Research Findings

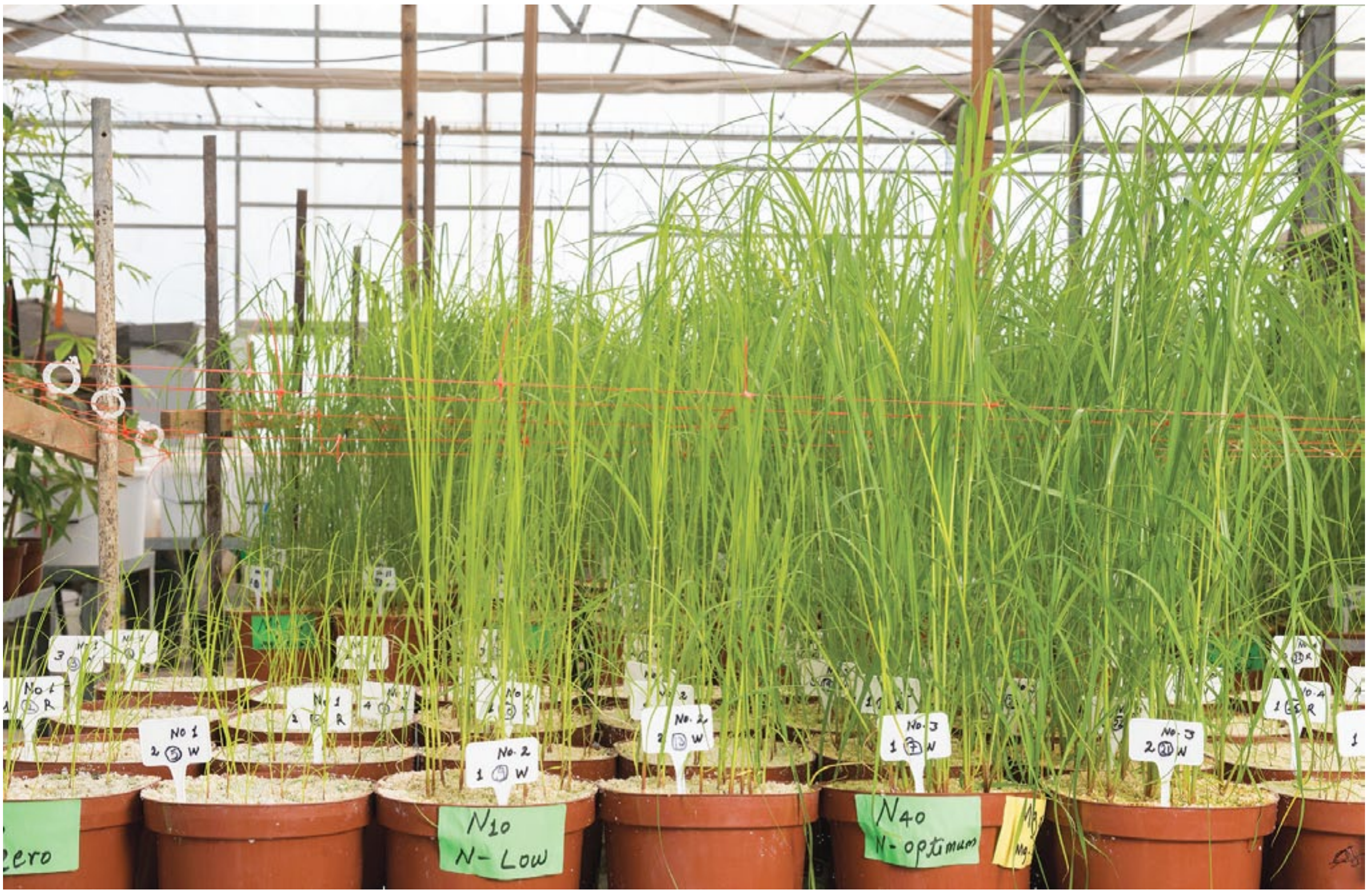

Photo 1. Teff pot experiment at the Center for Fertilization and Plant Nutrition (CFPN), Gilat, Israel. Photo by the authors.

Response of Teff [*Eragrostis tef* (Zucc.) Trotter] to Potassium Fertilizer Application in Four Districts of North Shewa, Ethiopia

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Abstract

Teff [*Eragrostis tef* (Zucc.) Trotter] is a cereal crop species unique to Ethiopia, where it is an important staple crop. It is grown on more than 3 million ha of land. In recent decades, soil fertility has significantly declined in Ethiopia. While nitrogen (N) and phosphorus (P) are traditionally applied by teff growers, potassium (K) has been ignored due to the perceived notion that soils in Ethiopia provide all K requirements. However, recent studies have led to opposite conclusions. Teff K requirements, and its response to K application, have seldom been addressed.

The objectives of the present study were to examine teff response to rising K application rates on Vertisols in four regions in the Ethiopian Central Highlands: Sululta, Mulu, Bereh, and Moretena

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Jiru. Potassium was applied at rates of 0, 30, 60, 90, and 120 kg K_2O ha^{-1} along with urea + NPSZn blend applied at 64 kg N ha^{-1} and 20 kg P_2O_5 ha^{-1}.

Generally, crop performance and yield parameters displayed significant increases up to K application range of 60-90 kg K_2O ha^{-1}, with grain yield rising by 26-30% at Moretena Jiru; 21-50% at Bereh; 36-82% at Sululta; and 60-130% at Mulu. Crop yields were between 1-3 Mg ha^{-1}. The large differences between regions may be attributed to the teff genotype cv. Dega at Moretena Jiru and cv. Konchu at the other regions, and to soil fertility traits that require further exploration.

Economically, the incentive of local teff growers to choose an appropriate K application rate would emerge from the expected increment in the marginal profit although this differed considerably between regions, being positive up to 30, 60, 90, and 120 kg K_2O ha^{-1} at Moretena Jiru, Bereh, Mulu, and Sululta, respectively. Potassium application significantly increased N, P, and K concentrations in grains and straw, indicating that K was a principal limiting factor in teff crop development. Consequently, the uptake rates of these nutrients rose significantly, which indicates a possible need to increase their application rates when K is adequately supplied.

In conclusion, the potential of K supply to substantially enhance teff productivity is significant but largely depends on local soil traits that should be thoroughly examined in advance.

Keywords: Eragrostis tef (Zucc.) Trotter; nitrogen uptake; potassium; soil fertility; Vertisol.

Introduction

Teff [*Eragrostis tef* (Zucc.) Trotter], a self-pollinated, C-4 cereal crop belonging to the genus Eragrostis under the family Poaceae (Ketema, 1997; Assefa *et al.*, 2015; Paff and Asseng, 2017), originated in Ethiopia, where it is an important staple crop grown on more than 3 million ha of land. Among the cereals produced in Ethiopia, teff is first in area cultivated but second and last in production and productivity, respectively. Teff is grown by over 6.6 million households and constitutes the major staple food grain for over 50 million Ethiopians (CSA, 2016). The major teff producing areas are Amhara, Central Oromia and West Tigray, where productivity ranges from 1.3-1.5 Mg ha^{-1} (CSA, 2012). There are two groups of teff cultivars - improved and traditional. The national average yield of traditional varieties is 0.91 kg ha^{-1} and that of the improved varieties is estimated to be 1.7-2.2 Mg ha^{-1} on farmers' fields or 2.2-2.8 Mg ha^{-1} on large research-managed farms (Berhe, 2008). However, teff productivity potential is much higher, and can be realized through further practical improvements and enhanced soil nutritional status (Feyera *et al.*, 2014; Mebratu *et al.*, 2017; Tesfahun, 2018).

