



# Liming improves wheat nutrient use efficiency, yield, and quality on acid soils in Ethiopia

Kari Ylivainio · Refissa Leta · Martti Esala ·  
Lauri Jauhiainen · Tommi Peltovuori ·  
Tegist Chernet

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**Abstract** Soil acidity is a major constraint for food production in the Highlands of Ethiopia, the main cereal growing area. We conducted two field trials in nutrient-poor, acidic fields in the Highlands of Ethiopia to evaluate the effects of dolomitic lime at rates of 0, 6 and 12 t ha<sup>-1</sup> on the utilization of commonly used phosphorus (P) and nitrogen (N) fertilizers. Blended fertilizer (at a liming rate of 12 t ha<sup>-1</sup>), containing potassium (K), sulfur (S), zinc (Zn) and boron (B) were also evaluated. The liming rate of 12 t ha<sup>-1</sup> improved the utilization of P fertilizer most and only 20 kg P ha<sup>-1</sup> was needed to reach 90% of the maximum wheat yield in soils with a high P sorption capacity. Liming and P fertilization, increased the N use efficiency from 0 to 30%, whereas the P use efficiency increased from 3 to 25%. Liming also

increased the concentrations of calcium (Ca), magnesium (Mg), sulfur (S), molybdenum (Mo) and Zn and retained the concentration of copper (Cu) in wheat grain at a higher level than in unlimed treatments. This indicates that even high liming rates did not depress the utilization of nutrients from fertilizers, lime or soil. Regarding harmful heavy metals, liming reduced the nickel (Ni) concentration in wheat to about half of that in unlimed treatments. This study demonstrated how liming was a prerequisite for improving the quantity and quality of wheat growing in the acidic soils of the Ethiopian Highlands.

**Keywords** Fertilization · Macronutrients · Micronutrients · Ethiopian highlands

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K. Ylivainio (✉) · M. Esala · L. Jauhiainen  
Natural Resources Institute Finland (Luke), Jokioinen,  
Finland  
e-mail: kari.ylivainio@luke.fi

R. Leta  
Nekemte Soil Research Center, Nekemte, Ethiopia

T. Peltovuori  
University of Helsinki, Helsinki, Finland

T. Chernet  
Geological Survey of Finland (GTK), Espoo, Finland

## Introduction

Africa is expected to account more than half global population increase, from 8 billion in end of 2022 to 9.7 billion in 2050 (<https://www.un.org/en/global-issues/population>). Ethiopia has the second largest population after Nigeria (216 million), with a current count of 123 million and an expected population of 200 million in the year 2050. Malnutrition is frequent, and the demand for food is increasing with the growing population. In Ethiopia, maize is the most important source of consumed calories, followed by wheat. Wheat represents 14% of the country's total calorie intake (Anteneh and

Asrat 2020). The main wheat growing areas are located in the Highlands of Ethiopia, where 57% of the country's wheat is produced in rainfed conditions (Anteneh and Asrat 2020). However, Ethiopia has the highest wheat production area in SSA (Tadesse et al. 2018), with a total of 2.1 Mha and grain production of 6.7 Mt; about 1.5 Mt of wheat is annually imported (Tadesse et al. 2022). Fortunately, there is great potential for increasing wheat production in Ethiopia. The average wheat yield in rainfed conditions is 3.1 t ha<sup>-1</sup> but yields up to 7 t ha<sup>-1</sup> have been achieved under favorable rainfed conditions (Tadesse et al. 2022). The main limiting factor for higher yields in Ethiopia and whole Sub-Saharan Africa (SSA) in recent decades appears to have been poor soil fertility (Pradhan et al. 2015; Stewart et al. 2020).

In the future, climate change scenarios predict additional constraints on agricultural productivity (Shiferaw et al. 2013). This calls for more sustainable soil management to secure food production in the area. In the past, most attempts at improving soil fertility in SSA have relied on inorganic fertilizers, with the constraints caused by declining soil organic carbon content and soil acidity (Stewart et al. 2020) receiving less attention. In Ethiopia, 40.9% of the arable land is estimated to be acidic, with a pH less than 5.5. These acidic soils are mainly located in the Highlands, the most important wheat-producing area (Demil et al. 2020). By nature, these highly weathered, acidic tropical soils have a high capacity for immobilizing phosphorus (P) due to their large content of aluminum and iron oxides (Haynes 1984); hence, large amounts of P fertilizers are required for high yields (Sánchez and Salinas 1981). Despite the constraints, these soils have a high potential for increasing food production (von Uexküll and Mutert 1995). In the north-central Highlands of Ethiopia, productivity further benefits from having the highest average rainfall in Ethiopia, 1300–1600 mm, together with a mean annual temperature of 22–25 °C during the growing season from June to September (Elias 2017).

Before 2014, only nitrogen (N) and P fertilizers were available in the form of urea and diammonium phosphate (DAP), and a typical fertilization recommendation was 100 kg ha<sup>-1</sup> of both. Incomplete fertilization of crops with only N and P has led to deficiencies in other essential plant nutrients, and an

increased risk of calcium (Ca) and zinc (Zn) malnutrition exist in Ethiopia (Joy et al. 2014).

In 2014, fertilizers blended with sulfur (S), potassium (K), Zn and boron (B) became available in Ethiopia, improving the availability of these nutrients in agricultural soils. Actions against the deleterious acidity of agricultural soils in Ethiopia through the application of lime have only recently started, and there are only a few published studies of its effects on crop production (see Gurmessa 2021) and on the quality of harvested crops, e.g. nutrient and harmful heavy metal concentrations. Therefore, knowledge of the potential of liming to reduce the use of excess fertilizers, i.e. yield increases based solely on the use of fertilizers for crop production as has been already seen in Western Europe and North America (Dobermann et al. 2022) is needed to ensure food security in Ethiopia.

Lime application rate of 2–5 t ha<sup>-1</sup> is considered to be sufficient to neutralize acid soils for crop production in Ethiopia (Gurmessa 2021), far less than that used in Western countries. Recommended liming rates are rationalized based on simultaneous attempts to neutralize the exchangeable acidity that restricts root growth and nutrient acquisition and to avoid deficiencies of essential micronutrients sensitive to elevated pH (Zn, Mn, Fe, Cu and B) (Fageria and Baligar 2008). In this study, we evaluated liming rates, higher than commonly recommended, for reaching soil pH considered to be optimal for P availability, and consequent effect on the yield and quality of wheat grown in acidic soils (Nitisols) in the Highlands of Ethiopia. Experiments were conducted on farmers' fields cultivated using conventional local farming practices.

## Materials and methods

### Experimental sites

Two field experiments were established in the Oromia region, Nekemte, located in the high plateau of Ethiopia, in 2014. Both sites (Field 1: 9.127585° N and 36.513798° E, 2000 m a.s.l, Field 2: 9.046271° N and 36.575511° E, 2020 m a.s.l) were cultivated using customary agricultural practices. Neither had been treated with lime, and the fields were low in

**Table 1** Characteristics of the soils in the experimental fields (0–20 cm)

	Field 1	Field 2
Soil pH	4.9	5.0
Exchangeable acidity, meq/100 g	5.54	2.36
Oxalate extractable elements, mg kg <sup>-1</sup>		
Fe	13709	12741
Al	7690	4364
P	370	240
AAAc*, mg l <sup>-1</sup> soil		
P	0.32	0.26
Ca	540	895
Mg	106	225
K	269	340
Olsen-P, mg kg <sup>-1</sup>	2.4	2.6
AAAc-EDTA, mg kg <sup>-1</sup> soil		
Cu	5.4	6.0
Fe	229	349
Zn	0.45	1.04
Mo	0.038	0.132
Cd	0.005	0.008
Pb	3.4	4.9
Co	2.8	15.9
Ni	0.54	3.07
Total, % (air-dried soil)		
C	4.9	3.1
N	0.35	0.25
S	0.05	0.04
Particle size distribution, %		
Clay (<0.002 mm)	80	79
Silt (0.002–0.06 mm)	19	19
Sand (0.06–2 mm)	2	2

\*Acid ammonium acetate, pH 4.65

soluble nutrients (Table 1). Field 1 had been under pasture until previous growing season when teff was grown without fertilization. Also, on Field 2 the previous crop was teff, fertilized using urea (50 kg ha<sup>-1</sup>) and DAP (100 kg ha<sup>-1</sup>); the estimated teff yield was 800 kg ha<sup>-1</sup>. Prior to this, niger seed (year 2012) and finger millet (2011) were grown. Rainfall and temperature data was obtained from Nekemte weather station (Abebe 2017) and monthly rainfall and temperature data in 2005–2014 is presented in Supplementary material (Supplementary Table 1 and 2).

