




Cereal yields in Ethiopia relate to soil properties and N and P fertilizers

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Abstract There is an urgent need to increase cereal yields in the Ethiopian Highlands to ensure national food security. A major crop response-to-fertilizer program was set up in 2017–2019 as part of the CAS-CAPE project in the Ethiopian Highlands. It covered 33 experiments on maize, teff and wheat in five reference soil groups (Nitisols, Luvisols, Vertisols, Lep-tosols and Andosols). Five levels of multi-nutrient

fertilizer (50–300 kg NPSZnB ha⁻¹ and 100 kg urea ha⁻¹) were applied. At the lower fertilizer level, average yields were 5500, 1500 and 3300 kg ha⁻¹ for maize, teff and wheat, respectively. At the highest rate, yields were 7900, 2100 and 5000 kg ha⁻¹. Maize and wheat yields were strongly correlated to the reference soil groups, but not to rainfall differences. Wheat yields were also positively correlated to soil organic carbon levels, underpinning the need to apply integrated soil fertility management. Comparing NPSZnB fertilizers with NPS and DAP fertilizers

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revealed a lack of statistically significant advantage for the fertilizers including Zn and B. As B was present in fine-granular form in the fertilizer bags, being prone to segregation, firm conclusions on the need for this micronutrient cannot be drawn. The use of ‘recommendation windows’ is suggested to group results into concrete packages at district levels and below, preferably combined with soil maps since soil types were correlated with maize and wheat yields. The windows could then be the starting point to develop ‘last mile’ fertilizer use policies, relevant to farmers and the way they manage their fields in the landscape.

Keywords Fertilizer · Maize · Teff · Wheat · Blend · Micronutrients · Ethiopian Highlands

Introduction

Achieving food security is key to Ethiopia’s national policy agenda. As particularly wheat production is way below consumption, food importation has increased, becoming a burden to the national trade balance. Therefore, a need is felt to increase crop yields and production to meet domestic food grain needs, substituting imports. In Ethiopia, recent national average yields of the major cereals, based on annual crop cut samples from different regions (crop belts) were 3.94 Mg ha⁻¹ for maize, 1.75 Mg ha⁻¹ for teff, and 2.74 Mg ha⁻¹ for wheat (CSA 2018). This is not bad, but generally regarded to be substantially below potential yields (Cochrane and Bekele 2018; Elias et al. 2019). Agriculture in the Ethiopian Highlands is dominated by continuous cultivation on increasingly smaller plots, removal of crop residues

for animal feed in oxen-driven production systems, sales of farm yard manure as fuel, and the local soil burning practice of *guie* in Vertisols causing loss of topsoil organic matter (Elias 2016; Tadesse 2015). Soil erosion rates in the mountainous landscapes with steep and long slopes can exceed 100 Mg ha⁻¹ year⁻¹ (Getnet and Mulu 2021; Woldemariam and Harka 2020), colouring rivers brown with precious topsoil. This is compensated to some extent by a national fertilizer rate of 43 kg ha⁻¹ urea and 65 kg ha⁻¹ diammonium phosphate, DAP (Elias 2017), and by the fact that by average African standards, the Ethiopian Highlands are fertile by virtue of their volcanic origin. The agricultural extension system of Ethiopia initially attempted to implement a national blanket recommendation of 100 kg DAP (18% N, 20% P) and 100 kg urea (46% N) ha⁻¹ for most cereals. From 2015 onwards, a program was started to make recommendations more soil and area-specific, and therefore more cost-effective: the Ethiopian Soil Information System (EthioSIS; ATA/EthioSIS 2014). It also marked the shift from conventional fertilizers (urea, DAP) to multi-nutrient fertilizers, as deficiencies of potassium, sulphur, zinc and boron were noted (Abera and Kebede 2013; ATA/EthioSIS 2014; Haile and Mamo 2013).

Based on these observations and on an EthioSIS topsoil survey campaign, a new NPS compound fertilizer (19% N, 17% P, 7% S) was introduced and combined mainly with fertilizing products containing K (muriate of potash), Zn (zinc sulphate) and B (sodium borate or borax), according to observed soil nutrient deficiencies. Currently, NPS + ZnB compound fertilizer is the widely used multi-nutrient fertilizer in Ethiopia, based on the EthioSIS Soil Fertility Atlas. The atlas based assessments of S, Zn, B and K deficiencies in Ethiopia on ‘critical levels’ of these nutrients, below which a crop is expected to respond to their applications as fertilizer nutrients. In Ethiopia, these critical levels were chosen as 20 ppm SO₄-S, 1.5 ppm Zn, 0.8 ppm B, and 120 ppm K using the Mehlich-3 method. These levels are somewhat arbitrary, as they were based on a literature assessment that did not account for soil analysis extraction procedure or crop (Karlton et al. 2013). The choices of critical levels had far-reaching consequences as for example the relatively high threshold for B of 0.8 mg kg⁻¹ (taken from four literature values of 0.5 and just one of 0.8 mg kg⁻¹) turned most of the Ethiopian

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Highland soils into being B-deficient on the EthioSIS map, translating into the need for B in the fertilizer mix.

