Research Findings

Ms. Hillette Hailu with Prof. Tekaling Mamo (center) at field research plot with different levels of K and P in Akaki woreda, Oromia Region, Ethiopia. Photo by E. Sokolowski.

Response of Wheat (*Triticum aestivum* L.) to Phosphorus and Potassium Fertilization on Vertisols in Ethiopia's Central Highlands

Hailu, H.[(1)*], **T. Mamo**[(2)], **and R. Keskinen**[(3)]

Abstract

Nutrient depletion is one of the major causes that contribute to declining soil productivity in the highlands of Ethiopia. Applications of urea and diammonium phosphate (DAP) were started four decades ago to improve soil fertility for enhanced crop production. However, the average national wheat yield is much lower than Africa's, as well as the world's average. In order to improve wheat yields, field experiments were established in the 2012 and 2013 cropping seasons on two rainfed locations in central highland Vertisols in Ethiopia to determine the response of bread wheat (*Triticum aestivum* L.) to phosphorus (P) and potassium (K) fertilization along with other limiting nutrients. A total of 16 treatments were tested in a 4 x 4 factorial design involving four P (0, 10, 20 and 30 kg ha^{-1}) and four K (0, 26, 39 and 52 kg ha^{-1}) fertilization levels with three replications.

[(1)] College of Agriculture, Wollo University, Dessie Ethiopia
[(2)] Center for Soil and Fertilizer Research in Africa (CESFRA), Mohammed VI Polytechnic University, Benguerir, Morocco
[(3)] Natural Resources Institute Finland (Luke), Jokioinen, Finland
[*] Corresponding author: hillette16@gmail.com

Analysis of variance revealed a significant difference ($P < 0.01$) between treatments in yield and nitrogen (N), P and K uptake by wheat at both sites over the two cropping seasons. In addition, the study showed that concurrent use of P and K significantly increased yield and the N, P and K uptake of wheat, compared to the levels obtained with either P or K applied alone. The fertilization treatments had no significant effect on grain size. In the Cheffe Donsa site, the highest grain yields, 6.4 and 7.6 t ha^{-1}, were exhibited by a combination of 10 kg P ha^{-1} and 26 kg K ha^{-1} in the 2012 and 2013 cropping seasons, respectively. In the Akaki site the highest grain yields, 2.8 t ha^{-1} (2012) and 4.8 t ha^{-1} (2013), were acquired with 30 kg P ha^{-1} and 26 kg K ha^{-1}. In conclusion, the concurrent use of P and K fertilizers enhanced the yield and nutrient uptake of wheat in the studied sites.

Keywords: Wheat (*Triticum aestivum* L.), phosphorus, potassium, yield, nutrient uptake.

Introduction

Wheat (*Triticum aestivum* L.) is one of the major global cereal crops, ranking second after paddy rice both in area and production, and provides more nourishment than any other food crop (Curtis, 2002). Ethiopia is one of the largest wheat producers in sub-Saharan Africa (Tanner and Mwangi, 1992; FAOSTAT, 2014) with an estimated area of 1 million ha under wheat production (CSA, 2000). The central highlands of Ethiopia are historically an important wheat-growing region. In this region, wheat ranks second in total area, production and market demand after tef (*Eragrostis tef*) (CSA, 1997a; CSA, 2000), and is produced across a range of soil conditions, particularly on well-drained highly-weathered reddish-brown soils (Nitisols) and poorlydrained heavy dark clay soils (Vertisols) (Woldeab *et al.*, 1991; Asamenew, 1991; Gebremariam, 1991). Despite the significant area of wheat production in Ethiopia, the mean national wheat yield of 1.3 t ha^{-1} is 24% below the mean yield for Africa and 48% below the global mean yield (Gavian and Degefa, 1996). The national average yield of the crop is estimated at 2.11 tonnes ha^{-1} (CSA, 2013), which is very low compared to the world's average yield of 3.09 tonnes ha^{-1} (FAOSTAT, 2012). Low productivity is attributed to the use of old and low-yielding varieties, depletion of soil nutrients, poor weed management practices, low levels of fertilizer application, waterlogging in Vertisol areas, prevalence of aggressive and virulent crop pathogens, and unavailability of modern crop management inputs (Mamo *et al.*, 1988; Gorfu *et al.*, 1991; Woldeab *et al.*, 1991; Asamenew, 1991; Tanner and Mwangi, 1992; Tarekegne *et al.*, 1997a,b; CSA, 1997b; Zegeye *et al.*, 2001).

Vertisols are considered to be suitable for producing cereals like wheat. They cover about 12.61 million ha of land in Ethiopia and the country ranks third in Vertisols abundance in Africa after Sudan and Chad. The majority of Ethiopian Vertisols, about 8 million ha, are located in the highlands (Debele, 1985). As in many other tropical and subtropical regions (Sanchez, 1976), soils in the highlands of Ethiopia, particularly in the central region, exhibit low levels of essential plant nutrients and organic matter content (Woldeab *et al.*, 1991; Mamo *et al.*, 1988). Poor soil fertility (Tarekegne *et al.*, 1997a), especially low availability of nitrogen (N) and phosphorus (P) (Woldeab *et al.*, 1991; Mamo *et al.*, 1988), has been demonstrated to be a major constraint to wheat production in Ethiopia. This is largely a consequence of the cereal-dominated cropping history of most fields and continuous nutrient mining by crop removal (Tarekegne *et al.*, 1997b; Gorfu *et al.*, 1991), which eventually leads to depletion of soil nutrients (Woldeab *et al.*, 1991; Tanner and Mwangi, 1992). Soil nutrient depletion has been exacerbated by low levels of chemical fertilizer usage (Woldeab *et al.*, 1991; CSA, 1997b) due to both high costs, and constraints to timely availability of fertilizers (Ayele and Mamo, 1995). Generally, N and P are the most limiting nutrients in Vertisols (Finck and Venkateswarlu, 1982) and this holds true for Ethiopian soils as well. The lack of response to P fertilizer application on Vertisols could be attributed to various factors including high P sorption capacity of the soil and soil moisture conditions (Sahrawat *et al.*, 1995; Abunyewa *et al.*, 2004), and limitation of nutrients other than P (EthioSIS, 2015; Hailu *et al.*, 2015). The risk of yield decline can be minimized by application of balanced mineral fertilizers in terms of all nutrient elements (Öborn *et al.*, 2005).

In Ethiopia, potassium (K) status of agricultural soils is generally found to be adequate for crop production, though a few studies show acutely deficient soil K levels (Mamo and Haque, 1988; Gebeyehu and Mamo, 1999; Bellete, 2014; Tilahun, 2014; Mekonnen, 2014; EthioSIS, 2015; Laekemariam, 2015). Fixation of K is correlated with the percentage of clay and is highest in Vertisols. Potassium fixation is enhanced by the presence of smectite and amorphous materials. The limited response of crops to applied K and the often high levels of exchangeable K found in most Ethiopian soils have led researchers and development agents to conclude that the K fertilization need in these soils is minimal. However, continuous cropping, in which fertilizer responsive varieties and improved management practices are used, results in K mining from the soil. Wheat crops can remove more than 400 kg K_2O ha^{-1} year^{-1} (IFA, 1986). The total absence or low application level of K fertilization combined with intensive continuous cropping leads to the depletion of soil K reserves. Even soils which are initially well supplied with K will become deficient under such management systems. Total consumption of K from soil by wheat producing yields of 10 t ha^{-1} varies from 160 to 242 kg K ha^{-1} (Kemmler, 1983).

In Ethiopia, reports which indicate crop response to applied K on Vertisols have started to emerge. A study conducted by Abiye *et al.* (2004) found that wheat responded significantly to K application on Vertisols at Cheffe Donsa, in east Shoa. They recommended the need to reassess the traditionally practiced system of not applying K fertilizer to Ethiopian soils. However, there is no information concerning P and K fertilization for wheat grown on highland Vertisols. Thus, this study was conducted to investigate the effect of different levels of P and K additions on yield as well as nutrient uptake of bread wheat (HAR 3116) on two central highland Ethiopian Vertisols.

Materials and methods

Experimental site description

The experiments were conducted on farmers' fields at two representative central highland locations, Akaki and Cheffe Donsa, during the main cropping seasons in 2012 and 2013. Akaki is located 25 km south east of Addis Ababa (08°49'40.5''N lat. and 38°49'17.9''E long.) at an altitude of 2,400 meters above sea level (m a.s.l.) (Fig. 1). Akaki receives a mean annual rainfall of 930 mm, and a mean annual minimum and maximum temperature of 8 and 27°C, respectively (Table 1). The Cheffe Donsa site is positioned about 80 km east of Addis Ababa (08°57'59.6''N lat. and 039°06'28.4''E long.) at an altitude of 2,444 m a.s.l. (Fig. 1). Cheffe Donsa receives a mean annual rainfall of 1,098 mm, and a mean annual minimum and maximum temperature of 10 and 25°C, respectively (Table 1).

