Experimental Agriculture (2022), vol. 58, e6, 1–18
doi:10.1017/S0014479721000296

CAMBRIDGE UNIVERSITY PRESS

RESEARCH ARTICLE

Understanding factors influencing wheat productivity in Ethiopian highlands[‡]

J. Kihara[1,*], B. Gurmessa[2], L. Tamene[2], T. Amede[3] and R. Sommer[1]

[1]Alliance of Bioversity International and International Center for Tropical Agriculture (CIAT), c/o ICIPE Duduville Complex, Off Kasarani Road, P.O. Box 823-00621, Nairobi, Kenya, [2]Alliance of Bioversity International and International Center for Tropical Agriculture (CIAT), c/o ILRI, P.O. Box 5689, Addis Ababa, Ethiopia and [3]International Center for Research in Semi-Arid Tropics, c/o ILRI, PO Box 5689, Addis Ababa, Ethiopia
*Corresponding author. Email: j.kihara@cgiar.org

(Received 24 June 2021; revised 30 November 2021; accepted 13 December 2021)

Summary

Increasing yields in farmer fields is a priority to address increasing food demands. The study was conducted within four wheat-growing areas in Ethiopia: Debre Birhan, Hosaina, Sinana and Maychew. The objectives were to identify (1) best-bet soil fertility management options based on agronomic performance and economic evaluation and (2) key yield-reducing factors in farmer fields based on an agronomic survey among 55 participating farmers. Two types of on-farm experiments were conducted: researcher-managed trials that tested combinations of nutrients, including micronutrients, organic resources or both over two cropping seasons and farmer-managed trials comparing '*improved practice*' against '*farmer's practice*'. Fertilizer treatment affected wheat productivity in Debre Birhan ($p < 0.01$), a site limited in sulphur. Here, full NPK increased yields over the control ($p < 0.05$), whereas a combination of NPK and manure was better than the application of manure as the only source of added nutrients ($p < 0.05$). Applying half the recommended NPK with micronutrients and manure achieved similar yields as the full fertilizer treatment. In Hosaina, treatment had no significant effect on wheat productivity, although a combination of NPK and zinc resulted in an additional 26–57% yield relative to the other treatments. In Maychew, a significant treatment effect ($p < 0.05$) was observed. Here, the treatment with lower rates of nitrogen and phosphorous had lower yields than the full NPK treatment. A significant effect of plant densities on on-farm productivity was also observed. We conclude that although nutrient management including use of micronutrients is important in specific cases, investments to optimize plant densities have a huge potential to increase food productivity.

Keywords: Zinc; Micronutrients; Soil fertility; Technology evaluation

Introduction

Productivity of major crops should increase, and post-harvest losses and wastes reduce, in order to meet food and energy demands of a growing human population. The productivity increases require understanding and appropriate management of factors such as varieties and soil- and water-related constraints that affect yields (Van Ittersum *et al.*, 2013). Wheat, a staple crop that constituted 14% of all cereal production in Africa in 2019 (FAO, 2020), is the second most important crop in Ethiopia (Bezabeh *et al.*, 2015), mostly grown by smallholder farmers. Ethiopia is the largest producer of wheat in sub-Saharan Africa (SSA), with wheat area of up to 1.79 million ha in 2019 (FAO, 2020). Here, wheat is widely grown in Bale and Arsi plateaus and in the central and northern highlands (White *et al.*, 2001). A majority of smallholder farmers are using improved

‡The original version of this article was published with incorrect funding information. A notice detailing this has been published and the errors rectified in the online PDF and HTML version.

varieties, with about 30% of the farmers still using local varieties (Shiferaw *et al.*, 2014). Even with the uptake of the improved varieties productivity is still low in farmer fields, with wheat grain yield of about 2.7 t ha^{-1} relative to >5 t ha^{-1} on research stations (Zegeye et al, 2020). An evaluation of the impact of adoption of improved wheat varieties on food security concluded that if farmers adopted new rather than outdated improved varieties, they would realise better food security (Shiferaw *et al.*, 2014). The use of new cultivars, combined with good agronomic management practices, is expected to reduce the gap between potential yield and low actual yield observed in farmer fields (Van Ittersum *et al.*, 2013).

Addressing the factors that influence yields such as soil, management and cultivars and their interaction (Van Ittersum *et al.*, 2013) is particularly essential due to limited opportunities for land expansion (increases in production area) for increased production. In the Ethiopian highlands, besides low fertilizer applications (White *et al.*, 2001), poor agronomic practices such as poor plant populations, pest and diseases such as stem rust and yellow rust and climate-related constraints such as droughts undermine wheat productivity (Negassa *et al.*, 2013). Weeds, for example, reduce wheat grain yield by up to 50% (Tana *et al.*, 2015), and fertilisation of crops without appropriate weed management leads to inefficiencies as weeds outcompete wheat for the applied nutrients (Tana *et al.*, 2015). Use of improved seeds without appropriate use of agronomic inputs such as fertilizers and weeding also reduces yields (Heap, 2014; Bhattacharyya *et al.*, 2008). Also, to tackle rusts, a number of resistant varieties have been released for adoption by farmers. Further, addressing soil fertility constraints has been challenging as it requires site-specific recommendations that generally depend on the inherent soil characteristics and maximisation of yields. There is also the need to consider the socioeconomic conditions that determine affordability of interventions. As such, it is the uptake and implementation of integrated technological package of good agricultural practices (GAP) that have the potential to address the widening gap between actual and water-limited potential yields. Actual yield is average yield observed in a farmer field while water limited potential yield is the yield of a crop cultivar when grown with nutrients non-limiting and biotic stress effectively controlled (Van Ittersum *et al.*, 2013).

The widely advocated blanket recommendation (100 kg DAP and 100 kg urea) is insufficient for increased wheat production in all areas and farmer socioeconomic conditions. Several studies (Amante *et al.*, 2014; Agegnehu *et al.*, 2014; Tana et al. 2015; Habte *et al.*, 2015) have shown that higher and sometimes lower application rates are required for specific sites. Further, combinations with micronutrients are deemed necessary, with wheat showing significant response to sulphur (S), for example (Habtegebrial and Singh, 2009). Most agronomic studies so far have been researcher-managed and considered on-station evaluation of impacts of different fertilizer—mainly nitrogen (N) and phosphorous (P) rates—with few studies on micronutrients (Habtegebrial and Singh, 2009). Besides, use of integrated fertilizers, both organic and inorganic ones, to enhance wheat productivity is not well demonstrated in the areas despite being widely conducted for maize and potato (Bayu *et al.*, 2006). In our study, we demonstrate these integrated options in farmer fields within action sites of the Africa Research in Sustainable Intensification for the Next Generation (Africa RISING) project of the Feed the Future initiative in Ethiopia. The specific objectives are to identify (1) best-bet soil fertility management options for each of the action sites based on agronomic performance and economic evaluation and (2) key yield-reducing factors in farmer fields based on agronomic survey among participating farmers. This is done under farmer conditions and also integrates participatory approaches such as evaluation of technology performances with the aim of closing farmers' knowledge gap on the use of appropriate agronomic practices.

