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Response of Wheat to NP Fertilizer Rates, Precursor Crops and Types of Vertisols in Central Highlands of Ethiopia

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Abstract

The objective of this work was to evaluate the performance of bread wheat under different NP fertilizer rates, precursor crops and types of Vertisols in order to determine higher agronomic and economic yielding combination of levels of these factors. The first field experiment comparing factorial combinations of 0, 80, 160 and 240 kg N ha^{-1} with 0, 20, 40 and 60 kg P ha^{-1} in 2006-2007 on four farmers' fields, with four replications in each field, resulted in recommendation of 151/40 and 192/60 kg N/P ha^{-1} for further on-farm evaluation as compared to old recommendation (87/20 kg N/P ha^{-1}) and to the farmers' highest rate (256/80 kg N/P ha^{-1}) under dominant precursor crops and types of Vertisols. Thus the second field experiment compared the above four treatments on 32 farmers' fields (no replication in each field) on lentil (*Lens culinaris*) and tef (*Eragrostis tef*) precursors on *Bushella* and *Mererie* Vertisols in 2012-2013. Grain yield response of bread wheat to N/P rates following lentil precursor on *Mererie* was significantly ($p < 0.01$) quadratic while responses following lentil precursor on *Bushella*, and tef precursor on both types of Vertisols were significantly ($p < 0.05$) linear. Application of the highest rate (256/80 kg N/P ha^{-1}) on wheat following lentil precursor gave grain yield of 5001 and 3407 kg ha^{-1} on *Mererie* and *Bushella* Vertisols, respectively. The same rate on wheat following tef precursor gave grain yield of 4143 and 3904 kg ha^{-1} on *Mererie* and *Bushella* Vertisols, respectively. However, application of 167/45 kg N/P ha^{-1} was more economical (79.7-134.1% marginal return) and is suggested to be promoted for bread wheat production following tef and lentil precursors on both types of Vertisols of the test locations and similar areas in the central highlands of Ethiopia. Further studies are also suggested to improve fertilizer use efficiency and reduce such high rate recommendations which could pose environmental risks.

Keywords: Ethiopia, NP levels, precursor crops, trend analyses, Vertisols, wheat

1. Introduction

Wheat with production area of about 1.66 million hectares is one of the most important cereal food crops cultivated in Ethiopia, ranking fourth after teff (*Eragrostis tef*), maize (*Zea mays*) and sorghum (*Sorghum bicolor*) in area coverage (Central Statistical Agency, 2016). However, its productivity in Ethiopia is one of the lowest in the world, the national average grain yield being about 2.54 tons ha^{-1} in the smallholder farmers' production system (CSA, 2016). Waterlogging on Vertisols, soil degradation, declining soil fertility and low input production system have been some of the most important constraints limiting food production in Ethiopia (Abate, de Brauw, Minot, & Bernard, 2014; FAO, 2013; Henao & Baanate, 1999; Hurni, 1983, 1988).

Vertisols are black clayey soils which are prone to waterlogging that seriously reduce their productivity. The Ethiopian highland Vertisols, higher than 1500m altitudes above sea level, covers about 7.6 million hectares, of which 35000 ha of land on the high elevation of Enewarie plateau is considered as wheat belt that has been supported by relatively efficient traditional drainage method (broad bed and furrows) of smallholder farmers in the central highlands of Ethiopia (Asamenew, Jutzi, Tedla, & McIntire1988). Simple random field observations by the author of this paper in 2006 growing season revealed that smallholder farmers believe types of Vertisols affect productivity: relatively heavy Vertisols called *Mererie* is more productive than relatively light Vertisols called *Bushella*. Smallholder farmers' fertilizer application rate for wheat production ranged from 63/14 to 161/29 kg N/P ha^{-1} as was determined from 28 farmers in Deneba and Enewarie areas. This indicates that farmers' application rates were by far higher than the old recommendation, which is 87/20 kg ha^{-1} of N/P for Vertisols in general (Woldeab, Mamo, Bekele, & Ajema, 1991). The field observations also indicated that smallholder farmers in Enewarie and Deneba areas harvest higher wheat yield (as high as 3.5 tons ha^{-1}) because of their efficient traditional soil drainage method on Vertisols, higher fertilizer input than the old recommendation and cereal-legume crop rotation. The most important precursor crops for wheat were pulse crops (lentil, chick pea and grass pea) and tef occupying the respective land area share of 20 and 15%. It is established fact that diversifying crop rotations with pulse crops enhances system productivity (Gan et al., 2015). The old recommendation, which was dropped by farmers for being lower rate, did not take into account the effects of soil fertility variations caused by precursor crops and productivity differences by types of Vertisols. It is important to use farmers' knowledge to take into account productivity differences by types of Vertisols since realization of soil test based fertilizer recommendations have been difficult and unaffordable in general and in Ethiopia in particular because of well justified reasons recently published by Molla (2013). The old recommendation is by far overdue and it is time to revise it for optimizing combination of the above stated factors' levels for higher wheat productivity.

