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Liming remediates soil acidity and improves crop yield and profitability - a meta-analysis

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Soil acidity reduces base cations required for plant growth and may result in phytotoxic concentrations of soluble aluminum. Liming acidic soils is generally promoted as an effective management practice to increase soil pH, base cation concentrations, and ameliorate toxicity caused by aluminum and manganese. Through a global literature review using data published from field experiments on liming, the objective of this paper is to understand the effects of liming on soil pH, crop yields, and economic profitability. The results show that liming positively influenced crop yields and soil pH, implying that various lime sources can increase soil pH and crop productivity. The effect sizes of liming on crop yields when lime was incorporated into soils were higher than surface application irrespective of tillage practice. Liming under no-tillage (NT) compared to conventional tillage (CT) management showed higher effect sizes for crop yields. Liming increased effect sizes for crop yields in fertilized compared with unfertilized trials. Gypsum, calcium hydroxide and calcium carbonate showed higher effect sizes when compared with Cement Klin Dust (CKD), dolomite and wood ash. The results show that liming increased yields for all crops except potatoes and oats. Liming generally increases soil pH and changes in soil pH increased with higher lime application rates and yield increases were proportional to the magnitude of increases in soil pH. The profitability of liming differed with crop type and liming rate, being more profitable at lower liming rates. Overall, this meta-analysis shows that liming decreases soil acidity and improves crop yields. Attaining maximum gains from liming agricultural crops under acidic soil conditions requires an understanding of the appropriate lime rates required for specific crops and soil types to ensure overall profitability for producers and sustainable improvement of soil health.

KEYWORDS

lime, fertilizer, crop yield, soil acidity, management practice

1 Introduction

Soil acidification is the process through which soil pH declines causing soils to be acidic (Buni Adane, 2014; Smith & Hardie, 2022). It is caused by hydrogen ions (H^+) being discharged into soils during the cycling of carbon (C), nitrogen (N), sulfur (S) and fertilizer reactions which trigger the displacement and leaching of base cations and enhance the solubility of toxic elements i.e., aluminum (Al^{3+}) and manganese (Mn^{2+}) (Bolan et al., 2003; Lesturgez et al., 2006). As soil acidity increases (pH decreases), the concentrations aluminum (Al^{3+}) and hydrogen (H^+) cations in the soil increase while base cations such as calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+) and sodium (Na^+) are leached out of the soil (von Uexküll and Mutert, 1995; Agegnehu et al., 2021). Soil acidification processes are buffered by the presence of base cations in the soil, and deficiency of these base cations is a major concern because they play an active role in soil acid neutralization and plant development (Tian & Niu, 2015; Fenn et al., 2006). Acidic soils negatively impact agricultural productivity and occupy approximately 30-40% of agricultural land globally (von Uexküll & Mutert, 1995; Bian et al., 2013; Alemu et al., 2022).

Crops differ in their sensitivity to low soil pH (Hijbeek et al., 2021). Generally, with low soil pH, Al^{3+} enters the cells of root tips and inhibits root elongation thus causing stunted root growth leading to diminished water and nutrient uptake. However, Al^{3+} tolerant plants have the ability to remove Al^{3+} from roots by releasing organic acids such as citrate and malate that chelate Al^{3+} (Sanjib Kumar Panda and Matsumoto, 2009). The optimal soil pH for many crops ranges between 6.0 and 7.0 because all essential nutrients can exist in available forms in this range (Rosen & Bierman, 2005). Soil pH can be increased using soil amendments with a neutralizing effect, such as lime (Hijbeek et al., 2021). Several studies have reported liming as a strategy for increasing soil pH and it is one of the most inexpensive practices for managing soil acidity (Orton et al., 2018). Liming materials are mostly hydroxides, oxides, carbonates and silicates of calcium and magnesium (Anderson et al., 2013). Application of lime can increase soil pH, availability of essential plant nutrients, crop yields and prevent solubility of manganese and aluminum (Goulding, 2016; Holland et al., 2018; Holland et al., 2019). Liming promotes nitrification and N-mineralization in no-till soils thus increasing soil nitrate (Fuentes et al., 2006). It enhances microbial activities in soils, triggering the mineralization of soil organic matter and residues (Liao et al., 2020). Liming promotes the survival of healthy soil microorganisms and can advance earthworm colonization in soils which positively impacts soil structure (Costa, M.C.G, 2012; Mahmud & Chong, 2022). Also, previous review studies have shown that lime can be utilized to remediate cadmium (Cd) in Cd-contaminated soils (He et al., 2021). In addition, increased nutrient use efficiency in grasslands within livestock grazing systems was associated with liming (Abdalla et al., 2022).

Research on liming reports that management or agricultural practices plays a significant role in the effectiveness of liming. Agricultural management practices pertinent to liming are sources of lime materials, rate of application, method, and frequency of application (Anderson et al., 2013). In studies conducted in Australia and the United States on wheat and clover respectively, it was reported that finer particle size compared to coarse lime material was more efficient in increasing soil pH regardless of lime rate (Scott et al., 1992; Haby & Leonard, 2002). Viadé et al. (2011) reported that the degree of fineness of liming material is vital because liming materials with finer particles are more soluble and disperse faster in the soil, while coarse lime materials react slowly. Blumenschein et al. (2018) found that deep vertical placement of lime at different soil depths with the aid of a custom-built shank in addition to surface lime application significantly increased maize growth when compared with the control. Furthermore, the chemical effects of lime were only observed in the layer of application. Smith et al., (1986) found that the combination of $CaCO_3$ + 3% Mg gave higher responses for tomatoes, sweet corn and cabbage when compared with dolomitic lime in Pennsylvania. de Campos et al. (2022) noted that higher lime rates increased Ca^{2+} and Mg^{2+} concentrations while lime moved to deeper soil layers more efficiently with higher lime rates in fields planted with sugarcane in Brazil. Contradictory findings have been reported on the impact of liming on soil acidity under various tillage practices. Soon & Arshad (2005) reported that liming under NT systems significantly increased crop yields and N uptake when compared with liming under tillage systems. Arshad & Gill (1996) found that liming increased yields of field pea in NT and CT, however, higher yields were observed in NT due to higher soil moisture. Though, Auler et al. (2019) found that lime incorporation *via* plowing and harrowing increased crop dry mass when compared with surface application in NT systems.

Liming soils is beneficial but comes at a financial cost, as a large amount of lime is generally required to increase soil pH. The use of agricultural lime is low because of uncertainties on return of investment, crop yields and different factors such as lack of government support and poor lime supply chain dissuade farmers from lime use (Ennich & Lynn Forster, 1993). In a study conducted in Canada on wheat, barley, and canola by Haak (1990), a loss of income was recorded with liming while Bongiovanni & Lowenberg-Deboer (2000) reported increased economic returns for corn and soybeans with liming. These contrasting results make it important to assess the impact of liming on profitability and producers' return on investments.

Different review papers have looked at liming effects on soil properties, agricultural emissions, and yields (Paradelo et al., 2015; Holland et al., 2018; Li et al., 2019; Hijbeek et al., 2021). However, there is a lack of published research or review on understanding liming under different management practices on crop yields, soil pH and economic profitability. This meta-analysis on soil liming can provide relevant information to producers and researchers on the benefits and constraints of liming for better efficiency by synthesizing results from published literature and pinpointing research gaps and needs to allow producers to make informed decisions for sustainable soil management and improved agricultural productivity. This study review attempts to summarize and capture how liming can increase soil pH and crop yields under different agricultural practices. The specific objectives are to assess: 1) The effect of liming on soil pH and crop yields, 2) The role of management practice on the efficacy of liming, and 3) The profitability of liming.

2 Materials and methods

2.1 Literature search and selection

A literature review and meta-analysis were carried out to assess liming effects under different tillage, fertilizer type, crop type, lime method of application, lime rate and lime material on yield, soil pH and the economics of liming. A literature review search was carried out in Google Scholar and SCOPUS, peer reviewed journals published between 1966 – 2022 using the topic: "liming, soil amendment and soil acidification". In this review, lime materials were defined as any calcium or magnesium material applied to the soil prior to planting with the aim of raising soil pH. The lime materials considered were dolomite, calcium hydroxide ($Ca(OH)_2$), calcium oxide (CaO), cement kiln dust (CKD), gypsum ($CaSO_4$), calcium carbonate ($CaCO_3$) and wood ash. The following criteria were used for a study to be included in the meta-analysis i) non-limed plots (e.g., no lime was applied. We defined our control treatments as plots where no lime was applied.) ii) lime treatment plots to compare with the no lime plots, iii) the initial and final soil pH was recorded, iv) type of lime material used was stated (studies were excluded if this was not stated in the published study), v) agronomic practices stated such as tillage, method of lime application, liming rate and fertilizer type. This paired treatment was used to calculate the percentage yield increase due to liming.