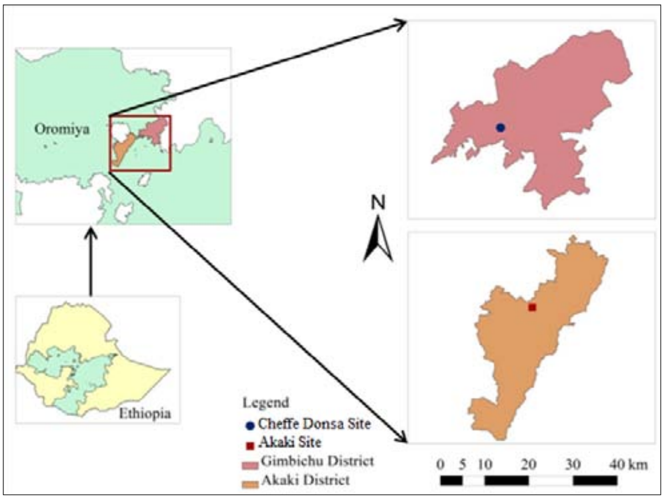

Fig. 1. Location map of the experimental sites.

Table 1. Climate data of Akaki and Cheffe Donsa area in the 2012 and 2013 cropping season.

	Akaki		Cheffe Donsa	
	2012	2013	2012	2013
Total annual rainfall (mm)	826	1,033	936	1,259
Mean annual maximum temperature (°C)	27	27	25	24
Mean annual minimum temperature (°C)	9	7	11	9

Source: National Meteorological Agency of Ethiopia.

Experimental design

The experimental design was a randomized complete block design in a factorial combination of P and K. A plot size of 3 m by 3 m was used and adjacent plots and blocks were spaced 1 m apart. Both experiments contained the following treatments; four rates of P as triple super phosphate (0, 10, 20 and 30 kg ha^{-1}) and four rates of K as murate of potash (0, 26, 39 and 52 kg ha^{-1}) (Table 2). There were three replications. Nitrogen as urea (60 and 92 N kg ha^{-1} in the first and second cropping season, respectively), sulfur (S) as gypsum (20 S kg ha^{-1}) and zinc (Zn) as zintrac (700 g Zn ha^{-1}) were applied as a basal dose.

Table 2. Details of the experimental treatments.

Treatment	Fertilizer dozes	
	P	K
	----------------------*kg ha^{-1}*----------------------	
T_1 (control)	0	0
T_2	0	26
T_3	0	39
T_4	0	52
T_5	10	0
T_6	10	26
T_7	10	39
T_8	10	52
T_9	20	0
T_{10}	20	26
T_{11}	20	39
T_{12}	20	52
T_{13}	30	0
T_{14}	30	26
T_{15}	30	39
T_{16}	30	52

Experimental materials and procedures

The experimental fields were prepared using a local plow (maresha) according to farmers' conventional farming practices. The fields were ploughed two times, after which broad beds and furrows were constructed by a broad bed maker (BBM). The BBM is an oxen-drawn traditional wooden plow, modified for the construction of raised beds and furrows to facilitate surface drainage through the furrows between the beds so that the crops are grown on the beds (Jutzi and Abebe, 1986).

Wheat is grown at an altitude ranging from 1,500 to 3,000 m a.s.l., between 6-160 N latitude and 35-420 E longitude. The most suitable agroecological zones, however, fall between 1,900 and 2,700 m a.s.l (Kotu *et al.*, 2000). The major wheat producing areas in Ethiopia are located in Arsi, Bale, Shewa, Ilubabor, Western Hareghe, Sidamo, Tigray, Northern Gonder and Gojam zones (Kotu *et al.*, 2000). The test variety used in the study areas was an improved bread wheat variety (HAR 3116), which is a high yielding variety widely grown in the wheat belt highlands in the central part of the country. Digalu (HAR 3116) occupied over 0.5 million ha (approx. 31% of production acreage) in Ethiopia and made a major contribution to the record wheat harvest of 3.92 million tons in the 2013/2014 season (CSA, 2014). This variety is semi-dwarf and was released by Kulumsa Agricultural Research Centre in 2005 (Alemayehu *et al.*, 2015). The seed was sown at a rate of 80 kg ha^{-1}, which is about half of the recommended rate (150 kg ha^{-1}) for broadcast and maresha incorporated seed (Gorfu, 1988), with row spacing of 20 cm.

The entire amount of P and S designed for each treatment was applied once at sowing, whereas N and K fertilization was split into two applications. One third of the N and half of the K were applied at sowing and the remaining was top dressed after 35 and 45 days, respectively. Zn was applied twice, at the tillering stage and again 14 days after that. Weed control was done by hand 20 days after sowing and as needed throughout the growing season in all the treatments. Planting and harvesting were also done by hand. Sowing was done within the range of July 5 to 15 whereas the wheat was harvested between the end of October and early November.

Soil sampling and analysis

For assessing the fertility of surface soil, 12 composite soil (0–15 cm) samples, four per block, were taken from each experimental site before planting. Each composite soil sample comprised 15 sub samples collected in a zigzag pattern within the replication and mixed thoroughly following a standard procedure for soil sampling and sample preparation (Paetz and Wilke, 2005).

The analyses of soil particle size distribution, pH and electrical conductivity (EC) were conducted at the Debre Ziet Agricultural Research Center (DZARC). All other parameters were analyzed by Natural Resources Institute Finland (former MTT Agrifood Research Finland). Soil particle size distribution was analyzed by hydrometer method (Gee and Bauder, 1986). Soil textural class names were assigned based on the relative contents of the sand, silt and clay separates using the soil textural triangle of the United States Department of Agriculture (USDA, 1951). Soil pH (McLean, 1982) and EC (Rhoades, 1982) were determined from a suspension of 1:2.5 soil:water ratio. Soil organic carbon (OC) and total nitrogen (TN) content were determined by dry combustion methods based on ISO 10694 (1995) and ISO 13878 (1998) protocols, respectively. For available P determination, soil samples were extracted with 0.5M $NaHCO_3$ at a nearly constant pH of 8.5 in 1:20 of soil to solution ratio for half an hour, as described by Olsen *et al.* (1954), and thereafter measured using Perkin Elmer Optima 8300 Inductively Coupled Plasma - Optical Emission Spectrometer (ICP-OES). Available S was determined by the extraction of SO_4-S with $CaCl_2{\cdot}2H_2O$. Sulfate - sulfur (SO_4-S) concentration in the extracts was measured by a turbidimetric procedure using barium chloride (Williams and Steinbergs, 1959). Exchangeable bases (calcum [Ca], magnesium [Mg], K and sodium [Na]) of the soil samples were extracted with 1M buffered ammonium acetate extractant (Cottenie, 1980) and basic cations were determined by ICP-OES. The cation exchange capacity (CEC) of the soils was determined by 1M buffered ammonium acetate extraction method and distillation of the ammonium saturated soil in a Kjeldahl distillation apparatus while receiving the distillate in boric acid and then titrating with sulfuric acid (Cottenie, 1980). Base saturation percentage (BSP) was calculated by dividing the sum of base-forming cations by CEC (Coyne and Thompson, 2006). Micronutrients (copper [Cu], iron [Fe], manganese [Mn] and zinc [Zn]) were determined from ammonium bicarbonate di-ethylene tri-amine penta-acetic acid (AB-DTPA) extracts (Soltanpour and Schwab, 1977). The micronutrient concentrations were determined by ICP-OES.

Crop data collection and analysis

The wheat crop was harvested by collecting the above ground plant mass from the central 2 m^2 area of each plot when the plants showed clear signs of maturity (complete yellowing of leaves and spikes). The total above ground plant biomass (biological yield) obtained was weighed, after which grains were separated and weighed to record the grain yield. Straw yield was determined by subtracting the grain yield from the biological yield. Thousand grain weight was recorded for each plot in five replicates by weighing 1,000 randomly selected grains.

Grain and straw samples from each treatment were oven dried at 60-70°C to a constant weight and thereafter ground and analyzed for N, P and K contents. Total N concentrations of the samples were determined using the modified Kjeldahl method (Jackson, 1958). For the P and K analyses, the samples were first re-dried at 60°C and then ashed at 550°C for eight hours. Thereafter, the ashes were digested in 20% HNO_3 (Zarcinaas *et al.*, 1987). Phosphorus concentration of the digests was measured with a spectrophotometer and the K concentration with a flame photometer.

