillage x depth, as well as the individual effects of lime and tillage, was significant to increase soil pH (Figure 4) and decreasing EAC (Figure 5). There was no significant interaction observed with gypsum or a main effect of gypsum to increase soil pH or decrease EAC (Appendix 3).

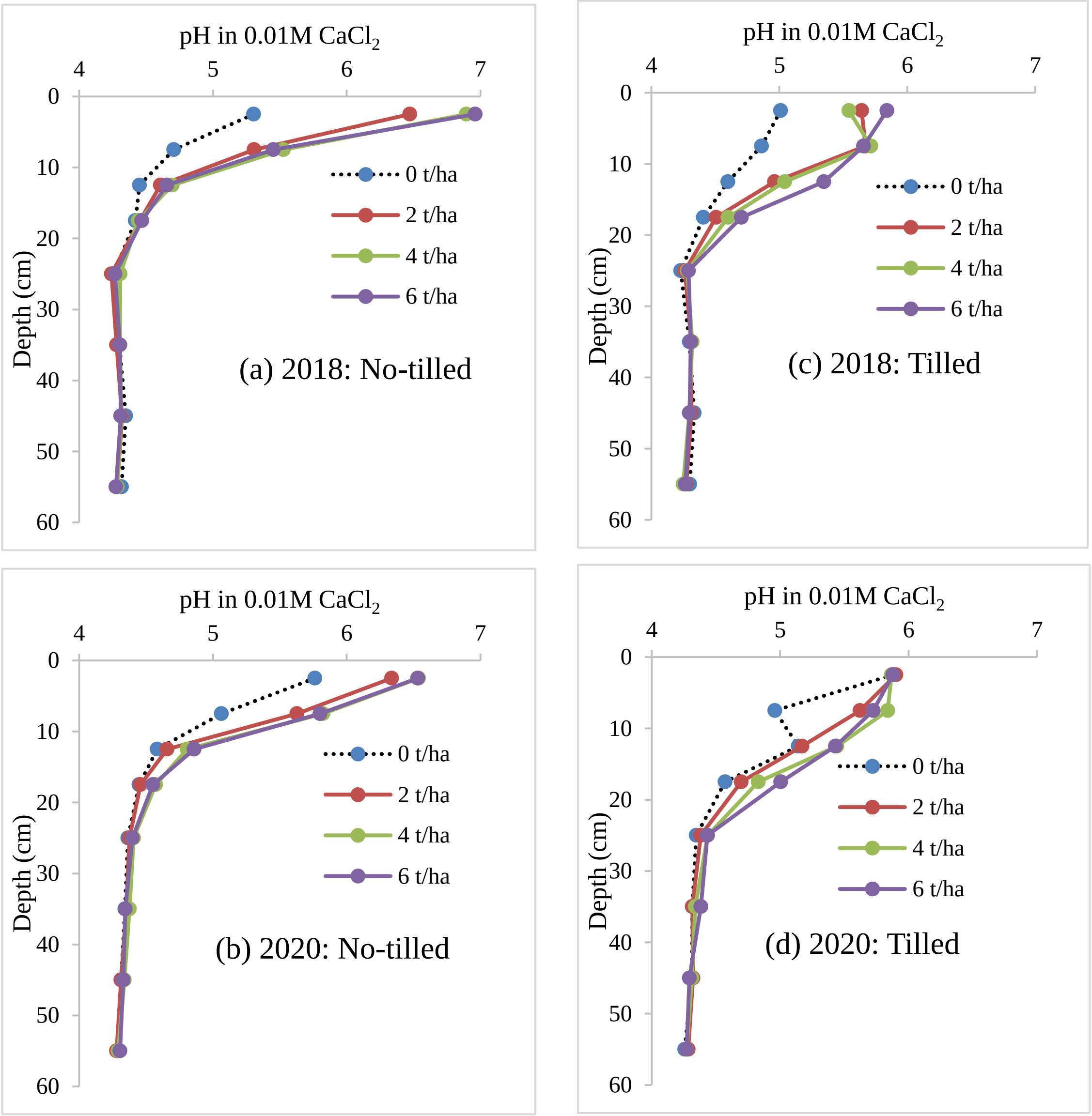

Figure 4. Soil pH profiles for different lime treatments under no-tilled (a and b) and tilled (c and d) treatments in 2018 (a and c) and 2020 (b and d). Statistics: Least significant difference at 5% (2018) lime rates x depth = 0.17 and tillage x depths = 0.12 pH units and (2020) lime rates x depth = 0.17 and tillage x depths = 0.13 pH units