Several studies since then reported substantial yield increases in maize and teff when applying NPS fertilizers that include Zn, B or both (Berhe and Marie In press; Haileselassie et al. 2018). These studies however do not show whether the yield increases can be attributed to the addition of S, B or Zn, as the crops received different levels of N and P fertilizers in addition to the multi-nutrient fertilizer. On-farm trials on poorly drained Vertisols in Bichena, north-western Ethiopia, for example, showed wheat yield increases from 981 kg ha⁻¹ (no fertilizer) to 3300 kg ha⁻¹, when applying just 138 kg N and 40 kg P ha⁻¹ (Liben et al. 2006). In 2014 and 2015, the Ethiopian Institute of Agricultural Research (EIAR) and regional research stations compared the response of wheat, maize, and barley to DAP with seven NPS-based fertilizers, both with urea topdressing. In 12 maize trials, 18 wheat trials, and 7 barley trials, slight differences in grain yields were observed among treatments, mostly in favour of multi-nutrient fertilizers, but hardly statistically significant (Niguse et al. 2017). An early publication on the 2017 wheat trials in the current paper revealed some but no significant effect of five-nutrient fertilizers (Elias et al. 2019). Demisse and Bekele (2017) concluded in a country review that ‘the profit potential is generally much greater with application of N and P fertilizers compared with K and the secondary and micronutrients, particularly Zn for all cereals. In short, all results so far show that crop response to fertilizer is generally existent and promising, but the evidence that fertilizers that contain S, Zn and B do better than their conventional equivalents is (at best) mixed.

Two other key issues stand out that hamper solid evaluation of available experimental data. First, 100 kg multi-nutrient and 100 kg conventional fertilizer can be compared but have different N and P concentrations. Therefore, a per kg fertilizer evaluation is different from a per kg nutrient evaluation which does not receive due attention in published material so far. Second, it is not always clear whether the multi-nutrient fertilizers were made up of granules containing all nutrients (compound) or of separate fertilizers being physically mixed (blended). In the latter case, uneven distribution of granules in fertilizer bags and particularly mixing of coarse granules

fine-granular substances turned out to be a bone of contention. An inspection of the blending facility in Enderta, Mekelle, shows how the fine-granular B fertilizer is unevenly distributed in the bag (Supplementary Fig. 1).

This paper intends to come up with more conclusive evidence on the performance of multi-nutrient fertilizers in the Ethiopian Highlands. Therefore, a series of on-farm but researcher-managed fertilizer trials was run to establish response patterns of the major cereals (maize, teff and wheat) to different levels of NPS + ZnB blend and conventional fertilizers in a wide range of reference soil groups (Nitisols, Luvisols, Vertisols, Andosols, and Leptosols). The experiments were part of the CASCAPE project (Capacity building for Scaling up of Evidence-based Best Practices for increased Agricultural Production in Ethiopia), that supported the national Agricultural Growth Program (AGP).

More specifically, the objective of the paper is:

1. to show how increasing levels of NPS + ZnB fertilizer affect the performance of maize, teff and wheat, per trial site, per soil reference group and per year, covering a total of 33 trials in the 2017–2019 period,
2. to compare yields obtained with five-nutrient fertilizers with those realized with NP and NPS fertilizers without Zn and B,
3. to study the effects of soil organic carbon and soil pH on wheat yield,
4. to suggest ‘recommendation windows’ to turn findings into policy-relevant packages that come closer to farmer reality and allow targeted fertilizer marketing and adoption.

Materials and methods

Crop choice

The study focuses on the three major staple crops. Maize (*Zea mays L.*) is the most widely cultivated cereal crop in terms of grain area coverage (16.8%) and grain production (27.4%) with about 8.4 million Mg of production in Ethiopia (CSA 2018). Teff (*Eragrostis tef [Zucc] Trotter*) was planted to more than 3 million ha that accounted for about 24% of grain-cultivated area. Nearly 50% of smallholder farmers

grows it for *enjera* preparation and cash income. The country relies on teff for two-thirds of the daily protein intake and 11% of the per capita caloric intake (Elias 2016). Teff straw is a highly marketable commodity as well, for animal feed and wall plastering to build the traditional Ethiopian houses. Wheat (*Triticum aestivum*) is considered a strategic crop to meet food needs of the growing Ethiopian population. In 2017/18, wheat was planted on 1.7 million ha (13.4% of the grain-cultivated land) and provided about 15% of the daily caloric intake of the population (Elias et al. 2019; CSA 2018; FAO 2015).

Site selection and experimental design

Site selection considered dominant reference soil groups and major maize, teff and wheat belts in the AGP mandate area and in the 10 key intervention woredas of the CASCAPE project. Soil-landscape maps prepared in the first phase of CASCAPE were used for further site selection (Elias 2016). Selection and fertilizer rate further took into consideration the recommended multi-nutrient fertilizer type and indicative rate following from the EthioSIS regional soil fertility maps, which were the yardstick references for the regional Bureaus of Agriculture. Site locations are given in Supplementary Fig. 2 and site-soil-crop combinations in Supplementary Table 1.

Treatment selection

The recommended multi-nutrient fertilizer that covers the largest part of the Ethiopian Highlands according to the EthioSIS atlas is NPS + ZnB. Therefore, this was the key fertilizer used in the 33 experiments,

at the then recommended nutrient ratios of 17% N + 15% P + 7.3% S + 2.2% Zn + 0.67% B. Currently in Ethiopia (2023) ratios are used that contain smaller B contents. The trial design is shown in Table 1. It is meant to serve two purposes: (i) to evaluate the effect of increasing levels of NPS + ZnB on crop yield for different sites, rainfall totals across years, reference soil groups and soil properties (treatment 1–5), and (ii) to compare crop yield response to NPS + ZnB against NPS and DAP (treatments 2 vs. 6 and 3/4 vs. 7).