Methods

Description of study site

The study was conducted in 2014 and 2015 in four districts of Ethiopia: Maychew in Tigray region, Debre Birhan in central Ethiopia within Amhara region, Sinana in Oromia and

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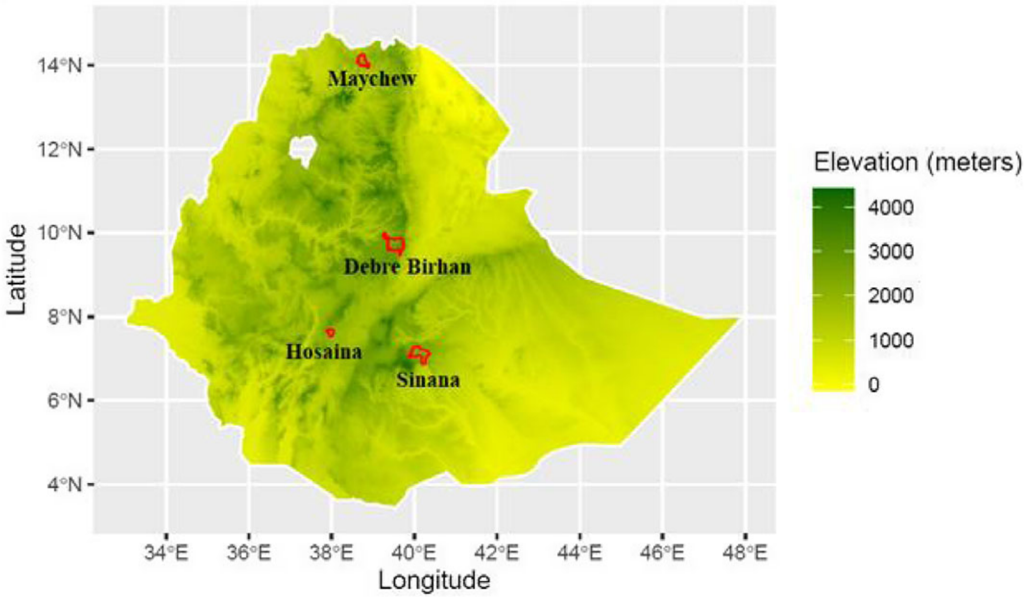

Figure 1. Four of the Africa RISING sites in Ethiopia where the agronomic study has been conducted.

Hosaina in southern Ethiopia in the Southern Nations, Nationalities and People's Region (Figure 1). The key biophysical characteristics of the four sites vary, with Maychew in a relatively hilly and degraded environment relative to Hosaina (Table 1). The four sites are characterised by low fertilizer use and one growing season (between November and June). Wheat, the key cereal crop at all the sites, is mainly grown as sole crop. The four sites had been selected to represent different agro-ecologies for research on sustainable intensification by the Africa RISING program.

Field selections

Farmer fields used for this study were selected by Africa RISING site coordinators (resident within the sites) considering the crop a farmer intended to plant (our interested was wheat), ensuring fields were distributed widely within the sites for representativeness, and the farmers expressed willingness to cooperate in management and allowing access for data capture. Since the on-farm trials fields were also to serve as learning places for farmers (in field days), they had to be within easy access.

Soil sampling and analysis

Soil sampling and analysis were done following a stratified random sampling approach (see also Kihara *et al.*, 2015). Using this method, 320 soil samples (160 at 0–20 cm and another 160 at 20–50 cm depth) were obtained from a 10 x 10 km block to characterise each site. The block had been stratified into 16 clusters, each with 10 sampling plots. Within a plot, soil samples were collected from four points determined based on a y-sampling methodology. The soil samples were analysed for P, potassium (K), calcium (Ca), magnesium (Mg), zinc (Zn), S, pH, carbon (C) and N as well as texture. These were determined using the International Centre for Research in Agroforestry (ICRAF) prediction engine based on soil mid-infrared spectroscopy. The prediction model had been calibrated with wet chemistry data analysed at the Crop Nutrition Laboratories in Nairobi following Mehlich 3 extraction procedure (Mehlich, 1984) for available soil P,

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Table 1. Selected biophysical characteristics of the Africa rising sites used in the study

Site	Latitude (decimal degrees)	Longitude (decimal degrees)	Altitude (m asl)	Rainfall (mm)*	Major farming system	Landform	Wheat variety¥	Attainable yield (t ha^{-1})
Maychew	12.5	39.1	2300	753	Mixed-legume-cereal system	Steep slopes with benched terraces	MeKelle-01/ HUW-468	3.5[α]
Hosaina	7.5	37.8	2200	540	Mixed-legume-cereal system	Gentle slopes	Dand'aa	5.5[∞£]
Debre Birhan	9.7	39.6	2900	800	Mixed-legume-cereal system	Hilly	Tsehay	3.8[£]
Sinana	7.06	40.2	2400	750	Wheat system	Flat	Tsehay	3.8[£]

*Mean annual rainfall.
¥ Name of the variety tested within the experimental trials.
£Ferede (2016).
αZemichael and Dechassa (2018).
∞Gari et al. (2019).

exchangeable S, Zn, K, Ca and Mg and on pH determined in water (1:2.5). The R^2 of the prediction varied from 0.946 for zinc to 0.984 for pH.

Research design

Two approaches were used to understand and analyse the wheat variability in Ethiopian highlands. The first approach combined farmer experimentation and an agronomic survey in 2014 conducted in 55 farmer fields according to the approach of Kihara *et al.* (2015). Thus, farmer fields where the agronomic survey was conducted had also been selected for on-farm experimentation and therefore included both "*improved practice*" and "*farmer's practice*" in the same field. The agronomic management information was obtained based on a questionnaire interview as well as on visual observations from a 10 x 10 m farm section (main plot). It included questions to farmers on distance of cropping field from farmer homestead, manure application in the current and previous seasons, crop residue management, cropping systems, history of cultivation (years since land conversion to agriculture), commonly grown wheat varieties, land sizes and wealth scores. Field slope was obtained from an SRTM 30m DEM. For the *improved practice* (the research recommendation practice), we provided the target farmers with improved technologies, including technical advice (e.g. row planting, appropriate spacing and best nutrient application practices) as well as the recommended amount of fertilizers and improved seeds. These farmers then implemented the improved practice on a small plot of ½ acre within their field of farmers practice. In the end, wheat under the *improved practice* was planted in rows in Hosaina and by broadcasting in both Debre Birhan and Maychew since farmers opted to use their customary planting methods due to drudgery of row planting. All farmers applied fertilizers. The *farmer's practice* at the three sites was planted by broadcasting; used recycled seed in a majority of cases; had reduced fertilizer application on a per-hectare basis—that is, 0–150 kg urea (median = 48) and 0–200 kg DAP (median = 31) and were often not weeded on time.