## Establishment of field trials

On both fields, the experimental area (27.5 m \* 42.5 m) was divided into 72 plots (3 m \* 4 m) with a 0.5 m untreated area around each plot. Row-column experimental design of 3\*6 was replicated four times within both areas. The experimental treatments consisted of three liming rates of 0, 6 and 12 t ha<sup>-1</sup> of dolomitic lime, originating from Guder limestone quarry. The target for the two liming treatments was to reach a soil pH of 5.5 and 6.5, respectively. At both sites, there were five P application rates within each liming treatment. Phosphorus (0, 10.5, 31.5, 63 and 94.5 kg P ha<sup>-1</sup>) was applied as DAP (20.1% of P), and the application rates were based on the calculated P concentration of the commercial fertilizer as actual P content of DAP was analyzed after field trials were fertilized. Blended fertilizer was included in the lime treatment of 12 t ha<sup>-1</sup>, originating from a blending factory in Tullo Bollo and, according to the producer, containing P (15.4%), N (17.7%), S (6.5%) and Zn (2.5%); this was applied to provide 94.5 kg P ha<sup>-1</sup>. The blended fertilizer was further supplemented with K as KCl (94.5 kg K ha<sup>-1</sup>) and B (4.2 kg ha<sup>-1</sup>) as borax (Na<sub>2</sub>B<sub>4</sub>O<sub>7</sub>\*5H<sub>2</sub>O). All treatments, except those with zero fertilization in lime application rates of 0 and 12 t ha<sup>-1</sup>, received 108 kg N ha<sup>-1</sup>, either as DAP or as a blended fertilizer supplemented with urea. Each lime application rate had a control treatment that received no P application, but N was supplemented equal to P fertilization treatments.

All fieldwork, including plowing, planting, weeding and harvesting, was carried out as usual by the local farmers. Prior to liming, fields were plowed with oxen and a composite soil sample was taken from the surface soil (0–20 cm) of each replicate, consisting of 18 sub-samples, one from each plot. On both fields, the lime was spread by hand in mid-May 2014, 6 weeks before planting. Lime was mixed into the soil by plowing with oxen (see Supplementary Fig. 1) and the fields were further plowed twice and weeded by hand prior to planting. A second set of soil samples were taken prior to fertilization and seeding, with a third set taken after harvesting. Second and third sampling covered all lime application rates on plots that received 94.5 kg P ha<sup>-1</sup> as DAP or blended fertilizer. The composite soil samples consisted of ten subsamples from each plot.

Wheat (var. *Danda'a*) was planted at the beginning of July at a rate of 84 kg ha<sup>-1</sup>. Seeds and fertilizers for each plot were weighed at the National Soil Testing Center (NSTC) in Addis Ababa, and fertilizers (DAP, urea, blended fertilizer, KCl and borax) were mixed together prior to spreading. Seeds and fertilizers were spread by hand and covered with soil by plowing with oxen.

Weeds were removed from the plots by hand one month after planting. At this stage, wheat was at a five-leaf stage. After weeding, an additional dose of urea at a rate of 30 kg N ha<sup>-1</sup> was top-dressed to all except unfertilized treatments. Two weeks after the first weeding, the plots were sprayed with a herbicide [(Dichlorophenoxy) acetic acid], 2,4-D: 720 g l<sup>-1</sup>]. The plots were weeded again by hand four weeks after herbicide treatment (mid-September).

#### Grain yield and elemental composition and use efficiencies of N and P fertilizers

An area of 4 m<sup>2</sup> in the middle of each plot was harvested using a sickle on the 20th (Field 2) or the 22nd (Field 1) of November (see Supplementary Fig. 1). The harvested plants were threshed by hand, and the grain was cleaned and weighed at the Nekemte Soil Research Center. The moisture content of the grain was determined by drying at 105 °C overnight, and the grain yields were calculated to a constant moisture content of 15%. Wheat yields were fitted to a Mitscherlich-type equation to calculate P fertilization requirement for achieving 90% of the maximum yield:  $y = A + B * (1 - e^{Cx})$ , where A is the minimum wheat yield, B is the maximum yield response, C is the fitting coefficient, and x is the amount of P applied (kg ha<sup>-1</sup>).

Grain samples of about 50 g were packed in paper bags, sealed in plastic bags, and sent to Finland (Natural Resources Institute Finland, Luke) to analyze the thousand-grain weight (TGW) and their elemental composition. The TGW was analyzed by weighing six sets of one hundred grains, with the smallest and largest values disregarded and the TGW was calculated as the average of the four weighings. The elemental composition of wheat was analyzed using either an ICP-OES, Perkin Elmer Optima 8300 (P, K, Ca, Mg, S, Zn, Fe, Mn, Cu, B) or with an ICP-MS, Thermo Elemental X7 (molybdenum (Mo), cadmium (Cd), nickel (Ni), lead (Pb), cobalt (Co)) after the

dissolution of the ground grain samples on a heated plate with 7 M HNO<sub>3</sub>. The Kjeldahl method was used to determine the N content of the wheat samples.

The P (PUE) and N (NUE) use efficiencies of wheat were calculated by determining the effect of P fertilization on both the P and N uptake by subtracting grain N and P content of the control treatment (in kg ha<sup>-1</sup>) from the P fertilizer treatments and by dividing this with the application rates of N or P. Calculation of NUE in the control treatment (without P application) was done as above, except that N uptake in the treatment without any fertilization (unlimed and 12 t ha<sup>-1</sup> liming rates) was subtracted from the control treatment.

#### Fertilizer, lime and soil analysis

The elemental content of the lime, DAP, blended fertilizer (not B) and KCl was analyzed using ICP-OES after aqua-regia dissolution. X-ray diffraction (XRD) analysis was conducted for the dolomitic lime to determine its mineral composition, which was 74% dolomite, 23% calcite and 3% quartz. The acid neutralizing capacity of the lime was determined by reacting 2 g of lime with 75 ml of 1 M HCl and 100 ml of deionized water at room temperature for one hour, and then heating it on a hot plate for 45 min. The mixture was titrated with 1 M NaOH. The acid-neutralizing capacity of the lime was 18.3 cmol kg<sup>-1</sup>.