The uptake of nutrients (N, P and K) into straw and grain was calculated by multiplying the nutrient content (%) with the respective straw and grain yield ha^{-1} on dry weight basis. Total nutrient content in the biological yield was obtained by summing up the nutrient uptakes by grain and straw.

$$\text{Nutrient uptake of the grain} = \frac{\text{nutrient content of the grain (\%) x grain yield (kg ha}^{-1}\text{)}}{100}$$

$$\text{Nutrient uptake of the straw} = \frac{\text{nutrient content of the straw (\%) x straw yield (kg ha}^{-1}\text{)}}{100}$$

Total nutrient uptake = nutrient uptake of the grain + nutrient uptake of the straw.

Statistical analysis

The data on crop yield and yield related traits were subjected to analysis of variance (ANOVA) using SAS statistical software and the statistical procedures described by Gomez and Gomez (1984). The least significant difference (LSD) was used for comparing the means of wheat yields and nutrient uptake obtained with the different rates of P and K applications.

Results and discussion

The results of compound analysis on the studied characteristics were significantly different in 2012 compared to 2013. Accordingly, data from each year were analyzed separately for all characteristics.

Soil characteristics

The results of initial soil properties, as presented in Table 3, reveal that the particle size distribution of the surface soils (0–15 cm) of both experimental fields was dominated by clay fraction (above 53%). Debele (1985) and Tsegaye (1992) also reported that Vertisols in Ethiopia generally contain more than 40% clay in the surface horizons. The surface soil (0–15 cm) analysis showed that prior to sowing, the experimental soils had a pH of 7.2-7.8 (slightly to moderately alkaline), which is typical for Ethiopian Vertisols (Debele, 1985; Kebede and Charles, 2009). This pH range is favorable for most crops (Tadesse, 1991; FAO, 2000). The soil organic matter (Tadesse, 1991; Debele, 1980) and available S (Lewis, 1999) contents, however, were in low ranges. According to the ratings of Cottenie (1980), the available P (Olsen extractable) was low and moderate at Akaki and Cheffe Donsa sites, respectively.

Exchangeable Ca and Mg were the dominant cations in the surface soils of both experimental fields (Table 3). Calcium comprised 77 and 78% of the soil cation exchange sites of Akaki and Cheffe Donsa, respectively. Similarly, Mg occupied 19 and 12.3% of the soil cation exchange sites in Akaki and Cheffe Donsa. The exchangeable K was in the high range (0.7 to 2 $cmol_{(+)}$ kg^{-1}) (Hazelton and Murphy, 2007; Peverill *et al.* 1999). Sodium had the lowest concentration (0.16-0.27 $cmol_{(+)}$ kg^{-1} of soil) among the base forming cations found in the top soil cation exchange complex in both experimental fields. The K:Mg ratio of the soil in the experimental sites varied from 0.17:1 to 0.35:1, which indicates Mg induced K deficiency using the rating of Loide (2004). The CEC of the surface soils of Akaki and Cheffe Donsa were 49.4 and 42.1 cmol kg^{-1}, respectively. The CEC of the study area can be termed as very high according to the ratings given by Hazelton and Murphy (2007). The surface horizons of Ethiopian Vertisols have generally been found to have very high CEC (Debele, 1985; Tsegaye, 1992). These high CEC values might result from the dominant smectite clay mineral constituents of the Vertisols in the study area (Debele, 1985). The base saturation of the surface soil of the study area was in the very high range based on the ratings given by Hazelton and Murphy (2007). The high base saturation is explained by the very low rate of leaching due to the very low hydraulic conductivity and low infiltration rates of Vertisols (Pimentel, 2006). According to Soltanpour (1985) and Jones (2003), the AB-DTPA-extractable Cu, Mn and Fe contents of the surface soil of the experimental sites were rated as adequate, while Zn content was deficient and hence inadequate for plant growth (Table 3).

Biological yield

The above ground biomass of cereal crops (straw and grain) is an important agronomic parameter that is sensitive to soil and applied nutrients (Mirutse *et al.*, 2009). Application of P and K significantly ($P \leq 0.01$) improved the aboveground biomass yield (Tables 4 and 5).

At Akaki, the highest biological yields of 7,662 kg ha^{-1} (first growing season) and 10,739 kg ha^{-1} (second growing season) were recorded from T_{14} (30-26 P-K kg ha^{-1}) and T_{11} (20-39 P-K kg ha^{-1}), respectively. These were statistically higher over P alone, K alone and the control (without P and K) treatments. In the 2012 cropping season, the second highest biological yield of

Table 3. Physical and chemical properties of surface soil (0-15 cm) of the experimental sites.

Soil property	Experimental sites Akaki (Akaki)	 Cheffe Donsa (Gimbichu)
Particle size distribution		
Sand (%)	15	21
Silt (%)	18	25
Clay (%)	67	54
Textural class	Heavy clay	Clay
pH (1:2.5 suspension)	7.4	7.8
EC (1:2.5 suspension) (dS m^{-1})	0.15	0.2
Total nitrogen (%)	0.1	1.1
Organic carbon (%)	1.2	1.1
Soil organic matter (%)	1.9	1.9
Olsen's P (mg kg^{-1})	5.9	7.5
Sulfate-S (mg kg^{-1})	1.8	1.2
Ammonium acetate extractable		
Ca ($cmol_{(+)}$ kg^{-1})	38	32.8
Mg ($cmol_{(+)}$ kg^{-1})	9.4	5.2
K ($cmol_{(+)}$ kg^{-1})	1.6	1.8
K:Mg	0.17	0.35
Na ($cmol_{(+)}$ kg^{-1})	0.16	0.27
CEC ($cmol_{(+)}$ kg^{-1})	49.4	42.1
PBS (%)	99	95
AB-DTPA extractable		
Cu (mg kg^{-1})	3.86	3.5
Fe (mg kg^{-1})	40.8	33.6
Mn (mg kg^{-1})	34.8	46
Zn (mg kg^{-1})	1.14	1.1

Table 4. Wheat yield as affected by different P and K application rates at Akaki in the 2012 (S1) and 2013 (S2) cropping season.

Treatment	Biological yield		Grain yield		Straw yield		Thousand grain weight	
P + K	S1	S2	S1	S2	S1	S2	S1	S2
	--*kg ha^{-1}*--						----------*g*---------	
T_1 (0+0) control	5,185	8,926	1,947	3,011	3,238	5,915	29	38
T_2 (0+26)	5,585	8,691	2,098	3,812	3,487	4,879	34	36
T_3 (0+39)	4,970	8,652	1,852	3,948	3,118	4,703	31	38
T_4 (0+52)	5,807	9,237	2,150	3,913	3,657	5,324	31	38
T_5 (10+0)	3,648	8,324	1,372	3,698	2,277	4,627	29	36
T_6 (10+26)	5,148	9,921	1,820	4,208	3,228	5,713	31	35
T_7 (10+39)	4,382	9,126	1,615	3,988	2,767	5,138	30	39
T_8 (10+52)	5,650	10,325	2,393	4,426	3,257	5,900	32	38
T_9 (20+0)	4,098	8,716	1,282	3,693	2,817	5,023	32	37
T_{10} (20+26)	5,013	9,340	1,973	4,061	3,040	5,279	34	39
T_{11} (20+39)	6,478	10,739	2,682	4,476	3,797	6,263	31	37
T_{12} (20+52)	5,308	8,821	2,232	3,997	3,077	4,824	32	39
T_{13} (30+0)	5,842	8,574	2,055	3,804	3,787	4,770	29	38
T_{14} (30+26)	7,662	10,497	2,815	4,797	4,847	5,700	32	39
T_{15} (30+39)	6,490	10,078	2,688	4,651	3,802	5,427	30	37
T_{16} (30+52)	5,423	9,878	1,992	4,339	3,432	5,539	31	38
LSD	1,224	600	857	1,123	1,335	653	4.2	2.3
SE	243	192	110	109	144	124	1.5	1.2
P value	**	**	**	**	**	ns	ns	ns

Note: ** and 'ns' indicate significance at $P \leq 0.01$% and non significant difference, respectively. LSD: Least significant difference; SE: Standard error.

Table 5. Wheat yield as affected by different P and K application rates at Cheffe Donsa in the 2012 (S1) and 2013 (S2) cropping season.