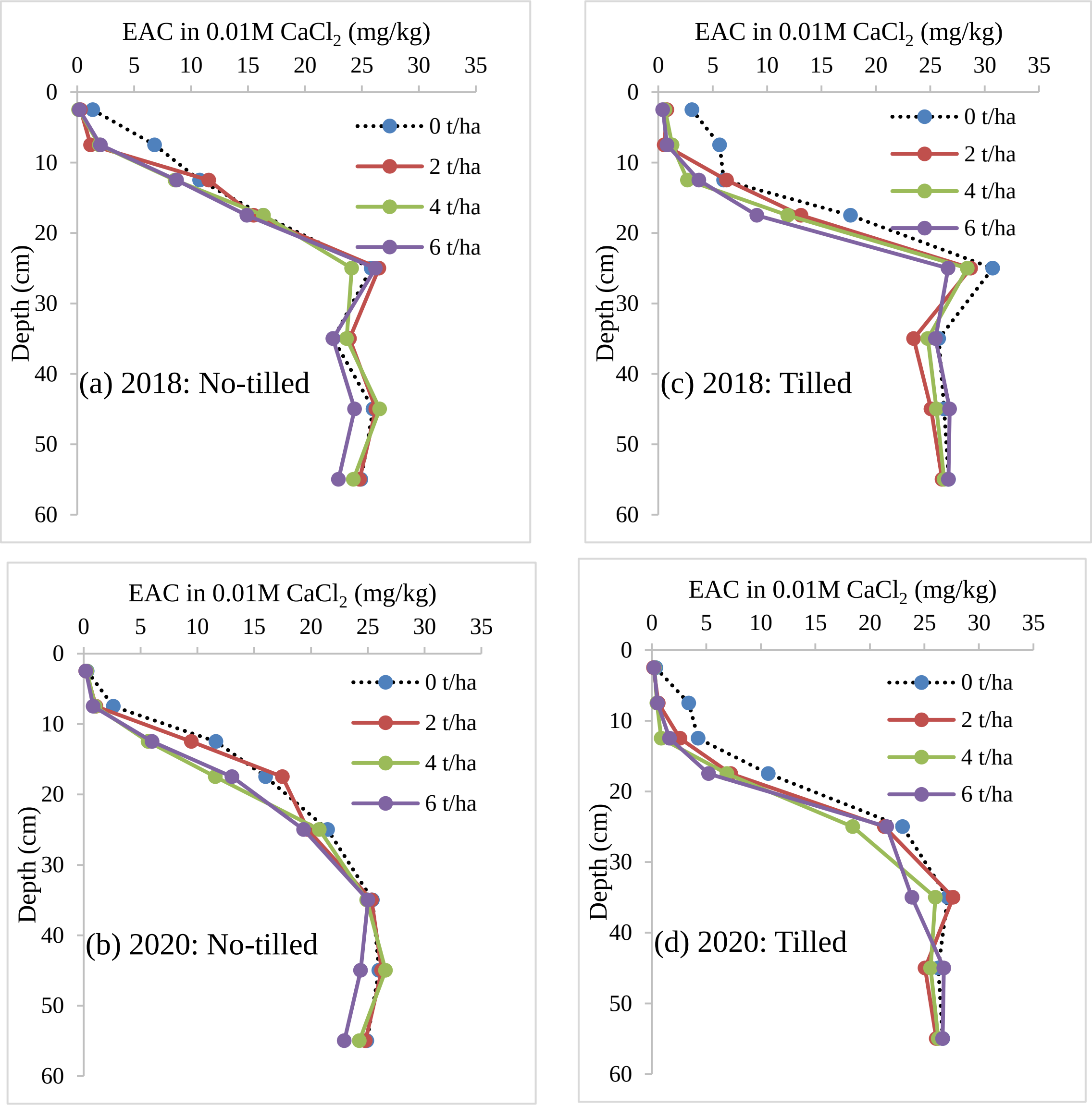

Figure 5. Extractable aluminium concentration profiles for different lime treatments under no-tilled (a and b) and tilled (c and d) treatments in 2018 (a and c) and 2020 (b and d). Statistics: Least significant difference at 5% for (2018) lime rates x depth = 2.44 and tillage x depths = 1.72 mg/kg and (2020) lime rates x depth = 2.02 and tillage x depths = 1.43 mg/kg