Therefore, the objective of this work was to evaluate the performance of bread wheat under different NP fertilizer rates, precursor crops and types of Vertisols in order to determine higher agronomic and economic yielding combination of levels of these factors.

2. Materials and Methods

2.1 Study Area

Two experiments were conducted on farmers' fields at two locations, Deneba and Enewarie in the main rainy season (June to September) while the crop growing period extends up to November/December on the residual soil moisture. Ten years (2004-2013) average annual rainfall, maximum and minimum temperatures were 1219.3 mm, 21.3 °C, and 9.6 °C for Enewarie, respectively. There is no meteorology station at Deneba since the distance between Deneba and Enewarie is 20 km with the respective altitude of 2662 and 2693 m.a.s.l. A total of four sites representing *Mererie* and *Bushella* were used for the first experiment in 2006 and 2007. In the second experiment of 2012-2013, 32 sites, representing *Mererie* and *Bushella*, precursor crops of lentil and tef were selected with the participation of farmers and development agents. Lentil and tef were the dominant precursor crops among legumes and cereals, respectively, for wheat. All sites represent Vertisols areas in geographical coordinates of 9°47′ N and 38°54′ E to 9°53′ N and 39°13′ E. The altitude of the testing sites in Deneba and Enewarie areas ranged from 2600-2750 m.a.s.l. Some physical and chemical characteristics of Vertisols of the study area are presented in Table 1, including interpretations (Agriculture and Fisheries of the Netherlands, 1989; Ryan, Garabet, Harmsen, & Rashid, 1996).

Table 1. Selected properties and nutrient status of *Mererie* and *Bushella* Vertisols to the depth of 0-20cm in Deneba and Enewarie areas

Properties & nutrient status	*Meririe*	*Bushella*	Rating range	Rating	Analysis method
pH	6.84	6.31	6.5-7.5	Neutral#	1:2.5 soil to water ratio
Organic C (%)	0.70	0.86	0.60-1.25	Low*	Walkley-Black
Total N (%)	0.06	0.09	0.05-0.125	Low*	Kjeldahl
Available P (ppm)	6.95	6.11	5-10	Medium*	Olsen
Available K (ppm)	136.98	124.51	< 150	Low*	Ammonium acetate
Texture class	*Mererie*		*Bushella*		Aggregate dispersant and hydrometer
Clay	65.23%		62.50%		
Silt	21.69%		24.67%		
Sand	13.08%		12.83%		

Note. Each value for texture analysis, soil pH, organic carbon and available P was average of samples from 12-13 sites; each value for total N and available K was average of samples from 9-10 sites.

Source: # Ryan et al. (1996); * Agriculture and Fisheries of the Netherlands (1989).

2.2 Experimental Design and Treatments

2.2.1The First Experiment

A Factorial combination of four levels of N (0, 80, 160 and 240 kg ha^{-1}) and four levels of P (0, 20, 40 and 60 kg ha^{-1}) were compared in Randomized Complete Block Design with four replications at each site and a total of four sites in 2006 and 2007. Each of two sites in two years represented *Mererie* and *Bushella*. Plot size for each treatment was 19.2 m^2.