The practice-specific agronomic information was obtained from similarly sized plot (10 x 10 m) situated close by, mostly side by side, to ensure similar management history. Plant population was obtained from two 1 m by 1 m quadrats/plots (for broadcast wheat) and from two subplots of 3 rows by 1 m (for row-planted wheat) within the selected 10 m x 10 m plots. The quadrats/subplots were located at the opposite diagonals of the net plot (leaving 1 m at the edges). Here, all plants within the plots were counted (as the separate hills/stations but also number of tillers). At harvest, two 3 x 3 m subplots, one at each end of the main plot diagonal (Kihara *et al.*, 2015) was

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Table 2. Fertilizer treatments applied at the two experimental sites

	Debre Birhan 2014	Hosaina 2014	All sites in 2015 (Hosaina, Maychew and Sinana)
T1	Control (No fertilizer)	Control (No fertilizer)	50N + 16P
T2	135N + 30P + 50K	64N + 20P	50N + 16P + 30K[¥]
T3	135N + 30P + 50K + 5 tonnes Manure	64N + 20P + 50K	50N + 16P + 30K[£] + 14S
T4	135N + 30P + 50K + 8Zn+5 tonnes Manure	64N + 20P + 50K + Zn sulphate	50N + 16P + 30K[£] + 14S + 4Zn
T5	Manure (5 ton ha^{-1}) only	20N + 20P	34N + 10P
T6	67N + 15P + 25K + 8Zn + 5 tonnes Manure	34N + 10P + 25K + Zn sulphate	50N + 16P + 30K[¥] + Manure
T7			50N + 16P + 30K[£] + 14S + 4Zn + Manure
T8			34N + 10P + Manure

The amounts are in kilogram of nutrient per hectare.
[¥] K source = potassium nitrate.
[£] K source = potassium sulphate. Zn was from Zinc sulphate.

measured, wheat aboveground biomass obtained and sub-samples taken and later air-dried to constant weight and dry weights taken. However, not all of the 55 survey fields were harvested, as some fields were harvested by farmers before researchers could obtain harvest data. All the crop data collected were expressed on per hectare basis.

Second, we conducted experiments that were designed by researchers and managed by farmers for testing the impact of integrated application of different fertilizers on wheat yield (Table 2) using the improved varieties (MeKelle-01/HUW-468, Dandáa and Tsehay) indicated in Table 1. These experiments were conducted in 8 farmers each in Debre Birhan and Hosaina in 2014. In 2015, an additional 16 farmers (i.e., 4 in Hosaina, 5 in Sinana and 7 in Maychew) were involved. The trials were planted (in rows) and harvested by the researchers, while other aspects of management (weeding, for example) were done by farmers under the guidance of researchers.

The fertilizers treatments used in the trials conducted in 2014 were tailored specifically for each site (i.e. treatments varied among the sites) based on national (and where applicable local) recommendations, availability of organic resources (manure) and interests of stakeholders. In Ethiopia, the most widely applied rate of diammonium phosphate (DAP) and urea is 100 kg ha^{-1} each. This rate was used as the benchmark for setting our experiment in Hosaina. For Debre Birhan, however, the new application rates of 225 kg urea and 150 kg DAP have been demonstrated to farmers through the Debre Birhan Agricultural Research Center. At both sites, the trials included combinations of recommended rates of N and P with K and secondary and micronutrients (S and Zn); an unfertilized control and a treatment with half recommended N and P. There were no available recommendation rates for K, and the micronutrients or crop nutrients that had not been applied by farmers at the study sites. Therefore, researcher estimates were used with KCl as source of K (except Maychew, with potassium nitrate and potassium sulphate since S was intended as a nutrient) and $ZnSo_4$ as source of Zn and S. The trials in Debre Birhan also included integrated inorganic fertilizers with locally recommended rate of manure. Within a site, we used one source of manure for the different field trials to reduce the confounding error due to the difference in nutrient content. In 2015 and in order to allow cross site comparisons, the treatments were the same across all the sites and included, in addition to Hosaina, 2 new sites of Sinana and Maychew where Africa RISING program expanded to.

Crop management in all trials (except the farmer experimentation) followed basic principles. Seeds were sown within recommended inter- and intra-row spacing within plot sizes of 5 x 5 m. Weeding was done twice in the season. Harvesting was done within 3 x 3 m subplots and involved grain and biomass (straw) measurements in the field. These were followed by air-drying of subsamples to constant weight and determining moisture content used in final yield calculations.

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Participatory technology evaluation

Participatory evaluation of effect of the different fertilizers on stand performance of wheat was undertaken in Hosaina, in early October when wheat was at grain-filling stage (it could not be conducted at the other sites due to logistical challenges.) One expert from the International Center for Tropical Agriculture and two Africa RISING site coordinators took part in facilitating the scoring. Participating in the evaluation were 31 farmers on whose field trials were being conducted and some of their neighbours. The farmers were asked to provide the parameters to consider in evaluation of crop performance. They came up with four key aspects of evaluation: spike length, plant height, grain size and expected yield. Three groups of farmers were formed, each containing about 10 or 11 members. Every group of farmers was asked to score a crop stand for each of the six treatments against the four key aspects. The scores requested for each aspect were 1 = poor, 2 = good, 3 = very good and 4 = excellent. Three field trials were evaluated with the same groups of farmers.

Data analysis

For data from farmer-managed two-treatment trials, we used the variables that mostly influence crop yields (Kihara *et al.*, 2015)—namely site, slope, plant density, distance from homestead, timing of planting, weeding frequency, manure application and period since conversion—in classification trees generated based on recursive partitioning (ctree package in R) to understand their effects on wheat yield for the tested sites. Crop variety was previously shown to be important in influencing yield in Tanzania; but this was not included in our model since most farmers at a site used only one predominant variety. Slope for each field was extracted from a 30-m digital elevation model. Timing of planting was taken as number of days since the first recorded planting date for each site. The classification trees were run on yield data obtained in *farmer's practice* averaged over the two replicates.

Cumulative percentage plots of yield gain (i.e., differences in yield) observed with *improved practice* relative to *farmer's practice* were made. For each site, the yield advantage was ordered by magnitude, and the number of farmers was expressed as a percentage.

Scores resulting from participatory technology evaluation were averaged over the three evaluating groups and the means for each treatment presented in a radar chart. The treatments whose scores are towards the outer rings are preferred to those with scores towards the centre of the chart.

For data from researcher-managed trials, analysis of variance (ANOVA) was done in R using aov function followed by separation of means using Duncan's multiple range test within agricolae (Statistical Procedures for Agricultural Research) library. Significance was determined based on $p < 0.05$. For 2014, the ANOVA was done separately for each site owing to the different treatments implemented; farmers were used as replicates. For 2015, where same treatments were applied across all the sites, a model including site and farmer as blocking variables was run. Because of significant site by treatment interaction, the results are presented per site.