In both years, in the no-till treatments, all lime treatments had significantly higher soil pH (Figures 4a and 4b) and lower EAC (Figures 5a and 5b) in 0–5, 5–10 cm depths compared to the unlimed, no-till, control plots. In no-till treatments, there was no increase in soil pH or decline in EAC below 10 cm depth, irrespective of lime application. On the other hand, with tillage, all lime rates (except for the 2 t/ha lime rate in 2020) had significantly increased soil pH (Figures 4c and 4d) and decreased soil EAC (Figures 5c and 5d) in 0–20 cm depths in both 2018 and 2020 compared to the unlimed control treatment. No significant increase in soil pH and decrease in EAC were recorded below 20 cm depth in either year of measurement (Figures 4c, 4d, 5c and 5d).

4. Discussion

4.1 Shallow Strategic Tillage Improves Soil Acidity and Root Growth Instantaneously but Does not Increase Grain Yield and Water Use Efficiency (WUE).

Results from the controlled environment experiment demonstrate that the incorporation of lime at low rates to a subsoil and a mixed soil can increase the soil pH and decrease EAC to non-toxic levels within five weeks. Field incorporation of lime at comparatively higher rates using shallow ST was also more effective in increasing soil pH and decreasing EAC to the depth of incorporation, i.e., 0–20 cm depth, compared to the surface application of lime at equivalent rates. For the 0–10 cm depth, however, the surface application of lime was superior to the incorporation of lime for increasing soil pH and decreasing EAC, but lime did not move below the 10 cm depth. Similar results were observed by Li et al. (2019) and Azam and Gazey (2020) where the surface application of lime didn't increase soil pH at a depth below 20 cm from the surface even after 8–24 years of application.

In this experiment, surface liming was as efficient as lime incorporation by tillage in increasing grain yield and WUE from the first year through to the fourth year of observation. In contrast, Li et al. (2019) only observed a significant yield response from surface liming after a few years following lime application in acidic soil. In the current study, the soil was highly acidic (pH 4.35 for the top 15 cm and 3.95 for 20–40 cm) and aluminium was at toxic concentrations (Table 1, Figure 4, and Figure 5). Application of lime promptly increased soil pH and decreased EAC which can improve root growth that could result in improved uptake of major macronutrients (Scanlan & Davies, 2019). In these responsive circumstances, an increase in crop grain yield and subsequently WUE from the first year of application to the fourth year might be expected.

Although lime incorporation by shallow tillage improved soil acidity up to 20 cm depth in the current study, there was not any significant yield benefit observed over surface liming. The reason for this might include the subsoil (20–40 cm) pH which was still very acidic (pH < 4, Figure 5) even after lime incorporation which might continue to restrict root growth and nutrient exploration (Reynolds et al., 2018). Another reason for not gaining any yield advantage by lime incorporation from shallow tillage could be related to the damage to the soil structure (Nunes, Karlen & Moorman, 2020) without any improvement in the deeper acidic subsoil below 20 cm depth. Shallow tillage can also increase the loss of soil water through enhanced evaporation rates (Betti & Azam, 2019). If lime could be incorporated to deeper than 25–30 cm depth, then crop yield and WUE could increase further beyond that achieved with surface liming (Davies et al., 2019; Azam & Gazey, 2020).

4.2 Gypsum Application with Lime Improved Root Growth in the Pots but did not Improve Soil pH or Cereal Grain Yield and Water Use Efficiency (WUE).

The combined application of lime and gypsum did increase the early root growth of major grain crops in a subsoil and a mixed soil in the pot experiment though this was not consistent across all treatment combinations. The improvement in root growth was influenced more by lime than by gypsum because lime increased soil pH and decreased EAC (Whitten, 2002; Delhaize & Ryan, 1995). While gypsum application may have an additive effect on root growth due to decreased activity of aluminium as reported in the literature (Ulrich, Mayer & Khanna, 1980), the amount of aluminium in soil solution (>50 µM) was still high enough to stop production of fine roots and root hairs (Menzies, Edwards & Bell, 1994). Therefore, the additive effect of gypsum may be through improving the uptake of nutrients (e.g. phosphorus and sulfur) which play an important role in the early growth of seedlings (Sumner et al., 1986).