Teff has a number of particular features, which make it a preferred crop among farmers. As the most favored staple food in the country, the demand for the product is ever increasing; annual teff production increased from 3.0 to 4.8 million metric tons, from 2007 to 2013, respectively (CSA, 2014). Teff has an excellent resistance to drought, as well as to water logging stresses (Tefera and Ketema, 2001) and it is relatively invulnerable to weevils and other pests. It is also suitable for multiple cropping. In addition, teff straw provides a valuable animal feed during the dry season. Recently, teff has been recognized and is highly appreciated as a 'superfood' (Baye, 2015; Heuzé *et al.*, 2016; Shumoy and Raes, 2017). It is relatively rich in protein, ranging from 8.4-19.4% of dry matter, depending on the cultivar, location, and year (CGIAR, 2009), but is gluten-free, and therefore considered an excellent solution for the increasing gluten-sensitive population worldwide (Baye, 2015). Teff has a good amino acid composition, with lysine (3.7% protein) and sulfuric amino acids levels (methionine 4.1% protein) higher than in wheat or barley (Bekele and Lester, 1981). Teff grains are also richer in iron (Fe), calcium (Ca), and copper (Cu) than other common cereals (Mengesha, 1966). In spite of its importance in Ethiopia, and its worldwide appreciation, teff nutrient requirements and its response to modern fertilizer sources have not yet been fully studied.

Soil fertility is a primary constraint affecting agricultural production in sub-Saharan Africa (SSA) (Sanchez *et al.*, 1997; Bationo *et al.*, 2007; Vanlauwe *et al.*, 2010; Guta *et al.*, 2014; Tadele, 2017). The scenario with regards to soil fertility and productivity in Ethiopia is similar to other neighboring eastern and central African countries that have high annual rates of nutrient depletion (Esilaba *et al.*, 2000). Three primary biophysical limitations, among others, that decrease agricultural production in Ethiopia are poor soil health, low soil fertility, and crop nutrient imbalances (Gete *et al.*, 2010). Core constraints in Ethiopian soils include depletion of soil organic matter due to widespread use of biomass as fuel, depletion of macro- and micronutrients, removal of top soil by erosion, change of soil physical properties, and increased soil salinity with time (Gete *et al.*, 2010).

More than five decades ago, nitrogen (N) and phosphorus (P) were identified as being the most deficient nutrients in the majority of Ethiopian agricultural soils. As a result, application of fertilizers containing N and P (urea and DAP) began in the late 1960s, which produced dramatic increases in the yields of several crops. Consequently, the use of urea and DAP have been by far the most widely adopted inputs by farmers (Haile and Mamo, 2013). Due to this long-term unbalanced fertilization practice, deficiency of other nutrients, mainly potassium (K), sulfur (S), zinc (Zn) and boron (B) started to become apparent (Astatke *et al.*, 2004; Haile and Mamo, 2013; EthioSIS, 2014). Based on recent findings by EthioSIS, the Ethiopian Ministry of

Agriculture (MoA) has recommended the use of a new type of blended or compound fertilizers: NPS, NPSB, NPSZn, NPSZnB. However, in spite of their significant positive response, Ethiopian farmers still lag far behind those of other developing countries in fertilizer consumption. Currently, only 40% of Ethiopian smallholder farmers use fertilizers, at average rates of less than 40 kg ha^{-1}, significantly below recommended rates (Feyera *et al.*, 2014). Furthermore, this MoA reform in fertilization policy has not yet addressed crop K requirements.

Potassium is one of the essential elements required by plants for their healthy growth and development (Marschner, 2011; Zörb *et al.*, 2014). It plays a very important role in the activation of enzymes, photosynthesis, starch synthesis, nitrate reduction and sugar degradation (Askegaard *et al.*, 2004). Potassium is the only nutrient that is not a constituent of organic structures. Its function is mainly in osmoregulation, the maintenance of electrochemical equilibria in cells and its compartments, and the regulation of enzyme activities (Hsiao and Laüchli, 1986). It also has a crucial role in the energy status of the plant, translocation and storage of assimilates, and maintenance of tissue water relations (Imas *et al.*, 1999). Thus, soil K deficiency may result in high susceptibility of crops to diseases, pests, frost, and drought, leading to poor development and, subsequently, to serious reduction in produce yield and quality (Umar and Moinuddin, 2002). Potassium deficient plants, especially small grains and maize, are prone to lodging (Hodges, 2010).

In Ethiopia, so far, there has been a general understanding that soils are rich in K, and K fertilizers have not been part of the fertilizer extension program, mostly based on the reports of the Freedom From Hunger Campaign, in which inconsistent crop response to K fertilizers were found. Murphy (1968), as well as other fragmented reports on exchangeable K analysis, brought evidence for high soil K values. Similar to the case with other macro- and micronutrients, until 1998, little has been known about the exact K status in Ethiopian soils (Mamo and Haque, 1988). However, cumulative findings (Astatke *et al.*, 2004; Haile and Mamo, 2013; EthioSIS, 2014) have reported that K deficiency is becoming a common phenomenon in wide areas in the country. Possible causes for the occurrence of K deficiencies in some Ethiopian highland soils are soil erosion and K leaching, caused by torrential rainfalls, deforestation, and continuous K mining through crop uptake (Haile, 2009). Recent findings from the national soil fertility mapping work (EthioSIS, 2014) have also proved that, in Tigray region, 58% of the agricultural land required K fertilization, while in the case of the Amhara National Regional State more than 90% of the agricultural lands require K fertilization (EthioSIS, 2014).

One of the major reasons for lack of K fertilizer recommendation on clay soils (Vertisols) is the fact that their exchangeable K analyses were often higher than the established critical levels. These results were assessed by the commonly employed ammonium acetate extraction method, or the Mehlich III multi-extractant (Astatke *et al.*, 2002). Recently, these methods were shown to significantly overestimate the available soil K phase. Furthermore, more accurate methods revealed that many Vertisol soils in Ethiopia exhibit very poor K availability (Kassahun, 2017). In a countrywide experiment, the contribution of a modest K application, 50 kg KCl ha^{-1}, gave rise to significant yield increases of teff and wheat, but this varied with site and soil properties (Mulugeta *et al.*, 2017). Under controlled fertigation, K application brought about significant increases in grain yields in potted plants as well as in field experiments (Gashu, 2017). Nevertheless, there is a substantial knowledge gap regarding teff K requirements and response to K fertilization in situ on Ethiopian arable Vertisols.

Photo 2. Soil surveying at the research site in Sululta woreda, Oromia region, Ethiopia, 50 km from Addis Ababa. Photo by the authors.