Partial economic analysis

Economic analyses were done based on wheat market price of $480 a tonne (WFP, 2015). Costs of fertilizer inputs and manure and variable labour costs for crop management practices are provided in Table 3. Fertilizer costs were used where the particular fertilizer was applied and were zero for the control treatment. All labour costs were based on average person-day charges in Ethiopia. To account for researchers' influences, including penalty on small plot sizes used in yield determination, grain yield was adjusted downwards by 15% (Byerlee, 1998). The minimum and maximum net benefits that a treatment would obtain were also calculated from yield standard errors.

Table 3. Fertilizer and manure input prices and labour costs used in the calculation of gross margins and net benefits

Variable	Cost (in USA $)
50-kg bag of DAP	38.6 (36.8 in Debre Birhan)
50 kg of urea	34.1 (32.3 in Debre Birhan)
50 kg bag of KCl	34.1 (38.2 in Debre Birhan)
Zn sulphate	21.8
A tonne of manure	9.1
Fertilizer transportation cost (150 kg)	1.1
Fertilizer application at planting ha^{-1}	13.6
Top-dressing ha^{-1}	6.8
Harvesting $tonne^{-1}$	9.1
Threshing and bagging $tonne^{-1}$	11.4

Results

The soils of the sites are of moderate acidity to near neutral pH and have low available P, with the exception of Maychew (Table 4). Average soil extractable bases range from 14 to 51 cmolc kg^{-1}, the higher being in Maychew. Micronutrients (Zn and S) concentrations are within good range, except for low S characterising a majority of fields in Debre Birhan.

Farms in Debre Birhan have been under cultivation from 20 to more than 100 years. Those in Hosaina and Maychew have been under cultivation for less than 50 years in most cases (own survey data). Use of organic resources in wheat production is very low, especially in Hosaina. Digalu, a popular local variety resistant to most types of rust, is grown by most farmers in Hosaina and Debre Birhan, based on responses obtained during farmer interviews. In Maychew, Dashen is the variety grown by over 90% of the farmers. In general, 96% of the farmers considered in the survey planted either Digalu or Dashen.

In 2014, a highly significant ($p < 0.01$) effect of treatment on wheat grain and straw yield was observed in Debre Birhan. Application of NPK, combined with manure or manure and micronutrients, significantly increased yield over the control (unfertilized) and manure-only treatments (Figure 2). Application of recommended NPK alone also increased yields over the control ($p < 0.05$). Use of half rate of NPK with added manure and micronutrients resulted in a wheat grain yield increment of 63% over the control treatment (not significant). This treatment still achieved similar yield as the full NPK treatments with and without additional manure and micronutrients. Application of manure only (5 t ha^{-1}) resulted in a modest wheat yield increase of 19% (0.5 t ha^{-1}) over the yield of the control treatment. In Hosaina, there was no significant treatment effect on grain and straw yield. Nevertheless, application of macronutrients (N, P and K) combined with Zn fertilizer resulted in the greatest grain yield increase of 57% over the control treatment; the other treatments achieved less than 24% increase. Omission of K does not result in yield penalty—that is, DAP (the NP treatment) achieved similar yield as N, P and K. Similar to Debre Birhan, application of these nutrients at half the recommended rate, together with micronutrients S and Zn, achieved similar yield as treatments receiving only the macronutrients at full rate.

In 2015, a significant effect of site on wheat yield ($P < 0.05$) was observed resulting in 2.5 t ha^{-1} in Maychew > 1.36 t ha^{-1} in Sinana > 1.07 t ha^{-1} in Hosaina. In Maychew, a significant treatment effect ($p < 0.05$) was observed, where the treatment with lower rates of P had lower grain and biomass yield than the full NPK treatment (Figure 3). Application of secondary and micronutrients (S and Zn) or amendment with manure did not significantly influence yields at this site. Lack of significant differences, even for treatments with yield higher by >1 t ha^{-1}, reflects differences in treatment performances from one farmer's field to another (i.e., a highly significant farm block effect). At low P application rates, application of manure increased productivity of wheat grain by 400 kg ha^{-1}, but this increase was not statistically significant. In Sinana, a highly significant treatment effect ($P < 0.01$) was observed, where the full rate NP treatment had significantly

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Table 4. Major characteristics of soils at the study sites

	Maychew		Hosaina		Debre Birhan		Sinana	
Parameter	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil
%Clay	54.7 (5.7)	55.2 (5.7)	56.1 (6.0)	57.7 (6.5)	61.1 (6.3)	62.0 (5.9)	64.1 (5.8)	67.9 (4.4)
%Sand	17.2 (5.1)	17 (4.9)	16.3 (4.1)	16.2 (5.1)	13.8 (4.5)	13.7 (4.4)	14.6 (2.5)	13.6 (1.8)
pH (water 1:2)	7.32 (0.3)	7.36 (0.32)	6.12 (0.14)	6.09 (0.14)	6.3 (0.1)	6.3 (0.2)	7.06 (0.37)	7.15 (0.36)
%C	2.07 (0.74)	1.94 (0.76)	2.56 (0.64)	2.07 (0.57)	2.46 (1.53)	2.19 (1.52)	2.21 (0.54)	1.99 (0.45)
%N	0.17 (0.06)	0.16 (0.06)	0.19 (0.05)	0.16 (0.04)	0.17 (0.1)	0.15 (0.1)	0.17 (0.03)	0.16 (0.02)
S (mg kg^{-1})	93.8 (60.8)	100.9 (88.6)	223 (106)	245 (92)	6.7 (0.5)	11.0 (8.1)	294 (304)	420 (325)
Zn (mg kg^{-1})	2.9 (0.7)	2.8 (0.8)	3.3 (0.6)	3.1 (0.9)	2.1 (0.1)	2.0 (0.1)	2.1 (0.3)	2.0 (0.3)
Ex bases (cmolc kg^{-1})	50.6 (5.6)	50.8 (5.5)	23.8 (5.5)	25.6 (5.4)	15.4 (1.1)	15.0 (1.9)	39.6 (8.6)	44.3 (8.8)
P (mg kg^{-1})	55.9 (18.8)	54.7 (9.6)	28.9 (14.6)	25.3 (16.1)	17.8 (2.6)	17.2 (2.8)	29.7 (10.3)	24.2 (8.1)
K (cmolc kg^{-1})	1.42 (0.46)	1.40 (0.45)	1.1 (0.26)	1.1 (0.26)	0.4 (0.04)	0.4 (0.03)	2.1 (0.2)	2.2 (0.3)

Values are provided as medians, and the numbers in brackets are standard deviations.