The total number of papers searched was over 500. The data collected comprised of only field experiments (irrespective of soil type, climatic conditions, and crop) from 29 papers covering several countries (Canada, The United States, Nigeria, Ethiopia, Indonesia, China, Brazil, Turkey, Sweden, and Australia) and climatic zones (tropical regions, arid and temperate regions) (see: Table 1).

2.2 Data extraction and analysis

Information extracted included lime type, lime application rate, lime application method, initial and/or final soil pH, crop type and yield. In instances where yield and soil pH were presented graphically, data were extracted using the Web Plot Digitizer v. 3.8 (http://arohatgi.info/WebPlotDigitizer). The yield data were categorized according to crop species (i.e., legume, grain, root and tuber crops and vegetables). From the total 29 papers reviewed, only 23 reported an initial and final soil pH. Therefore, our effect size analysis was limited to final yields while the effect of other management practices on soil pH was summarized (Table 1). Where the papers reported multiple yield values, we used averages for all years. In some studies, different methods were used for soil pH determination. We made no conversions for the methods used to determine soil pH. Most of the studies were short-term liming experiments ranging between 1-5 years while some were long-term experiments ranging between 6-10 years. Crop yields were converted to tonnes per hectare (t ha^{-1}). Liming rates were also converted to t ha^{-1} for uniformity.

Data were analyzed with the R software (R core team 4.0). To assess the impacts of liming on crop yields between control and lime-treated plots in different crops, we used the "effsize" package and the cohen.d function" in R to calculate effect size and to understand how large an effect size is within a study (Cohen, 1998) (see: Figure 1). We did not apply the "effsize" method on soil pH due to missing data points on the final pH in the original studies.

To understand liming effects on yields, we use scatter plots (ggplot2 package in R) to assess the relationship between yields with and without liming (Figure 2B), yield increase due to liming and soil pH (Figure 2C) and changes in soil pH and lime rate (Figure 2D).

The percentage yield increase from liming was determined by equation 1.

$$\%\ yield\ \ increase = \left(\frac{\Delta Yield}{Yield\ \ from\ \ no\ \ lime\ \ treatment}\right)x\ \ 100 \quad [1]$$

where,

$$\Delta Yield = Yield\ \ from\ \ lime\ \ treatment - Yield\ \ from\ \ no\ \ lime\ \ treatment$$

and yield has units of t ha^{-1}.

To estimate the net revenue generated from a one-time lime application, we used the following equation.

$$Net\ \ revenue\ \ from\ \ lime\ \ application = (crop\ \ price\ \ x\ \ \Delta Yield - cost\ \ of\ \ lime\ \ application)x\ \ T \quad [2]$$

where crop price (\$ kg^{-1}) is the commodity price recorded in the 2020 FAOSTAT database, ΔYield is calculated according to Eq. [1] and was assumed to hold annually over the entire efficacy period (t ha^{-1} yr^{-1}), cost of lime application (\$ ha^{-1}) is the cost of a one-time lime application – the produce of application rate and lime price, and T the lime efficacy period for which values of 5, 10 and 15 yr were assumed.

A simple financial analysis was conducted to evaluate the profitability of liming by calculating net and gross revenue for different crop types and liming rates (low, medium, and high rates). The results were used to estimate the cumulative probability distribution of net revenue to better quantify the probability of positive or negative net revenue over the assumed efficacy period following a one-time lime application for each major crop type (Figures 3, 4). The bar plots in Figure 4 summarize the net revenue as a function of relative lime rates (low, med, and high rates as used in literature) and average overall assumed efficacy periods (5, 10, 15 years) according to crop type. We collected the price of the different crops used in this study from FAOSTAT database for 2020. We collected lime cost from local lime retailers in Alberta Canada.

3 Results and discussion

3.1 Global yield responses and crop-specific yield response to liming

The magnitude of the response of yield to liming varied for different studies and crop types (Table 2). Crops respond differently to lime application because of differences in their tolerance to soil acidity (Cifu et al., 2004; Holland et al., 2019). This meta-analysis

TABLE 1 Published studies on effects of liming on soil pH.

Country	Type of lime	Rate of lime (t/ha)	Application method	Effect on pH	source
Australia	Agricultural lime	2.5	Incorporation	Increased pH	Coventry et al., 1992
Australia	Agricultural lime	2.5	Soil surface (direct drill)	Increased pH	Coventry et al., 1992
Australia	Agricultural lime	2.5	Incorporation	Increased pH	Coventry et al., 1992
Australia	Agricultural lime	2.5	Soil surface (direct drill)	Increased pH	Coventry et al., 1992
Australia	Agricultural lime	1–4	Soil surface	NA	Farhoodi and Coventry, 2008
Australia	Calcitic	2.5-15	Incorporation	Increased pH	Maier et al., 2002
Brazil	Calcitic, Calcitic and Dolomitic blend	7.5	Soil surface	No effect	Bortoluzzi et al., 2014
Brazil	Dolomite	3.8	Soil surface	Increased pH	Castro and Crusciol, 2013
Brazil	Dolomite	1.5-4.5	Soil surface and incorporation	No effect	Costa et al, 2012
Brazil	Dolomite	1.3	Soil surface	NA	Ratke et al., 2014
Canada	NA	7.5	Incorporation	Increased pH	Arshad and Gill, 1996
Canada	CKD and Calcitic	0.5-2	Incorporation	No effect	Lafond and Simard, 1999
Canada	Limestone	6.7-20.1	Soil surface and incorporation	Increased pH	(Maclean et al., 1967)
Canada	Limestone	11–44	Incorporation	NA	Kowalenko et al., 1980
Croatia	Calcitic	5–20	NA	Increased pH	Andric et al., 2012
China	$Ca(OH)_2$	2.1	Soil surface	Increased pH	Liao et al, 2020
Ethiopia	$CaCO_3$	0.06-14	Soil surface (microdosing), incorporation and soil surface(broadcasting)	Increased pH	Alemu et al., 2022
Ethiopia	$CaCO_3$	3.6-7.2	Incorporation	NA	Fekadu et al., 2018
Ethiopia	$CaCO_3$	2.9-7.5	Incorporation	Increased pH	Lulu et al., 2022
Indonesia	NA	8	Incorporation	Increased pH	Hale et al., 2020
Nigeria	Gypsum Ag_lime and Agricultural lime + Gypsum	2.5-7.5	Incorporation	Increased pH	Anikwe et al., 2016
Nigeria	$CaCO_3$	2–20	Incorporation	Increased pH	Adeoye and Singh, 1985
Nigeria	$Ca(OH)_2$	0.5-2	Incorporation	Increased pH	Okpara et al., 2007
Nigeria	Calcitic	0.5	Incorporation	NA	Victoria et al., 2019
South Africa	Calcitic Lime	1	Soil surface	NA	van der Nest et al., 2022
United states of America	$CaSo_4$, Ag_lime,CaO, Calcitic and Dolomitic blend	0.448-1.15	Incorporation	Increased pH	Mayfield et al., 2001

(Continued)

TABLE 1 Continued

Country	Type of lime	Rate of lime (t/ha)	Application method	Effect on pH	source
United states of America	Wood ash	0.56-8.96	Incorporation	Increased pH	(Huang et al., 1992)

NA, Not Applicable.

shows that lime application increased yields in all crops except oats (*Aveno sativa*) and potatoes (*Solanum tuberosum*) (Table 2). Pan et al. (2019), in a study conducted in China, reported significant yield increases with liming of 505.3% and 20.7% for canola (*Brassica napus*) and sweet potatoes (*Ipomoea batatas*), respectively. Similarly, Cifu et al. (2004), in a 15-year long-term experiment, reported yield increases of 57.3% and 53.4% for wheat and sesame seeds, respectively. Higher crop yields with liming are linked to a decrease in soil acidity which leads to improvement in soil fertility in short- and long-term experiments. The effect size analysis (± 95% confidence intervals) showed significant effect sizes due to liming for grains and oilseeds, legumes, and vegetable crops (Figure 1). For all crops, yield increases due to liming ranged between 10-50%. The relationship between lime and no lime treatment yields also shows that liming increased yields for most crops except for some root and tuber crops such as potatoes (Figures 2A, B and Table 2). Negative responses of potatoes to liming might be because they are well adapted and can attain optimal yields at low soil pH and bring down the average ΔYield for root and tuber crops (Holland et al., 2018). This can be corroborated with studies conducted in Australia by Maier et al. (2002) where liming significantly decreased potatoes yields even at higher liming rates. Hence, the adaptation of crops like potatoes to soil acidity can reduce the effect of liming on yield (Li et al., 2019). In this meta-analysis, there was a positive effect of liming on legumes and this finding agreed with a previous report by Rice et al. (1977) which shows that liming can increase legumes yields by enhancing the growth and survival of soil rhizobia and nodule formation. Sirisuntornlak et al. (2021) reported that acidic soil can reduce leaf area, root-to-shoot ratio and dry matter resulting in lower grain yields; liming can ameliorate these detrimental effects. Increased crop yield following a one-time lime application can be sustained over longer periods of time. For example, studies conducted in Canada by Hamilton et al. (1964) showed that the liming effect on crop yields was observed 7 years after application. These results suggest that under conditions of low soil pH producers should consider lime application because of the cumulative benefits in overall crop productivity.