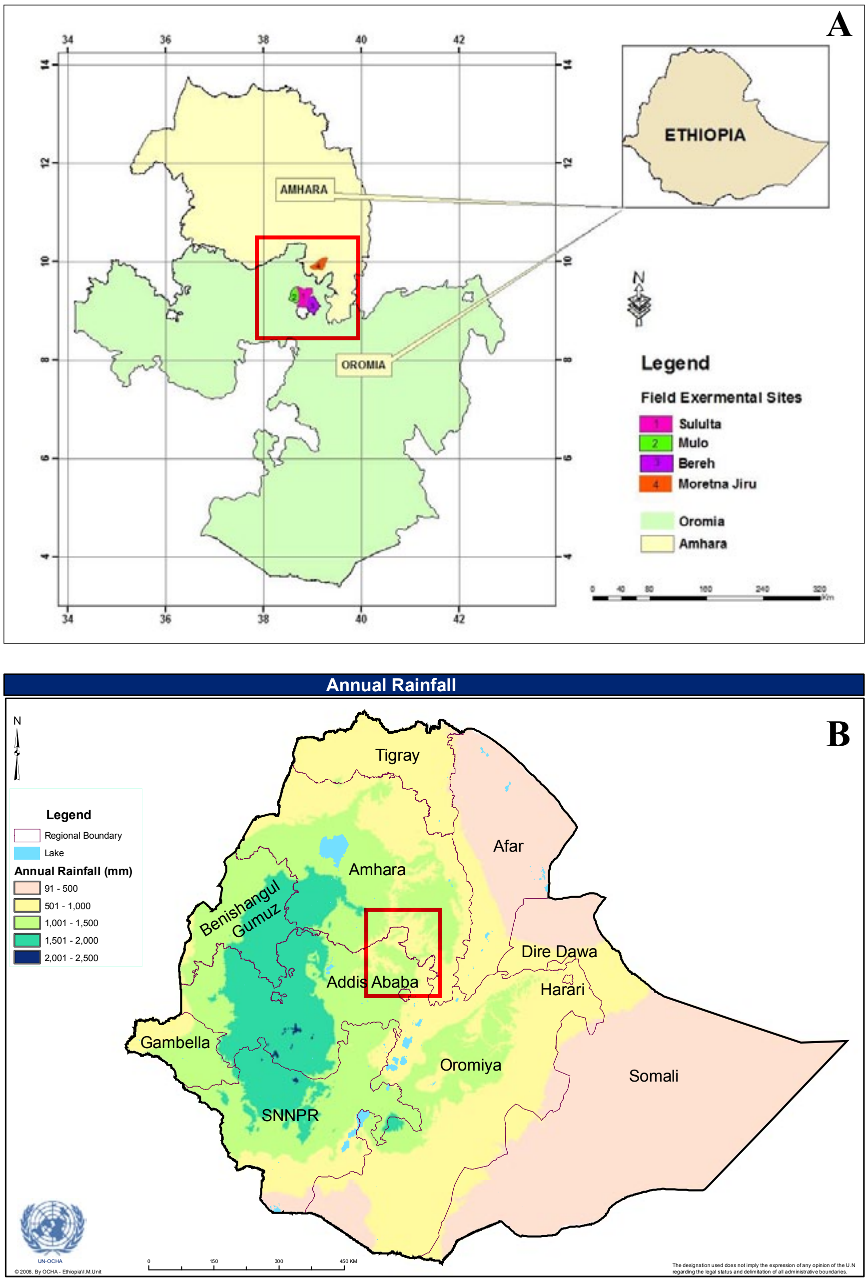
Photo 3. Threshing teff at the research site. Photo by the authors.

The specific objective of the present study was to characterize teff crop response to rising K application rates on Vertisols at field level, including crop performance, grain and straw yields, and macronutrient uptake. In general, the study is aimed to provide a basic K fertilization perception that will lead to practical recommendations for agricultural development officers and farmers, in order to enhance teff production in the Ethiopian Central Highlands, and to highlight future directions on aspects of soil K and nutrient stress research in Ethiopia.

Materials and methods

Field studies were conducted in three woredas of the central highlands of Oromia Regional State - namely Sululta, Mulo, Bereh - and in Moretena Jiru of Amhara Regional State, in Ethiopia. All four sites are located at close proximity to Addis Ababa or 195 km away (Moretena Jiru) (Map 1).

Altitude of all experiment sites is high, above 1,500 m a.s.l., with an average daily temperature range of 15-18°C and minimum temperature of 6-10°C with very rare frost events, and maximum temperature of 18-22°C. Annual precipitation ranges of 1,000-1,300 mm distributed between a relatively dry season from October to February, with 3-5 wet days and less than 40 mm per month; a rainy season during July-August, with 28 wet days and more than 250 mm a month; and intermediate seasons from March to June and in September, with 9-23 wet days and 50-100 mm a month, averagely (http://www.addis-ababa.climatemps.com/graph.php).



Map. 1. The experiment sites in Ethiopia (A); mean annual precipitation in Ethiopia (B). *Source:* UN Office for the Coordination of Humanitarian Affairs; https://reliefweb.int/map/ethiopia/ethiopia-annual-rainfall.

Soil was sampled at each site before fertilizer application. Surface soil (0-20 cm deep) was sampled in three replicates at each site and pooled together. The samples were air-dried, ground on a 2-mm sieve, thoroughly mixed and readied for physicochemical analysis. Soil pH was determined in H_2O using 1:2.5 soil to solution ratio; electrical conductivity was measured using a Hanna EC 215 conductivity meter. Soil available P and exchangeable basic cations (K, Na, Ca, and Mg) were extracted using the Mehlich-III procedure (Mehlich, 1984), after which an inductively coupled plasma (ICP) spectrometer was used to determine their concentrations. Soil N concentration was determined using the Kjeldahl method. Soils of all sites were characterized as Vertisol, Nitisol, and Cambisol with dominant clay texture (60-80%), slightly acidic (pH 6-6.7), and with very low to low nutrient availability (Table 1).

Table 1. Soil properties and climate conditions at the experimental sites.