Treatment	Biological yield		Grain yield		Straw yield		Thousand grain weight	
P + K	S1	S2	S1	S2	S1	S2	S1	S2
	--*kg ha^{-1}*--						----------*g*---------	
T_1 (0+0) control	11,450	7,910	4,370	5,520	7,080	2,390	39	41
T_2 (0+26)	14,695	10,120	5,545	6,197	9,150	3,924	39	46
T_3 (0+39)	13,383	9,283	5,183	6,328	8,200	2,955	38	42
T_4 (0+52)	14,998	10,362	5,725	6,395	9,273	3,967	38	44
T_5 (10+0)	13,283	8,834	4,385	5,962	8,898	2,873	38	41
T_6 (10+26)	16,955	11,668	6,380	7,568	10,403	4,100	39	44
T_7 (10+39)	14,525	9,951	5,378	6,164	9,147	3,788	38	43
T_8 (10+52)	15,173	10,518	5,862	7,069	9,312	3,449	39	44a
T_9 (20+0)	13,842	9,473	5,105	7,024	8,737	2,450	39	43
T_{10} (20+26)	16,152	11,118	6,085	7,223	10,067	3,896	37	45
T_{11} (20+39)	15,260	10,369	5,478	6,608	9,782	3,761	38	44
T_{12} (20+52)	15,995	10,938	5,880	6,701	10,115	4,236	40	44
T_{13} (30+0)	14,760	10,118	5,475	6,539	9,285	3,579	39	48
T_{14} (30+26)	15,965	10,981	5,997	7,217	9,968	3,765	38	44
T_{15} (30+39)	17,190	11,706	6,222	7,235	10,968	4,471	39	44
T_{16} (30+52)	16,553	11,352	6,150	6,935	10,403	4,417	39	46
LSD	1,907	836	1,315	1,403	1,317	886	2.4	4.4
SE	378	261	149	138	238	161	0.18	0.47
P value	**	**	**	**	**	ns	ns	ns

Note: ** and 'ns' indicate significance at $P \leq 0.01$% and non significant difference, respectively. LSD: Least significant difference; SE: Standard error.

6,490 kg ha^{-1} was recorded from 39-30 P-K kg K ha^{-1} application. Results in 2013, however, indicated that a combined application of 26 kg K ha^{-1} with the highest P rate of 30 kg P ha^{-1}, exhibited the second highest biological yield of 10,497 kg ha^{-1} (Table 4).

In Cheffe Donsa the T_{15} (30-39 P-K kg ha^{-1}) treatment resulted in the highest biological yields of 17,190 kg ha^{-1} and 11,706 kg ha^{-1} in the 2012 and 2013 growing seasons, respectively (Table 5). In a similar manner, these were statistically higher than the control and treatments of P and K alone. In both cropping seasons, the second highest biological yields of 16,955 and 11,668 kg ha^{-1} were recorded from 26 kg K ha^{-1} when applied with the lowest P rate, 10 kg P ha^{-1}. The biological yields were gradually decreased by increasing the rate of P from 10 to 20 and 20 to 30 kg ha^{-1} when applied in combination with the low rate of 26 kg K ha^{-1} over the two cropping seasons. However, a gradual biological yield increment was recorded by increasing the rate of P from 10 to 20 and 20 to 30 kg ha^{-1} when applied in combination with the highest K rate of 52 kg ha^{-1}.

Generally, the highest biological yields obtained from P by K combinations were 48 and 50% higher than the control at Akaki in the first and second cropping seasons, respectively. Similarly, the highest values of biological yield recorded from P by K combination at Cheffe Donsa were 20 and 48% higher over the control in the first and second cropping seasons, respectively. Greater yields were recorded in the second cropping season at both sites. This is attributed to the relatively higher amount of N fertilizer (92 kg N ha^{-1}) applied in the second cropping season as well as higher rainfall recorded in the second cropping season. Other authors (Haile *et al.*, 2012; Cui *et al.*, 2005; Ricardo *et al.*, 2010) also reported an increase in grain yield with an increase in N rate. The highest biological yield was recorded at Cheffe Donsa site which could be due to the medium available P content prior to planting. Generally, the highest biological yield was obtained from plots treated with P and K at both sites over the two cropping seasons. This is expected because soils of the experimental sites were deficient in both P and K. The potential benefits of providing sufficient P and K for wheat, as well as other plants, often include promoting early plant maturity, resistance to diseases and other pests, reduced lodging, tillering, vigorous growth, and improved yield (Liakas *et al.*, 2001; Ma *et al.*, 2006; Slaton *et al.*, 2007).

Grain yield

Application of P and K significantly ($P \leq 0.01$) increased grain yield of wheat at both sites over the two cropping seasons (Tables 4 and 5). At Akaki, there were no significant grain yield differences in applying T_8, T_{11}, T_{12} T_{14} and T_{15}, but T_{14} (30-26 P-K kg ha^{-1}) resulted in the highest grain yield of 2,815 kg ha^{-1}, significantly higher than P alone and the control in the first growing season. In the same growing season, the addition of P with K at the rates of 39 kg K ha^{-1} with 20 and 30 kg P ha^{-1}, didn't significantly increase grain yield over treatments with K alone with the possible exception of K applied at the rate of 39 kg K ha^{-1}. In the 2013 cropping season, grain yield was significantly increased over the control (without P and K) in all treatments but the magnitudes of responses were highest in three P and K rate combinations (T_{11}, T_{14} and T_{15}). Among these treatments the highest grain yield (4,797 kg ha^{-1}) was recorded from T_{11} (30-26 P-K kg ha^{-1}).

The trend of response was different at Cheffe Donsa where the highest grain yields of 6,380 and 7,568 kg ha^{-1} were obtained from a P and K rate combination (20 kg P ha^{-1}, 26 kg K ha^{-1}) in 2012 and 2013 cropping seasons, respectively (Table 4). When the highest rate of both P and K (30 kg P ha^{-1} and 52 kg K ha^{-1}) were applied together, the resultant yield was apparently lower than the yields from P and K combinations (T_6 and T_{15}) though not significantly lower. A tendency to achieve significantly higher grain yields over the control was observed by two K only treatments (26 kg ha^{-1} and 52 kg ha^{-1}) in the first growing season. In contrast, the apparent yield increments by all treatments of K only over the control (without P and K) were not significant in the 2013 growing season.

The combined analysis of variance in each location on grain yield is presented in Table 6. The significant difference in grain yield between the locations was caused by the difference between the sites. Even though the interaction of P and K rates did not show a significant difference in grain yield at Cheffe Donsa (both seasons) and the second season in Akaki, their combination gave the highest grain yield and showed a significant ($P \leq 0.01$) difference in grain yield as compared to P alone, K alone and the control (without P and K). The highest grain yields (2,815, 4,797 kg ha^{-1} and 6,380, 7,568 kg ha^{-1}) were obtained on the interaction of 30-26 and 10-26 P-K kg ha^{-1} in the first and second cropping season at Akaki and Cheffe Donsa, respectively. Soils of the experimental sites were deficient in both P and K, so P and K fertilization induced grain yields of 45%, 59% and 46%, 37% over the control plots at Akaki and Cheffe Donsa in the first and second cropping seasons, respectively. The potential benefits of providing sufficient P and K for wheat, as well as other plants, often include promoting early plant maturity, resistance to diseases and other pests, reduced lodging, tillering, vigorous growth, and improved yield (Liakas *et al.*, 2001; Ma *et al.*, 2006; Slaton *et al.*, 2007). Snyder and Mascagni (1998), Sharshar *et al.* (2000); Liakas *et al.* (2001); Akhtar *et al.* (2002); Ghulam *et al.* (2010) reported similar benefits of P and K fertilization on wheat grain yield.

Thousand grain weight

The fertilization treatments had no effect on ($P \leq 0.05$) the thousand grain weights in either of the seasons or sites. Heavier seeds were observed in the second season compared to the first season at both sites. The interaction of P and K (T_{12}, T_{13}, T_7 and T_{10}) showed a trend towards heavier seeds compared to P alone, K alone and the control (without P and K). Zero fertilization and applying T_5 (P-K 10-0 kg ha^{-1}) had lighter seed weight (Table 4 and Table 5) compared to P and K interaction at both sites over the two cropping seasons. Although the mean thousand grain weight appeared to be relatively similar under the various treatments at Akaki in the 2012 growing season, few differences (non-significant) were observed in the 2013 growing season (Table 4). In 2013, a heavier thousand grain weight of 39 g was resulted from two P and K combinations (10, 39 and 20, 26) though were statistically similar with the control (without P and K) and most other treatments.

At Cheffe Donsa, the trend was different, thousand grain weight appeared to be similar in 2012 but few differences were

Table 6. Analysis of variance on grain yield of wheat for Akaki and Cheffe Donsa in the 2012 (S1) and 2013 (S2) cropping season.

Source of variance	Akaki		Cheffe Donsa	
	S1	S2	S1	S2
	kg ha^{-1}			
P	ns	**	*	*
K	ns	ns	ns	ns
P x K	**	ns	ns	ns
Mean yield of 0-0 P-K	1,947	3,011	4,370	5,520
Highest mean yield	2,815	4,797	6,380	7,568
P-K combination for highest yield	30-26	30-26	10-26	10-26

Note: *, ** and 'ns' indicate significance at P <0.05, 0.01 probability levels.

observed in the 2013 cropping season (Table 5). Increasing the rate of P from 10 to 20 and 20 to 30 kg ha^{-1} when applied with the various rates of K over the two cropping seasons didn't affect the thousand grain weights significantly. These results agree with the finding of Cruz *et al.* (2013) who reported that thousand grain weight was not significantly affected by P and K application.