Given that surface applied lime can take many years to increase soil pH below the depth of lime incorporation and subsequently increase grain yield (Li et al., 2019), compared to much quicker results from gypsum application (Mclay, Ritchie & Porter, 1994), the expectation was a combined application of the two ameliorants would be a solution to manage subsoil acidity. The results from the field experiment demonstrated that gypsum was not effective in improving soil acidity or the yield and WUE of wheat and barley but did improve canola yield and WUE of canola. The grain yield of canola was poor in 2019 and didn't exceed 0.2 t per hectare even for the highest 3 t per hectare gypsum application rate. These results also support findings from previous studies that an improvement in soil pH and EAC through liming or combined application of lime and gypsum has the potential to benefit high-value crops such as canola (Whitten, 2002), which are more responsive than cereals to improved nutrition (e.g. phosphorus, sulphur) supply (Balint, Rengel & Allen, 2008).

4.3 Measurements of pH and Aluminium are Equivalent in Diagnosing Soil Acidity.

When soil pH and EAC are measured in $CaCl_2$ extract, they are strongly and exponentially related for a single soil type (Anderson, Pathan, Easton, Hall & Sharma, 2020). In our pot experiment, the relationship between pH and EAC was strong for both subsoil and mixed soil under lime and lime plus gypsum treatments (Figures 1c and 1f). Therefore, the measurement of one parameter such as pH, where pH measurement is much cheaper and less complicated (Rayment & Lyons, 2011), could be used to predict the status of other parameters such as EAC (Conyers & Poile, 2018). As farming system practices are evolving toward precision agriculture, farmers are adopting variable rate liming so they can accurately estimate the lime requirement for specific areas within their paddocks (Johnson & Richard, 2010). In our pot experiment, barley (r^2 = 0.91), wheat (r^2 = 0.77) and canola (r^2 = 0.70) root length had a moderate to a strong relationship with soil pH in the subsoil (Figure 6). Root length of barley (r^2 = 0.93), wheat (r^2 = 0.78) and canola (r^2 = 0.72) also had an equally moderate to strong relationship with soil EAC. Therefore, while diagnosing subsoil acidity, considering the EAC measurement as superior over the pH, as recommended by Anderson and Bell (2019), might not be applicable to the management of a specific soil type.