Soil property	Units	Location			
		Sululta	Mulu	Bereh	Moretena Jiru
Sand	%	7.63	21.1	12.94	8.61
Silt	%	11.61	20.26	20.73	10.42
Clay	%	80.76	58.63	66.32	80.97
Textural class		Clay	Clay	Clay	Clay
pH (H_2O)		6.4	6.0	6.7	6.6
P	ppm	11.28	9.70	10.57	16.01
Total carbon	%	1.81	1.53	0.85	0.73
Total N	%	0.15	0.14	0.07	0.06
C:N ratio		11.9	11.2	12.9	12.8
EC_e	dS m^{-1}	0.13	0.11	0.11	0.2
Ca	$Cmol^{(+)}$ kg^{-1}	33.03	26.99	34.55	38.20
K	$Cmol^{(+)}$ kg^{-1}	0.76	1.22	1.02	0.70
Mg	$Cmol^{(+)}$ kg^{-1}	9.62	9.89	8.51	9.89
Na	$Cmol^{(+)}$ kg^{-1}	0.19	0.15	0.17	0.13
CEC	$Cmol^{(+)}$ kg^{-1}	54.93	51.94	55.00	61.36
K:Mg ratio		0.08	0.12	0.12	0.07
Region altitude	m a.s.l.	1,500-2,500	1,500-2,800	1,800-3,000	1,600-3,000
Mean annual rainfall	mm	1,000-1,200	1,200	1,300	1,200
Min/max temp.	ºC	10/18	8/20	6/20	9/22

Fertilizers used in all treatments were NPSZn [a granulated blend of N (12%), P_2O_5 (45%), sulfur (5%, sulphate origin), and zinc (1%)] and urea. Urea was used in a split application, 1/3 at sowing and 2/3 at the tillering stage. Nitrogen and P rates were 64 kg N ha^{-1} and 20 kg P_2O_5 ha^{-1}, according to MoA recommendations (Feyera *et al.*, 2014). Five K application rates (0, 30, 60, 90 and 120 kg K_2O ha^{-1}) were assigned to the plots. The experiment was laid out in a randomized complete block design (RCBD) with three replications. Teff cultivars used were Kuncho (at Sululta, Mulu, and Bereh) and Dega (at Moretena Jiru). Seeds were sown at a rate of 7 kg ha^{-1} in a plot size of 6 x 4 m with row spacing of 20 cm apart. The spacing between plots and blocks was 0.5 and 1 m, respectively. All cultural and agronomic practices were applied on each plot as per the recommendation for teff.

After planting, the fields were supervised weekly and parameters of crop performance were recorded at their optimum time. Plant height (cm) - from the ground level to the tip of the main panicle - and the main panicle length (cm) - from the base of the first panicle branch to the tip of the main panicle - were determined at physiological maturity as an average of 10 randomly selected mother plants within 1 m^2 of each plot. The number of fertile tillers was also counted and calculated in a similar way. At harvest, the aboveground biomass of 9 m^2 of each plot was weighed. After hand threshing, total grain and straw yields were determined and the harvest index calculated as the ratio between grain and total aboveground biomasses.

Grain and straw were then sampled, dried, ground to a fine powder, weighed and burnt to ash for 4 hours in an oven at 480ºC before chemical analyses of NPK. Phosphorus and K concentration in the biomass samples were analyzed using an ICP spectrometer and N concentration was determined using the Kjeldahl method. Total crop N, P and K uptakes were calculated from nutrient concentrations multiplied by the relevant grain or straw yield.

Crop performance and yield parameters, as well as nutrient concentrations, were subjected to ANOVA using SAS software (SAS, 2004) to detect variations among treatments. Where the ANOVA test was significant, further mean separation was carried out using least significant difference (LSD) method at 0.05 probability level.

Results

Crop performance and yield parameters

Potassium application had significant effects on most parameters of plant development and yield determinants, and was effective through the four regions (Table 2). Although small differences occurred in the mean plant height, it increased significantly under rising K application rates from 0-60 kg K_2O ha^{-1}, but remained stable under further increase in K rates. The mean number of fertile tillers produced by a plant rose steadily from 5.8-8.4 (45%) in response to the rising K rates from 0-90 kg K_2O ha^{-1}. Panicle length, another important yield determinant, was significantly responsive within a K rate range of 0-60 kg K_2O ha^{-1}, growing from 39.6-47.7 cm, while further K rate increases did not promote a response. Consequently, mean grain yield rose from 1.6-2.3 Mg ha^{-1} under K rates ranging from 0-90 kg K_2O ha^{-1}, with no further increases above this application rate. In contrast, straw yield response to K application rates was insignificant, although some tendency to increase could be noticed (Table 2). The mean harvest index rose substantially from 0.37 in the absence of K supply to 0.49 under K rates equal or higher than 60 kg K_2O ha^{-1}. The effect of K application on teff performance displayed significant differences between the experiment sites, as well as the different cultivar used at the Moretena Jiru (MJ) site (Table 2).

Specific and detailed information on the effects of K application rates on teff crop performance is given in Fig. 1. Differences in plant height between regions were insignificant, while its response pattern to the elevated K application rates was obvious, with significant increases up to 90 kg K_2O ha^{-1} and a tendency to slightly

Table 2. A two-way analysis of K fertilization experiments on teff crop in Ethiopia. The upper part demonstrate the effects of five K application rates, and the lower part shows the influence of the four experiment sites on mean plant height, fertile tiller production, panicle length, grain and straw yields, and harvest index.

	Plant height	Fertile tillers	Panicle length	Grain yield	Straw yield	Harvest index
	cm	*plant*$^{-1}$	*cm*	---------*kg ha*$^{-1}$----------		
K rates (kg K_2O ha^{-1})						
0	93.7c	5.8c	39.6c	1.6c	4.0	0.37c
30	95.4cb	5.9bc	42.5b	2.0b	4.4	0.45b
60	96.3ab	7.1b	47.7a	2.2ab	4.5	0.49a
90	99.8a	8.4a	48.1a	2.3a	4.7	0.49a
120	98.2a	8.3a	48.0a	2.4a	4.6	0.49a
CV (%)	14.9	4.8	3.6	5.2	2.34	0.3
LSD (5%)	2.5	0.79	1.9	0.21	0.7	0.02
Location						
SU	97.0ab	7.5a	39.1d	1.7b	4.4c	0.42b
MU	97.5a	6.1c	42.4c	1.9b	4.7bc	0.42b
BR	96.9ab	7.1a	45.2b	1.8b	5.0b	0.41b
MJ	95.4b	6.8b	51.2a	2.8a	6.0a	0.51a
CV (%)	13.2	5.5	5.1	6.3	1.6	1.3
LSD (5%)	1.9	0.41	2.3	1.0	0.5	0.06

Note: Similar letters within a column of each part indicate no significant differences at 5%. The different Ethiopian regions of the experiment sites: Sululta (SU); Mulu (MU); Bereh (BR); and Moretena Jiru (MJ). CV: Covariance; LSD: Least Significant Difference.

decline under the highest K rate. Plant height at Moretena Jiru fluctuated substantially compared to the other locations (Fig. 1A).

Similar to plant height, the production of fertile tillers did not differ between locations, while the effect of K rate was very significant and stable up to 90 kg K_2O ha^{-1}. Tiller production increased under a further rise in K rate only at Moretena Jiru (Fig. 1B). In contrast, panicle length differed significantly between locations (Fig. 1C). The shortest panicles and the weakest response to K rate was observed at Sululta. In the other three sites, panicle length was similar under no K application, about 43-44 cm. Potassium application resulted in different response patterns at the low rate of 30 kg K_2O ha^{-1}. However, as K rates rose, panicle length increased, being somewhat greater at Bereh than at Mulu, and significantly greater at Moretena Jiru, reaching a maximum of 53.3 cm already under 60 kg K_2O ha^{-1} (Fig. 1C).