3.2 Lime type and application method affect crop yield responses

Crop yield was influenced by the type of lime material (Figure 1), in the following order: Calcium hydroxide > gypsum > calcium carbonate > dolomite > calcium oxide > CKD > wood ash. Calcium hydroxide ($Ca(OH)_2$) resulted in the highest yield increase (44.4%) while negative responses were observed with wood ash -3.25% compared to the control. The rate at which lime neutralizes soil acidity differs with lime material and the degree to which it can raise soil pH is strongly linked to the rate of solubility and

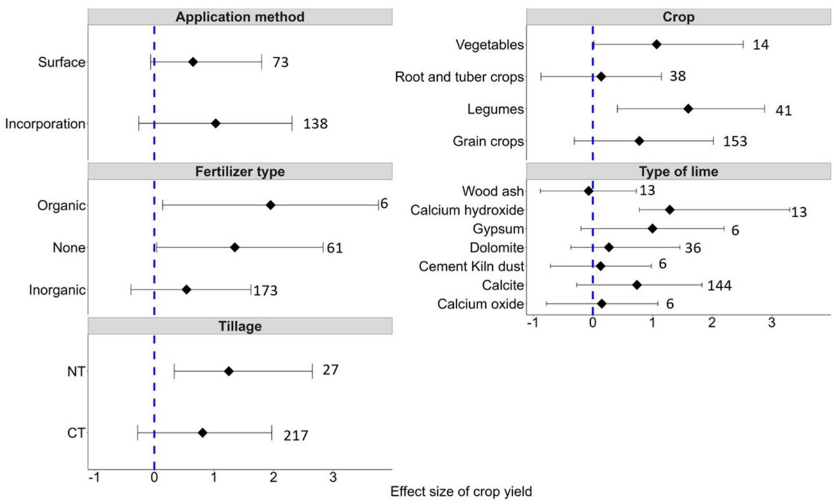

FIGURE 1
Effect size of crop yield under liming compare without liming in different management practices such as i) application method, ii) fertilizer type, iii) crop type, iv) type of lime, v) tillage (NT, No till and CT, conventional tillage). The effect of liming is consider significant if the 95% CI does not overlap with zero. The numbers indicate sample sizes.

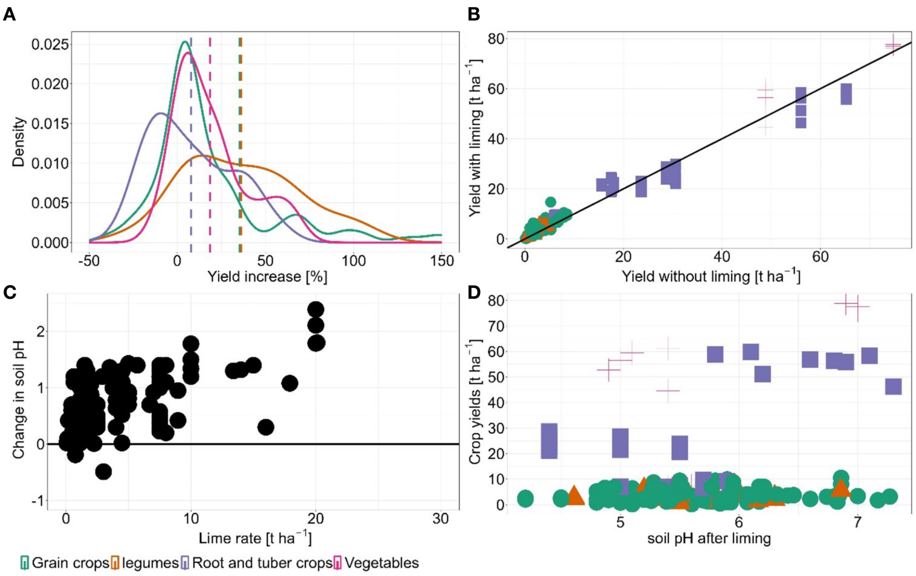

FIGURE 2
(A) Density plot indicating percentage yield increases due to liming for different crop types [colored dashedlines indicate the average yield increase]; **(B)** Crop yield due to liming versus without liming; black line indicates the 1: 1 line; **(C)** Changes in soil pH, at different lime application rates in (t ha^{-1}); **(D)** Crop yields of different crop type at various soil pH.

hydrolysis (Rippy et al., 2007). Goulding (2016) compared the neutralizing value of different liming materials. The neutralizing value of any lime material is related to the amount of carbonate or oxide the lime material comprises. A higher neutralizing value indicates higher carbonate or oxide levels in the lime material with better capacity in neutralizing soil pH. The neutralizing value of calcium hydroxide is higher than the other types of lime materials (Goulding, 2016). This may be the reason for higher effect sizes with calcium hydroxide However, calcium oxide and calcium hydroxide react very fast and are hard to manage under field conditions (Mahmud & Chong, 2022). Calcitic limestone reacts more quickly than dolomitic limestone because it is more soluble (Rippy et al., 2007; du Toit et al., 2022); this may also be the reason for larger effect sizes for calcitic limestone when compared with dolomitic limestone (Figure 1).

The effect size on yields when lime was incorporated into soils was 58.5% higher than when surface applied (Figure 1). To increase soil pH in deeper soil layers, incorporation is recommended because

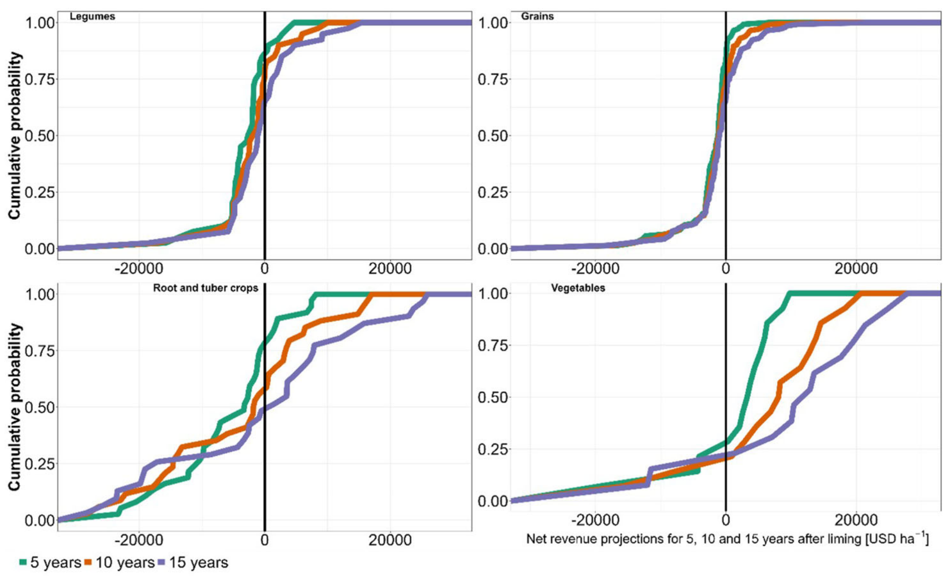

FIGURE 3
The cumulative probability of the net revenue generated from liming based on crop yields after liming (USD ha^{-1}) for legumes, grains, root and tubers and vegetables.

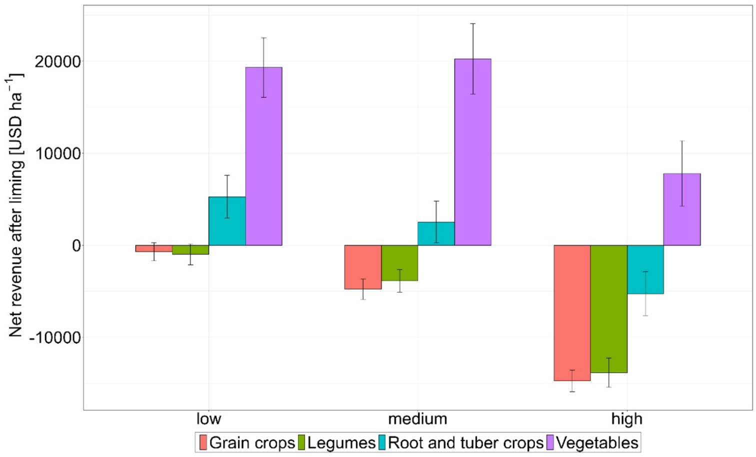

FIGURE 4
The effect of first-time lime applications at different lime rates (low=<5 t/ha, medium=5-10 t/ha, and high =>10 t/ha) on net revenue for grains, legumes, root and tuber crops and vegetables. Error bars represent standard errors.