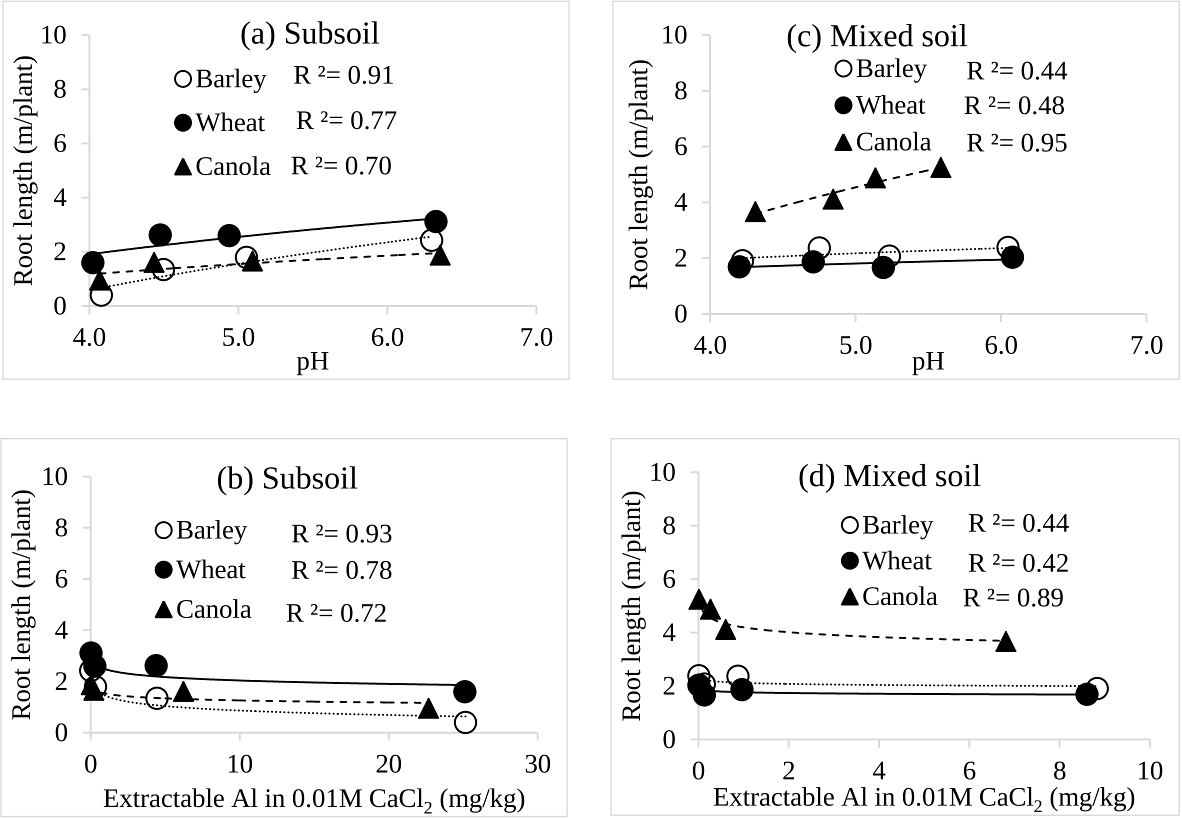

Figure 6. Relationship of soil pH and extractable aluminium with root length of barley, wheat and canola in subsoil (left) and mixed soil. Axis values are different for different variables. Values on X and Y-axes vary due to different parameters and levels of response by different crops

While tillage is used for amelioration of subsoil acidity, tillage without addition of lime may mix undissolved lime or dilute acidic subsoil with higher pH topsoil resulting in an increase in pH and a decrease in EAC, as we have also seen in both glasshouse (for mixed soil) and field experiments (tilled soil without lime). In tilled soil, the relationship between soil pH and root growth or EAC and root growth of most crops can be weaker than that of non-tilled subsoil (Robert, 1989). Nevertheless, measurement of both soil pH and EAC can equally be used for the diagnosis of tilled soil for prediction of the improvement in plant root growth and grain yield. In such cases, farmers may consider the cheaper and less complicated measurement of their acidic soil (soil pH) to be superior for determining the lime requirement.

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Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Informed consent

Obtained.

Ethics approval

The Publication Ethics Committee of the Canadian Center of Science and Education.

The journal's policies adhere to the Core Practices established by the Committee on Publication Ethics (COPE).

Provenance and peer review

Not commissioned; externally double-blind peer reviewed.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Data sharing statement

No additional data are available.

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Appendix

Appendix 1. Effect of gypsum application on plant establishment, biomass yield, grain yield and 1000-grain weight of wheat, barley and canola

Year and crop	Gypsum rates (t/ha)	Establishment (plant/m$^{2)}$	Biomass yield (t/ha)	Grain yield (t/ha)	1000-grain weight (g)
2017 (wheat)	0	8	2.02^{a}	0.92^{a}	40.39^{a}
	1	7	2.02^{a}	0.96^{a}	40.32^{a}
	2	7	2.08^{a}	0.95^{a}	40.06^{a}
	3	7	2.05^{a}	0.96^{a}	39.96^{a}
	LSD 5%	*2*	*0.19*	*0.05*	*0.70*
2018 (wheat)	0	57^{a}	4.45^{a}	1.79^{a}	36.06^{a}
	1	58^{a}	4.68^{a}	1.87^{a}	36.07^{a}
	2	58^{a}	4.60^{a}	1.87^{a}	35.88^{a}
	3	55^{a}	4.52^{a}	1.88^{a}	35.75^{a}
	LSD 5%	5	0.35	0.09	0.62
2019 (canola)	0	N/A	0.16^{a}	0.15^{a}	3.47^{a}
	1	N/A	0.17^{a}	0.18^{b}	3.48^{a}
	2	N/A	0.17^{a}	0.18^{b}	3.57^{a}
	3	N/A	0.17^{a}	0.19^{b}	3.51^{a}
	LSD 5%	N/A	0.01	0.02	0.08
2020 (barley)	0	77^{a}	3.93^{a}	1.72^{a}	32.42^{a}
	1	90^{a}	3.99^{a}	1.73^{a}	32.36^{a}
	2	78^{a}	4.08^{a}	1.72^{a}	32.14^{a}
	3	76^{a}	4.02^{a}	1.72^{a}	32.15^{a}
	LSD 5%	16	0.35	0.13	0.59

Notes: N/A = not assessed; LSD = least significant difference; mean value of different parameters accompanying different letters is significant (within the same season) at P≤0.05.