Sieved (2 mm) soil samples taken before liming were analyzed for pH (water suspension, 1:2.5, v:v), acid ammonium acetate (pH 4.65) extractable P, K, Ca and Mg (Vuorinen and Mäkitie 1955), acid ammonium acetate-EDTA extractable Cu, Fe, Mn and Zn (Lakanen and Erviö, 1971), Olsen-P concentration (Kuo 1996) and oxalate extractable Fe, Al and P (Schwertmann 1964). The total C, N and S contents were analyzed according to the Dumas method using a Leco628 CN instrument. The soil samples taken before planting and after harvest were similarly analyzed for soil pH, acid ammonium acetate (pH 4.65), and acid acetate-EDTA extractable nutrients as above. The sorption of P in the experimental soils was studied by determining P isotherms for unlimed soil samples taken before planting (four plots which later received 94.5 kg DAP-P ha<sup>-1</sup>) by equilibrating 2 g of soil with a 20 ml of water solution containing the following P concentrations: 0, 5, 10, 50, 75, 150 or 250 mg l<sup>-1</sup>. Suspensions were agitated in

a reciprocal shaker at 180 rpm for 2 h, centrifuged (3000 g for 10 min.), filtered (0.2  $\mu\text{m}$  Nuclepore) and analyzed for P according to Murphy and Riley (1962). Data was fitted to a Freundlich sorption equation ( $Q = k * I^b$ , where Q is the quantity of P sorbed in soil ( $\text{mg kg}^{-1}$ ), I is the concentration ( $\text{mg l}^{-1}$ ) of P in the solution after equilibration and k and b are fitting parameters) with non-linear least square fitting.

The exchangeable acidity of each replicate of Field 1 and Field 2 before liming was analyzed at the Nekemte Soil Research Center by extracting the soil samples with 1 M KCl and by titrating the extract and phenolphthalein indicator with 0.1 M NaOH (McLean 1965).

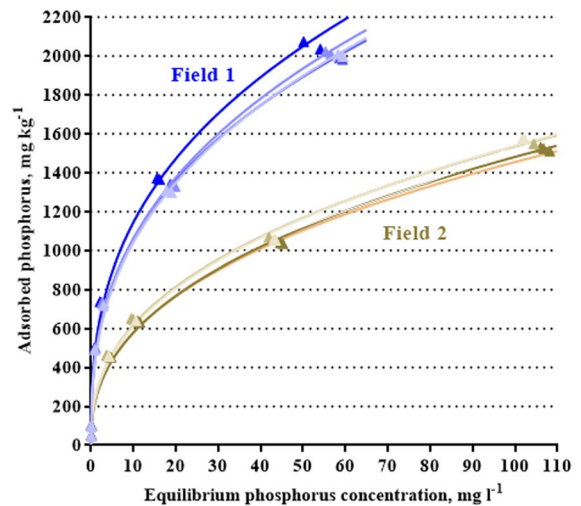
### Statistical analyses

Both fields were analysed separately. Statistical analysis of yields and elemental composition of harvested wheat based on row-column experimental design. The design was repeated four times. Randomization and analysis (using the SAS/MIXED software) were based on recommendations of Williams et al. (2002). The estimated means of the model were applied in a trend analysis in which a non-linear model (Mitscherlich) was fitted separately for both fields. In addition, the least significant difference (LSD) was calculated for pairwise comparisons of the treatments.

## Results

### Properties of the experimental fields and nutrient concentrations of the fertilizers

Both experimental fields had equally low pH values and very low available P (Table 1). Soluble Ca, Mg, K, Cu, Fe and Zn concentrations were higher in Field 2 than in Field 1, whereas the opposite was true for exchangeable acidity and oxalate extractable Al and Fe (Table 1). Both soils had extremely large capacities for adsorbing P, as indicated by the steep slopes and the large Q values of the P isotherms (Fig. 1). There was not much variability in the sorption properties within each field. In the sorption experiments, soil from Field 2 retained 90% and the soil from Field 1 as much as 98% of the added P at the level of  $50 \text{ mg l}^{-1}$ . Neither Field 1 nor Field 2 soils were saturated, even with the extreme P addition of  $250 \text{ mg l}^{-1}$ . However,



**Fig. 1** Phosphorus sorption isotherms for soils in Field 1 and Field 2, determined for four replicates of unlimed treatment plots before fertilization and planting

the curve for Field 2 started to plateau sooner than that for Field 1, indicating a slightly smaller affinity for P in Field 2 (Fig. 1). Liming increased the soil pH significantly in both fields. The pH values before planting were 5.0, 5.4 and 5.8 in Field 1 and 5.3, 6.0 and 6.4 in Field 2, after liming with 0, 6 and  $12 \text{ t ha}^{-1}$ , respectively (Supplementary Fig. 2). Current liming recommendations, based on exchangeable acidity and used dolomitic lime, for Field 1 and Field 2, were  $5.7$  and  $2.4 \text{ t ha}^{-1}$ , respectively.

The analyzed P contents of the fertilizers used were slightly smaller than reported by the manufacturer (Supplementary Table 3). The true application rates of P based on analyzed concentrations were  $9.7$ ,  $29.0$ ,  $58.1$  and  $87.1 \text{ kg ha}^{-1}$  as DAP and  $88.6 \text{ kg ha}^{-1}$  as blended fertilizer. In the text, these application rates are referred to as 10, 30, 60 and  $90 \text{ kg ha}^{-1}$ , although the actual application rates were used in calculations. Blended fertilizer contained slightly less S (5.9%) than reported on the label (6.5%), whereas the Zn concentration was more than twice (6.5%) what was reported on the label (2.5%). The potassium content of KCl was 50.5%.

### Wheat yields and TGW

In Field 1, omitting liming and P fertilization (control) leads to a total crop failure (yield  $8 \text{ kg ha}^{-1}$ ) despite N fertilization. Liming alone ( $12 \text{ t ha}^{-1}$ )

increased the wheat yield to 368 kg ha<sup>-1</sup> ( $p < 0.001$ ), whereas fertilization without lime only increased the wheat yield to a maximum of 628 kg ha<sup>-1</sup> with 60 kg P ha<sup>-1</sup> (Fig. 2). The combined effect of P fertilization and liming was prominent. The highest wheat yield obtained, 1274 kg ha<sup>-1</sup>, was reached using P fertilization of 60 kg ha<sup>-1</sup> and 12 t ha<sup>-1</sup> of lime. The impact of liming on the wheat yield was obvious even with smaller P applications. Wheat yields with a liming rate of 12 t ha<sup>-1</sup> were significantly higher than those at a liming rate of 6 t ha<sup>-1</sup> only at the P fertilization rate of 10 kg ha<sup>-1</sup>. Phosphorus fertilization of only 20 kg ha<sup>-1</sup> was sufficient to reach 90% of the maximum yield after applying 12 t ha<sup>-1</sup> of lime, whereas 90 kg P ha<sup>-1</sup> was required to produce 89% of the maximum yield at a liming rate of 6 t ha<sup>-1</sup>, based on the yield response curves in Fig. 2.

In Field 2, yield increase as compared to the control treatment after liming and P fertilization was smaller than in Field 1 due to distinctively higher overall yields even with zero P fertilization (Fig. 2). Liming alone (12 t ha<sup>-1</sup>) without any fertilization increased the wheat yield from 336 to 925 kg ha<sup>-1</sup> ( $p = 0.025$ , Fig. 2). Nitrogen fertilization further raised the yield to 984 (unlimed) and 1402 kg ha<sup>-1</sup> with liming (lime 12 t ha<sup>-1</sup>) (Fig. 2). The smallest P application rate of 10 kg ha<sup>-1</sup> significantly increased the yields, both with 6 t ha<sup>-1</sup> ( $p = 0.019$ ) and 12 t ha<sup>-1</sup> ( $p = 0.003$ ) of lime (Fig. 2). The differences at higher P fertilization rates were smaller, and at P rates of 60 and 90 kg ha<sup>-1</sup>, the yields were not significantly