As fertilizers are modestly yet commonly used in the Ethiopian Highlands, it was decided not to include a zero-fertilizer control treatment due to lack of relevance. Treatment 1 (T1), including 50 kg multi-nutrient and 100 kg urea, was seen as a desirable minimum fertilizer level, and therefore taken as a control. Trials were laid out in a randomized complete block design with three replications on neighboring farms (i.e., using farm fields as replicates), and with a plot size of 5 * 5 m. An improved bread wheat variety (*Hidase* for Addis Ababa, *Damphie* for all others) was planted with the full-package of recommendations for seed rate (125 kg ha⁻¹), row planting, two hand weeding and spray (*dimethoate*) for pest control. Split application of urea (100 kg ha⁻¹) was standard for all plots and applied in three equal amounts, at planting, two weeks after emergence and at booting stages. For teff, *Kuncho* (for Bahir Dar and Addis Ababa) and *Boset* (for Hawassa) were used, and for maize BH-540 (Bahir Dar), BH-546 (Addis Ababa) and BH-661 (Jimma). The multi-nutrient fertilizer was applied at planting (basal application) while urea (100 kg/ha standard treatment) was applied in two splits: at planting and top-dressed after hand weeding.

Table 1 Fertilizer treatments and nutrient contents used in the fertilizer trials of the CASCAPE project

Treatment	Description ^a	Input (kg ha ⁻¹)					
		N	P	K	S	Zn	B
T1	50 kg/ha NPS + ZnB	8.5	7.5	0	3.5	1.1	0.3
T2	100 kg/ha NPS + ZnB	17	15	0	7	2.2	0.7
T3	150 kg/ha NPS + ZnB	26	22	0	11	3.3	1.1
T4	200 kg/ha NPS + ZnB	34	30	0	14	4.4	1.4
T5	300 kg/ha NPS + ZnB	51	45	0	21	6.6	2.1
T6	100 kg/ha NPS	19	17	0	7	0	0
T7	150 kg/ha DAP	27	30	0	0	0	0
T8	300 kg/ha NPKSB	42	36	36	15	0	1.6
T9	300 kg/ha NPKSZn	42	36	36	15	6.6	0

^aAll treatments additionally include 100 kg urea ha⁻¹ (46 kg N ha⁻¹)

Basal application followed standard practice of side dressing 5 cm from the seed row and 5 cm deeper than the seed.

Rainfall, soil analysis and classification

Annual rainfall totals for the sites were taken from the most nearby weather stations (Supplementary Table 2). Substantial differences between years occur, Farta having a dry 2017, Burie a wet 2018, and Bako Tibe a wet and Omo Nada an excessively wet 2017.

Soil samples were collected at 0–20 cm depth for determination of soil organic carbon (SOC) and soil pH-H₂O. This choice was made because the two properties showed a relatively strong and positive correlation with wheat yields in the 2017 experiments (Elias et al. 2019). The pH-H₂O was measured using 1:2.5 soil to solution suspension using a pH meter. The Walkley and Black method was applied to determine the SOC content (Bremner and Mulvaney 1982). Zn and B were extracted by using the DTPA extraction method (Tan 1996).

Data analysis

First, T1 up to T5 results (Table 1) were analysed to evaluate the effect of increasing fertilizer rates. Including replications, 520 data points were available to assess the effect of different rates of multi-nutrient fertilizer. Maize covered 120 data points (30 Andosols, 90 Nitisols, covering 4 sites), teff covered 155 data points (15 Luvisols, 30 Nitisols, 110 Vertisols), and wheat covered 245 data points (30 Andosols, 30 Luvisols, 30 Vertisols, 60 Leptosols, 95 Nitisols).

The changes in grain yields with increased fertilizer rates were analysed through a non-parametric Mann-Whitney U test (McKnight and Najab 2010). The effect of rainfall and reference soil groups on grain yields was analysed while looking at the base fertilization (T1), through a two-way analysis of variance. Reference soil groups typically still exhibit considerable variation in soil properties. This variation was described through basic summary statistics of key soil properties (organic carbon, pH) for the different reference soil groups. No statistical tests were performed to indicate differences between the different reference soil groups. Although a relatively large number of soil samples were taken, reference soil groups were sampled in a different way (e.g., in some

cases a reference soil group was found at a single experimental site, whereas other reference soil groups were found at multiple sites).

The effect of nutrients applied in multi-nutrient fertilizers including Zn and B was evaluated by comparing (i) T2 with T6 and (ii) T4 with T7. The first comparison investigates the effects of Zn and B added into the fertilizer. T2 has 2 kg/ha less N and 2 kg/ha less P than T6 (Table 1), which causes a small bias, but the key difference in performance would be due to Zn and B. The second comparison provides the response effects to S, Zn and B. Comparing T3 and T7 seems logical as the ‘per kg fertilizer’ comparison, and in both cases 150 kg fertilizer was applied. At the farm level, this is relevant as the choice is between bags of equal size. However, comparing T4 and T7 is the ‘per kg nutrient’ comparison as the treatments come a lot closer in terms of nutrients. They have the same amount of P (30 kg P/ha), but T4 has more N than T7 (80 vs. 73 kg N/ha including urea).