2.2.2 The Second Experiment

Based on agronomic and economic yield response of bread wheat obtained from the first experiment, 151/40 and 192/60 kg ha^{-1} of N/P rates were selected and compared against the old recommendation of 87/20 kg N/P ha^{-1} and the farmers' highest rate of 256/80 kg N/P ha^{-1} in 2012 and 2013. These four N/P fertilizer levels were tested on each of 32 sites, of which each of eight sites represented lentil precursor, tef precursor, *Mererie* and *Bushella* soil types. There was no replication at either site (a site in this context indicates a cultivated field of a smallholder farmer at which the experiment was conducted). Plot size of each treatment was 100 m^2; replication at each site was not possible as each precursor required a large area to create workable plot size for oxen plow. Moreover, replication across site was more advantageous than within site replication for the simple reason that across site variation was by far larger than within site variation.

2.3 Management Practices

2.3.1 First Experiment

Cereal precursor crops, tef and wheat were used in 2006 on *Bushella* and *Mererie*, respectively. According to farmers' practice, plowing was done twice following these cereal precursors before sowing the test wheat crop. Traditional plow called *Maresha*, drawn by a pair of oxen, was used to prepare the seedbed. First plowing was done in April to May, while the second plowing was in late May to late June. Legume precursor crop lentil was used in 2007 on both types of Vertisols. According to farmers' practice, plowing was done once as they do for legume precursors before sowing wheat. Plowing was done in May to June by using the traditional plow, *maresha*.

Bread wheat variety HAR604 was the test crop at the broadcast seed rate of 175 kg ha^{-1}. Nutrient sources were urea and di-ammonium phosphate (DAP) for N, and DAP and triple super phosphate (TSP) for P. Triple super phosphate was used when P fertilizer was a treatment applied alone at sowing. Urea as the source of each treatment of N fertilizer was applied half as basal application at sowing and the other half as top-dress application at tillering stage of wheat. Sowing was done on 10-11 July in 2006 based on the recommended practice (Asamenew, Beyene, Haile, & Negatu, 1993). However, crop performance was not good especially on *Mererie*, and hence sowing time was changed to 23-27 July in 2007 based on the dominant practice of farmers in the test locations. Farmers in the test locations believe that *Mererie* is more productive than *Bushella*, and sowing time of *Mererie* is usually delayed by 10-15 days compared to *Bushella*. At sowing, broad beds of 80 cm width and furrows 40 cm width and 15 cm depth were made manually to drain out excess soil water. One hand weeding was done at tillering stage of the wheat crop.

2.3.2 Second Experiment

As HAR604 was hit by yellow rust in 2008, it was replaced by bread wheat variety Menzie in the second experiment that was conducted in 2012-2013. The seed rate used for broadcast sowing was 175 kg ha^{-1}. Sowing dates were 16 to 26 July on *Bushella*, and 22 to 31 July on *Mererie*, as per the recommendation from a sowing date trial conducted in 2007 and 2008 (Molla, 2014). In order to drain excess soil water, broad beds having approximate width of 80 cm and furrows with the respective approximate width and depth of 40 cm and 15 cm were shaped manually after the furrows were made by oxen drawn plow at sowing. The sources of N and P nutrient levels were urea and DAP. There was no need for TSP in this second experiment since there were no treatments which require only phosphorus. Only DAP was applied at sowing while half of urea was applied at tillering stage of wheat soon after weeding and the other half was applied at stem elongation, before booting. Di-ammonium phosphate fertilizer contains 18% N and therefore urea was not applied at sowing so as to minimize wet soil leaching loss of soil nitrate before the crop establishes active absorption. Timing of urea application was also changed according to hand weeding pattern of farmers and application timing that was found to be important. Applying more splits before wheat heading reduces leaching loss without affecting yield than applying more urea in less number of splits (Kamyab-Talesh, Razavipour, Rezaei, & Khaledian, 2014).