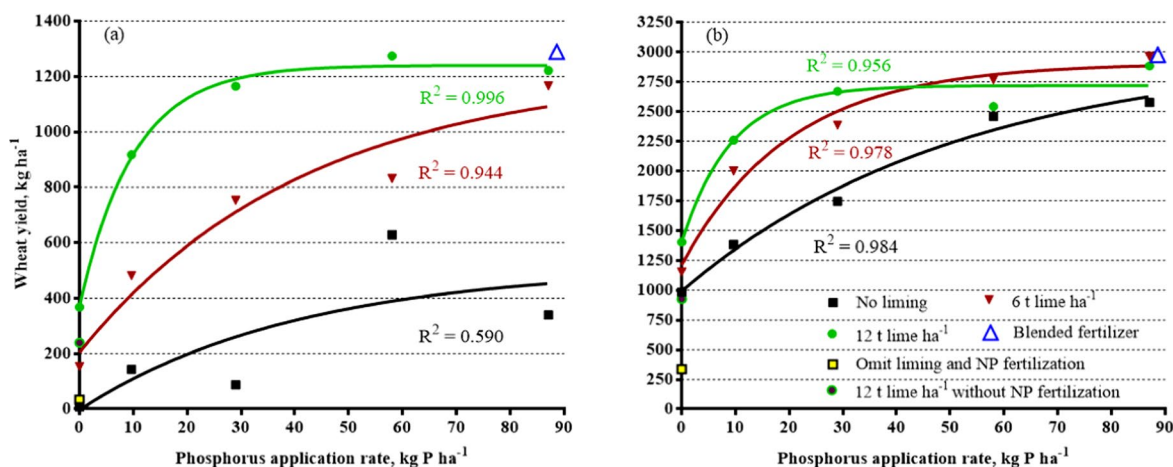
different between the limed treatments. In Field 2, 36 and 15 kg P ha<sup>-1</sup> were sufficient to reach 90% of the maximum yield after lime application rates of 6 and 12 t ha<sup>-1</sup>, respectively. Without liming, 90 kg P ha<sup>-1</sup> was required to produce 86% of the maximum yield. At a liming rate of 12 t ha<sup>-1</sup>, blended fertilizer produced similar yields to those obtained with DAP in both fields (Fig. 2).

P fertilization had an unclear effect on the TGW in both fields (Table 2). In Field 1, P fertilization and liming had a synergistic effect on the TWG, although it was only significantly increased by P fertilization with 12 t ha<sup>-1</sup> of lime. In Field 2, the TGW was diminished by P fertilization, the effect being more explicit at the higher liming rate. In Field 2, the blended fertilizer with 12 t ha<sup>-1</sup> of lime increased the TGW to its peak value among the treatments ( $p < 0.001$ ), whereas in Field 1, there were no significant differences in TGW with P application rates equal to or above 10 kg ha<sup>-1</sup>.

#### Nutrient concentration in wheat

##### Phosphorus and nitrogen

Liming and P fertilization had a synergistic effect on the P concentration of wheat, especially in Field 1 (Table 3). In the unlimed treatments, the P concentration of wheat remained at a lower level in Field 1 compared to Field 2, even at the highest P application rates. However, liming increased the



**Fig. 2** Wheat grain yields (15% moisture) obtained from Field 1 (a) and Field 2 (b) with various lime and P application rates. Note the different scale on the y-axes

**Table 2** Thousand grain weight (g) of wheat grown in Field 1 and 2 with different liming (t ha<sup>-1</sup>), nitrogen (N) and phosphorus (P) application rates (kg ha<sup>-1</sup>) Least significant difference (LSD) for pairwise treatment comparisons indicated in bold The blend fertilizer contained P, N, K, S, Zn and B

Liming rate, t ha <sup>-1</sup>	Field 1			Field 2		
	0	6	12	0	6	12
Without N and P fertilization	28.4		27.0	29.6		32.9
Control (no P)	27.3	28.0	27.6	32.3	34.0	32.7
10 kg P ha <sup>-1</sup>	27.7	30.2	31.4	33.3	32.8	32.5
30 kg P ha <sup>-1</sup>	25.2	30.4	31.1	33.0	30.0	28.1
60 kg P ha <sup>-1</sup>	30.3	30.0	31.9	29.7	30.5	29.1
90 kg P ha <sup>-1</sup>	28.8	30.9	31.5	32.1	30.3	31.1
Blend (90 kg P ha <sup>-1</sup> )			31.9			37.3
<i>LSD</i> , ( $p < 0.05$ )	<b>3.1</b>			<b>2.4</b>		

concentrations in Field 1 to comparable levels to those in Field 2 (Table 4). Liming (12 t ha<sup>-1</sup>) alone increased wheat P concentrations significantly in Field 1 ( $p=0.044$ ) and Field 2 ( $p=0.047$ ). Nitrogen fertilization without P (control treatment) reduced the P concentrations in the unlimed ( $p<0.001$ ) and limed ( $p=0.023$ ) treatments in Field 1 but not in Field 2 (Table 3).

The N concentration of wheat decreased with the increasing P fertilization rate in the unlimed treatments in both fields (Table 3). This led to significant differences in N concentration between the unlimed and limed (12 t ha<sup>-1</sup>) treatments at P levels of 60 and 90 kg ha<sup>-1</sup> in Field 1 and at 90 kg ha<sup>-1</sup> in Field 2. Unlike in Field 1, the N fertilization alone increased the N concentration of wheat significantly in both unlimed and limed treatments in Field 2 (Table 3). Blended fertilizer did not affect the N concentration of wheat compared to the limed (12 t ha<sup>-1</sup>) and N fertilized treatments.

Both PUE and NUE correlated positively with the yields (Table 4). In Field 1, P fertilization had a clear effect on the NUE only in limed soil, whereas in Field 2, the NUE was also improved in unlimed soils. Harvested wheat contained a maximum of 14 and 30% of the amount of the applied N in Fields 1 and 2, respectively (Table 4). The PUE values reached their peaks at fertilization levels close to the application rates, where yield response-curves levelled off (Fig. 2). Maximal PUE values were observed with 12 t ha<sup>-1</sup> of liming and 10 kg ha<sup>-1</sup> P fertilization: 14% in Field 1 and 25% in Field 2. In the unlimed soils, the PUE were poor, at the most 3% in Field 1 and 11% in Field 2.

### *Calcium, magnesium, sulfur and potassium*

Liming increased the concentrations of Ca and Mg of wheat, and P fertilization had a synergistic effect on Mg (Table 3). In both fields, P fertilization slightly increased the concentration of Mg in the unlimed treatments ( $p=0.10$ ). The effect was significant, with the two highest P levels at a liming rate of 12 t ha<sup>-1</sup> in Field 1 and at a P level of 30 kg ha<sup>-1</sup> and above at both liming rates in Field 2. Although the Ca concentration was less affected by P fertilization than by liming, a significant increase was observed with 60 kg P ha<sup>-1</sup> at a liming rate of 12 t ha<sup>-1</sup> in Field 2 (Table 3;  $p=0.03$ ).

Liming, especially with 12 t ha<sup>-1</sup>, increased the concentration of S of wheat and sustained it at a constant level as the P fertilization rates increased in both fields (Table 3). In the unlimed treatments in Field 1, the S concentration of wheat was at the highest level when both N and P fertilization were omitted; fertilization decreased the S concentrations. In Field 2, N fertilization alone (control treatments) increased the S concentration of wheat (Table 3,  $p<0.001$ ), whereas further addition of P fertilization without liming reduced it. Liming and P fertilization clearly increased the K concentration of wheat, and in Field 2, the effect of P was evident even in the unlimed treatments (Table 3). The only observable outcome for the blended fertilizer on wheat, as compared to DAP plus urea only, was a decreasing effect on the K concentration in Field 2 (Table 3).