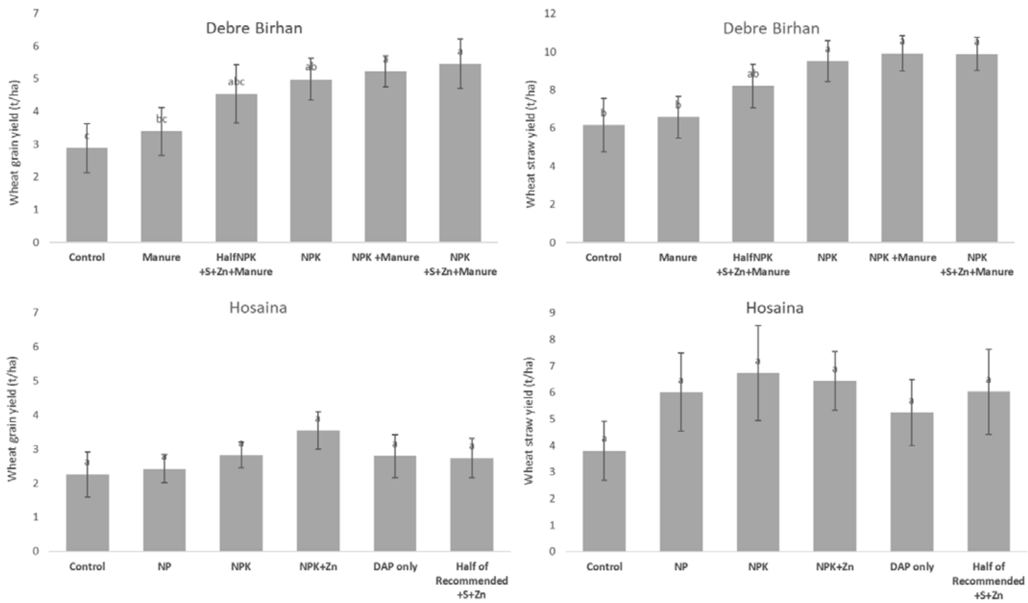

Figure 2. Effect of different treatments on wheat grain and straw yield in Debre Birhan and Hosaina, Ethiopia, during the 2014–2015 cropping seasons. Error bars are standard errors. Bars with different letters within a site are significantly different.

higher wheat grain yield than the two treatments with reduced application rates and also the two treatments applied with zinc sulphate. In Hosaina, treatment was significant at $P < 0.05$ where only the treatment at half rate had significantly lower yields than full NPK treatment. None of the other treatments were significantly different. Although not significant, the highest yields were with S or Zn and S treatments.

Average harvest index across the treatments was in the range of 32–36% in Debre Birhan, 29–37% in Hosaina and 21–25% in Maychew. There were no significant treatment effects on the harvest index.

Wheat crop on plots receiving the full recommendations of fertilizers, i.e., full rate of N and P, had the highest rating scores assigned by the farmers (Figure 4). The lowest scores were to the control (unfertilized), one-third N and P fertilizers, and treatment receiving half of the recommended fertilizer together with some micronutrients.

In farmer experimentation, high variability in yields is clearly observed between fields within a site (Figure 5). The yield difference between the lowest and highest yielding fields are 2.8, 1.6 and 2.9 t ha^{-1} for Debre Birhan, Hosaina and Maychew, respectively. These translated into field-to-field yield differences that were two to six times in magnitude. On the basis of field observations, very poor performance of wheat under *farmer's practice* is associated with weeds (Plate 1). In Debre Birhan, for example, the highest yield obtained under *farmer's practice* is the same as that achieved with half rate of fertilizers in the researcher-managed trials. Also, control from the researcher-managed trials achieved similar or higher yields than seven of the 11 fields surveyed at this site (Debre Birhan), despite *farmer's practices* sometimes having fertilizer applied. Thus, farmers practices resulted in lower yield than researcher-managed treatments attributable to the variety used (Plate 2).

Classification trees showed that site was the most significant in influencing yields (first node with Maychew having 3.6 t ha^{-1} relative to 2 t ha^{-1} in other sites). It also showed a strong effect of plant population as a key determining factor of yield in farmer fields. In *farmer's practice* in Dedre Birhan and Hosaina, density of at least 160 plants per m^2 resulted in 0.8 t ha^{-1} more wheat grain yield than at lower density (data not shown). Also, timeliness of planting influenced yield with up

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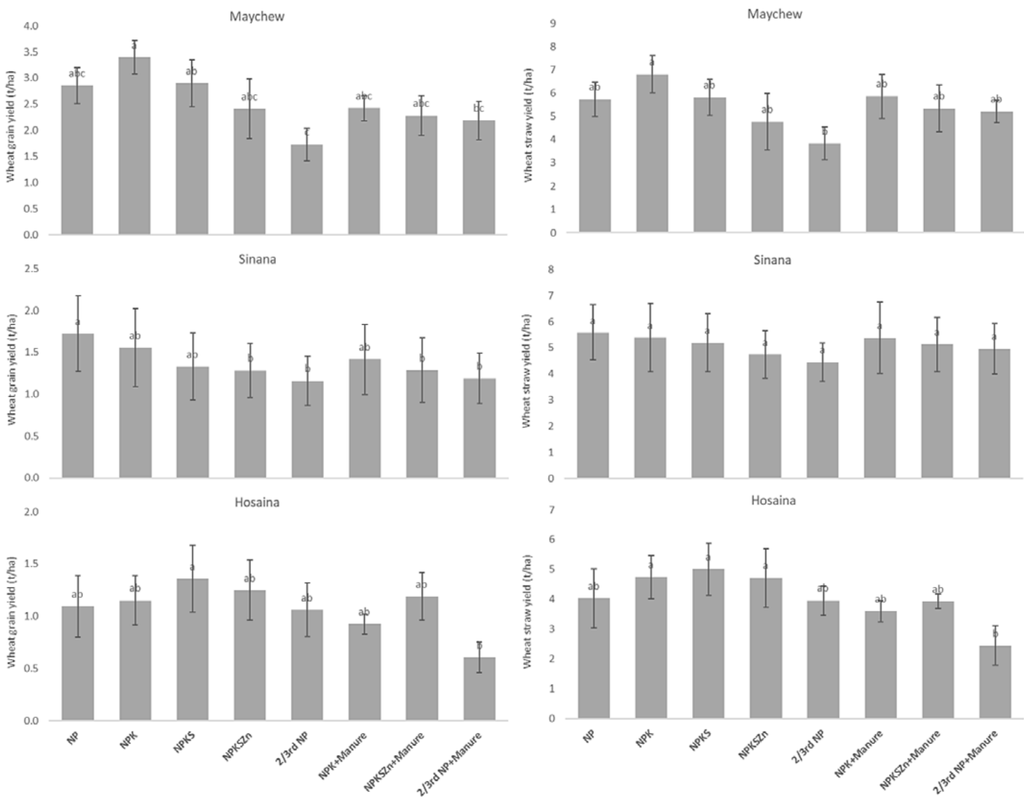

Figure 3. Effect of different treatments on wheat grain and straw yield in Hosaina, Sinana and Maychew in Ethiopia, during the 2015–2016 cropping seasons. Error bars are standard errors. Bars with different letters within a site are significantly different.

to 0.6 t ha^{-1} more yield for farmers who planted early than those who planted late (at least 13 days after the earliest farmer planted). Planting dates for this practice varied by up to 18 days in Debre Birhan, 17 days in Hosaina and 36 days in Maychew. Although wealth category did not seem as an important factor from the classification trees, it influenced yields in Maychew (Figure 6). In this site, the yields obtained by rich farmers were significantly higher than those from poor farming households. The rich farmers planted on average 4 days earlier than the poor while the medium ones were the earliest to plant (5 days on average ahead of the rich). As poor farmers applied on average half the manure applied by medium and rich farmers, although the manure effect on yields were not statistically significant.