TABLE 2 The effect of liming on different crop yields (t ha^{-1}) and soil pH (N indicates the number of observations per crop type).

Crop	Crop type	N	Yield t ha^{-1} unlimed	Yield t ha^{-1} limed	pH unlimed	pH limed	Reference
Wheat	Grains	35	2.43	2.71	5.37	5.97	Coventry et al, 1992; Huang et al, 1992; Lulu et al, 2022; Caires et al, 2005; Farhoodi and Coventry, 2008
Durum	Grains	6	2.45	2.67	4.66	4.87	Farhoodi and Coventry, 2008
Oats	Grains	4	4.32	3.79	4.2	5.5	Kowalenko et al, 1980, Castro and Crusciol, 2013
Barley	Grains	13	1.92	2.14	4.58	5.3	van der Nest et al, 2022, Caires et al, 2005; Farhoodi and Coventry, 2008
Maize	Grains	54	3.67	5.13	4.6	5.42	Victoria et al, 2019, Tshiabukole et al, 2022; Ratke et al, 2014; Hale et al, 2020Adeoye and Singh, 1985; Andric et al, 2012; Castro and Crusciol, 2013; Alemu et al, 2022 , Opala et al 2018, Caires et al, 2005
Rice	Grains	8	1.95	2.39	5.4	5.65	Castro and Crusciol, 2013, Liao et al 2020
Canola	Grains	6	1.97	2.02	4.51	4.94	Farhoodi and Coventry, 2008,
Sorghum	Grains	8	1.04	1.38	3.96	5.5	Adeoye and Singh, 1985
Soybean	Legumes	23	3.11	3.93	4.83	5.57	Caires et al, 2005; Okpara et al, 2007; Andric et al, 2012; Bortoluzzi et al, 2014 Castro and Crusciol, 2013
Groundnut	Legumes	8	2.05	2.36	4.03	5.19	Adeoye and Singh, 1985
Fababean	Legumes	9	0.87	1.43	5.1	NA	Fekadu et al., 2018
Pea	Legumes	6	2.63	3.16	4.93	6.18	Arshad and Gill, 1996
Cassava	Root and tuber	6	6.1	7.8	4.65	5.53	Anikwe et al, 2016
Potatoes	Root and tuber	32	32.22	31.13	4.96	5.62	Maclean et al, 1967; Maier et al, 2002, Lafond and Simard, 1999
Tomatoes	Vegetables	5	48.76	54.89	4.3	5.16	Mayfield et al, 2001
Cucumber	Vegetables	5	4.53	6.19	4.3	5.36	Mayfield et al, 2001
Sugarbeet	Vegetables	4	74.74	77.39	6.7	6.97	Olsson et al 2019

NA, Not Applicable.

lime is only effective on the soil layer it comes in contact with (Caires et al., 2005). Also, due to the gradual mobility of lime in soils, the incorporation of lime into soils is an effective method of ameliorating soil acidity rapidly (Azam & Gazey, 2021). On farmlands, the process of incorporating lime requires tillage, e.g., plowing and harrowing while surface lime application is commonly practiced in NT systems (de Moraes et al., 2023). Guzman et al. (2006), in a long-term study conducted in the United States, showed that when lime was surface-applied, soil pH in NT and CT plots decreased with soil depth. However, soil pH was significantly higher on soil surfaces for NT systems up to a depth of 2.5 cm but lower from 2.5 - 5.0 cm when compared with CT signifying that the movement of lime may be constrained in NT systems. Therefore, a liming approach that can accomplish a quicker lime response into deeper soil layers for surface application needs to the developed to enable the amelioration of subsoil acidity under conditions of minimal soil disturbance.

3.3 Liming effect on yield response was dependent on tillage

The effectiveness of lime differs based on the tillage method adopted (Holland et al., 2018). The liming effect size on yields for NT was higher than CT by 54.3% (Figure 1). Ebelhar et al., 2011 reported high magnesium and calcium content on soil surfaces of NT systems when compared with CT. Greater pH, calcium and magnesium in surface layers of NT fields following surface applications of lime may help to explain the greater effect size under NT, especially for shallow-seeded crops like grains and oilseeds. Furthermore, in the same study, liming acidic soils under NT systems for a period of 10 years increased both surface soil pH and pH at soil depths. Tiritan et al. (2016) also reported that surface application of lime was effective in improving crop yields and soil chemical attributes in NT systems. The choice of tillage can have positive or negative consequences on soil structure (Hellner et al., 2018). Calcium and magnesium components of liming can promote the formation of soil aggregates by promoting flocculation of clay particles thus creating stable aggregates which improve soil structure, porosity, aeration and infiltration (Filipek, 2011). Intensive or continuous tillage can disintegrate and weaken soil structure (Zheng et al., 2018). Soil acidity management studies have shown that the combined effect of NT and liming can promote Nitrogen (N) cycling and boost soil carbon content thus, increasing N availability for plant use (Vazquez et al., 2019). However, other studies show that for liming to be more effective, deeper soil incorporation is required and this involves tillage (Blumenschein et al, 2018a). Studies by Doss et al. (1979) conducted in the United States on cotton and maize show that incorporating lime using rotary tillage up to a 30 cm soil depth promoted plant height, root depths and yields. In this meta-analysis, irrespective of the tillage method there was a positive response to liming (Figure 1).

3.4 Liming effect on crop yield was dependent on fertilizer application

Liming and fertilizer use is a common practice used to increase soil pH and yield, ensure nutrient availability and address soil fertility challenges caused by acidity (Castro & Crusciol, 2013; Tshiabukole et al., 2022). Application of lime and fertilizer may be vital to attain and sustain competitive crop production on acidic soils because lime ensures nutrient availability for plants while liming without fertilizer use may decrease soil fertility thus negatively impacting long-term crop productivity (Ayalew, 2011). The extent of soil acidification from fertilizer use is dependent on the fertilizer type (Ejersa, 2021). The liming effect size for yields in combination with organic fertilizer was 261.1% compared to 150% for inorganic or no fertilizer (Figure 1). Irrespective of the fertilizer type, there was a positive increase in yield with liming. A long-term experiment conducted by Qaswar et al. (2020) in China on wheat and maize showed that long-term inorganic fertilizer use without liming decreased soil pH, calcium (Ca^{2+}), magnesium (Mg^{2+}), crop yields and increased aluminum (Al^{3+}) while the combination of fertilizer and lime consistently increased wheat and maize yields. The authors further report a significantly higher increase in soil pH was attained when lime was combined with inorganic fertilizer and incorporated with straw. Application of lime and organic fertilizer in acid soils can avert rapid changes in soil pH and enhance the availability of phosphorous thus, increasing crop yields and promoting a higher return of crop residues and soil organic matter (Haynes & Naidu, 1998; Islam et al., 2021).

3.5 Effect of lime rate on soil pH

This meta-analysis showed that irrespective of the lime material, method of application, lime rate and crop type, most studies reviewed reported an increase in soil pH due to liming (Table 1 and Figures 2C, D). Higher lime rates resulted in the highest increase in soil pH and higher yields (Figures 2C, D). Oliver et al. (2021) reported that the strongest factor that influences yield and pH changes under acidic soil conditions is the liming rate and it was inferred that a higher liming rate will solve issues relating to subsoil acidity. Bennett et al. (2014), in studies conducted in semi-arid regions, reported that the use of lime up to 5 t ha^{-1} can improve crop vegetative cover, hydraulic conductivity, and soil health. In this meta-analysis, the positive effect of a higher lime rate on soil pH might be due to the high buffering capacity of acidic soils which would thus require a higher lime rate to neutralize acidity (Bravo Tutivén et al., 2022). However, the magnitude of the increase in soil pH might differ depending on management practice. In the analysis reported in this work, the response of the different crops to soil pH after liming was marginal, even though there were increases in soil pH after liming for all crop types (Table 1). The ability of arable crops to acidify the soil differs. However, the contribution of arable crops to soil acidification is marginal when compared with fertilizer use (Hinsinger et al., 2003; Goulding, 2016). Nevertheless, without lime applications, soil pH and crop yields will most likely continue to decrease.

3.6 Effect of liming rate across different crop types on profitability

The net revenue analysis conducted in this work was aimed at roughly assessing the probability that a sustained crop yield increases for 5, 10, or 15 years following a one-time lime application would exceed or offset the cost of the lime and its application. It is not likely that the same crop type would be grown year after year, as assumed in the analysis. Given these flaws, this analysis is considered as the best-case potential net revenue change following a one-time lime application.