**Table 3** Nutrient concentrations in wheat grains at different N and P fertilization and liming rates, g kg<sup>-1</sup> DW

Liming rate, t ha <sup>-1</sup>	P (3.69)						N (22.2)						Ca (0.47)					
	Field 1			Field 2			Field 1			Field 2			Field 1			Field 2		
	0	6	12	0	6	12	0	6	12	0	6	12	0	6	12	0	6	12
Without N and P fertilization	3.15	3.07	3.13	2.46	2.97	2.76	21.2	21.2	22.8	19.3	20.8	0.33	0.33	0.33	0.41	0.28	0.35	0.35
Control (no P)	2.26	3.07	3.13	2.39	2.76	2.76	23.1	23.1	23.0	25.8	25.3	0.32	0.32	0.32	0.40	0.33	0.34	0.36
10 kg P ha <sup>-1</sup>	2.60	2.86	3.26	2.71	2.83	3.07	21.0	20.8	22.4	25.6	25.2	0.34	0.34	0.36	0.39	0.32	0.35	0.38
30 kg P ha <sup>-1</sup>	2.78	3.53	3.59	2.74	3.56	3.88	21.1	21.6	23.0	23.6	25.3	0.37	0.37	0.40	0.37	0.31	0.36	0.40
60 kg P ha <sup>-1</sup>	3.16	3.60	4.09	3.42	3.62	4.12	21.3	21.1	24.0	23.7	25.2	0.33	0.33	0.36	0.38	0.36	0.34	0.41
90 kg P ha <sup>-1</sup>	3.17	3.90	4.11	3.59	3.94	4.09	20.5	21.1	23.1	23.2	25.2	0.34	0.34	0.36	0.38	0.32	0.37	0.39
Blend (90 kg P ha <sup>-1</sup> )	3.98				4.03		24.4				25.0	0.36						0.35
<b>LSD (<i>p</i> &lt; 0.05)</b>	<b>0.38</b>			<b>0.52</b>			<b>2.0</b>		<b>1.7</b>			<b>0.05</b>		<b>0.04</b>				
Liming rate, t ha <sup>-1</sup>	Mg (1.25)						S (1.43)						K (4.42)					
	Field 1			Field 2			Field 1			Field 2			Field 1			Field 2		
	0	6	12	0	6	12	0	6	12	0	6	12	0	6	12	0	6	12
Without N and P fertilization	1.04	1.06	1.07	1.03	1.07	1.07	1.55	1.55	1.72	1.26	1.45	4.63	4.63	4.63	4.90	4.77	4.89	4.89
Control (no P)	0.88	1.06	1.07	1.03	1.07	1.07	1.46	1.46	1.72	1.74	1.60	4.51	4.51	4.67	4.63	4.41	4.48	4.59
10 kg P ha <sup>-1</sup>	0.94	1.02	1.11	1.06	1.08	1.13	1.47	1.47	1.54	1.63	1.57	4.56	4.56	4.74	4.84	4.66	4.76	4.79
30 kg P ha <sup>-1</sup>	1.00	1.12	1.13	0.98	1.20	1.29	1.37	1.37	1.63	1.44	1.60	4.51	4.51	5.44	4.97	4.49	5.20	5.19
60 kg P ha <sup>-1</sup>	0.99	1.12	1.30	1.15	1.23	1.31	1.43	1.43	1.51	1.65	1.69	4.92	4.92	5.24	4.97	5.14	5.17	5.35
90 kg P ha <sup>-1</sup>	0.94	1.13	1.26	1.14	1.34	1.38	1.39	1.39	1.50	1.65	1.61	4.82	4.82	5.28	5.06	5.30	5.41	5.41
Blend (90 kg P ha <sup>-1</sup> )	1.24				1.31		1.59				1.61	5.05						5.03
<b>LSD (<i>p</i> &lt; 0.05)</b>	<b>0.12</b>			<b>0.12</b>			<b>0.16</b>		<b>0.11</b>			<b>0.39</b>		<b>0.32</b>				

Least significant difference (LSD) for pairwise treatment comparisons indicated in bold

Values in parenthesis after elemental symbols indicate the concentrations in the wheat seeds used for planting (Danda'a). The blend fertilizer contained P, N, K, S, Zn and B

**Table 4** Apparent N (NUE) and P (PUE) utilization efficiencies (%) in Field 1 and 2 after liming and P fertilization. The blend fertilizer contained P, N, K, S, Zn and B

Liming rate, t ha <sup>-1</sup>	NUE/PUE					
	Field 1			Field 2		
	0	6	12	0	6	12
Control (no P)	0/–	–	2/–	12/–		10/–
10 kg P ha <sup>-1</sup>	2/3	4/7	7/14	6/11	16/24	13/25
30 kg P ha <sup>-1</sup>	1/1	8/6	11/8	10/7	20/16	20/18
60 kg P ha <sup>-1</sup>	8/3	9/3	14/5	20/8	26/10	18/9
90 kg P ha <sup>-1</sup>	4/1	13/4	12/3	21/6	30/8	23/7
Blend (90 kg P ha <sup>-1</sup> )			14/3			24/7

### Micronutrients

Of the micronutrients, liming had the most drastic effect on Mo concentration. In Field 1, at liming rates of 0 or 6 t ha<sup>-1</sup>, the Mo concentration of wheat was 98 µg kg<sup>-1</sup> DW (detection limit 30 µg kg<sup>-1</sup> DW) at the most. Liming with 12 t ha<sup>-1</sup> increased the concentration to 7.5-fold (Table 5). In Field 2, the effects were also prominent, although less drastic. In Field 2, P fertilization also tended to increase the Mo concentration of wheat at a liming rate of 12 t ha<sup>-1</sup> (Table 5).

Liming also increased the Zn concentration of wheat in both fields, whereas P fertilization decreased it at all liming rates, with the effect more pronounced in Field 1 (Table 5). However, as P fertilization rates increased, Zn concentration tended to decline slower at higher liming rates. The Zn-containing blended fertilizer increased wheat Zn concentrations to the highest level in both fields, and comparable Zn concentrations were only observed in the unfertilized, poorly grown plots in Field 1.

In Field 2, P fertilization in unlimed and 6 t ha<sup>-1</sup> treatments decreased the Fe concentration of wheat but increased it with 12 t ha<sup>-1</sup> of lime. Blended fertilizer increased it significantly as compared to the control ( $p=0.03$ ). In Field 1, liming alone, or together with N fertilization, seemed to increase the Fe concentration of wheat. Still, the largest P doses at a liming rate of 12 t ha<sup>-1</sup> decreased it significantly.

Nitrogen fertilization alone (control treatment) clearly diminished the Mn concentration of wheat when compared to unfertilized and unlimed treatment in Field 1, but P fertilization sustained the Mn concentrations at the levels of the unfertilized treatment. Increasing liming rates clearly reduced the concentrations of Mn in wheat in both fields. At a liming

rate of 12 t ha<sup>-1</sup> in Field 1, the Mn concentration of wheat was not responsive to P fertilization, whereas, in Field 2, the Mn concentration increased alongside the P fertilization rate at all liming rates and, most distinctively, at the high P application rates (up to 65.9 mg kg<sup>-1</sup>) in the unlimed treatment.

The Cu concentration of wheat was fairly constant in both fields when only N fertilization was applied (Table 5). Phosphorus fertilization depressed the Cu concentration in the unlimed plots in both fields, but liming counteracted this effect. Blended fertilizer increased the Cu concentration, especially in Field 2, compared to only DAP and urea fertilization.