To gain further insight into the responses to fertilizer, yield increase due to implementation of *improved practice* over *farmer's practice* from 38 farmer fields at the three sites (16 in Maychew, 8 in Debre Birhan and 14 in Hosaina) were plotted as cumulative percentage (Figure 7). With *improved practice* in Maychew and Debre Birhan, a clear majority (at least 90%) of farmers stand to obtain a positive yield gain (the difference in yield), whereas only 60% are gaining in Hosaina. Also, at least 50% of all the farmers in Maychew and Debre Birhan obtain an additional wheat grain yield of at least 1 t ha^{-1} when they use *improved practice*. Yet, none of the farmers in Hosaina achieve a 1 t ha^{-1} wheat yield increase over the local practice. The greatest increases in yield are observed in Debre Birhan and Maychew and least in Hosaina.

Economic analyses of the treatments in Debre Birhan and Hosaina show profitability over the control in all the cases apart from NP and HalfNPK + S + Zn treatments in Hosaina (Table 5).

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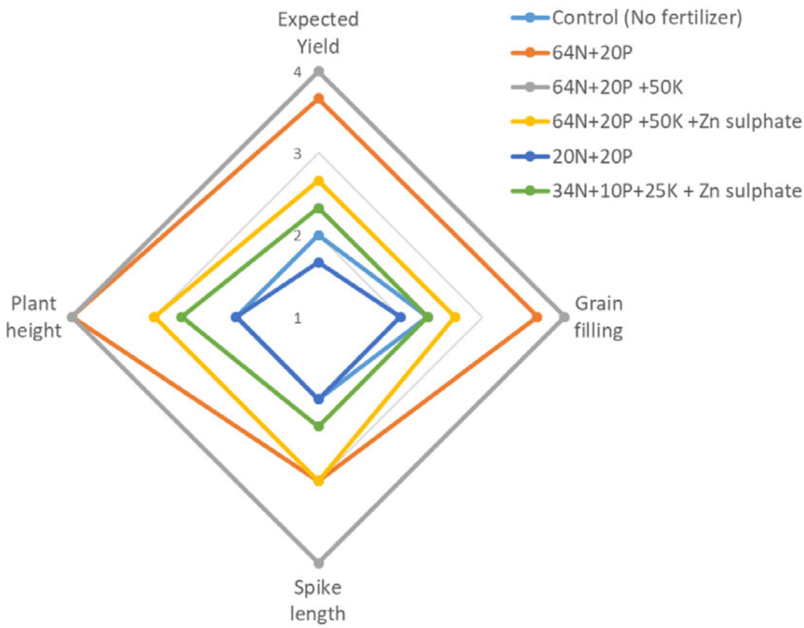

Figure 4. Preference ranking effects of different fertilizer types and rates on wheat crop in Hosaina, Ethiopia, during the 2014–2015 cropping season (n = 37), where 1 = poor, 2 = fair, 3 = good, and 4 = very good.

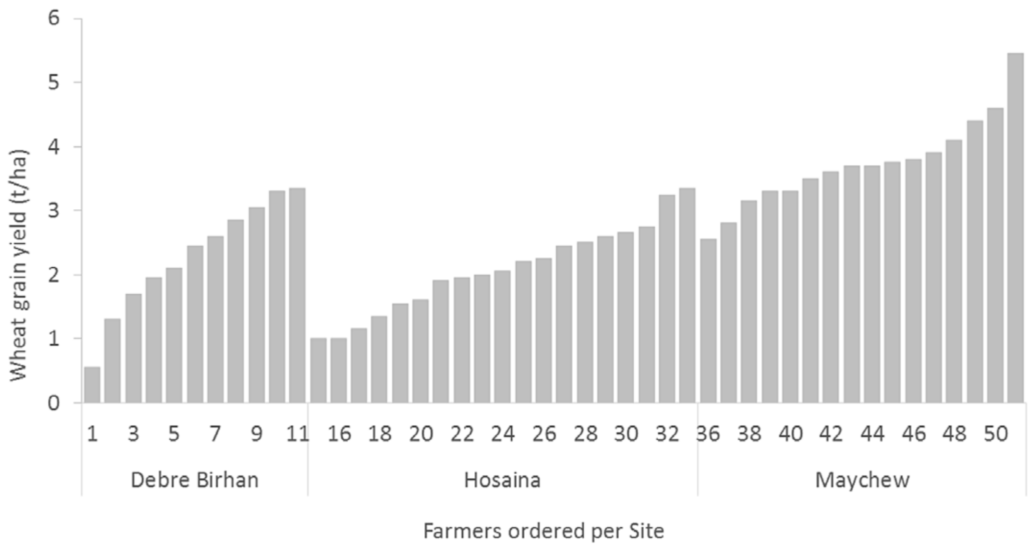

Figure 5. Wheat grain yield observed *farmer's practices* in Debre Birhan, Hosaina and Maychew, Ethiopia, during the 2014–2015 cropping seasons.

Overall, application of inorganic fertilizer with or without manure was profitable and attracted a marginal rate of return (MRR) of 2.1–2.5 in Debre Birhan, and application of manure alone attracted an MRR of 3.4. Also, in Debre Birhan, half recommended NPK + S + Zn+manure attracted an MRR of 2.5 and NPK and NPK+manure treatments attracted an MRR of 2.3 and 2.1, respectively. In Hosaina, application of NPK was most profitable, attracting an MRR

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Plate 1. A field showing different responses of wheat to different management inputs. The photo was taken twice, but the different responses shown here are on the same field. **A** is *farmer's practice*; **B** has received both the recommended fertilizer package and manure and **C** has no fertilizer input but is weeded, unlike that in **A**.

Plate 2. Wheat stand in **A** researcher-managed experimental plot under recommended management and new improved variety and **B** *farmer's practice* with old improved variety.

of 3.0. Application of DAP attracted an MRR of 2.6, whereas that of NPK + Zn attracted an MRR of 2.0. Half recommended NPK + S + Zn and NP treatments were not profitable and attracted the lowest MRR (1.4 and 0.4, respectively).