Results

Effect of increasing rates of multi-nutrient fertilizers on crop yields

Averaged for trial sites and years

Table 2 shows crop yields and standard deviation for each location, averaged for years (and hence rainfall) and reference soil group. When comparing trial sites, yield differences for the three crops turned out to be statistically highly significant ($p < 0.01$). When looking at treatments, the lowest level (T1) has average yields of approximately 5500 kg ha⁻¹ for maize, 1500 kg ha⁻¹ for teff, and 3300 kg ha⁻¹ for wheat. For teff and wheat, these levels are close to CSA-reported national average values (CSA 2018). When moving from T1 (50 kg multi-nutrient + 100 kg urea) to T3 (150 kg multi-nutrient + 100 kg urea), average yields increase by 20 to 30%, with teff at the lower and wheat at the higher end. At the highest rate (300 kg multi-nutrient), yields were 7900, 2100 and 5000 kg ha⁻¹ respectively. Nonetheless, and despite T5 giving higher yields than T1, one maize and three wheat experimental sites did not show significant differences between treatments when averaged in this way.

Table 2 Crop yields (in kg ha⁻¹) at the different experimental sites (and standard deviation in brackets) at increasing rates of multi-nutrient fertilizer, averaged over 2 years in the 2017–2019 period

	Treatment				
	T1	T2	T3	T4	T5
Maize (n = 120)					
Bako Tibe	8631 ^a (1735)	9990 ^a (2099)	10,456 ^a (2177)	9932 ^a (1604)	10,345 ^a (1764)
Burie	6006 ^a (595)	7002 ^b (377)	7512 ^{bc} (1395)	7757 ^{bc} (1000)	8374 ^c (740)
Omo Nada	3586 ^a (1749)	4210 ^{ab} (1555)	4979 ^b (1845)	5565 ^c (1773)	6471 ^c (1659)
All sites	5452 ^a (2594)	6353 ^{ab} (2847)	6981 ^{bc} (2898)	7205 ^{bc} (2388)	7915 ^c (2190)
Teff (n = 155)					
Becho	1968 ^a (142)	2014 ^{ab} (274)	2293 ^c (257)	2164 ^b (205)	2395 ^c (231)
Burie	1591 ^a (366)	1897 ^b (404)	1682 ^a (352)	2085 ^b (394)	2130 ^b (543)
Enamore	836 ^a (307)	1097 ^{ab} (517)	1403 ^{bc} (220)	1708 ^c (357)	1375 ^{ac} (676)
All sites	1549 ^a (510)	1758 ^{ab} (525)	1824 ^{bc} (456)	2028 ^d (367)	2051 ^{cd} (615)
Wheat (n = 245)					
Burie	2312 ^a (422)	2810 ^{ab} (550)	3239 ^b (362)	3239 ^b (281)	3460 ^b (771)
Enamore	2950 ^a (1095)	3206 ^a (956)	3022 ^a (894)	3376 ^a (1371)	3601 ^a (1554)
Endamohoni	4211 ^a (1661)	5128 ^{ab} (1676)	5481 ^b (1261)	5020 ^{ab} (1950)	6230 ^b (1801)
Farta	1888 ^a (490)	1958 ^a (323)	2058 ^a (363)	2262 ^a (500)	2290 ^a (321)
Girar Jarso	2975 ^a (1457)	3212 ^a (1469)	3555 ^a (1635)	3737 ^a (1391)	3960 ^a (1110)
Omo Nada	4347 ^a (1324)	5425 ^b (1460)	6158 ^b (1476)	6717 ^c (1370)	7687 ^c (1617)
All sites	3328 ^a (1505)	3917 ^b (1775)	4274 ^b (1896)	4431 ^{bc} (2017)	5001 ^c (2353)

Different letters indicate significant differences; $p < 0.05$

Per year, soil reference group, and soil property

Yields per reference soil group are shown in Fig. 1a–c for the three crops. Despite the large number of observations ($n = 795$), the number of observations for each combination of crop, year, soil reference group, and treatment ($n = 3$) are too

limited to allow for a proper statistical comparison. Figure 1a for maize shows substantial differences between treatments as well as between Andosols and Nitisols (T1 ranging between 2000 and 6500 kg grain ha⁻¹). The pattern for the two years does not differ much, showing parallel lines, but 2018 being more or less consistently better year than 2019. The reasons for the Andosols performing worse than the Nitisols may be in colder temperatures higher up in the mountains, and in stronger P sorption. Leaf purpling was observed in the Omo Nada Andosols during growth. Yields continuously increasing up to T5 in the Andosols may also point to P hunger that is still not satisfied at this level. Figure 1b for teff shows T1-yields of roughly 1300–2000 kg ha⁻¹, all increasing towards T5, but at a modest level, no yields surpassing values of 2500 kg ha⁻¹. The averaged T1-T5 yields for the Vertisols (1670 kg ha⁻¹) were markedly below average yields on other soils (2050 kg ha⁻¹). Figure 1c for wheat shows a large range of T1-level yields, from 1700 to 5700 kg ha⁻¹. Andosols have high yields and respond well to increasing rates of fertilizers, Leptosols have high yields as well but are less to non-responsive, perhaps due to high inherent fertility. The Nitisols are responsive up to middle level yields. Vertisols and particularly Luvisols are in the lower yield range, with modest responses to increased levels of multi-nutrient fertilizer.

Statistical analysis then shows (Table 3) that reference soil groups were significant in explaining yield differences for maize and wheat, but not for teff. Differences in rainfall and the soil * rainfall interaction were however not significant. The r^2 shows that slightly above (maize) and below (wheat) 60% of yield differences were explained by reference soil group. Table 4 shows the spread of some key soil properties per reference soil group. SOC ranges between 1.4 (Vertisols) and 3.1% (Andosols), and pH-H₂O between 5.2 (Nitisols) and 6.5 (Vertisols). Figure 2a, b then show that wheat yields in 2017 and 2018 increase at higher SOC (range between < 1 and 5%) and pH levels (range between 4.5 and 7.5). The regression line shows that SOC explains yield differences better than pH. In an earlier description of the 2017 wheat experiments, SOC explained 28% of yield differences (Elias et al. 2019). Including 2018 still leaves an explanation of 22%.