In most cases, the boron concentration of wheat was below the detection limit of 1 mg kg<sup>-1</sup> DW. In Field 1, only 16 plots out of 72 had B concentrations slightly above the detection limit, varying between 1.0–1.7 mg kg<sup>-1</sup> DW. Out of these plots, 15 were limed, nine had 6 t ha<sup>-1</sup>, six had 12 t ha<sup>-1</sup>. In Field 2, only six limed plots had B concentrations above the detection limit (max. 1.7 mg kg<sup>-1</sup> DW); out of these six plots, five received 12 t ha<sup>-1</sup> of lime. In plots fertilized with blended fertilizer, the B concentration of wheat was below the detection limit.

### Harmful heavy metals

Cd, Pb and Co concentrations in wheat were below the detection limits of 30, 30 and 60 µg kg<sup>-1</sup> DW, respectively. The Ni concentration of wheat was about three-fold higher in Field 2 than in Field 1. However, liming with 12 t ha<sup>-1</sup> reduced the Ni concentration to about half of that found in the unlimed treatments in both fields (Table 5). The concentration decreased systematically in the treatments, unlimed > 6 t ha<sup>-1</sup> > 12 t ha<sup>-1</sup> in both fields. In Field

**Table 5** Concentrations of Mo ( $\mu\text{g kg}^{-1}$  DW) and Zn, Fe, Mn, Cu and Ni ( $\text{mg kg}^{-1}$  DW) in wheat grains at different N and P fertilization and liming rates. Values in parenthesis after elemental symbols indicate the concentrations in seeds used for planting (Danda a). The blend fertilizer contained P, N, K, S, Zn and B

Liming rate, $\text{t ha}^{-1}$	Mo (530)			Zn (26)			Fe (30)					
	Field 1		Field 2	Field 1		Field 2	Field 1		Field 2			
	0	6	12	0	6	12	0	6	12			
Without N and P fertilization	63	243	38	100	28.7	30.5	20.6	25.8	36.8	53.4	36.9	31.5
Control (no P)	42	98	33	55	22.8	25.3	27.1	25.6	27.9	36.8	42.4	33.4
10 kg P $\text{ha}^{-1}$	57	64	181	70	20.6	23.8	24.6	23.1	25.0	54.2	37.1	23.1
30 kg P $\text{ha}^{-1}$	54	77	166	45	18.3	23.7	22.1	19.3	26.3	51.7	45.7	21.6
60 kg P $\text{ha}^{-1}$	<30	88	223	18	16.6	21.4	23.5	19.8	22.2	41.3	35.9	27.1
90 kg P $\text{ha}^{-1}$	45	73	181	118	16.4	19.3	22.0	20.6	22.6	39.9	42.5	27.9
Blend (90 kg P $\text{ha}^{-1}$ )		164		140		33.0		33.8		35.1		34.5
<b>LSD (<math>p &lt; 0.05</math>)</b>	<b>65</b>		<b>70</b>		<b>4.2</b>		<b>4.1</b>		<b>19.6</b>		<b>9.9</b>	
Liming rate, $\text{t ha}^{-1}$	Mn (34)			Cu (3.5)			Ni (0.38)					
	Field 1		Field 2	Field 1		Field 2	Field 1		Field 2			
	0	6	12	0	6	12	0	6	12			
Without N and P fertilization	51.6	43.6	46.7	44.8	4.96	5.45	4.73	4.61	0.43	0.24	1.69	0.59
Control (no P)	43.9	46.1	42.7	51.1	44.6	43.8	5.16	5.76	5.67	0.40	0.27	1.37
10 kg P $\text{ha}^{-1}$	48.3	49.7	43.8	48.1	50.1	46.7	4.78	5.14	5.66	0.55	0.31	1.20
30 kg P $\text{ha}^{-1}$	54.9	52.8	44.0	52.8	54.5	48.5	4.71	4.43	5.83	0.72	0.33	1.45
60 kg P $\text{ha}^{-1}$	49.8	51.7	42.6	61.2	55.8	50.6	4.95	4.28	5.30	0.44	0.40	0.95
90 kg P $\text{ha}^{-1}$	51.4	49.8	42.5	65.9	57.5	51.9	4.67	4.22	5.11	0.59	0.34	1.64
Blend (90 kg P $\text{ha}^{-1}$ )		40.9		51.7		5.12		5.59		0.21		0.75
<b>LSD (<math>p &lt; 0.05</math>)</b>	<b>5.3</b>		<b>5.3</b>		<b>0.94</b>		<b>0.39</b>		<b>0.10</b>		<b>0.36</b>	

Least significant difference (LSD) for pairwise treatment comparisons indicated in bold

1, P fertilization increased the Ni concentration of wheat in the unlimed treatments, and the same tendency was present at a liming rate of  $6 \text{ t ha}^{-1}$  but not at a liming rate of  $12 \text{ t ha}^{-1}$ . Only the highest P fertilization rate increased wheat Ni concentration in the unlimed soil in Field 1.

#### Soil pH and nutrient status after harvest

One cropping season did not change the soil pH in Field 1, but a slight decrease was observed in Field 2 (Supplementary Fig. 2). Soluble Ca (Supplementary Fig. 3) and Mg (Supplementary Fig. 4) concentrations in the experimental soils increased upon liming and remained at the same level after one cropping season. The soluble P concentration of soil was only slightly increased despite a heavy P application rate of  $90 \text{ kg ha}^{-1}$ . In Field 1, the P concentration was highest in the unlimed treatment, whereas in Field 2, it was slightly higher in limed treatments (Supplementary Fig. 5). The soluble Zn concentration in the soil after harvest was distinctly higher in both fields when blended fertilizer was used (Supplementary Fig. 6). The cropping season did not affect the soluble Fe, Cu and Mn concentrations, irrespective of liming rates (data not shown).

## Discussion

### Liming reduces fertilizer need for optimal yields

Liming greatly improved the efficiency of P fertilization and increased the wheat yields on the experimental fields. The outcome of this study is similar to those of earlier studies conducted in Ethiopia (Desalegn et al. 2017; Fekadu et al. 2018), although liming rates were far higher in this study. Weather conditions, especially rainfall during the growing season (June–October) was about 450 mm more than the average during the years 2005–2013. Temperature ranges were about at the same level as in previous years, indicating that the yields were probably not depressed by the unfavorable weather conditions. In this study, the P fertilization rate ( $20 \text{ kg ha}^{-1}$  on Field 1 and  $15 \text{ kg ha}^{-1}$  on Field 2) that produced 90% of the maximum yield at the liming rate of  $12 \text{ t ha}^{-1}$  increased the wheat yield by about  $1000 \text{ kg ha}^{-1}$  in both fields as compared to the unlimed soil with equal

P application rate. For low-productive fields, like Field 1 in this study, even extreme fertilization rates cannot compensate for the poor crop growth caused by severe soil acidity. Hence, fertilization, one of the major investments made by farmers, does not reach its full potential in terms of crop production. Liming improved root growth, which in turn enhanced foraging of nutrients from a larger soil volume. Despite almost identical soil texture, pH and P content, the effects of liming on wheat growth and yield were more pronounced in Field 1 than in Field 2. Still, the yields in Field 1 remained lower than those in Field 2. The increase in soil pH after liming in Field 1 was smaller than in Field 2, indicating a higher acidity. Alongside pH, Field 1 also had higher concentrations of oxalate-extractable Fe and Al and smaller concentrations of many plant nutrients, suggesting a higher degree of soil weathering. All these differences in soil properties partly explain the large yield gap observed between the sites.