Discussion

Appropriate management of soil fertility is important for increasing productivity and improving food security in Ethiopia and beyond. Although Ethiopian agro-climatic conditions are suitable for wheat production, especially the country's highlands, large yield differences between farms still remain and these need to be addressed in order to achieve food security. The resulting wheat

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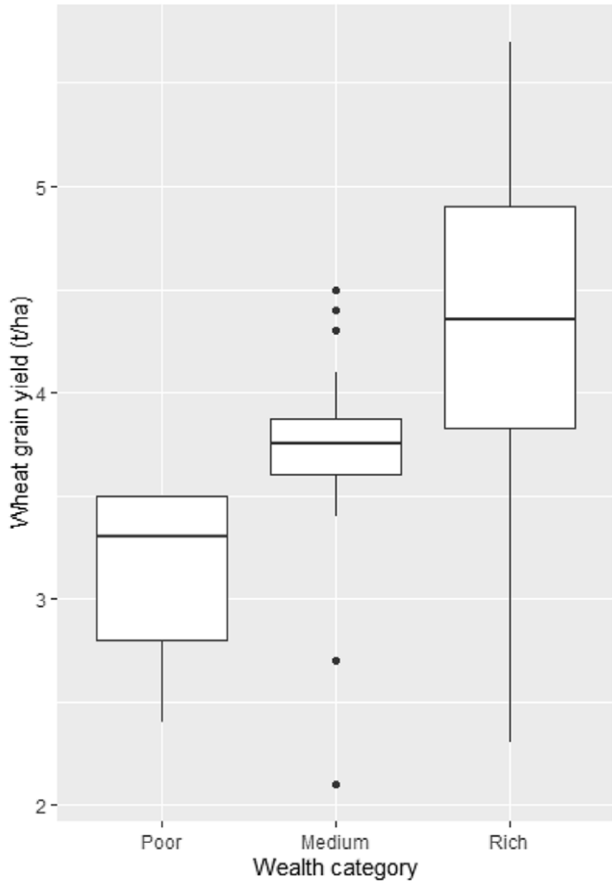

Figure 6. Wheat grain yield observed by farmers of different wealth categories in Maychew, Ethiopia, during the 2014–2015 cropping season.

productivity, particularly with application of full dosage of fertilizers recommended such as in Debre Birhan, is far above the current national average of 2.7 t ha^{-1} for Ethiopia (Zegeye *et al.*, 2020). High response to fertilizer is observed at the site with lower soil fertility (Debre Birhan) and is consistent with increased profitability. For instance, increase in yield has been reported, doubling and even tripling in some cases with proper rate, timing and type of fertilizer (Habte *et al.*, 2015; Habtegebrial, 2013; Habtegebrial and Singh, 2009) in Ethiopia. The response to micronutrients in Hosaina is interesting since soil test values indicated lack of deficiency in a majority of fields. Micronutrients are important in increasing wheat productivity, as also observed elsewhere (Habtegebrial and Singh, 2009). Further investigations are necessary, however, to ascertain the conditions under which positive responses are expected. Besides, the use of organic resources such as manure and crop residues is an option that improve soil properties and decreases dependence on inorganic fertilizer (Giller *et al.*, 2011; Agegnehu *et al.*, 2014). For farmers applying organic resource, yield increases may still be observed if they apply half recommended rates of the inorganic fertilizers, e.g., in Debre Birhan.

High productivity following the use of improved wheat varieties, especially the rust-resistant Tsehay variety (in Debre Birhan) and Dand'aa (in Maychew), is consistent with other studies and demonstrates the importance of such varieties in increasing yields. Improved varieties are also associated with increased efficiency of fertilizer use relative to local varieties (Vanlauwe *et al.*, 2011). Several factors—for example, poor agronomic practices, including low use of inputs

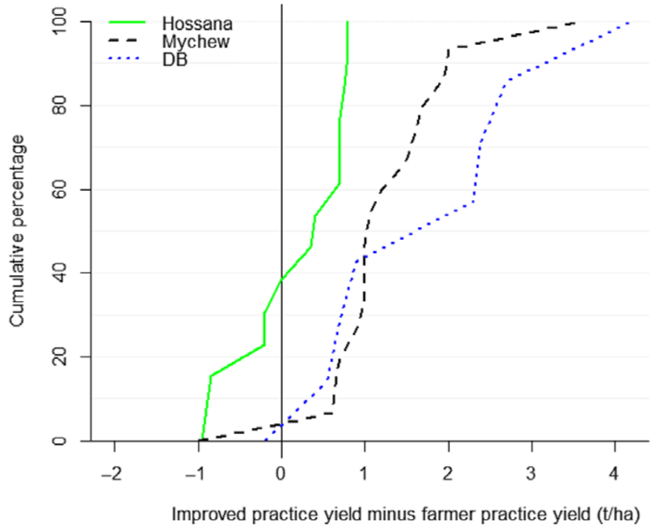

Figure 7. Yield gain obtained over *farmer's practices* by farmers in Debre Birhan, Maychew and Hosaina, Ethiopia, during the 2014–2015 cropping season.

(Agegnehu *et al.*, 2016; Zelalem, 2014; Bekeko, 2013)—besides outdated varieties (Shiferaw *et al.*, 2014) are argued to be responsible for low yields observed in farmer fields. Yet, inappropriate plant densities appear to be the most important factor at the studied sites. The additional effort required to optimise plant densities can be expected to be less than the associated increase in yield of up to 1.3 t ha^{-1}. Indeed, if 55% of farmers in Ethiopia (0.88 million ha of the 1.6 million ha for wheat production) can increase yield by 62% (i.e. 1.3 t ha^{-1}) as in *farmer's practice* through use of appropriate plant densities, 1.15 million t of wheat grain can be added to Ethiopia's food basket (based on national production statistics for 2012; wheatatlas.org, accessed October 2016). But the optimisation of plant densities requires access to technological options to facilitate uptake of row-planting methods and replace the common practice of seed broadcasting, especially in rural Africa where access to labour is declining (Greiner and Sakdapolrak, 2012). At harvest, the average plant population per square meter in farmers practice was 76 in Mychew, 85 in Debre Birhan and 121 in Hossaina compared to 170 in researcher-managed fields where row planting was implemented. As such, training farmers on wheat row planting and introducing row planter technologies are needed. The significant effect of plant densities on yield observed under *farmer's practice* is in agreement with previous finding for maize in Tanzania (Kihara *et al.*, 2015). The efforts promoting fertilizer use in SSA, while commendable, will be hampered by low response due to poor plant densities; consequently, benefits of fertilizer use (e.g. of *improved practice* in our case) are constrained by plant densities.