In this review, it was observed that the profitability of lime application was a function of crop type, the lime rate applied and the assumed period of efficacy of a one-time lime application (Figures 3, 4). The change in yield due to liming in the first year of lime application was mostly marginal (Table 2). Even if these marginal increases were assumed to be sustained for 15 years after lime application, on average, the increased revenue did not offset the costs associated with the one-time lime application for all crop types except vegetables. This agrees with studies of Haak (1990) in an experiment conducted in Canada under three different lime rates (i.e., low, recommended, and high) for annual crops in which a marginal increase in crop yields due to liming resulted in net revenue losses because the yield increase was too small hence could not cover the cost of liming. Bongiovanni & Lowenberg-Deboer (2000) reported that liming was profitable in scenarios where low lime rates were applied. This meta-analysis showed that the profitability of liming also decreased with a higher lime rate, irrespective of crop type (Figure 2). Liu et al. (2003), in a wheat-canola crop rotation study conducted in Australia for 10 years, for six different soil types ranging from highly to weakly weathered soils reported that the most profitable rate of lime ranges between 2.0 - 5.5 t ha^{-1}.

In the short and long term for our analysis: at an assumed period of efficacy (5, 10, 15 years), a greater decrease in net revenue was observed for grains and legumes; and at higher lime application rates (Figures 3, 4). For legumes, approximately 75% of the studies resulted in negative net revenue even with a 5 to 10-year efficacy period and a 60% probability of negative net revenue with a 15-year efficacy period (Figure 3). For grains, few cases i.e., less than 30 attained profits after 5, 10 and 15 years of lime application. While for root and tuber crops, 75% of studies resulted in negative net revenue after 5 years of lime and decline to 60% and 50% at 10 and 15 years after lime application. Finally, for vegetables, only approximately 25% of studies resulted in negative net revenue with higher profit margins observed (Figure 3). Long-term studies conducted by Li et al. (2010) in the United States for annual, perennial and pasture-crop rotations have shown that the profitability of lime can be influenced by crop type with negative net revenue for peas (legumes) and lupins (*Lupinus polyphyllus*) under lime and no lime treatments were reported due to their tolerance to soil acidity and low yields while higher gross margin for wheat and canola were observed with liming due to the doubling of yields under lime treated plots. Also, in the same study by Li et al. (2010) from the third crop rotational cycle, an increase in gross margins between 18 - 25% was observed due to a 10% additional increase in crop yields and a further decline in soil acidity. The favorable effects of liming can last between 5 to 12 years, suggesting that the positive effects of lime application are long-term (Warner et al., 2023). In this meta-analysis, we observed that liming was more profitable with time for root and tubers and leguminous crops. Also, in a long-term study conducted in western Canada by Malhi et al. (1995) on wheat, barley, canola and legumes, a single application of lime increased yields for 16 to 27 years.

Return on investment is reliant on the magnitude of yield increase, crop value and cost of lime. In another long-term 35-year study in the United Kingdom on the economics of liming by Holland & Behrendt (2021), it was inferred that large gross margins exist with liming and large variations in the economic gains exist between crops e.g., larger gross margins were observed with spring barley while marginal increases were observed with spring oats. Furthermore, in the same study, the highest economic gains were attained with higher lime application rates. However, it took 20 years for a significant return on investment in liming to be actualized thus making it a profitable capital investment. Therefore, it is important to investigate the economic gains of liming over a long-term period (Kalkhoran et al., 2020). The decision by a farmer to cultivate a particular crop should not only be determined by profitability and market price but also by its overall improvement of the cropping system (Li et al., 2010). The combination of crops and their overall productivity in a rotation determines if liming is advantageous. The best liming approach under acidic soil conditions may involve diversifying the crop rotation sequence to include acid-tolerant and intolerant crops to increase farmers' income compared to monocultural practices (Kalkhoran et al., 2020). According to Li et al., 2010, producers can cultivate legumes such as pulses in the first season for nitrogen fixation to reduce the cost of fertilizers in the next season even though the gross margins on crops like pulses may be poor. This could increase the yields for non-leguminous crops in the following season thus improving soil health. Cost comparisons were made between lime and fertilizer use and it was reported that fertilizer was 260% more expensive than lime when wheat was cultivated for a 0.3 mt ha^{-1} yield increase thus liming can reduce the cost of production and increase income (Warner et al., 2023). Finally, with continuous improvement of soil pH by liming, producers have the flexibility to cultivate a wide range of crops without restrictions. For example, without liming, crops like alfalfa and canola with high economic value cannot be grown on acidic soils. Although acid-tolerant crops like lupin and potatoes can be grown in soils with low pH with minimal or no yield reductions, this can place a cap on the producer's ability to diversify cropping system with heavy reliance on inorganic fertilizers which in the long run will not be sustainable (Malhi et al., 1995; Li et al., 2010).

4 Conclusions

Globally, research studies investigating the effects of liming on arable crops have been carried out. However, a complete understanding of the implications of liming on crop yields and economic profitability for crop producers is underreported. In our review on the impact of liming on crop yields, soil pH, and profitability, we found that the extent of changes in crop yield, soil pH, and net revenue is influenced by the specific crop type and lime application rates. In general, higher rates of lime application resulted in greater increases in soil pH. However, for certain crops, yield responses reached a plateau or were marginal with higher lime rates which caused negative net revenues. This implies that crop producers should prioritize growing the right crops and diversify the cropping systems to include suitable crop rotational sequences. This approach allows the addition of acid-tolerant crops into crop rotational sequences which can maintain soil pH balance and sustain the effectiveness of lime over a long or extended period. There is a need for additional information on how various crop rotational sequences can influence liming efficiency and that was not tested in this meta-analysis due to the lack of sufficient reporting in various studies. According to Kalkhoran et al. (2020), the sequence of crops in a rotation can affect appropriate lime application rates and may influence site-specific responses to liming. Therefore, soil acidification under different crop rotations and various lime application rates should be investigated. Also, the practice of soil liming can come at a significant cost for crop producers thus government subsidies can assist crop producers by covering the cost of buying and applying lime on their farms. This will encourage crop producers adopt this practice thus improving soil health. Understanding the economics of liming will help crop producers make better agronomic decisions. It is pertinent for crop producers to know that the beneficial effects of lime on soil pH and crop yields may not be immediate as it often takes time (i.e., years) for lime to increase soil pH and improve yields. Hence net revenue calculations or estimations must consider the time between lime application and when benefits are maximized to avoid under/overestimating the profitability of lime practice. In this study, one limitation is that cumulative yield data over a long period of time associated with one time lime application was not used in the net revenue analysis thus future studies should consider assessing long term yield variability in yields due to liming to improve the accuracy of net revenue or profitability assessment.

Research on liming mostly focuses on how liming influences crop yields and soil pH without considering how agricultural practices play a role and this can restrict our knowledge of the overall effect on crop production. This study provides adequate information on how soil liming interacts with various agricultural practices which will help inform crop producers on how to maximize crop yields for specific crops and their pH tolerance and better nutrient management to optimize nutrient use efficiency. This meta-analysis shows that with the use of appropriate management practices, crop producers can improve the effectiveness of lime applications. Application of organic fertilizer and liming increase yields more than liming and inorganic fertilizer. This shows that crop producers can adopt this method to promote long term improvement of soil health which aligns with sustainable agricultural practices. The liming effect on crop yield was greater in NT than in CT systems. The importance of attaining higher crop yields with liming in NT systems shows the significance of organic matter accumulation, moisture retention and improved soil structure in NT systems. Finally, most research reported were conducted at small plot-size levels, thus may be difficult to scale the recommendations from this study to a larger scale or landscape due to within field or spatial variability of soil physical and chemical properties. Thus, future research studies may consider participatory on-farm and large-scale studies to provide deeper understanding on the effects of liming, capture variability in farming systems to allow for more robust conclusions and to tailor lime recommendations suitable for specific conditions.

Author contributions

RE: Conceptualization, analysis, drafting, and writing. MD: Conceptualization, editing, and revision of the manuscript. SC: Editing and revision of the manuscript. MT: Editing and revision of the manuscript. XF: Editing and revision of the manuscript. SS: Editing and revision of the manuscript. LG: Conceptualization, editing, and correction of the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Abdalla, M., Espenberg, M., Zavattaro, L., Lellei-Kovacs, E., Mander, U., Smith, K., et al. (2022). Does liming grasslands increase biomass productivity without causing detrimental impacts on net greenhouse gas emissions? *Environ Pollut.* (Elsevier Ltd) 300, 118999. doi: 10.1016/j.envpol.2022.118999

Adane, B. (2014). Effects of liming acidic soils on improving soil properties and yield of haricot bean. *J. Environ. Analytical Toxicol.* 05 (01), 248. doi: 10.4172/2161-0525.1000248

Adeoye, K. B., and Singh, L. (1985). The effect of bulk application of lime under two tillage depths on soil pH and crop yield. *Plant Soil* 85, 295–297. doi: 10.1007/BF02139634

Agegnehu, G., Amede, T., Erkossa, T., Yirga, C., Henry, C., Tyler, R., et al. (2021). Extent and management of acid soils for sustainable crop production system in the tropical agroecosystems: a review. *In Acta Agriculturae Scandinavica Section B: Soil Plant Sci.* Vol. 71, Issue 9, 852–869). doi: 10.1080/09064710.2021.1954239

Alemu, E., Selassie, Y. G., and Yitaferu, B. (2022). Effect of lime on selected soil chemical properties, maize (*Zea mays*) yield and determination of rate and method of its application in northwestern Ethiopia. *Heliyon* 8 (1), 2405–8440. doi: 10.1016/j.heliyon.2021.e08657

Anderson, N. P., Hart, J. M., Sullivan, D. M., Horneck, D. A., and Pirelli, G. J. (2013). *Applying lime to raise soil pH for crop production (Western Oregon)* (Corvallis (OR: Oregon State University Extension), EM 9057.