The productivity of potentially fertile Nitisols is commonly limited by low P availability and high exchangeable acidity. Both experimental fields were extremely P deficient; both had an Olsen-P value of about  $3 \text{ mg kg}^{-1}$ , far below the  $30 \text{ mg kg}^{-1}$  considered critical for many crops of the tropics (Sanchez 2019). The poor availability of P in these soils is a consequence of the extreme content of typically clay-sized, short-range-ordered Fe and Al oxides (Table 1), which allow for a great deal of P sorption in these soils, especially in acid conditions. Phosphorus sorption in tropical soils has been shown to correlate with clay content, and in the study by Brenner et al. (2019) of 23 tropical soils, clay content varied between 2 and 47%, far below the levels found in the present study (80%). In this study, we were not able to determine the P sorption maximum, but Fig. 1 shows that it is evident that in Field 1, it was far above the mean value of  $2060 \text{ mg kg}^{-1}$  observed by Brenner et al. (2019).

Liming improved the wheat yields, especially in Field 1, up to one order of magnitude at P fertilization rate of  $30 \text{ kg ha}^{-1}$ . This high yield response is probably due to reduced sorption of P on oxide surfaces and cutting down the toxicity of soluble Al (Marschner 1991). The latter is clearly visible in Supplementary Fig. 7, which depicts the improved growth of wheat roots in limed soil, which allows a larger soil volume to be foraged for P. These

mechanisms explain the improved P utilization and the 90% of the maximum yield obtained with only 15 kg P ha<sup>-1</sup> in Field 2 (only about twice the offtake in harvested grain) and with 20 kg P ha<sup>-1</sup> in Field 1. The very low yields (1.2 t ha<sup>-1</sup>) in Field 1, even at large P fertilization, indicate how other growth factors were depressing yields. One of these might have been weed pressure due to the previous cropping history of Field 1 (Supplementary Fig. 8).

#### Liming greatly improved nutrient use efficiencies

Without liming, both N and P utilization was only a few percent in Field 1. Liming improved N and P uptake, yet NUE and PUE was at the most 14% due to low yields. Improved NUE in both fields after liming had a positive effect on the quality of wheat by increasing the N content, and thus, the protein content of wheat. Although P fertilization increased the yields in the unlimed soils in both fields, the wheat quality was reduced due to decreased N concentration. This might be due to N leaching deeper into the soil profile caused by heavy rainfall during the rainy season and poor root growth in the unlimed soil. Also, molybdenum might play a role in boosting the NUE, as it is essential in N metabolism for converting nitrate into amino acids (Kaiser et al. 2005). The concentrations of Mo in wheat were very small in the unlimed treatments, and lime, together with P fertilization, greatly enhanced the Mo nutrition of wheat. The smallest Mo concentrations found in this experiment were below the detection limit (30 µg kg<sup>-1</sup>), and the critical concentration for reaching 90% of the maximum wheat yield is 20 µg kg<sup>-1</sup>, according to Brennan (2006). In two other field trials in the region of Nekemte with similar soil properties (soil pH 5.0 and 4.9), the Mo concentrations of wheat at the tillering stage were below the critical level (70 µg kg<sup>-1</sup>) for reaching 90% of the maximum yield (Brennan 2006). However, liming (10 t ha<sup>-1</sup>) increased the Mo concentration at tillering up to 400 µg kg<sup>-1</sup> (unpublished data). These studies demonstrate how indigenous Mo reserves in acidic soil can be mobilized through liming to combat Mo deficiency in SSA topsoils (see Keskinen et al. 2019).

#### Blended fertilizer and liming increased wheat Zn, Fe and Cu concentrations

Liming, especially at 12 t ha<sup>-1</sup>, increased the Zn concentration of wheat. This is probably related to enhanced root growth (Friesen et al. 1980). This outcome contradicts some earlier studies, where liming reduced the Zn concentration in maize and wheat grown at soil pH 5.7 (Verma and Minhas 1987) or below 4.8 (0.01 M CaCl<sub>2</sub>) (Tagwira et al. 1993). The reduction of wheat Zn concentration after P fertilization in this study may be due to the antagonistic effect of P on Zn uptake (Ova et al. 2015) or the dilution effect caused by the increased wheat yield after liming and P fertilization. It is evident that the overall availability of Zn was very low in both soils. The Zn-containing blended fertilizer increased the Zn concentration of wheat and the TGW to peak values compared to all other treatments, even though this Zn concentration was below the level of 45 mg kg<sup>-1</sup> considered to be adequate for human nutrition (Cakmak et al. 2017). According to a global study conducted by FAO (Sillanpää, 1982), a hidden shortage of Zn has been observed in Ethiopia, and the Nekemte area is one of the regions with the lowest Zn content in soil. In other field trials in the Nekemte region with similar soil properties, the concentration of Zn in wheat leaves has been found to be below 15 mg kg<sup>-1</sup> (unpublished results), indicating that Zn deficiency is likely (Sillanpää, 1982). Besides liming and N fertilization, Zn fertilization has a great potential for improving the nutritional quality of wheat grown in the region.

Liming and P fertilization in the field with higher yield potential (Field 2), essential for improving yields in these soils, tended to increase wheat Fe concentrations. In spite of this, the Fe concentration of wheat remained lower than the recommended concentration of 50 mg kg<sup>-1</sup> and concentrations of 40–50 mg kg<sup>-1</sup> found in large datasets from various growing regions across the globe (Liu et al. 2014). Blended fertilizer further increased the Fe concentration of wheat as well as Cu concentration, which may be due to the positive effects of Zn on both Fe (Graham et al. 1999; Liu et al. 2014) and Cu uptake (Chaudhry and Loneragan 1970; Khurana and Chatterjee 2000). The results indicate the importance of balanced fertilization, especially for nutrients that can have antagonistic or synergistic effects on their

uptake. Blended fertilizer containing Zn may be especially beneficial in the Highlands of Ethiopia where increased Zn and Cu in the diet can reduce child morbidity and mortality (Berkhout et al. 2019).

The extractable Cu concentrations in both experimental soils were close to the average ( $n=125$ ) of  $4.6 \text{ mg l}^{-1}$  in Ethiopian agricultural soils (Sillanpää 1982), whereas the Cu concentration of harvested wheat was low compared to other studies (Shukla and Singh 1979). Increasing the P fertilization rate depressed the Cu concentration of wheat, especially in the unlimed soil. Similar results were observed in wheat grown in acid soil by Bolland et al. (1993). A diminished Cu concentration in maize after P fertilization was suggested to be due to reduced colonization of roots by arbuscular mycorrhizal fungi (Zhang et al. 2020). Unlike Cu, liming and P fertilization had the opposite effect on the Mn concentration of wheat, especially in the more productive Field 2. The Mn concentration in the unlimed conditions was far above the level of  $43.7 \text{ mg kg}^{-1}$ , considered a health risk for children living in the countryside and relying on locally produced whole wheat grain food (Shi et al. 2020).

Although the solubility of B decreases as soil pH increases (Goldberg 1997), liming had a positive effect on the B nutrition of wheat. Furthermore, blended fertilizer containing B did not improve the wheat yield, indicating that available B was not a growth-limiting nutrient. This may also be explained by the fact that wheat, among other cereals, has a low B requirement (Bell 1997).