Grain yield was remarkably higher at Moretena Jiru, while no significant differences occurred between the other regions (Fig. 1D). While steadily increasing with the rising K rates at Sululta and Mulu, grain yield at Bereh climbed to a maximum at 60 kg K_2O ha^{-1} and declined with further rises in K rates. At Moretena Jiru, however, grain yield peaked already at 30 kg K_2O ha^{-1} and remained stably high, at about 3 Mg ha^{-1}. The highest relative yield increase was obtained at Mulu at 120 kg K_2O ha^{-1} - 130% above control. At the other regions, the highest relative yield increases were 82, 50, and 30%, at Sululta, Bereh, and Moretena Jiru, respectively.

Straw yield was also much higher at Moretena Jiru, with no significant differences between the other sites (Fig. 1E). In spite of a tendency to increase in response to elevated K rates, this effect was rather weak, fluctuating, and insignificant. In contrast,

Photo 4. Inspecting teff deficiency symptoms at CFPN, Gilat, Israel. Photo by the authors.

Photo 5. International researchers and private sector delegates visiting the teff experiment at CFPN, Gilat, Israel. Photo by E. Sokolowski.

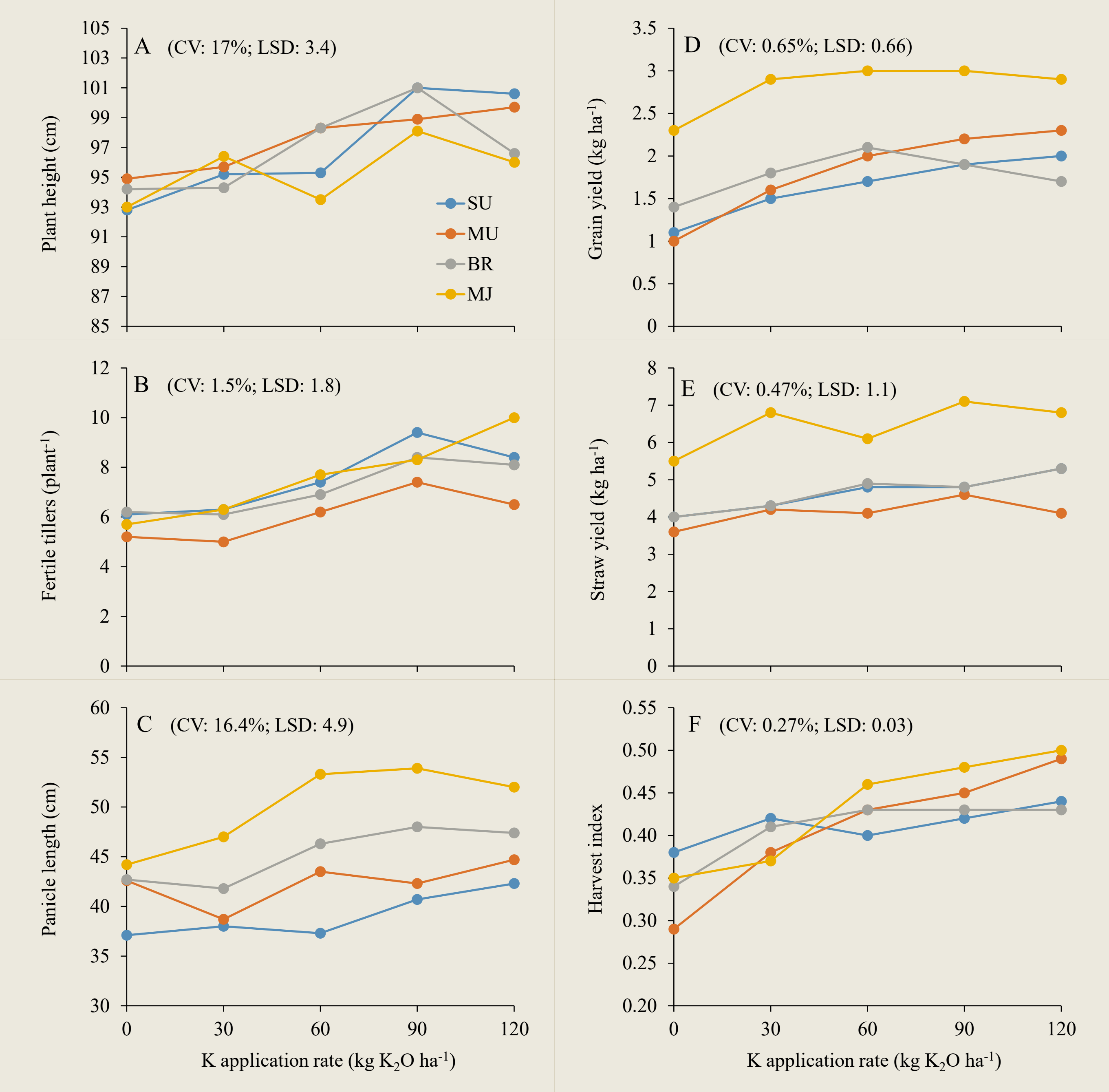


Fig. 1. Effects of K application rate on teff plant height (A), number of fertile tillers (B), panicle length (C), grain yield (D), straw yield (E), and harvest index (F). Significance of differences among treatments and locations are indicated by CV and LSD (5%) values. Experiment sites were Sululta (SU), Mulu (MU), Bereh (BR), and Moretena Jiru (MJ).

harvest index was extensively influenced by the K application rates, excluding Sululta, where it fluctuated within a narrow range (Fig. 1F). At Bereh, harvest index rose drastically from 0.34 under no K supply to 0.41 at 30 kg K_2O ha^{-1} and ranged from 0.41-0.43 with higher K rates. At Mulu, where harvest index was the lowest under no K supply (0.29), it up surged to 0.43 at 60 kg K_2O ha^{-1} and continued to increase up to 0.49 at 120 kg K_2O ha^{-1}. A significant harvest index climb was also obtained at Moretena Jiru, where it steadily rose from 0.35 in the absence of K fertilizer to 0.50 at the highest K rate (Fig. 1F).