Andric, L., Rastija, M., Teklic, T., and Kovacevic, V. (2012). Response of maize and soybeans to liming. *Turkish J. Agric. Forestry* 36 (4), 415–420. doi: 10.3906/tar-1107-23

Anikwe, M. A. N., Eze, J. C., and Ibudialo, A. N. (2016). Influence of lime and gypsum application on soil properties and yield of cassava (*Manihot esculenta crantz.*) in a degraded ultisol in agbani, enugu southeastern Nigeria. *Soil Tillage Res.* 158, 32–38. doi: 10.1016/j.still.2015.10.011

Arshad, M. A., and Gill, K. S. (1996). Field pea response to liming of an acid soil under two tillage sYstems. *Can. J. Soil Sci.* 76 (13), 549–555. doi: 10.4141/cjss96-068

Auler, A. C., Caires, E. F., Pires, L. F., Galetto, S. L., Romaniw, J., and Charnobay, A. C. (2019).). lime effects in a no-tillage system on inceptisols in southern Brazil. *Geoderma Regional* 16, e0026. doi: 10.1016/j.geodrs.2019.e00206

Ayalew, A. (2011). The influence of applying lime and NPK fertilizers on yield of maize and soil properties on acid soil of areka, southern region of Ethiopia. *Innovative Syst. Design Eng.* 2 (7), 33-42. Available at: www.iiste.orgwww.iiste.org.

Azam, G., and Gazey, C. (2021). Slow movement of alkali from surface-applied lime warrants the introduction of strategic tillage for rapid amelioration of subsurface acidity in south-western Australia. *Soil Res.* 59 (1), 97. doi: 10.1071/SR19329

Bennett, J., Greene, R. S. B., Murphy, B. W., Hocking, P., and Tongway, D. (2014). Influence of lime and gypsum on long-term rehabilitation of a red sodosol, in a semi-arid environment of new south Wales. *Soil Res.* 52 (2), 120. doi: 10.1071/SR13118

Bian, M., Zhou, M., Sun, D., and Li, C. (2013). Molecular approaches unravel the mechanism of acid soil tolerance in plants. *In Crop J.* Vol. 1, Issue 2, 91–104). doi: 10.1016/j.cj.2013.08.002

Blumenschein, T. G., Nelson, K. A., and Motavalli, P. P. (2018a). Impact of a new deep vertical lime placement practice on corn and soybean production in conservation tillage systems. *Agronomy* 8 (7), 104. doi: 10.3390/agronomy8070104

Blumenschein, T. G., Nelson, K. A., and Motavalli, P. P. (2018b). Impact of a new deep vertical lime placement practice on corn and soybean production in conservation tillage systems. *Agronomy* 8 (7). doi: 10.3390/agronomy8070104

Bolan, N., Curtin, D., and Adriano, D. (2003). *Soil acidification and liming interactions with nutrient and heavy metal transformation and bio-availability* (Advances in agronomy. Academic Press) 78, 215–272. doi: 10.1016/S0065-2113(02)78006-1

Bongiovanni, R., and Lowenberg-Deboer, J. (2000). Economics of variable rate lime in Indiana. *Precis. Agric.* 2 (1), 55–70. doi: 10.1023/A:1009936600784

Bortoluzzi, E. C., Parize, L., Korchagin, J., Rodrigues da Silva, V., dos Santos Rheinheimer, D., et al. (2014). Soybean root growth and crop yield in response to liming at the beginning of a no-tillage system. *R.Bras. Ci. Solo* 38, 262–271. doi: 10.1590/S0100-06832014000100026

Bravo Tutivén, J. C., Espinales Suarez, H. O., and Vásconez Montúfar, G. H. (2022). Buffer capacity as a method to estimate the dose of liming in acid. *Agro Productividad* doi: 10.32854/agrop.v15i10.2256

Caires, E. F., Alleoni, L. R. F., Cambri, M. A., and Barth, G. (2005). Surface application of lime for crop grain production under a no-till system. *Agron. J.* 97 (3), 791–798. doi: 10.2134/agronj2004.0207

Castro, G. S. A., and Crusciol, C. A. C. (2013). Effects of superficial liming and silicate application on soil fertility and crop yield under rotation. *Geoderma* 195–196, 234–242. doi: 10.1016/j.geoderma.2012.12.006

Cifu, M., Xiaonan, L., Zhihong, C., Zhengyi, H., and Wanzhu, M. (2004). Long-term effects of lime application on soil acidity and crop yields on a red soil in central zhejiang. *Plant Soil Sci.* 265 (1), 101–109. doi: 10.1007/s11104-005-8941-y

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences (2nd ed.)* (Hillside, NJ: Lawrence Erlbaum Associates).

Costa, M. C. G. (2012). Soil and crop responses to lime and fertilizers in a fire-free land use system for smallholdings in the northern Brazilian Amazon. *Soil Tillage Res.* 121, 27–37.

Coventry, D. R., Hirth, J. R., and Reeves, T. G. (1992). "Interactions of tillage and lime in wheat-subterranean clover rotations on an acidic sandy clay loam in southeastern Australia," in *Soil & tillage research* 25 (1), 53-65. doi: 10.1016/0167-1987(92)90062-G

Crusciol, C. A. C., Momesso, L., de Campos, M., Bossolani, J. W., Portugal, J. R., Moretti, L. G., et al. (2021). Liming optimizes nitrogen fertilization in a maize-upland rice rotation under no-till conditions. *Agronomy* 11 (10), 2005. doi: 10.3390/agronomy11102005

de Campos, M., Martello, J. M., de Siqueira, G. F., Garcia, A., Scudeletti, D., Dias, P. P., et al. (2022).). Lime rate in clayey soils influences chemical fertility and sugarcane yield. *Plants* 11 (16), 2110. doi: 10.3390/plants11162110

de Moraes, F. A., Moreira, S. G., Peixoto, D. S., Resende Silva, J. C., Macedo, J. R., Silva, M. M., et al. (2023). Lime incorporation up to 40 cm deep increases root growth and crop yield in highly weathered tropical soils. *Eur. J. Agron.* 144, 126763. doi: 10.1016/j.eja.2023.126763

Doss, B. D., Dumas, W. T., and Lund, Z. F. (1979). Depth of lime incorporation for correction of subsoil acidity 1. *Agron. J.* 71 (4), 541–544. doi: 10.2134/agronj1979.00021962007100040005x

du Toit, D. J. J., Swanepoel, P. A., and Hardie, A. G. (2022). Effect of lime source, fineness and granulation on neutralisation of soil pH. *South Afr. J. Plant Soil* 39 (3), 163–174. doi: 10.1080/02571862.2022.2043470

Ebelhar, S. A., Hart, C. D., and Wyciskalla, T. D. (2011). Tillage and lime rate effects on soil acidity and grain yields of a ten-year corn–soybean rotation. *Commun. Soil Sci. Plant Anal.* 42 (12), 1415–1421. doi: 10.1080/00103624.2011.577855

Ejersa, M. T. (2021). Causes of soil acidity and its management mechanisms in Ethiopia: a review. *J. Agric. Sci. Bot.* 5 (4), 054. doi: 10.18535/ijsrm/v7i11.em01"10.18535/ijsrm/v7i11.em01

Ennich, N., and Lynn Forster, D. (1993). *Analysis of agricultural lime demand and supply relationships project* (Department of Agricultural Economics and Rural Sociology the Ohio State University, Columbus).