Fig. 1 Grain yields for maize (a), teff (b), and wheat (c) per reference soil group, year and fertilizer treatment

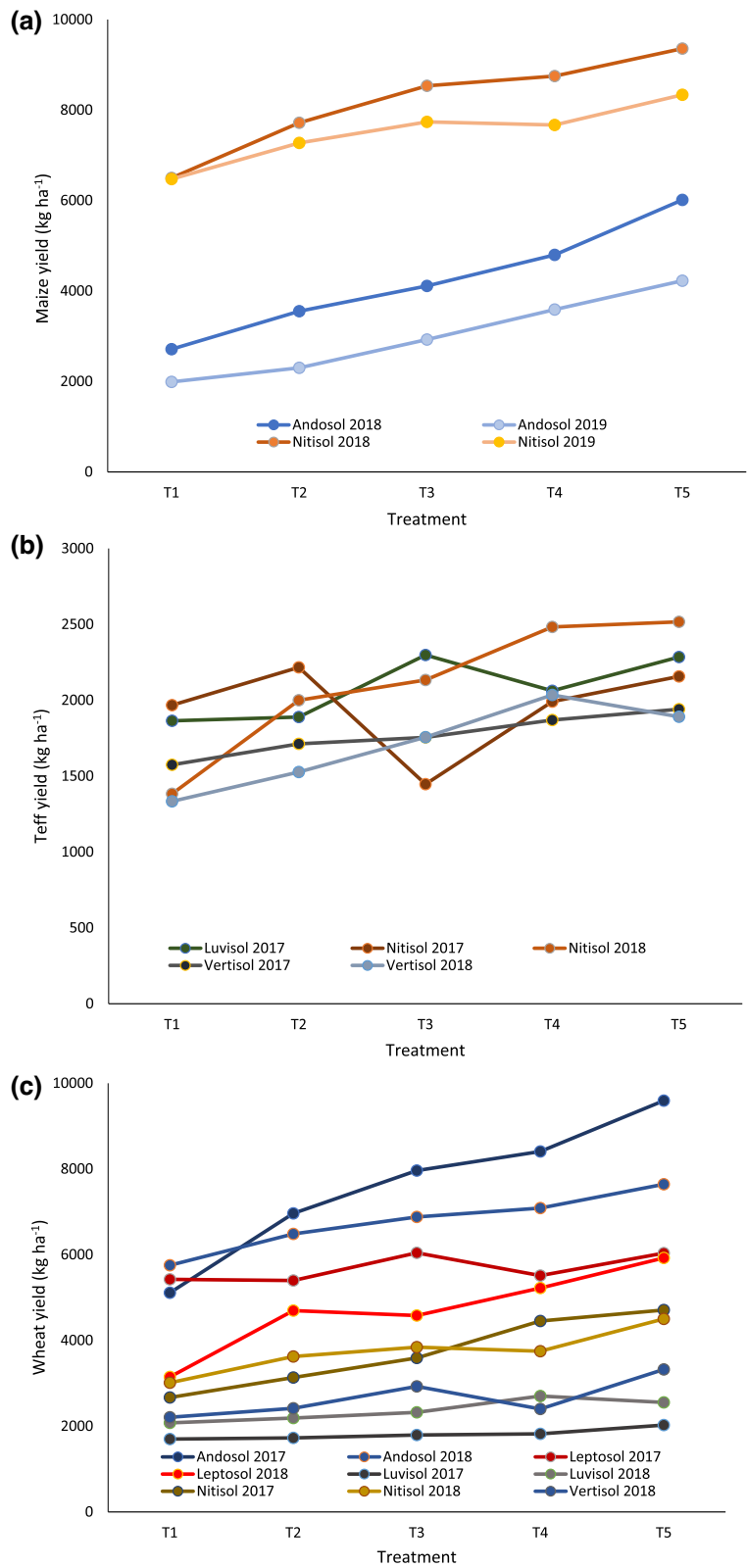


Table 3 Analysis of variance of the effect of the reference soil group and rainfall on grain yields of Treatment T1

	Levels of significance			R ²
	Soil	Rain	Soil*Rain	
Maize	0.001	0.233	0.299	0.637
Teff	0.475	0.446	n.d.	0.106
Wheat	0.000	0.716	0.657	0.589

Comparing yields obtained after application of five-nutrient (NPSZnB) and two-three nutrient (NPS, DAP) fertilizers

Comparing T2–T6 and T4–T7 gave results that are highlighted in Fig. 3. Out of 33 trial sites, only 2 showed statistically significant differences in yields between 100 kg ha⁻¹ NPSZnB and 100 kg ha⁻¹ NPS (plus 100 kg urea ha⁻¹). Average yields across crops were 3919 kg ha⁻¹ for T2 and 3856 kg ha⁻¹ for T6, implying that there is hardly any difference at the overall level. For T4 and T7, only 2 out of 33 trials sites showed statistically significant yield differences between 200 kg NPSZnB and 150 kg DAP (plus 100 kg urea ha⁻¹). Average yields across crops were 4448 kg ha⁻¹ for T4 and 4228 kg ha⁻¹ for T7. Also in this case, there is hardly any difference at the overall level.