Table 7. Total N, P and K uptake (kg ha^{-1}) of wheat as affected by application of P and K at Akaki during 2012 (S1) and 2013 (S2).

Treatment	Akaki					
	S1			S2		
P + K	Total N	Total P	Total K	Total N	Total P	Total K
	-----------------*kg ha^{-1}*-----------------					
T_1 (0+0) control	20	3	13	46	10	30
T_2 (0+26)	24	5	23	55	12	46
T_3 (0+39)	25	5	18	71	14	51
T_4 (0+52)	29	8	28	90	15	58
T_5 (10+0)	22	7	16	74	13	62
T_6 (10+26)	37	12	28	93	20	71
T_7 (10+39)	29	12	29	104	17	66
T_8 (10+52)	39	14	29	102	23	81
T_9 (20+0)	19	7	26	76	14	54
T_{10} (20+26)	46	11	29	88	20	70
T_{11} (20+39)	49	11	32	95	20	79
T_{12} (20+52)	41	11	32	93	21	64
T_{13} (30+0)	27	6	27	75	15	61
T_{14} (30+26)	68	12	34	107	15	79
T_{15} (30+39)	62	9	40	106	20	85
T_{16} (30+52)	40	10	44	93	17	86
LSD	10	4	12	15	5	13
SE	4	0.81	2	4.5	0.93	3.8
P value	**	**	**	**	**	**

Note: ** indicate significant difference at $P \leq 0.01$. LSD: Least significant difference; SE: Standard error.

Table 8. Total N, P and K uptake (kg ha^{-1}) of wheat as affected by application of P and K at Cheffe Donsa during the 2012 (S1) and 2013 (S2) cropping season.

Treatment	Cheffe Donsa					
	S1			S2		
P + K	Total N	Total P	Total K	Total N	Total P	Total K
	-----------------*kg ha^{-1}*-----------------					
T_1 (0+0) control	48	10	14	69	12	31
T_2 (0+26)	48	10	20	93	15	50
T_3 (0+39)	53	10	27	84	15	61
T_4 (0+52)	74	12	22	90	9	61
T_5 (10+0)	62	14	9	78	16	44
T_6 (10+26)	85	17	61	117	20	8
T_7 (10+39)	80	18	46	95	16	69
T_8 (10+52)	84	15	55	106	18	84
T_9 (20+0)	72	13	21	85	14	58
T_{10} (20+26)	92	16	70	116	17	83
T_{11} (20+39)	76	22	34	101	17	71
T_{12} (20+52)	81	17	54	104	23	64
T_{13} (30+0)	55	10	19	95	9	63
T_{14} (30+26)	92	19	37	112	3	87
T_{15} (30+39)	83	21	62	109	19	73
T_{16} (30+52)	79	21	70	115	20	69
LSD	15	4	24	18	6	17
SE	3.7	1.1	5.2	3.6	1.2	5.1
P value	**	**	**	**	**	**

Note: ** indicate significant difference at $P \leq 0.01$. LSD: Least significant difference; SE: Standard error.

Nutrient uptake

The data shown in Tables 7 and 8 revealed that there were significant ($P \leq 0.001$) differences among treatments in total N, P and K uptake by wheat (kg ha^{-1}) during the first and second cropping seasons. At Akaki in 2012, the total N uptake was significantly increased over the control and P and K only treatments on plots treated with combined application of P and K, with the possible exception of various K rates combined with a low rate of P. The highest total P uptake of 12.3 kg ha^{-1} was found on plots treated with 26 kg ha^{-1} of K and 10 kg ha^{-1} of P. The lowest total P uptake was obtained from the control plot (without P and K). The total uptake of K under the various P and K combinations was either significantly higher or comparable to P and K only treatments. In 2013, the pattern of total nutrient uptake and significance was similar. In addition the magnitude of total nutrient uptake was more noticeable in this growing season. This could be due to the relatively high amount of N fertilizer applied.

Among the various treatments, T_{10} (20-26 P-K kg ha^{-1}) resulted in the highest total N uptake of 92 kg ha^{-1} at Cheffe Donsa in the 2012 cropping season by some margin. Likewise, the highest total P uptake of 21.6 kg ha^{-1} was exhibited by T_{11} (20-39 P-K kg ha^{-1}). The total uptake of K was generally increased on plots treated with P and K combinations compared to the control and K only treated plots, but the differences were not significant in some of the cases. In 2013, increased uptake of N and K was noticed but total P uptake did not show a

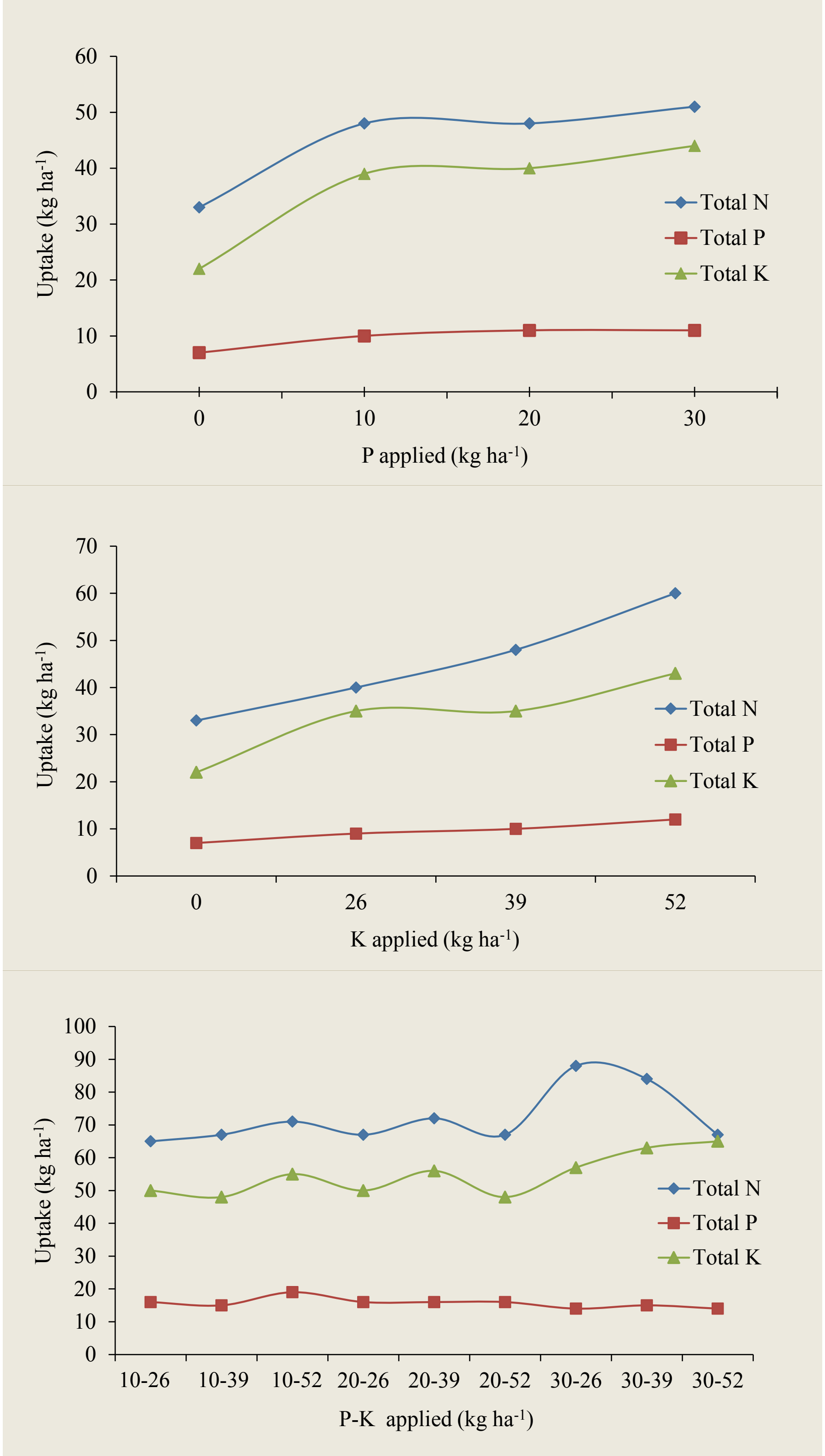

Fig. 2. Total N, P and K uptake as influenced by P alone, K alone and P and K fertilization at Akaki, respectively (means of 2012 and 2013 cropping seasons).

marked increase (Figs. 2 and 3). As can be seen from Figs. 2 and 3, P uptake was lower than N and K uptake under all the treatments. This is attributed to the lower P efficiency than N and K. Only about 15-20% of the applied P is used by the first crop. Most of the P applied to soils to meet P demand of plants is converted into unavailable forms of P (fixing by soil) that cannot be easily taken up by plant roots (Malavolta, 1979; Munson, 1982; Baligar *et al.*, 2001; Fageria *et al.*, 2010).