Appendix 2. Effect of tillage on plant establishment, biomass yield, grain yield and 1000-grain weight of wheat, barley and canola

Year and crop	Tillage	Establishment (plant/m$^{2)}$	Biomass yield (t/ha)	Grain yield (t/ha)	1000-grain weight (g)
2017 (wheat)	No-tilled	13	2.16^{b}	0.96^{a}	39.04^{a}
	Tilled	2	1.93^{a}	0.94^{a}	41.32^{b}
	LSD 5%	*1*	*0.14*	*0.04*	*0.35*
2018 (wheat)	No-tilled	52^{a}	4.59^{a}	1.82^{a}	35.53^{a}
	Tilled	59^{b}	4.54^{a}	1.88^{a}	36.36^{b}
	LSD 5%	*4*	*0.25*	*0.06*	*0.44*
2019 (canola)	No-tilled	30^{a}	0.16^{a}	0.18^{a}	3.49^{a}
	Tilled	55^{b}	0.17^{a}	0.17^{a}	3.52^{a}
	LSD 5%	*6*	*0.01*	*0.02*	*0.06*
2020 (barley)	No-tilled	83^{a}	4.07^{a}	1.79^{b}	32.11^{a}
	Tilled	77^{a}	3.94^{a}	1.66^{a}	32.43^{a}
	LSD 5%	*11*	*0.25*	*0.09*	*0.41*

Notes: N/A = not assessed; LSD = least significant difference; mean value of different parameters accompanying different letters is significant (within the same season) at P≤0.05.

Appendix 3. Effect of gypsum application on soil pH in no-tilled and tilled soils measured in 0.01M $CaCl_2$

Depth (cm)	No-tilled				Tilled			
	Gypsum rates (t/ha)				Gypsum rates (t/ha)			
	0	1	2	3	0	1	2	3
----------July 2018----------								
0 - 5	4.8	6.0	6.4	6.5	4.5	5.1	5.0	5.3
5 - 10	4.2	4.8	5.0	5.0	4.4	5.2	5.2	5.2
10 - 15	4.0	4.1	4.2	4.2	4.1	4.5	4.5	4.8
15 - 20	3.9	4.0	3.9	4.0	3.9	4.0	4.1	4.2
20 - 30	3.8	3.7	3.8	3.8	3.7	3.8	3.8	3.8
30 - 40	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8
40 - 50	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8
50 - 60	3.8	3.8	3.8	3.8	3.8	3.8	3.7	3.8
----------July 2020----------								
0 - 5	6.0	6.1	5.6	5.6	5.3	5.4	5.4	5.3
5 - 10	5.3	5.2	4.8	5.0	5.1	5.1	4.9	5.1
10 - 15	4.2	4.2	4.2	4.3	5.0	4.5	4.8	4.9
15 - 20	4.0	4.0	4.0	4.0	4.3	4.2	4.4	4.2
20 - 30	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9
30 - 40	3.9	3.8	3.9	3.9	3.9	3.8	3.8	3.8
40 - 50	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8
50 - 60	3.8	3.8	3.8	3.8	3.8	3.8	3.7	3.8

Appendix 4. Effect of gypsum application on extractable aluminium concentration in no-tilled and tilled soils measured in 0.01M $CaCl_2$

Depth (cm)	No-tilled				Tilled			
	Gypsum rates (t/ha)				Gypsum rates (t/ha)			
	0	1	2	3	0	1	2	3
----------July 2018----------								
0 - 5	1.4	0.3	0.1	0.2	3.1	0.8	0.6	0.4
5 - 10	6.8	1.2	2.0	2.1	5.6	0.6	1.3	0.8
10 - 15	10.8	11.6	8.6	8.7	6.0	6.3	2.7	3.7
15 - 20	16.3	15.5	16.4	14.9	17.7	13.1	11.9	9.1
20 - 30	25.8	26.5	24.1	26.2	30.7	28.7	28.4	26.6
30 - 40	22.5	23.9	23.7	22.5	25.8	23.5	24.8	25.5
40 - 50	26.0	26.2	26.6	24.4	26.3	25.1	25.6	26.8
50 - 60	24.9	24.8	24.3	22.9	26.7	26.1	26.3	26.7
----------July 2020----------								
0 - 5	0.1	0.1	0.4	0.3	0.2	0.3	0.3	0.2
5 - 10	1.8	0.7	1.7	1.4	1.1	1.1	1.6	1.2
10 - 15	8.8	7.8	9.2	7.0	1.0	2.9	3.0	2.5
15 - 20	14.3	12.2	15.1	16.5	6.0	9.4	6.8	7.9
20 - 30	20.5	21.0	18.5	21.3	21.2	23.2	19.6	20.2
30 - 40	27.1	25.8	24.2	23.5	25.7	26.9	25.6	26.4
40 - 50	27.6	25.1	24.7	25.7	26.5	26.5	25.1	25.6
50 - 60	25.1	24.3	24.2	23.3	25.1	28.3	25.4	27.0