Farhoodi, A., and Coventry, D. R. (2008). Field crop responses to lime in the mid-north region of south Australia. *Field Crops Res.* 108 (1), 45–53. doi: 10.1016/j.fcr.2008.02.013

Fekadu, E., Kibret, K., Melese, A., and Bedadi, B. (2018). Yield of faba bean (*Vicia faba.*) as affected by lime, mineral p, farmyard manure, compost and rhizobium in acid soil of lay gayint district, northwestern highlands of Ethiopia. *Agric. Food Secur.* 7 (1), 16. doi: 10.1186/s40066-018-0168-2

Fenn, M. E., Huntington, T. G., McLaughlin, S. B., Eagar, C., Gomez, A., and Cook, R. B. (2006). Status of soil acidification in north America. *J. For. Sci.* 52, 3–13. doi: 10.17221/10152-JFS

Filipek, T. (2011). "Liming, effects on soil properties," in *Encyclopedia of earth sciences series*. Eds. J. Gliński, J. Horabik and J. Lipiec (Dordrecht: Springer). doi: 10.1007/978-90-481-3585-1_84

Fuentes, J. P., Bezdicek, D. F., Flury, M., Albrecht, S., and Smith, J. L. (2006). Microbial activity affected by lime in a long-term no-till soil. *Soil Tillage Res.* 88 (1–2), 123–131. doi: 10.1016/j.still.2005.05.001

Goulding, K. W. T. (2016). Soil acidification and the importance of liming agricultural soils with particular reference to the united kingdom. *In Soil Use Manage.* Vol. 32, Issue 3, 390–399). doi: 10.1111/sum.12270

Guzman, J. G., Godsey, C. B., Pierzynski, G. M., Whitney, D. A., and Lamond, R. E. (2006). Effects of tillage and nitrogen management on soil chemical and physical properties after 23 years of continuous sorghum. *Soil Tillage Res.* 91 (1–2), 199–206. doi: 10.1016/j.still.2005.12.004

Haak, D. E. (1990). *Effect of lime on soil pH, crop yield and farm income results of eight demonstration site in the northwest region.* (Canada: Soil and crops workshop).

Haby, V. A., and Leonard, A. T. (2002). Limestone quality and effectiveness for neutralizing soil acidity. *Commun. Soil Sci. Plant Anal.* 33 (15–18), 2935–2948. doi: 10.1081/CSS-120014492

Hale, S. E., Nurida, N. L., Mulder, J., Sørmo, E., Silvani, L., Abiven, S., et al. (2020). The effect of biochar, lime and ash on maize yield in a long-term field trial in a ultisol in the humid tropics. *Sci. Total Environ.* 719, 137455. doi: 10.1016/j.scitotenv.2020.137455

Hamilton, H. A., Levesque, M., and Lessard, J. R. (1964). The residual effect of lime on crop yields, ph, and other chemical characteristics of a grey wooded soil broken to different depths. *Can. J. Soil Science.* 46 (1), 61–68. doi: 10.4141/cjss66-009

Haynes, R. J., and Naidu, R. (1998). Influence of lime, fertilizer and manure applications on soil organic matter content and soil physical conditions: a review. *Nutrient Cycling Agroecosystems* 51 (2), 123–137. doi: 10.1023/A:1009738307837

He, L.-L., Huang, D.-Y., Zhang, Q., Zhu, H.-H., Xu, C., Li, B., et al. (2021). Meta-analysis of the effects of liming on soil pH and cadmium accumulation in crops. *Ecotoxicology Environ. Saf.* 223, 112621. doi: 10.1016/j.ecoenv.2021.112621

Hellner, Q., Koestel, J., Ulén, B., and Larsbo, M. (2018). Effects of tillage and liming on macropore networks derived from X-ray tomography images of a silty clay soil. *Soil Use Manage.* 34 (2), 197–205. doi: 10.1111/sum.12418

Hijbeek, R., van Loon, M. P., Ouaret, W., Boekelo, B., and van Ittersum, M. K. (2021). Liming agricultural soils in Western Kenya: can long-term economic and environmental benefits pay off short term investments? *Agric. Syst.* 190. doi: 10.1016/j.agsy.2021.103095

Hinsinger, P., Plassard, C., Tang, C., and Jaillard, B. (2003). Origins of root-mediated pH changes in the rhizosphere and their responses to environmental constraints: a review. *Plant Soil* 248 (1/2), 43–59. doi: 10.1023/A:1022371130939

Holland, J. E., and Behrendt, K. (2021). The economics of liming in arable crop rotations: analysis of the 35-year rothamsted and woburn liming experiments. *Soil Use Manage.* 37 (2), 342–352. doi: 10.1111/sum.12682

Holland, J. E., Bennett, A. E., Newton, A. C., White, P. J., McKenzie, B. M., George, T. S., et al. (2018). Liming impacts on soils, crops and biodiversity in the UK: a review. *In Sci. Total Environ.* Vols. 610–611, 316–332). doi: 10.1016/j.scitotenv.2017.08.020

Holland, J. E., White, P. J., Glendining, M. J., Goulding, K. W. T., and McGrath, S. P. (2019). Yield responses of arable crops to liming – an evaluation of relationships between yields and soil pH from a long-term liming experiment. *Eur. J. Agron.* 105, 176–188. doi: 10.1016/j.eja.2019.02.016

Huang, H., Campbell, A. G., Folk, R., and Mahler, R. L. (1992). Wood ash as a soil additive and liming agent for wheat; field studies. *Commun. Soil Sci. Plant Anal.* 23 (1–2), 25–33. doi: 10.1080/00103629209368567

Islam, M. R., Jahan, R., Uddin, S., Harine, I. J., Hoque, M. A., Hassan, S., et al. (2021). Lime and organic manure amendment enhances crop productivity of wheat–mungbean–t. aman cropping pattern in acidic piedmont soils. *Agronomy* 11 (8), 1595. doi: 10.3390/agronomy11081595

Kalkhoran, S. S., Pannell, D., Thamo, T., Polyakov, M., and White, B. (2020). Optimal lime rates for soil acidity mitigation: impacts of crop choice and nitrogen fertiliser in Western Australia. *Crop Pasture Sci.* 71 (1), 36–46. doi: 10.1071/CP19101

Kowalenko, C. G., Ma, E. F., and Vanlaerhoven, C. I. (1980). Residual effects of high rates of limestone, p, K AND mg applications: evidence of induced Mn and Zn deficiency in oats. *Can. J. Soil. Sci.* 60, 757–761. doi: 10.4141/cjss80-084

Lafond, J., and Simard, R. R. (1999). "Effects of cement kiln dust on soil and potato crop quality," in *Amer J of potato res* 76, 83–90. doi: 10.1007/BF02855204

Lesturgez, G., Poss, R., Noble, A., Grünberger, O., Chintachao, W., and Tessier, D. (2006). Soil acidification without pH drop under intensive cropping systems in northeast Thailand. *Agriculture Ecosyst. Environ.* 114 (2–4), 239–248. doi: 10.1016/j.agee.2005.10.020

Li, Y., Cui, S., Chang, S. X., and Zhang, Q. (2019). Liming effects on soil pH and crop yield depend on lime material type, application method and rate, and crop species: a global meta-analysis. *J. Soils Sediments* 19 (3), 1393–1406. doi: 10.1007/s11368-018-2120-2

Li, G., Singh, R. P., Brennan, J. P., and Helyar, K. R. (2010). A financial analysis of lime application in a long-term agronomic experiment on the south-western slopes of new south Wales. *Crop Pasture Sci.* 61 (1), 12–23. doi: 10.1071/CP09103

Liao, P., Ros, M. B. H., Van Gestel, N., Sun, Y.-N., Zhang, J., Huang, S., et al. (2020). Liming reduces soil phosphorus availability but promotes yield and p uptake in a double rice cropping system. *J. Integr. Agric.* 19 (11), 2807–2814. doi: 10.1016/S2095-3119(20)63222-1

Liu, D. L., Conyers, M. K., and Helyar, K. R. (2003). "Simulation of the changes in soil pH of various acidic soils through lime applications," in *Proceedings of the international congress on modelling and simulation*, 1546–1551.