At a more detailed level for wheat, T2 outyielded T6 somewhat (3917 kg ha⁻¹ against 3733 kg ha⁻¹), while T4 outyielded T7 (4431 kg ha⁻¹ against 4263 kg ha⁻¹). On a closer look, some differences

exist between maize and wheat in the Omo Nada Andosols (Table 5). Wheat yields are high throughout, and NPSZnB fertilizers do better than NPS and DAP in 2017 (but not in 2018). For maize though, NPS and DAP perform markedly better than the multi-nutrient fertilizers in both years, only the difference between T2 and T6 (NPS) in 2018 for maize was statistically significant ($p=0.04$). Two reasons may be valid, i.e., the P hunger on Andosols may affect maize (NPS and DAP have more P per weight unit fertilizer than NPSZnB; Table 1), or the applied levels of B may be too high moving towards toxicity.

Table 4 also shows B and Zn concentrations in soils. B values range between 0.15 (Andosols) and 0.91 (Vertisols) mg kg⁻¹. The Zn values are between 3.2 (Leptosols) and 4.5 (Andosols) mg kg⁻¹, but Nitisols and Vertisols have average values of 15 mg kg⁻¹, all at high standard deviations.

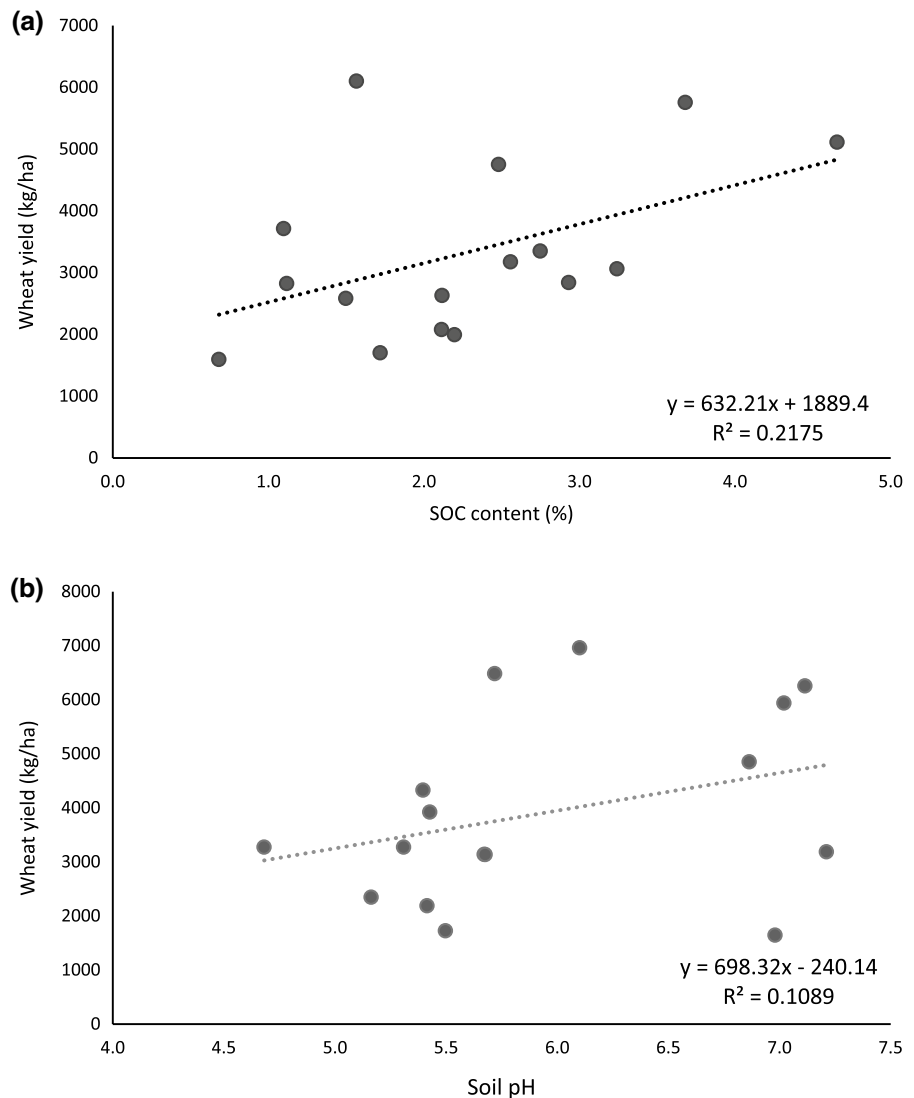
Recommendation windows

To further the policy relevance, production functions of Fig. 1a–c can be grouped according to four recommendation windows (Table 6). These can be portrayed on (sub)district maps and then become relevant for extension to increase last-mile delivery of fertilizers that are known to be effective and profitable. As the current study shows that reference soil groups are at least strongly correlated to maize and wheat yields, this can be turned into soil map-supported strategies.