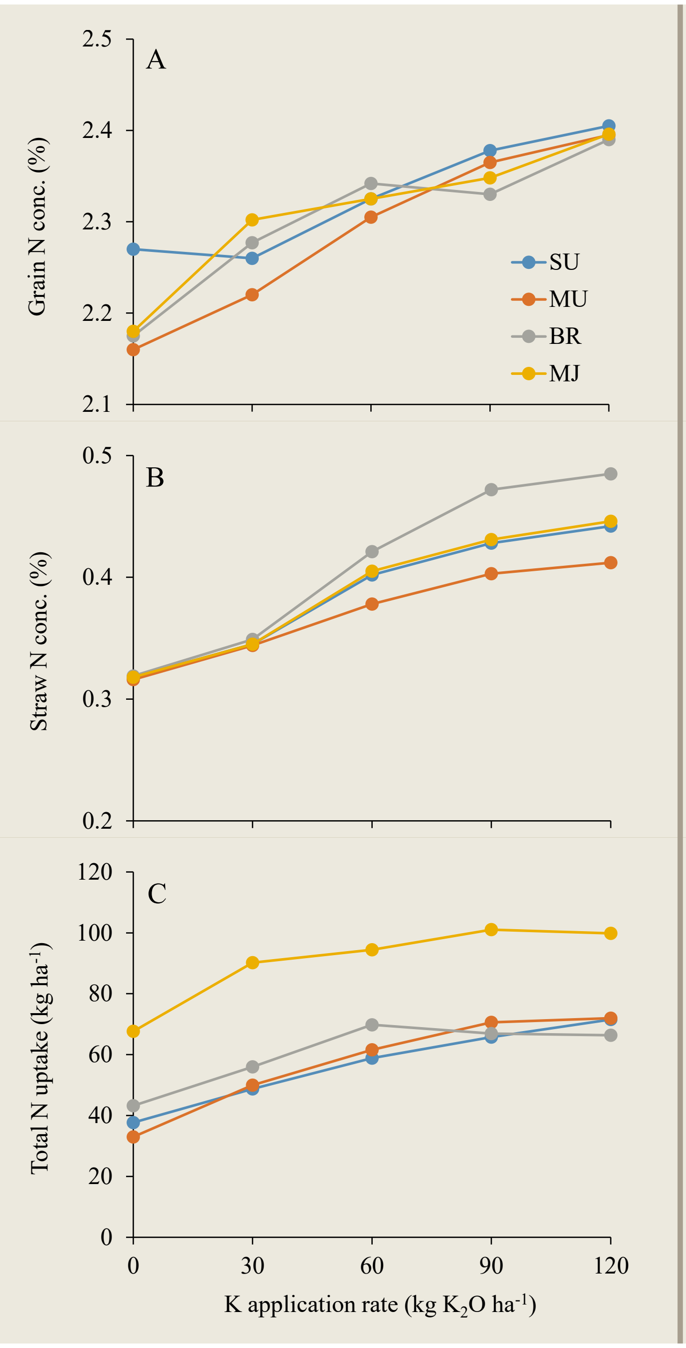


Fig. 2. Effects of K application rate on N concentration in teff grains (A), straw (B), and on total N uptake by teff crop (C). Experiment sites were Sululta (SU), Mulu (MU), Bereh (BR), and Moretena Jiru (MJ).

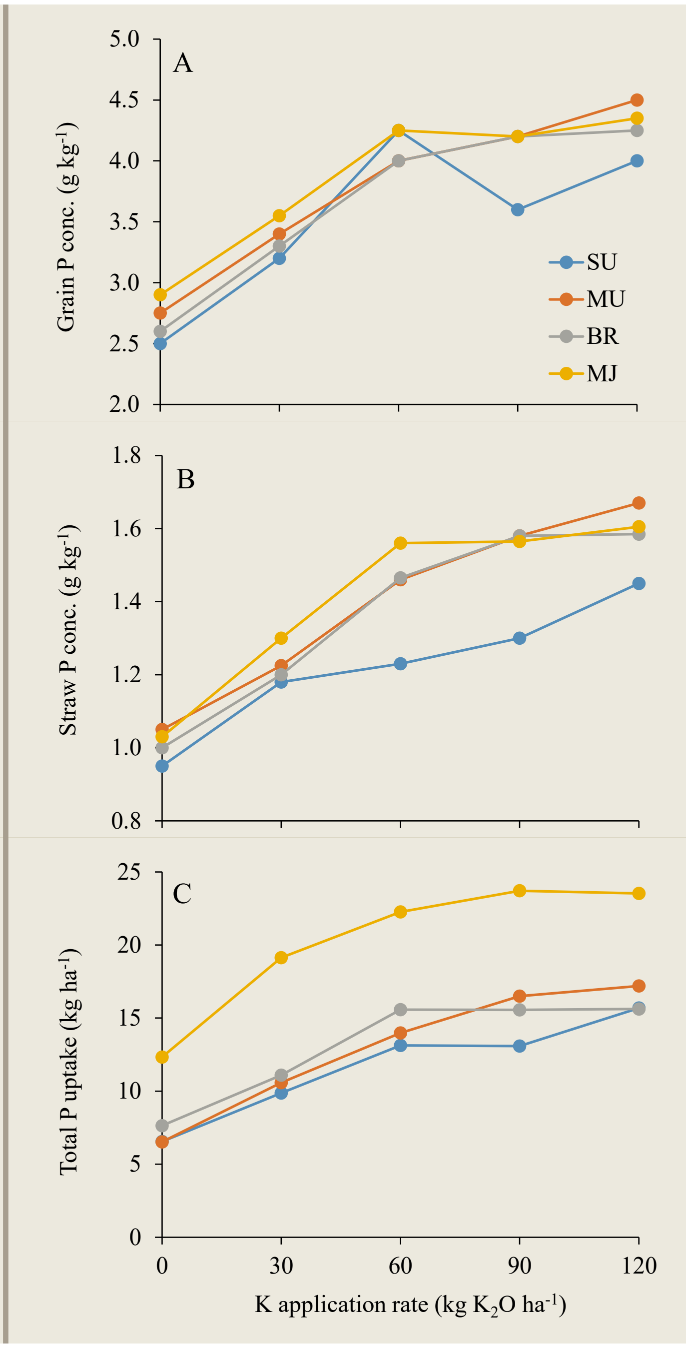


Fig. 3. Effects of K application rate on P concentration in teff grains (A), straw (B), and on total P uptake by teff crop (C). Experiment sites were Sululta (SU), Mulu (MU), Bereh (BR), and Moretena Jiru (MJ).

Effects of K application on plant N concentrations and uptake

The increasing K application rates brought about a significant rise in grain N concentration (Fig. 2A). This effect was quite similar in all experimental sites, where grain N concentration rose steadily from 2.17% in the absence of K supply up to 2.4% at the highest K rate. Straw N concentration was generally 5-fold lower than that of grain N concentration and this increased significantly in response to the elevated K application rate (Fig. 2B). However, the response of straw N concentration to K rates differed substantially between regions; Bereh had the