Increased yields obtained in a majority of the farms with the farmer-managed *improved practice* indicate the need to adopt this practice. The variability in responses to *improved practice* from field to field is expected due to differences in soils and management, timeliness of planting, seed variety, weed management and seasonal weather (Kihara *et al.*, 2015). High variability in responses between and even within farms has been reported elsewhere (Tittonell *et al.*, 2007; Tittonell *et al.*, 2005). Proxies of soil fertility associated with crop performance in many parts of SSA include distance of field from homestead and number of years since conversion from natural vegetation (Kihara *et al.*, 2015; Giller *et al.*, 2011; Zingore *et al.*, 2007). Preferential management, especially application of organic resources (farmyard manure), is largely responsible for the effect of distance from homestead on crop yield since frequency and amount of application often decrease with distance from homestead. Interestingly, such soil fertility proxies, including the

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Table 5. Results of partial economic analyses of effects of fertilizer application in Debre Birhan and Hosaina sites in Ethiopia during 2014/15 cropping season

Treatment	Gross benefit ($ ha^{-1})	Total cost that vary ($ ha^{-1})	Average net benefit ($ ha^{-1})$^{\beta}$	Marginal rate of return
Debre Birhan				
Control	1086.1	45.8	1040 (610, 1470)	
Manure	1295.9	106.9	1189 (759, 1619)	3.4
HalfNPK + S + Zn + Manure	1770.4	324.3	1446 (1016, 1876)	2.5
NPK	1952.6	447.3	1505 (1075, 1935)	2.2
NPK + Manure	2052.4	496.9	1555 (1125, 1985)	2.1
NPK + S + Zn + Manure	2148.6	513.0	1635 (1205, 2065)	2.3
Hosaina				
Control	933.7	23.6	894 (636, 1178)	
NP	1003.9	154.7	793 (632, 1312)	0.4
NPK	1155.4	227.8	870 (722, 1537)	3.0
NPK + Zn	1468.9	247.8	1160 (945, 1960)	2.0
DAPonly	1154.1	100.8	1029 (785, 1517)	2.6
HalfNPK + S + Zn	1136.4	144.1	949 (722, 1455)	1.4

$^{\beta}$Values in bracket are minimum and maximum net benefits.

slope, did not appear as important in our study, probably masked by the high effect of plant densities. But in our study case as well, farmers hardly use manure and fields closer to the homestead are equally starved of the organic resources. This was also reported by Selassie (2015) in Ethiopia, where organic fertilizer is scarce with competing uses; for instance, farmyard manure and crop residues are used as an energy source to cook food. The modest increases in yields following manure application are associated with a good marginal rate of return in Debre-Birhan, an indication that this is a good practice to improve farm income. Manure has known residual effects, positively influencing yields beyond the season of application (Chivenge *et al.*, 2011). To address observed heterogeneity in crop responses to fertilizers, tools to aid site-specific fertilizer recommendations are required in order to characterise which soils are poor and which are not.

The similarity between higher yields and farmers' high scores for best performing treatments in our study could point to future uptake of the improved technologies.

Clearly, application of the recommended amounts of inorganic fertilizer is profitable. Optionally, the profitable application of half recommended inorganic fertilizer with manure, as seen in Debre Birhan, may be suitable to smallholder farmers who in most cases can only afford limited amounts of inorganic fertilizer but can access some manure and other organic amendments. Use of combined organic and inorganic nutrient sources is known to achieve similar or higher yields than fertilizers alone applied at even higher rates (Chivenge *et al.*, 2011; Vanlauwe *et al.*, 2015) and has additional benefits, including improving the soil structure (Zingore *et al.*, 2008). But to completely resolve the role of manure and micronutrients (Zn), trials testing these applications should be repeated on the same plots for at least three seasons to account for expected residual effects.

From this study, it is evident that adoption of crop management practices such as appropriate spacing and fertilizer use can both increase yields and offer a step towards ensuring food security in Ethiopia. Land available for cultivation has been drastically reduced due to population pressure; thus, intensification with maximisation of inputs, coupled with GAP, is essential for the region's food basket. Also, a strong revitalisation of extension support at grassroots level, whether private, governmental, or both, is key to crop production even before any intervention promoting fertilizers and other measures that improve soil fertility. Grassroots agronomy that addresses key issue of plant spacing and organic resources utilization is needed to unlock yield potential for Ethiopia and the SSA region as a whole. Dysfunctional extension services across most of SSA are

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undermining agricultural productivity, and urgent attention is needed to reverse the situation. And though timeliness of planting depends on farmer preparedness at onset of the season, simple optimisation of plant population is well within the reach of most farmers, even if planting is by broadcasting and little training is offered. Rather than focusing on complex research projects, investments in grassroots agronomy are likely to result in huge returns on investment.

Conclusions

Application of fertilizers, especially when including S and Zn, is important for increasing the productivity of wheat at the studied sites of Ethiopia. The combination of NPK and manure results in higher wheat productivity than applying manure as the only source of added nutrients (as observed in Debre Birhan). By applying half the recommended NPK with micronutrients and manure, the same wheat yields as for the full fertilizer treatment can be achieved, although the full rate is required for Maychew, the site with lowest carbon content. The benefits of additional yield from fertilizer use are observed by a majority of farmers at the study sites except for low-lying places like Hosaina. By contrast, low plant populations reduce productivity of wheat in farmer fields. We conclude that although nutrient management which includes use of micronutrients is important in specific cases, investments to promote agronomic practices such as plant density optimisation have a potential in increasing food productivity.

Acknowledgements. The field experiments used in this study were financially supported by the Africa RISING of the Feed the Future through the International Livestock Research Institute. Staff time for some of the authors was supported through the CGIAR Research Program on Water, Land and Ecosystems (WLE) with support from CGIAR Fund Donors including: the Australian Center for International Agricultural Research (ACIAR); Bill and Melinda Gates Foundation; Netherlands Directorate-General for International Cooperation (DGIS); Swedish International Development Cooperation Agency (Sida); Swiss Agency for Development Cooperation (SDC) and the UK Department of International Development (DIFD). The work is aligned to the Excellence in Agronomy (EiA) Initiative of the One CGIAR. We acknowledge Isaac Savini for initial engagements in the establishment of the trials in Hosaina and Debre Birhan. We also acknowledge the support of Ministry of Agriculture staff in the three project areas for facilitating identification of sites and engaging with farmers with field maintenance. Africa RISING ground staff namely Workeneh in Hosaina, Temesgen in Debre Birhan, Addisu Asfaw in Sinana and Mohammed in Maychew are appreciated for coordinating the activities in their respective sites.

Funding Support. This work was supported, in whole or in part, by the Bill & Melinda Gates Foundation [INV-005460]. Under the grant conditions of the Foundation, a Creative Commons Attribution 4.0 Generic License has already been assigned to the Author Accepted Manuscript version that might arise from this submission.

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Cite this article: Kihara J, Gurmessa B, Tamene L, Amede T, and Sommer R. Understanding factors influencing wheat productivity in Ethiopian highlands. *Experimental Agriculture*. https://doi.org/10.1017/S0014479721000296