Generally, total N uptake was improved with P and K application and their combined use surpassed their application alone. This showed that the availability of extra K in these soils improved the extraction of N by the wheat crop. Sharma and Ramna (1993) indicated that the application of K released the fixed NH_4^+ ion from the soil and helped the crop improve its uptake of N. Total P uptake was highest with P+K, followed by P alone, and both showed significantly higher P uptake compared with K alone and the control. Total K uptake was highest with P+K, followed by K alone, and both showed significantly higher K uptake as compared with P only and the control (without P and K) (Figs. 2 and 3). These results agree with the findings of Slaton *et al.* (2007) and Sharshar *et al.* (2000) who reported that N, P and K uptake of wheat were significantly improved by integrated application of P and K.

Total nutrient uptake and yields varied significantly between the experimental years. In fact, higher yields and total uptake were recorded in the 2013 cropping season at both study sites. This may be attributed to the relatively high amount of N fertilizer (92 kg N ha⁻¹) applied in this growing season as well as high levels of rainfall compared to the 2012 growing season. Results obtained during long-term experiments revealed a direct relationship between yield and the amount of rainfall during the vegetative period of wheat (López-Bellido *et al.*, 1996).

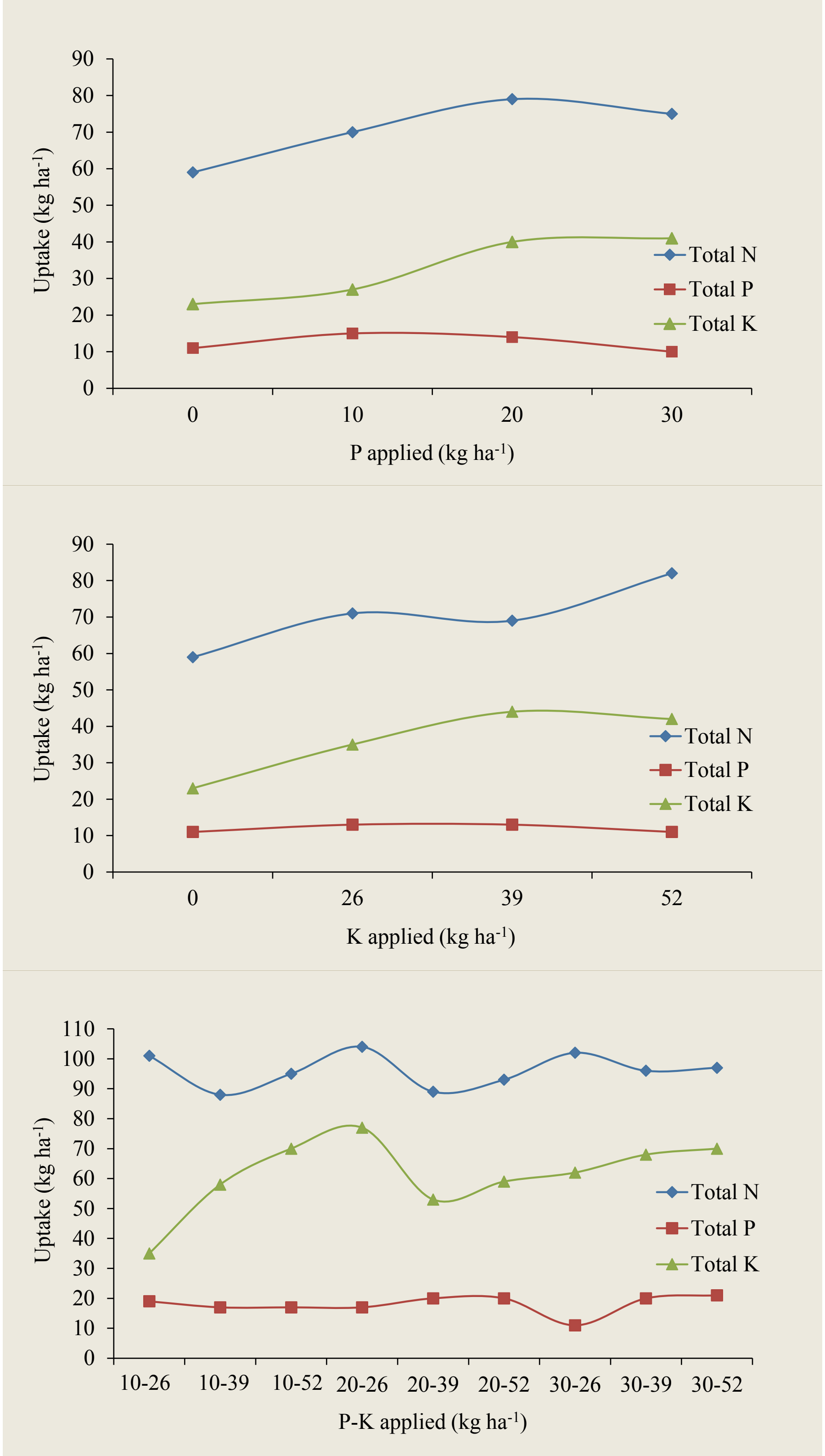

Fig. 3. Total N, P and K uptake as influenced by P alone, K alone and P and K fertilization at Cheffe Donsa, respectively (means of 2012 and 2013 cropping seasons).

In Ethiopia, farmers do not apply K fertilizers because researchers and development agents believe that the soil can supply the required K. This practice might hold true with low yield levels of traditional cultivars. However, the introduction of modern high yielding varieties has increased both cropping intensity and yields, which results in larger removal of K and other nutrients from soil. Data presented in this paper do not fully support the perception that the soil of the central highlands in Ethiopia can supply adequate K for achieving high yields of modern varieties. The results of this investigation indicated that integrated application of P and K fertilizers enhanced yields and nutrient uptake of wheat at both sites over the two cropping seasons. These results are supported by the findings of Abiye *et al.* (2004) who stated that there was appreciable yield response upon K fertilization at Cheffe Donsa. They further verified that K application enhanced N uptake of wheat. Overall, the benefits of K fertilization should be evaluated after long-term experimentation on Vertisols of Ethiopian highlands.

Conclusion

Wheat yield showed significant response to P and K application. Yield increase was observed at both locations over the two cropping seasons with the combined use of P with K. Thus, it can be concluded that the combined use of P with K could be beneficial to enhance productivity and nutrient uptake of wheat in central highland Vertisols of Ethiopia.

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Prof. Tekaling Mamo (center) with Ms. Hillette Hailu (right) at field research plot with different levels of K and P in Akaki woreda, Oromia Region, Ethiopia. Photo by E. Sokolowski.

Ms. Hillette Hailu (right) at field research plot with different levels of K and P in Akaki woreda, Oromia Region, Ethiopia. Photo by E. Sokolowski.

References

Abiye, A., T. Mamo, D. Peden, and M. Diedhiou, M. 2004. Participatory on Farm Conservation Tillage Trial in the Ethiopian highland Vertisols: The Impact of Potassium Application on Crop Yields. Experimental Agriculture 40(3):369-379.

Abunyewa, A., E.K. Asiedu, and Y. Ahenkorah. 2004. Fertilizer Phosphorus Fractions and their Availability to Maize on Different Land Forms on a Vertisols in the Coastal Savana Zone of Ghana. West African Journal of Applied Ecology 5:63-73.

Akhtar, M. E., M.Z. Khan, A. Sagheer, and A. Maqbool. 2002. Response of Wheat to Different N, P and K Rates of Applied Fertilizers under Rainfed Conditions of Pakisan. Asian Journal of Plant Science 4(1):337-339.

Alemayehu, H., W. Getaneh, D. Woubit, and H. Endale. 2015. Evaluation of Bread Wheat Varieties to Dominant Races of Stem Rust (*Puccinia graminis f. sp. Tritici*) Pathogen. Science Innovation 3(6):121-126.

Asamenew, G. 1991. A Study of the Farming Systems of Some Ethiopian Highland Vertisols Areas (draft report). ILCA (International Livestock Centre for Africa), Addis Ababa, Ethiopia.

Ayele, G., and T. Mamo. 1995. Determinants of Demand for Fertilizer in a Vertisol Cropping System in Ethiopia. Tropical Agriculture (Trinidad) 72:165-169.

Baligar, V. C., N.K. Fageria, and Z.L. He. 2001. Nutrient Use Efficiency in Plants. Communications in Soil Science and Plant Analysis 32(7/8):921-950.

Bellete, T. 2014. Fertility Mapping of Soils of Abay-Chomen District, Western Oromia, Ethiopia. MSc Thesis, Haramaya University, Ethiopia.

Cottenie, A. 1980. Soil and Plant Testing as a Basis of Fertilizer Recommendations. FAO Soil Bulletin 38/2. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.

Coyne, M.S., and Thompson, J.A. 2006. Math for Soil Scientists. Thomson Delmar Learning, Clifton Park, New York.