Lulu, M., Lemma, B., Hidoto, L., and Melese, A. (2022). Effect of biochar, farmyard manure, and lime on soil properties, and on growth and nutrient uptake of wheat on acidic soils in southern Ethiopia. *South Afr. J. Plant Soil* 39 (2), 112–122. doi: 10.1080/02571862.2022.2050316

Maclean, A. J., Jasmin, J. J., and Halstead, R. L. (1967). Effect of iime on potato crops and on properties of a sphagnum peat soil. *Can.J.Soil Sci.* 47 (2), 89-94. doi: 10.4141/cjss67-016

Mahmud, M. S., and Chong, K. P. (2022). "Effects of liming on soil properties and its roles in increasing the productivity and profitability of the oil palm industry in Malaysia," in *Agriculture (Switzerland)* (MDPI) 12 (3), 322. doi: 10.3390/agriculture12030322

Maier, N. A., McLaughlin, M. J., Heap, M., Butt, M., and Smart, M. K. (2002). Effect of current-season application of calcitic lime and phosphorus fertilization on soil pH, potato growth, yield, dry matter content, and cadmium concentration. *Commun. Soil Sci. Plant Anal.* 33 (13–14), 2145–2165. doi: 10.1081/CSS-120005754

Malhi, S. S., Mumeyl, G., Nyborg3, M., Ukrainetz, H., and Penney5, D. C. (1995). Longevity of liming in western Canada: Soil pH, crop yield and economics In: R.A. Date, N.J. Grundon, G.E. Rayment and M.E. Probert (eds) *Plant-Soil Interactions at Low pH: Principles and Management. Developments in Plant and Soil Sciences* (Dordrecht: Springer) vol 64. doi: 10.1007/978-94-011-0221-6_112

Mayfield, J. L., Simonne, E. H., Mitchell, C. C., Sibley, J. L., Eakes, D. J., Boozer, R. T., et al. (2001). Effect of liming materials on soil available nutrients, yield, and grade distribution of double-cropped tomato and cucumber grown with plasticulture. *J. Plant Nutr.* 24 (1), 87–99. doi: 10.1081/PLN-100000314

Okpara, D. A., Muoneke, C. A., and Ihediwa, C. A. (2007). Influence of liming on the performance of high-yielding soybean varieties in southeastern Nigeria. *J. Agric* 6, 16–24. doi: 10.4314/as.v6i2.1565

Oliver, Y. M., Gazey, C., Fisher, J., and Robertson, M. (2021). Dissection of the contributing factors to the variable response of crop yield to surface applied lime in Australia. *Agronomy* 11 (5), 829. doi: 10.3390/agronomy11050829

Olsson, Å., Persson, L., and Olsson, S. (2019). Influence of soil characteristics on yield response to lime in sugar beet. *Geoderma.* 337, 1208–1217. doi: 10.1016/j.geoderma.2018.11.020

Opala, P., Odendo, M., and Muyekho, F. (2018). Effects of lime and fertilizer on soil properties and maize yields in acid soils of Western Kenya. *Afr. J. Agric. Res.* 13. doi: 10.5897/AJAR2018.13066

Orton, T. G., Mallawaarachchi, T., Pringle, M. J., Menzies, N. W., Dalal, R. C., Kopittke, P. M., et al. (2018). Quantifying the economic impact of soil constraints on Australian agriculture: a case-study of wheat. *Land Degradation Dev.* 29 (11), 3866–3875. doi: 10.1002/ldr.3130

Pan, X. Y., Li, J. Y., Deng, K. Y., Xu, R. K., and Shen, R. F. (2019). Four-year effects of soil acidity amelioration on the yields of canola seeds and sweet potato and n fertilizer efficiency in an ultisol. *Field Crops Res.* 237, 1–11. doi: 10.1016/j.fcr.2019.03.019

Paradelo, R., Virto, I., and Chenu, C. (2015). Net effect of liming on soil organic carbon stocks: a review. *In Agriculture Ecosyst. Environ. (Vol. 202* pp, 98–107). doi: 10.1016/j.agee.2015.01.005

Qaswar, M., Dongchu, L., Jing, H., Tianfu, H., Ahmed, W., Abbas, M., et al. (2020). Interaction of liming and long-term fertilization increased crop yield and phosphorus use efficiency (PUE) through mediating exchangeable cations in acidic soil under wheat–maize cropping system. *Sci. Rep.* 10 (1), 19828. doi: 10.1038/s41598-020-76892-8

Ratke, R. F., Pereira, H. S., dos Santos Junior, J., de, D. G., Frazão, J. J., Barbosa, J. M., et al. (2014). Root growth, nutrition and yield of maize with applied finely limestone in surface of cerrado soil. *Am. J. Plant Sci.* 05 (06), 834–844. doi: 10.4236/ajps.2014.56097

Rice, W. A., Penney, D. C., and Nyborg, M. (1977). Effects of soil acidity on rhizobia numbers, nodulation and nitrogen fixation by alfalfa and red clover. *Can. J. Soil Sci.* 57, 197–203. doi: 10.4141/cjss77-024

Rippy, J. F. M., Nelson, P., Hesterberg, D. L., and Kamprath, E. J. (2007). Reaction times of twenty limestones. *Commun. Soil Sci. Plant Anal.* 38 (13–14), 1775–1783. doi: 10.1080/00103620701435530

Rosen, C. J., and Bierman, P. M. (2005). *Nutrient management for fruit & vegetable crop production: maintaining soil fertility in an organic system* (University of Minnesota Extension Service. Retrieved from the University of Minnesota Digital Conservancy). Available at: Https://Hdl.Handle.Net/11299/197961.

Sanjib Kumar Panda, F. B., and Matsumoto, H. (2009). Aluminum stress signaling in plants. *Plant Signaling Behav.* 4 (7), 592–597. doi: 10.4161/psb.4.7.8903

Scott, B. J., Conyers, M. K., Fisher, R., and Lill, W. (1992). Particle size determines the efficiency of calcitic limestone in amending acidic soil. *Aust. J. Agric. Res.* 43, 1175–1185. doi: 10.1071/AR9921175

Sirisuntornlak, N., Ullah, H., Sonjaroon, W., Anusontpornperm, S., Arirob, W., and Datta, A. (2021). Interactive effects of silicon and soil pH on growth, yield and nutrient uptake of maize *Silicon* 13, 289–299. doi: 10.1007/s12633-020-00427-z

Smith, C. B., Demchak, K. T., and Ferretti, P. A. (1986). Effects of lime type on yields and leaf concentrations of several vegetable crops as related to soil test levels. *J. Amer . So c . Hort . Sci.* 111 (6), 837–840. doi: 10.21273/JASHS.111.6.837

Smith, J. F. N., and Hardie, A. G. (2022). Long-term effects of micro-fine and class a calcitic lime application rates on soil acidity and rooibos tea yields under clanwilliam field conditions. *South Afr. J. Plant Soil* 39 (4), 270–277. doi: 10.1080/02571862.2022.2107244

Soon, Y. K., and Arshad, M. A. (2005). Tillage and liming effects on crop and labile soil nitrogen in an acid soil. *Soil Tillage Res.* 80 (1–2), 23–33. doi: 10.1016/j.still.2004.02.017

Tian, D., and Niu, S. (2015). A global analysis of soil acidification caused by nitrogen addition. *Environ. Res. Lett.* 10 (2). doi: 10.1088/1748-9326/10/2/024019

Tiritan, C. S., Büll, L. T., Crusciol, C. A. C., Carmeis Filho, A. C. A., Fernandes, D. M., and Nascente, A. S. (2016). Tillage system and lime application in a tropical region: soil chemical fertility and corn yield in succession to degraded pastures. *Soil Tillage Res.* 155, 437–447. doi: 10.1016/j.still.2015.06.012

Tshiabukole, J. P. K., Khonde, G. P., Phongo, A. M., Ngoma, N., Vumilia, R. K., and Kankolongo, A. M. (2022). Liming and mineral fertilization of acid soils in maize crop within the savannah of southwestern of democratic republic of Congo. *OALib* 09 (03), 1–10. doi: 10.4236/oalib.1108412

van der Nest, J. R., Hardie, A. G., Labuschagne, J., and Swanepoel, P. A. (2022). Effects of form, fineness and placement of lime with and without soil tillage on barley and canola growth and development. *South Afr. J. Plant Soil* 39 (4), 260–269. doi: 10.1080/02571862.2022.2086308

Vazquez, E., Benito, M., Espejo, R., and Teutscherova, N. (2019). Effects of no-tillage and liming amendment combination on soil carbon and nitrogen mineralization. *Eur. J. Soil Biol.* 93, 103090. doi: 10.1016/j.ejsobi.2019.103090

Viadé, A., Fernández-Marcos, M. L., Hernández-Nistal, J., and Alvarez, E. (2011). Effect of particle size of limestone on Ca, mg and K contents in soil and in sward plants. *Scientia Agricola* 68 (2), 200–208. doi: 10.1590/S0103-90162011000200010

Victoria, O., Ping, A., Yang, S., and Eneji, E. (2019). Liming and nitrogen effects on maize yield and nitrogen use efficiency. *Commun. Soil Sci. Plant Anal.* 50 (16), 2041–2055. doi: 10.1080/00103624.2019.1648663

von Uexküll, H. R., and Mutert, E. (1995). "Global extent, development and economic impact of acid soils," in *Plant and soil* (KluwerAcademic Publishers) 171, 1-15. doi: 10.1007/BF00009558

Warner, J. M., Mann, M. L., Chamberlin, J., and Tizale, C. Y. (2023). Estimating acid soil effects on selected cereal crop productivities in Ethiopia: comparing economic cost-effectiveness of lime and fertilizer applications. *PloS One* 18 (1), e0280230. doi: 10.1371/journal.pone.0280230

Zheng, H., Liu, W., Zheng, J., Luo, Y., Li, R., Wang, H., et al. (2018). Effect of long-term tillage on soil aggregates and aggregate-associated carbon in black soil of northeast China. *PloS One* 13 (6), e0199523. doi: 10.1371/journal.pone.0199523