Table 4 Values and standard deviation (s.d.) of relevant soil properties for the reference soil groups at the experimental sites of the CASCAPE project

	SOC (%)	pH (H ₂ O)	B (mg kg ⁻¹)	Zn (mg kg ⁻¹)
Andosol	3.07 (s.d.=1.04; n=60)	5.6 (s.d.=0.38; n=60)	0.15 (s.d.=0.20; n=53)	4.46 (s.d.=3.52; n=60)
Leptosol	1.59 (s.d.=0.84; n=40)	6.2 (s.d.=0.81; n=46)	0.32 (s.d.=0.07; n=30)	3.17 (s.d.=1.75; n=40)
Luvisol	2.03 (s.d.=0.47; n=34)	5.4 (s.d.=0.27; n=34)	0.40 (s.d.=0.05; n=27)	3.71 (s.d.=2.49; n=34)
Nitisol	2.60 (s.d.=0.63; n=183)	5.2 (s.d.=0.30; n=183)	0.66 (s.d.=1.21; n=162)	15.36 (s.d.=30.09; n=183)
Vertisol	1.35 (s.d.=0.61; n=111)	6.5 (s.d.=0.65; n=117)	0.91 (s.d.=1.00; n=111)	15.49 (s.d.=15.40; n=111)

Fig. 2 Relation between SOC content (a) and pH (b) and wheat yields for the baseline treatment (T1) across the Ethiopian highlands



Discussion

Trial design has limitations

The trial design may be criticized for not having a zero-fertilizer control. As this is not a common practice in the Ethiopian Highlands anymore, it was decided to take T1 as the control treatment (50 kg multi-nutrient + 100 kg urea ha⁻¹). Second, although T2/T6 and T3/T7 could be compared well on a ‘per kg fertilizer’ basis, for the latter a comparison a ‘per kg applied nutrient’ basis justified a shift to comparing T4/T7. Without performing economic analysis in this paper, this of course goes at a cost as T4 represents

a 200 kg multi-nutrient bag while T7 represents a 150 kg DAP bag. Third, the design reveals increasing levels of multi-nutrient fertilizer (50–300 kg ha⁻¹), whereas the urea topdressing levels remained the same. Hence, PSZnB levels doubled between T1 and T2 (50–100 multi-nutrient + 100 urea) and between T3 and T5 (150–300 multi-nutrient + 100 urea), but N-levels only doubled between T1 and T5 (Table 1). It implies that at increasing levels of fertilizer application, N may have become increasingly constraining. Plant tissue nutrient analysis would add valuable information if this were the case but was not considered in this study.

Fig. 3 Crop yields under NPSZnB fertilizer application (T2/T4) versus yields under NPS and DAP fertilizer (T6/T7)

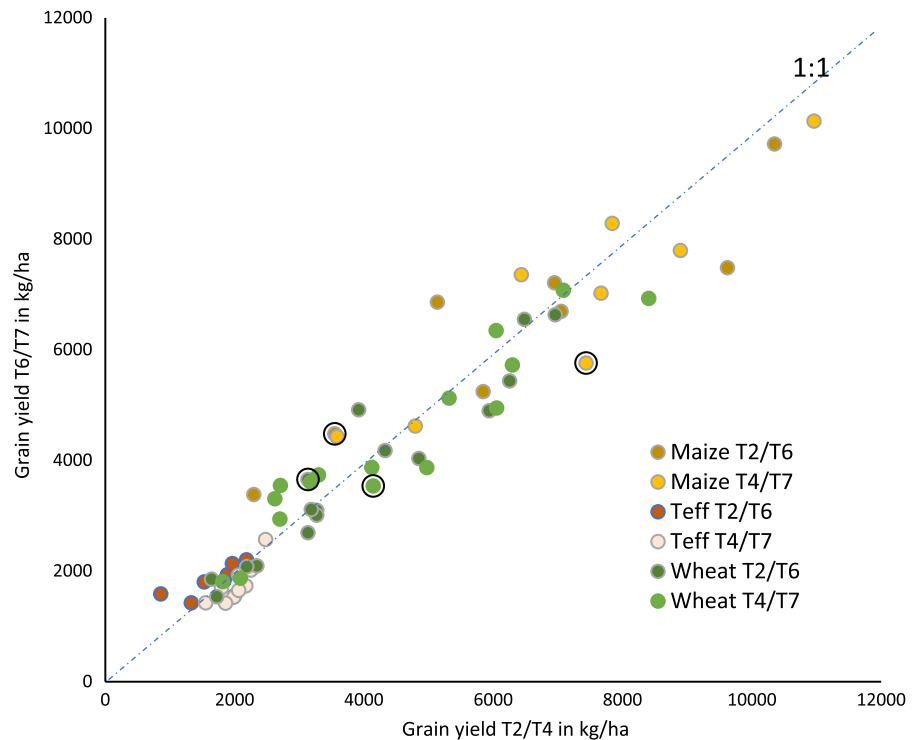


Table 5 Response of maize and wheat (in kg ha⁻¹) to multi-nutrient and conventional fertilizers on Andosols in western Oromia Highlands (Omo Nada)

Crop	Year	Treatment			
		T2	T6	T4	T7
Maize	2018	3553	4479	4797	4618
	2019	2300	3382	3588	4426
Wheat	2017	6963	6630	8407	6926
	2018	6484	6548	7087	7071

Added value of fertilizer nutrients other than N and P is not clear

The results show that *at an overall level* and with the slight inequalities when evaluating against ‘per kg applied nutrient’, hardly any significant yield differences occurred that favor multi-nutrient fertilizers including S, Zn and B over NP fertilizers. This is in line with most findings discussed in the Introduction and with a 2021 omission trials campaign led by EIAR. At the *more detailed level*, the study shows some relevant differences for maize and wheat where micronutrients play a role. As the experiments

comprised few low soil-Zn soils, this finding deserves further scrutiny. For B, it is hard to draw firm conclusions. The mixing of B with other fertilizer nutrients brought coarse and fine granular materials together in fertilizer bags. This causes uneven distribution in bags and even segregation to the extent that all B is finally at the bottom of the bag. Although this was observed during an inspection (Supplementary Fig. 1), this was not particularly observed during field application for the experiments described in this paper. As this cannot be excluded though, this paper refrains from bold statements about the effect of B on crops. Surprisingly, few areas on the fertilizer atlas show the need to include K fertilizer, even though this is normally the first nutrient after N and P to become deficient. This is partly due to the low threshold value selected by Karlton et al. (2013), as this results in many soils keying out non-deficient. It is justified to keep a sharp eye on K as a potentially deficient nutrient and of higher importance than Zn and B in some reference soil groups (e.g., Selassie et al. 2020). On a more general note, literature it is not always clear whether compound or blend fertilizers were applied in experiments, let alone the way in which it was