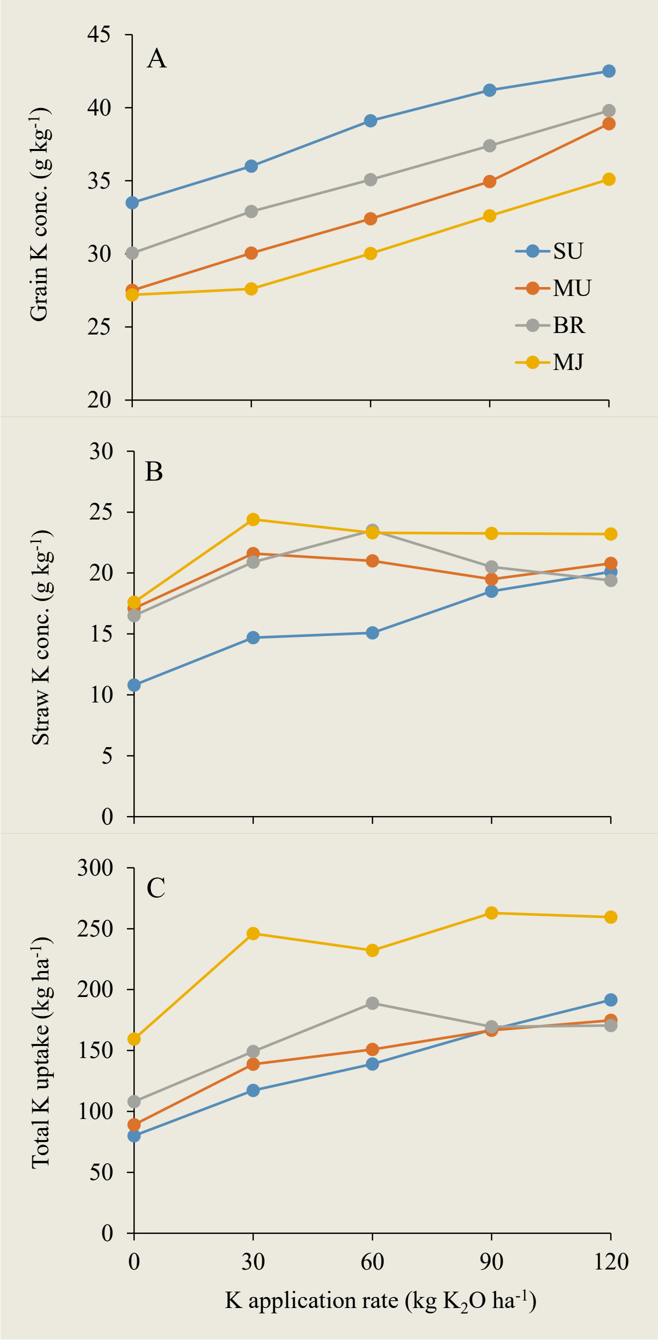


Fig. 4. Effects of K application rate on K concentration in teff grains (A), straw (B), and on total K uptake by teff crop (C). Experiment sites were Sululta (SU), Mulu (MU), Bereh (BR), and Moretena Jiru (MJ).

greatest, Mulu had the lowest, while intermediate responses were obtained at Moretena Jiru and Sululta. The consequent crop N uptake was significantly greater at Moretena Jiru, rising from 67 to 101 kg N ha^{-1} under K rates increasing from 0 to 90 kg K_2O ha^{-1}, respectively (Fig. 2C). Crop N uptake did not differ significantly between the other three regions. Nevertheless, it consistently increased with the rising K rates from about 35 to 72 kg N ha^{-1} at Mulu and Sululta, while at Bereh, crop N uptake peaked at 70 kg N ha^{-1} at 60 kg K_2O ha^{-1} but slightly decreased with further K rate increase.

Effects of K application on plant P concentrations and uptake

Potassium supply also had significant effects on crop P concentration and uptake (Fig. 3). Grain P concentration surged up from the range of 2.5-3 g kg^{-1} under no K supply to about 4-4.25 g kg^{-1} at 60 kg K_2O ha^{-1}, above which it declined (Sululta), remained stable (Moretena Jiru), or slightly rose (Bereh and Mulu) with further increases in K rates (Fig. 3A). Straw P concentrations under no K supply ranged from 0.95-1.05 g kg^{-1} and, excluding Sululta, significantly rose to 1.45-1.56 g kg^{-1} at 60 kg K_2O ha^{-1} (Fig. 3B). Straw P concentration continued to rise at Mulu as K rates increased, while remaining constant at Moretena Jiru, or continued to rise at 90 kg K_2O ha^{-1} at Bereh and then stabilized under the highest K rate. At Sululta, the rise in straw P concentration was significant but equal to that exhibited in the other regions between 0-30 kg K_2O ha^{-1}. However, above this rate and up to 90 kg K_2O ha^{-1} it rose much less, and then, at the highest K rate, it rose further than in the other regions (Fig. 3B).

Subsequently, K application rates had very significant effects on crop P uptake (Fig. 3C). The most dramatic effect was observed at Moretena Jiru, where crop P uptake doubled, from 12 to 24 kg P_2O_5 ha^{-1} between 0 and 90 kg K_2O ha^{-1}, respectively. At the other sites, crop P uptake was about 7 kg P_2O_5 ha^{-1} under no K supply, rose consistently to 13-15.5 kg P_2O_5 ha^{-1} at 60 kg K_2O ha^{-1}, and slightly increased (Sululta and Mulu) or remained stable (Bereh) under higher K rates (Fig. 3C).

Effects of K application on plant K concentrations and uptake

Grain K concentration increased significantly at a similar rate in all sites in response to elevated application of the nutrient (Fig. 4A). However, the values differed considerably between sites, being highest at Sululta, and lowest at Moretena Jiru. In contrast, straw K concentration only responded to the first step in K application rate (30 kg K_2O ha^{-1}) at all sites apart from Sululta, (Fig. 4B). Under higher K application rates, straw K concentration remained stable or even slightly declined. At Sululta, where the initial straw K concentration was much lower than at the other sites, it increased consistently with the rising K application rates. Potassium uptake rates increased steadily at Sululta and Mulu, beginning at 80 and 90 kg ha^{-1} under no K application, and ending at 190 and 170 kg ha^{-1} at the highest K application rate, respectively (Fig. 4C). At Bereh, maximum K uptake (190 kg ha^{-1}) was reached at 60 kg K_2O ha^{-1}, above which it slightly declined. This pattern was also observed at Moretena Jiru but with significantly higher rates of K uptake, reaching up to 250 kg ha^{-1} (Fig. 4C).

Economic analysis

Economic analysis carried out in the four regions revealed that Moretena Jiru, with the cultivar Dega, was the most profitable teff production site, with net return ranging from 50,000-62,000 ETB ha^{-1} (Fig. 5A). At Sululta and Mulu, the net return was much lower, ranging between 23,000-28,000 and 45,000 ETB ha^{-1}, under no K application and 120 kg K_2O ha^{-1}, respectively. Interestingly, at Bereh, the net return climbed from 33,000 under no K application up to 47,000 ETB ha^{-1} under 60 kg K_2O ha^{-1}, but it clearly declined with further elevation of the K application rate (Fig. 5A). The marginal profit, a parameter which focuses on the contribution of each K rate increment to the net profit, clarifies the incentive for farmers at each site to choose the appropriate K input (Fig. 5B). It clearly shows that the economically appropriate K rate is significantly different for each site. While at Moretena Jiru, the K rate upper threshold appears quite low, 30 kg K_2O ha^{-1}, it rises to 60, 90, and even 120 K_2O ha^{-1}, at Bereh, Mulu, and Sululta, respectively. It also appears that supplying K to teff crops is most cost effective at Mulu, with a maximum marginal profit of 22,000 ETB ha^{-1}, compared to 18,000 at Sululta, and to about 14,000 ETB ha^{-1} at Moretena Jiru and Bereh (Fig. 5B).