Cruz, R.P., R.A. Sperotto, D. Cargnelutti, J.M. Adamski, T.F. Terra, and J.P. Fett. 2013. Avoiding Damage and Achieving Cold Tolerance in Rice Plants. Food Energy Secur 2:96-119.

CSA (Central Statistical Authority). 1997a. Agricultural Sample Survey. Report on Area, Production and Yield of Meher Season Crops for Private Peasant Holdings. Volume I. Statistical Bulletin 171. Addis Ababa, Ethiopia.

CSA (Central Statistical Authority). 1997b. Agricultural Sample Survey. Report on Area, Production and Yield of Belg Season Crops for Private Peasant Holdings. Volume V. Statistical Bulletin 171. Addis Ababa, Ethiopia.

CSA (Central Statistical Authority). 2000. Agricultural Sample Survey 1999/2000. I. Report on Area and Production for Major Crops: Private Peasant Holding 'Meher' Season. Statistical Bulletin 227. Addis Ababa, Ethiopia.

CSA (Central Statistical Agency). 2013. Agricultural Sample Survey 2010/11. Report on Area Production of Crops (Private Peasant Holdings, Meher Season). The FDRE Statistical Bulletin. Addis Ababa, Ethiopia.

CSA (Central Statistical Agency). 2014. Agricultural Sample Survey 2014. Report on Area and Production of Major crops. CSA May 2014. Available at: www.csa.gov.et.

Cui, Z.L., L.W. Shi, J.F. Xu, J.L. Li, F.S. Zhang, and X.P. Chen. 2005. Effects of N Fertilization on Winter Wheat Grain Yield and its Crude Protein Content and Apparent N Losses. Chin. J.

Appl. Ecol. 16:2071-2075 (in Chinese with English abstract).

Curtis, B.C. 2002. Wheat in the World. *In:* Curtis, B.C., S. Rajaram, and H.G. Macpherson (eds.). Bread Wheat Improvement and Production. p. 1–19. FAO Plant Production and Protection Series, Rome, Italy.

Debele, B. 1980. The Physical Criteria and their Rating Proposed for Land Evaluation in the Highland Region of Ethiopia. Land Use Planning and Regulatory Department, Ministry of Agriculture, Addis Ababa, Ethiopia.

Debele, B. 1985. The Vertisols of Ethiopia: Their Properties, Classification and Management. *In:* Fifth Meeting of the Eastern African Sub-Committee for Soil Correlation and Land Evaluation, 5–10 December 1983. World Soil Resources Reports No. 56. p. 31-54. Wad Medani, Sudan. FAO (Food and Agriculture Organization), Rome, Italy.

EthioSIS (Ethiopian Soil Information System). 2015. http://www.ata.gov.et/highlighted-deliverables/ethiopian-soil-information-system-ethiosis/. Accessed 15 March 2015.

Fageria, N. K., V.C. Baligar, and C.A. Jones. 2010. Growth and Mineral Nutrition of Crops. CRC Press. Taylor and Francis Group LLC.

Food and Agriculture Organization of the United Nations (FAO). 2000. Fertilizers and Their Use. 4th Edition. International Fertilizer Industry Association, FAO, Rome, Italy.

FAOSTAT (FAO Statistical Databases) 2012. Agricultural Production Statistics. http://www.fao.org/faostat. Accessed 15 March 2016.

FAOSTAT (FAO Statistical Databases) 2014. http://faostat.fao.org/site/339/default.aspx. Accessed 20 March 2016.

Finck, A., and J. Venkateswarlu. 1982. Chemical Properties and Management of Vertisols. *In:* Symposium number II Transactions of the 12th International Congress of Soil Science, New Delhi, India. p. 61-79.

Gavian, S., and G. Degefa. 1996. The Profitability of Wheat Production in Ethiopia: The Case of Tiyo Woreda in Arsi Region. Ethiopian Journal of Agricultural Economics 1(1):38-62.

Gebeyehu, T., and T. Mamo. 1999. Forms of Soil Potassium and its Availability for Sugarcane Plant at Wonji Sugar Estate in Ethiopia. Ethiopian Journal of Natural Resources 1(1):17-28.

Gebremariam, H., 1991. Wheat Production and Research in Ethiopia. *In:* Gebremariam, H., D.G. Tanner, and M. Huluka (eds.) Wheat Research in Ethiopia: A Historical Perspective. p. 1-5. IAR, Addis Ababa. Ethiopia.

Gee, G.W., and J.W. Bauder. 1986. Particle Size Analysis. *In:* Klute, A. (ed.). Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods, 2nd Edition. American Society of Agronomy 9(1):383-411, Madison, WI.

Ghulam M.L., C.O. Fateh, T. Shamasuddin, W.G. Allah, H.S. Muzzammil, W.J. Allah, and M.O.S. Sono. 2010. Growth, Yield and Nutrient Uptake of Various Wheat Cultivars under Different Fertilizer Regimes. Sarhad Journal of Agriculture 26(4):489-497.

Gomez, K.A., and A.A. Gomez. 1984. Statistical Procedures for Agricultural Research, 2nd Edition. John Wiley and Sons Inc., London, UK.

Gorfu, A. 1988. Effect of Cultural Practices on the Grain Yield of Wheat. Paper presented at the IAR/CIMMYT/CIAT Workshop for Planning Research Projects. 20-24 September 1988. Nazret, Ethiopia.

Gorfu, A., A. Taa, D.G. Tanner, and W. Mwangi. 1991. On-Farm Research To Derive Fertilizer Recommendations For Small-Scale Bread Wheat Production: Methodological Issues And Technical Results. Research Report No. 14. IAR, Addis Ababa, Ethiopia.

Haile, D., N. Dechassa, and A. Ayana. 2012. Nitrogen Use Efficiency of Bread Wheat: Effects of Nitrogen Rate and Time of Application. Journal of Soil Science and Plant Nutrition 12(3):389-409.

Hailu, H., T. Mamo, R. Keskinen, E. Karltun, H. Gebrekidan, and T. Bekele. 2015. Soil Fertility Status and Wheat Nutrient Content in Vertisol Cropping Systems of Central Highlands of Ethiopia. Agriculture and Food Security 4:19. DOI 10.1186/s40066-015-0038-0.

Hazelton, P., and B. Murphy. 2007. Interpreting Soil Test Results: What do All the Numbers Mean? 2nd Edition. CSIRO Publishing, Australia.

International Fertilizer Industry Association (IFA). 1986. The Fertilizer Industry: World Food Supplies and the Environment. UNEP (United Nations Environment Programme), Paris.

ISO (International Organization for Standardization) 10694. 1995. Soil Quality-Determination of Organic and Total Carbon after Dry Combustion (elemental analysis).

ISO (International Organization for Standardization) 13878. 1998. Soil Quality-Determination of Total Nitrogen Content by Dry Combustion (elemental analysis).

Jackson, M.L. 1958. Soil Chemical Analysis. Prentice Hall Ind., Englewood. Cliffs. N.J., USA.

Jones, J.B. 2003. Agronomic Handbook: Management of Crops, Soils, and Their Fertility. CRC Press LLC, Boca Raton, Florida, USA.

Jutzi, S.C., and M. Abebe. 1986. Improved Agricultural Utilization of Vertisols in the Ethiopian Highlands. An Institutional Approach to Research and Development. *In:* Paper presented at the First International Board on Soil Research and Management, 1-6 December 1986. p. 10. Nairobi, Kenya.

Kebede, F., and Y. Charles, Y. 2009. Soil Fertility Status and NuMaSS Fertilizer Recommendation of Typic Hapluustertes in the Northern Highlands of Ethiopia. Journal of World Applied Science 6(11):1473-1480.

Kemmler, G. 1983. Modern Aspects of Wheat Manuring. IPI-Bulletin No. 1. Wheat. International Potash Institute (IPI), Switzerland.

Kotu, B.H., H. Varkuijl, W. Mwangi, and D.G. Tanner. 2000. Adaptation of Improved Wheat Technologies in Adaba and Dodola Woredas of the Bale Highlands, Ethiopia.

Mexico, D.F. International Maize and Wheat Improvement Centre (CIMMYT) and Ethiopian Agricultural Research Organization (EARO).

Laekemariam, F. 2015. Soil Spatial Variability Analysis, Fertility Mapping and Soil Plant Nutrient Relations in Wolaita Zone, Southern Ethiopia. PhD Dissertation, Haramaya University, Ethiopia.

Lewis, D.C. 1999. Sulfur. *In:* Peverill, K.I., L.A. Sparrow, and D.J. Reuter (eds.), Soil Analysis: An Interpretation Manual. CSIRO Publishing, Collingwood, Australia. p. 221-228.

Liakas, V., V. Rauckis, and V. Paltanaviius, 2001. Influence of Phosphorus and Potash Fertilizers on Germination, Tillering and Overwintering of Winter Wheat. Mokslo Darbai 74:3-12.