Dolomitic lime and P fertilization increased Ca, Mg, K and S concentrations in wheat

Both fields had a soluble Ca concentration of less than  $1000 \text{ mg l}^{-1}$ : in Field 1, it was extremely low compared to an international study conducted by Sillanpää (1982). In spite of this, the Ca concentrations of wheat ( $0.28\text{--}0.41 \text{ g kg}^{-1}$  DW) were comparable to those of wheat trials conducted in Finland ( $0.3 \text{ g kg}^{-1}$ ) with a soil Ca concentration of  $2300 \text{ mg l}^{-1}$  (unpublished results). The highest Ca concentrations in this study were similar to the median concentration reported from experiments conducted in Mexico (Graham et al. 1999). Cereals have a low requirement for Ca, and in this study, Ca was probably not the growth limiting factor as Ca concentrations in wheat

were similar in both fields. Low Mg concentrations were detected in both fields; in Field 2, it was just above the minimum value ( $189 \text{ mg l}^{-1}$ ) observed in the mapping of arable soils ( $n=54$ ) in Ethiopia (Sillanpää 1982). The low Mg concentration in the soil was reflected in the Mg concentration of grain being lower than the minimum concentration observed in a bread wheat study ( $n=132$ ) by Graham et al. (1999). Dolomitic lime and P fertilization had a synergistic effect on wheat Mg concentration as P fertilization improved the uptake of Mg, probably by reducing Mg efflux from the roots (Reinbott and Blevins 1991). Furthermore, it has been shown that if both Mg and P deficiency exist simultaneously, Mg deficiency may restrict yield formation more than P deficiency due to their synergistic effect on the utilization of N for yield formation (Weih et al. 2021). Lowest grain K concentration was in unlimed treatments, probably due to the abiotic stress (Khan et al. 2023) caused by soil acidity. Abiotic stress was alleviated by both liming and P fertilization leading to increased K uptake.

The main source of S for wheat probably originated from indigenous soil reserves, and the C:S ratio was less than 100 in both experimental fields suggests a release of S upon mineralization (Scherer 2005), enhanced by liming (Bolan et al. 2008). Although the blended fertilizer provided an additional  $36 \text{ kg S ha}^{-1}$ , DAP ( $90 \text{ kg P ha}^{-1}$ )  $6 \text{ kg ha}^{-1}$  and  $12 \text{ t ha}^{-1}$  of dolomitic lime  $5.5 \text{ kg ha}^{-1}$ , N fertilization together with liming was the main contributor to increased S concentrations in wheat in Field 2. In the low productive Field 1, only liming increased S concentration in wheat, probably by increasing the wheat's ability to absorb S from the soil's own reserves.

Liming reduced harmful heavy metals in wheat

The soluble Ni concentration in the soil in Field 2 was far above the 75th percentile values of  $1.4 \text{ mg kg}^{-1}$  detected in topsoils of SSA, while the concentrations in Field 1 were much smaller (Keskinen et al. 2019). The Ni concentration of wheat in the unlimed treatment in Field 2 was also higher than the median and the 95th percentile in grain and grain-based products of  $0.16$  and  $1.25 \text{ mg kg}^{-1}$ , respectively, found in a large dataset ( $n=5221$ ) in Europe (EFSA CONTAM PANEL et al. 2020). This indicates the potential for heavy metal accumulation and deterioration of wheat quality grown on acidic soils. Liming has the

potential to mitigate these risks. In this experiment, liming reduced the Ni concentration of wheat to half of the concentration in the unlimed treatments. Additionally, improved Cu and Zn uptake by wheat after liming may have depressed Ni uptake due to their antagonistic effect on Ni uptake (Chen et al. 2009). Although soluble Pb and Co concentrations in Field 2 were above the 95th percentile of SSA topsoil (Keskinen et al. 2019), their wheat grain accumulation was insignificant.

#### Liming of acidic soils is prerequisite for ensuring food security in Ethiopia

The liming rates used in this experiment were far higher than commonly recommended in acidic tropical soils. With the current liming recommendations in Ethiopia, 6 t ha<sup>-1</sup> equals with the recommended application rate (5.7 t ha<sup>-1</sup>) for Field 1, whereas for Field 2, recommended rate would be only 2.4 t ha<sup>-1</sup>. Appropriate liming rates for tropical soils have been controversial since the 1950s, because of the economic limitations and the potential for lime-induced chlorosis. Typically, only hundreds of kilograms per hectare have been considered an adequate liming rate in these soils (Richardson 1951). The application rates of lime are commonly based on the amount of exchangeable soil acidity (Kamprath 1971; Reeve and Sumner 1970), and the main goal for liming is reducing toxic Al in soil solutions and enhancing root growth. Excessive liming of tropical soils (to near neutrality) has been considered to endanger yields by reducing the bioavailability of certain nutrients, especially of P, Zn, Fe and B, due to the decrease of solubility or increase of sorption to soil colloids (Rengel et al. 1999; Sanchez 2019). In this study, the lower liming rate of 6 t ha<sup>-1</sup> increased the soil pH to about 5.5, sufficient for neutralizing exchangeable acidity. Liming with 12 t ha<sup>-1</sup> further increased the soil pH up to 6.4 in Field 2. This increased the utilization of P and wheat yields, demonstrating how higher liming rates were beneficial both for the wheat yield and quality. Large doses of lime also maintain the soil pH at an elevated level for a longer period, but further research is needed to determine the appropriate interval for re-liming.

Cereals and pulses dominate Ethiopian diets, especially in rural areas where more nutritious fruits and vegetables are rare (Ameye et al. 2021). This study

revealed that both liming and fertilization have a significant potential for increasing the essential nutrient content of wheat. The improved quality of cereals may alleviate “hidden hunger” (Cakmak et al. 2017; Joy et al. 2014) and help reduce child mortality, especially in the Highlands of Ethiopia (Berkhout et al. 2019). The mineral elements most often lacking in human diets are Fe, Zn, Cu, Ca, Mg, Se and iodine (I) (White and Broadley 2009). In Ethiopia, it is estimated that as much as 100 and 81% of the population is at risk of suffering from Ca and Zn deficiencies, respectively (Joy et al. 2014). Inadequate dietary Zn intake is prevalent in the entire SSA region (Wessells and Brown 2012). One of the consequences of such malnutrition is a high incidence of stunted growth (Central Statistical Agency (CSA) [Ethiopia] and ICF, 2016). Investment and capacity buildings is needed to improve local food production to ensure affordable and nutritious food (Ameye et al. 2021). Liming of the potentially very productive, acidic soils, together with N and P fertilization mixed with key nutrients, provides the basis for adequate production. The use of fertilizer, especially for cereals, has increased considerably in Ethiopia and is considered the most effective measure for increasing yields (Bachewe et al. 2018). This study showed how liming is an extremely efficient method of increasing the utilization of fertilizers’ nutrients and further improving wheat yields and quality. Supplementing fertilizers with micronutrients have been successfully conducted in Finland, where selenium supplementation of fertilizers started in 1982. The application depressed selenium deficiency in cattle through increased selenium concentrations in fodder. This has ensured humans’ increased uptake of selenium through milk, meat, and cereals (Alftan et al. 2015).

#### Conclusion

Liming the acid soils of the Ethiopian Highlands is highly beneficial for improving wheat yields and quality. Only a moderate amount (20 kg P ha<sup>-1</sup>) of P fertilizer was needed to reach 90% of the maximum yield at a high liming rate (12 t ha<sup>-1</sup>) despite high P fixing capacity of the soils. Fertilizing acid soils with N and P without liming leads to poor nutrient use efficiencies and a decline in the quality of wheat. Application of dolomitic lime and fertilizers containing

essential nutrients, especially Zn, increased concentration of all beneficial nutrients (P, N, Ca, Mg, S, K, Zn, Cu, Fe, Mo) and decreased harmful heavy metal concentration (Ni) in wheat. Higher liming rates than currently recommended in Ethiopia reduce the requirement for P fertilization and enable an improvement in the quality of wheat without inducing micro-nutrient deficiencies. Hence, current liming recommendations need to be revised and further studies are needed for determining optimal soil pH for wheat as well as for other crops. Also, re-liming interval needs to be determined for evaluating economic of liming. Furthermore, the delicate synergistic and antagonistic effects of nutrients need to be addressed, requiring information on the nutrient status of soils. Sufficient liming coupled with balanced fertilization of otherwise potentially productive vast areas of acid soils in SSA might provide a promising method of improving the food security of the region.

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## Declarations

**Competing interest** The authors declare no competing interest.

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