Table 6 Translating production functions (Fig. 1a–c) into recommendation windows and options for spatially and crop-specific intervention

Recommendation window	Maize	Teff	Wheat
1. Low yields throughout			Luvissols (2000 kg ha ⁻¹)
<i>Even T1 may be uneconomical. Other variables may be limiting</i>			
2. Yield increases up to T2–T4		Vertisols (1400–1800 kg ha ⁻¹) Luvissols (1800–2300 kg ha ⁻¹) Nitisols (1500–2500 kg ha ⁻¹)	Vertisols (2000–2500 kg ha ⁻¹)
<i>Do not exceed T2–T4 if that is plateau value. Adoption dependent on farming strategy and policies.</i>			
3. Yield increases up to T5	Andosols (2000–6000 kg ha ⁻¹) Nitisols (6000–10,000 kg ha ⁻¹)		Leptosols (3000–6000 kg ha ⁻¹) Nitisols (3000–4500 kg ha ⁻¹) Andosols (5000–10,000 kg ha ⁻¹)
<i>Great production potential, still untapped at T5. Adoption dependent on farming strategy and policies</i>			
4. High yields throughout			Leptosols (6000 kg ha ⁻¹)
<i>Even below T1 yields may already reach plateau value. Soils are apparently still rich, T1 recommendation</i>			

bagged. This needs more attention in order to render this research meaningful for future fertilizer policies.

Another systemic issue around the determination whether nutrients are deficient and need to be added in the fertilizer mix is the use of ‘critical values’. The choice of threshold values has far-reaching consequences if translated into spatially explicit Fertilizer Atlases, in the case of Ethiopia leading to few areas needing K and many needing B. This deficiency mapping should always be supported by evidence from the field to avoid ineffective investments.

Integrated soil fertility management and use of recommendation windows may be the way ahead for policy

Next to the relevance of reference soil groups at the meso-level, SOC contributes reasonably well to yield prediction at the farm level. Farmers often deliberately create diversity in soil fertility among fields on the farm by their SOC management, cherishing some plots and (high-value) crops (e.g., Elias et al. 1998; Kanmegne et al. 2006; Mesfin et al. 2020). Managing

SOC by combined use of mineral and organic fertilizers has shown to work very well in Bahir Dar and Jimma regions (Ejigu et al. 2021; Mamuye et al. 2021), not just in terms of yields but also in improving SOC content. Reuse of organic inputs needs a serious boost and further legislation is needed to establish norms and standards for organic amendments as a marketable product. Large quantities of chicken and pig manure, for example, remain unused in peri-urban environments (Tadesse et al. 2021a, b).

It is not easy to scale up point data to regions. Nonetheless, the ‘recommendation window’ approach may turn a set of experiments into relevant policy guidelines. This is particularly so because reference soil groups turned out to be significantly related to the yields of maize and wheat. A similar approach was taken in Kenya in the 1980s using traditional soil mapping approaches to establish locations for fertilizer response trials, also with the aim of creating recommendation windows (Smaling and Van de Weg 1990). For Ethiopia and also as part of the CAS-CAPE project, modern soil mapping techniques based on machine learning approaches were used to map

districts (*woredas*) in a short period of time (Leenaars et al. 2020). This can be of great added value to the findings in this paper, but at the end of the day it all boils down to input and output prices. Economic analysis was however not part of this study.

Conclusions

A major conclusion of the analysis of 2017 wheat trials (Elias et al. 2019), was that a T1 fertilizer application (50 kg NPKZnB and 100 kg urea ha⁻¹) could strongly contribute to reducing the need for importing wheat from abroad, even to the level of wheat self-sufficiency. The same conclusion is drawn from the current paper, but it also shows that this can be achieved by NP fertilizers as well, and most likely at cheaper rates and hence lower costs. As we speak (2023) and as a policy response to the published findings of these wheat trials, wheat self-sufficiency in Ethiopia has already been achieved.

Another earlier CASCAPE study revealed that Net Farm Income in the Ethiopian Highlands is partly driven by the use of N fertilizers (Okoth et al. 2023). It is an upper 20% of farmers in a large survey that have the income and the cash flow, and as a result the investment capacity, to purchase fertilizers. The other 80% lack investment opportunities or are risk averse. Targeted approaches, using recommendations windows and proper last-mile delivery systems, including small bag sizes may further increase adoption of fertilizers and food security. The market should of course be enabling. For maize and teff, home production and consumption are more important and so reasons to invest in fertilizers may be different. Teff shows the lowest responses, but the residues of this crop are very important as a source of animal feed.

The Highlands of Ethiopia face increasing land fragmentation down to the legal lower boundary of 0.25 ha. Even fertile lands seem no longer able to provide a food-secure basis for farm households at this farm size (Giller et al. 2021). In future, perhaps mechanization and cluster or cooperative farming may become more common to deal with this increasing land stress. This could change the production systems and social fabric in the country considerably. Yet it may have to be looked into for future national food security and open new avenues for fertilizer use and ISFM.

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Data availability Data archiving is not mandated but will be made available on reasonable request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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