Loide, V. 2004. About the Effect of the Contents and Ratios of Soil's Available Calcium, Ootassium and Magnesium in Liming of Acid Soils. Agron. Res. 2:71-82.

López-Bellido, L., M. Fuentes, J.E. Castillo, F.J. López-Garrido, and E.J. Fernández. 1996. Long-Term Tillage, Crop Rotation, and Nitrogen Fertilizer Effects on Wheat Yield under Rainfed Mediterranean Conditions. Agron. J. 88:783-791.

Ma, Q., S.R. Niknam, and D.W. Turner. 2006. Responses of Osmotic Adjustment and Seed Yield of *Brassica napus* and *B. junacea* to Soil Water Deficit at Different Growth Stages. Australian Journal of Agricultural Research 57:221-226.

Malavolta, E. 1979. Potassium, Magnesium and Sulfur in Brazlian Soils and Crops. Technical Bulletin 4. Potash and Phosphate Institute, Piracicaba, Brazil.

Mamo, T., and I. Haque, 1988. Potassium Status of Some Ethiopian Soils. East African Agricultural and Forestry Journal 53:123-130.

Mamo, T., I. Haque, and C.S. Kamara. 1988. Phosphorus Status of some Ethiopian Highland Vertisols. *In:* Jutzi, S.C., I. Haque, McIntire, and J.E.S. Stares (eds.). Management of Vertisols in sub-Saharan Africa. p. 232-249. ILCA, Addis Ababa, Ethiopia.

McLean, E.O. 1982. Soil pH and Lime Requirement. *In:* Page, A.L., R.H. Miller, and D.R. Keeney (eds.). Methods of Soil Analysis, Part 2. p. 199-224. American Society of Agronomy, Madison, WI.

Mekonnen, M. 2014. Fertility Mapping of Soils in Cheha Woreda, Gurage Zone, Southern Ethiopia. MSc Thesis, Haramaya University, Ethiopia.

Mirutse, F., M. Haile, F. Kebede, A. Tsegay, and C. Yamoah. 2009. Response of Teff (*Eragrostis* Trotter) to Phosphorus and Nitrogen on a Vertisol at North Ethiopia. Journal of the Drylands 2(1):8-14

Munson, R.D. 1982. Potassium, Calcium and Magnesium in Tropics and Subtropics. Technical Bulletin T-23. International Fertilizer Development Center, Muscle Shoals, TN.

Öborn, I., Y. Andrist-Rangel, M. Askekaard, C.A. Grant, C.A. Watson, and A.C. Edwards. 2005. Critical Aspects of Potassium Management in Agricultural Systems. Soil Use Management 21:102-112.

Olsen, S.R., C.V. Cole, C.V., F.S. Wanatabe, and L.A. Dean. 1954. Estimation of Available Phosphorus in Soils by Extraction with Sodium Bicarbonate. U.S. Departement of Agriculture Circular 939, USDA, Washington DC.

Paetz, A., and B.M. Wilke. 2005. Soil Sampling and Storage. In: Margesin, R., and F. Schinner (eds.). Manual for Soil Analysis Monitoring and Assessing Soil Bioremediation. p. 3-13. Springer-Verlag, Berlin Heidelberg.

Peverill, K.I., L.A. Sparrow, and D.J. Reuter. 1999. Soil Analysis: An Interpretation Manual. CSIRO Publishing, Melbourne, Australia.

Pimentel, D. 2006. Soil Erosion: A Food and Environmental Threat. Environment, Development and Sustainability 8(1):119-137.

Rhoades, J.D. 1982. Soluble Salts. *In:* Page, A.L. (ed.). Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties. p. 149-157. Book series No: 9. Soil Science Society of America (SSSA) Madison, USA.

Ricardo, C., J. Claudio, and U. Pablo. 2010. Effectd on Nitrogen on Productivity, Grain Quality and Optimal Nitrogen Rates in Winter Wheat Cv. Kumpa-Inia in Andosols of Southern Chile Chilean. Journal of Agricultural Research 70(1):122-131.

Sahrawat, K.L., T.J. Rego, J.R. Burford, M.H. Rahman, J.K. Rao, and A. Adam. 1995. Response of Sorghum to Fertilizer Phosphorus and its Residual Value in Vertisol. Fertilizer Research 41:41-47.

Sanchez, P.A. 1976. Properties and Management of Soils in the Tropics. John Wiley and Sons, New York.

Sharma, P.S., and S. Ramna. 1993. Response of Sorghum to Nitrogen and Potassium in Alfisol. Journal of Potash Research 9(27):171-175.

Sharshar, M.S., and A. Soad El-Said, 2000. Evaluation of Some Wheat Cultivars and Lines under Low and High Inputs. Journal of Agricultural Science 25(6):3109-3127.

Slaton, N.A., R.E. DeLong, M. Mozaffari, S. Clark, C. Allen, and R. Thompson. 2007. Wheat Grain Yield Response to Phosphorus and Potassium Fertilizer Rate. AAES Research Series 558 Wayne E. Sabbe Arkansas Soil Fertility Studies.

Snyder, C.S., and H.J. Mascagni. 1998. Phosphorus and Potassium Increase Wheat Yields and Help Reduce Disease Damage. International Plant Nutrition Institute. News and Views from the Southeast Region, at http://www.ipni.net/news.

Soltanpour, P.N., and A.P. Schwab. 1977. A New Soil Test for Simultaneous Extraction of Macro and Micro-Nutrients in Alkaline Soils. Communications in Soil Science and Plant Analysis 8(3):195-207.

Soltanpour, P.N. 1985. Use of AB-DTPA Soil Test to Evaluate Elemental Availability and Toxicity. Communications in Soil Science and Plant Analysis 16(3):323-338.

Tadesse, T. 1991. Soil, Plant, Water, Fertilizer, Animal Manure and Compost Analysis. Working Document No. 13. International Livestock Research Center for Africa, Addis Ababa.

Tanner, D.G., and W. Mwangi. 1992. Current Issues in Wheat Research and Production in Eastern, Central and Southern Africa: Constraints and Achievements. p. 17-36. *In:* Tanner, D.G., and M.W. Mwangi (eds.), The Seventh Regional Wheat Workshop for Eastern, Central and Southern Africa. CIMMYT, Nakuru, Kenya.

Tarekegne, A., D.G. Tanner, A. Gorfu, T. Geleto, and Z Yilma. 1997a. The Effect of Several Crop Management Factors on Bread Wheat Yields in the Ethiopian Highlands. African Crop Science Journal 5:161-174.

Tarekegne, A., D.G. Tanner, and C. Mandefro. 1997b. Effect of Cropping Sequence and Nutrient Application on Crop Parameters During the First Three Seasons of Wheat-Based Long-Term Trial in Ethiopia. African Crop Science Conference Proceedings 3:685-693.

Tsegaye, T. 1992. Vertisols of Central Highlands of Ethiopia: Characterization and Evaluation of the Phosphorus Status. MSc Thesis, Alemaya University of Agriculture, Alemaya, Ethiopia.

Tilahun, E. 2014. Fertility Mapping of Soils in Alicho-Woriro Woreda in Siltie Zone, Southern Ethiopia. MSc Thesis, Haramaya University, Ethiopia.

United States Department of Agriculture (USDA). 1951. Soil Survey Manual. U.S. Dept. Agriculture Handbook No. 18. Washington, DC.

Williams, C.H., and A. Steinbergs. 1959. Soil Sulphur Fractionations as Chemical Indices of Available Sulphur in Some Australian Soils. Australian Journal of Agricultural Research 10:340-352.

Woldeab, A., T. Mamo, M. Bekele, and T. Ajema. 1991. Soil Fertility Management Studies on Wheat in Ethiopia. *In:* Gebre-Mariam, H., D.G. Tanner, and Hulluka (eds.). Wheat Research in Ethiopia: A Historical Perspective. p. 112-144. IAR/CIMMYT, Addis Ababa, Ethiopia.

Zarcinas, B.A, B. Cartwright, and L.R. Spouncer, L.R. 1987. Nitric Acid Digestion and Multi-Element Analysis of Plant Material by Inductively Coupled Plasma Spectrometry. Communications in Soil Science and plant Analysis 18(1):131-146.

Zegeye, T., G. Taye, D.G. Tanner, H. Verkuiji, A. Agidie, and W. Mwangi. 2001. Adoption of Improved Bread Wheat Varieties and Inorganic Fertilizer by Small-Scale Farmers in Yelmana Densaand Farta Districts of Northwestern Ethiopia. EARO and CIMMYT. Mexico City, Mexico.

The paper "Response of Wheat (*Triticum aestivum* L.) to Phosphorus and Potassium Fertilization on Vertisols in Ethiopia's Central Highlands" also appears on the IPI website at:

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