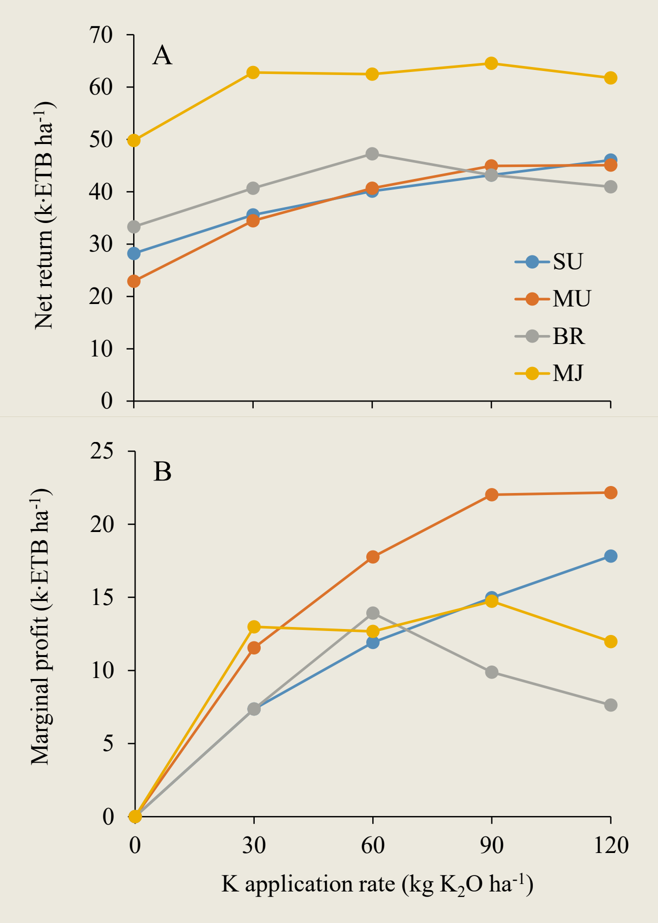


Fig. 5. Net return (A), and marginal net profit (B) calculated for teff response to K application rates on Vertisols in the Central Highlands of Ethiopia. Experiment sites were Sululta (SU), Mulu (MU), Bereh (BR), and Moretena Jiru (MJ).

Discussion

Overall, teff displayed significant positive responses to the rising K application rates, with an average optimum ranging from 60-90 kg K_2O ha^{-1} (Table 2). The response to K included general growth parameters such as plant height, but it was particularly significant in yield determinants - the number of fertile tillers and panicle length. These results are in agreement with earlier studies that described K significance to cereals' productivity (Fageria, 2007; Pettigrew, 2008; Verma and Ali, 2017) and particularly in teff (Fayera *et al.*, 2014; Gashu, 2017). Nevertheless, the most striking results are associated with the influence of K application dose on N and P concentration in the grain and the straw, which increased significantly (Figs. 2, 3, and 4). These results provide strong indications that soil K availability is a substantial limiting factor in teff development on Ethiopian Vertisols.

Beyond K's pivotal role in the maintenance of the plant water status, photosynthesis and carbon allocation, and in general crop performance, it has a significant positive effect on the development of the root system (Pettigrew, 2008). Potassium deficiency impairs both lateral root initiation and development (Armengaud *et al.*, 2004; Shin and Schachtman, 2004). It also seems to have a depressive effect on primary root growth (Gruber *et al.*, 2013; Kim *et al.*, 2010; Rengel and Damon, 2008). In rice, K deficiency decreased root growth and root-to-shoot ratio by reducing soluble sugar content in the roots (Cai *et al.*, 2012). Evidence for improved root establishment in response to elevated K rate was recently brought in a potted teff experiment under fertigation (Gashu, 2017). If an adequate K supply indeed supports a significantly larger root system, it can explain the higher concentrations and uptake of other macronutrients. Moreover, higher N and P uptake promotes further plant growth and development, which in turn demands more K, and so on. This feed-forward process would come to an end once a new limiting factor occurs. In the present study, the annual N application dose of 64 kg ha^{-1} seems to limit teff production at Sululta, Mulu, and Bereh under K doses greater than 60 kg K_2O ha^{-1}, while at Moretena Jiru, the sources of N are unclear, as N uptake exceeded 100 kg ha^{-1} (Fig. 2C).

While P limitation may be of some concern at Moretena Jiru only (Fig. 3C), K uptake unconditionally and by far exceeded K application doses at all sites (Fig. 4C). This result may suggest that teff plants can acquire considerable amounts from the exchangeable and non-exchangeable K phases in the clay minerals. However, these K resources are not endless and must be replenished through adequate fertilization. The exact dose for sustainable cropping management should be determined according to an in-depth analysis of the clay minerals at each site to determine the K distribution along the availability chain:

available (soluble); exchangeable; non-exchangeable; and, mineral phases, and to crop requirements (Askegraad *et al*., 2004; Firmano *et al*., 2017).

In spite of the clear and straightforward effects of K application rates on teff productivity, there were significant differences between the experiment sites (Table 2). Crop performance and yields were much higher at Moretena Jiru, compared to those obtained at Sululta, Mulu, or Bereh. This difference may be primarily attributed to the teff cultivar, Dega, which was employed at Moretena Jiru, in contrast to 'Konchu', the cultivar used at the other sites. While no additional information is available on specific differences between these two cultivars, the genetic diversity in teff is huge (Assefa *et al*., 2015), hence significant differences in productivity, as well as in other traits, would be largely expected (Tefera and Ketema, 1990; Mebratu *et al*., 2017; Paff and Asseng, 2018).

Having no information regarding exceptional weather events during the cropping season and given that climate conditions are quite similar at Sululta, Mulu, and Bereh, the differences between these three sites that occurred in teff performance and its response to K application (Table 2) can be attributed mainly to some dissimilarities in their soil properties (Table 1). However, it would be difficult to point to specific soil traits. Teff crops at Sululta and Mulu were highly responsive to the rising K rates, and further K rate increase could have resulted in even higher yields (Fig. 1). This was despite of the significant difference between the two sites in their soil texture: 58 and 80% clay, at Mulu and Sululta, respectively. On the other hand, at Bereh, with an intermediate clay proportion (66%), K application rates greater than 60 kg K_2O ha^{-1} did not bring about any further yield increases (Fig. 1). While no momentous differences between the other determined soil properties were observed (Table 1), these results suggest that an answer might rest in the mineral composition of the local clay and its interaction with K ions. Also, the K application regime, which was not addressed in the present study, may require a special assessment in order to provide optimum nutrient availability during crop development.

The different response patterns between sites were strongly reflected in the economic analyses carried out to elucidate a site-suitable K rate for teff production (Fig. 5). Thus, under the circumstances of the present study (weather conditions, cultivars, current fertilizer costs and local produce prices), Mulu appears the most cost effective site for K inputs. Second best would be Sululta, where a clear upper threshold of K application rates has not been reached. In contrast, the upper K rate that is still profitable at Moretena Jiru was 30 kg K_2O ha^{-1}, and 60 K_2O ha^{-1} at Bereh, where further increases in K rates significantly reduced the profit.

It can be unequivocally concluded, that K supply is necessary to obtain reasonable teff yields on Vertisols of the Ethiopian Central Highland, as it improves all crop performance parameters. In these soils, soil K availability is definitely a limiting factor, the removal of which brings about new horizons for teff productivity. Under the higher levels of K application rate, the recommended N and P rates might become restrictive, requiring some reassessment. However, due to significant divergence in soil properties and other environmental conditions among and within regions, site specific recommendations of fertilizer practices, for teff, or other crop species, must be founded on thorough local soil tests.

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