2.4 Data Collected

Harvesting at 100% maturity, when all grain bearing wheat peduncles turned yellow and dried for harvest, of bread wheat was done close to the soil surface from a plot area of 9.6 m^2 for the first experiment, and 4.8 m^2 for the second experiment so as to estimate grain and straw yield per hectare. Average input and output farm gate prices were recorded in 2008 and 2009 for the first experiment; in May to June 2012 for the second experiment. Thus urea, DAP, sun dried wheat grain and straw had a respective price of 5.78, 7.70, 5.00, and 0.95 Ethiopian

Birr kg^{-1} for the first experiment; and the respective price of 12.076, 14.909, 7.65 and 1.57 Ethiopian Birr kg^{-1} for the second experiment at Deneba and Enewarie. Fertilizer prices include interest and transportation costs. One USD was about nineteen Ethiopian Birr in 2012.

2.5 Statistical Analysis

Variances and trend analyses using stepwise regression procedures were done using SAS software Version 9.00 of 2002, SAS Institute Inc., Cary, NC, USA. Probability level of 5% was used for entering and retaining each term in stepwise regression analysis.

2.5.1 First Experiment

There was no well defined site selection in terms of precursors and hence the data were not included in the analysis. Thus the experimental design for each site representing soil type was RCB with complete factorial combinations of N and P levels, in four replications. In combined analysis, the design was changed into split plot comprising two main plots of *Mererie* and *Bushella* soils and 16 sub-plots of NP combinations in each year. General linear model was used to run analysis of variances. Types of Vertisols, N and P levels and their interactions were considered as fixed effects while all other effects were random (K. A. Gomez & A. A. Gomez, 1984; Petersen, 1994). Combinations of N and P levels were used to fit response curves for each of grain and straw yields

2.5.2 Second Experiment

General Linear Model was used to analyze the data by assigning tef and lentil precursor crops as two main plots (each main plot in separate farmer's field); each main plot was subdivided in two sub-plots to have *Bushella* and *Mererie* types of Vertisols; and each sub plot was divided into four sub-sub plots to have four NP levels (87/20, 151/40, 192/60 and 256/80 kg ha^{-1} of N/P). Thus there were eight replications. Even though there was no replication in each site (site in this case represented farmer's field), all treatments were replicated across eight farmers' fields so as to catch more variations rather than replicating within a field. In analysis of variance, only replication was a random effect while all other effects were fixed. The four NP levels (87/20, 151/40, 192/60 and 256/80 kg ha^{-1} of N/P) were used to fit response curve for the corresponding each of grain and straw yield means from each of precursor crop by types of Vertisols combinations (that is lentil-*Bushella*, lentil-*Mererie*, tef-*Bushella*, and tef-*Mererie* combinations).

2.6 Economic Analysis

Economic analysis (dominance, marginal rate of return & sensitivity analysis), using procedures in the economics workbook of International Center for Maize and Wheat Improvement (CIMMYT) was done on 155 combinations of N and P levels with the corresponding grain and straw yields generated from the fitted response curves of the first experiment (CIMMYT, 1998). In the second experiment, only 21 NP levels with the corresponding grain and straw yields generated from the fitted response curves were used. When NP levels are arranged in increasing order of their costs, an NP level is said to be dominated if it increases cost but not net income as compared to the immediate preceding NP level.

3. Results

3.1 First Experiment

The results of combined analysis over years on the fixed effects of types of Vertisols, N and P levels, and their interactions are presented in Table 2. The response of bread wheat to N levels was significantly ($p < 0.05$) affected by interaction of year and types of Vertisols for grain yield but not for straw yield (Table 2). Productivity of *Bushella* was higher than *Mererie* in all N levels in 2006 but *Mererie* was higher except on unfertilized control in 2007 (Figure 1). Productivity of *Mererie* on unfertilized plot and on plot received the highest rate of 240 kg N ha^{-1} was about 96 and 89%, respectively, of that of *Bushella* in 2006; but the respective productivity on *Mererie* in 2007 was about 86 and 123% of that of *Bushella* (Figure 1). Analysis of variance showed that main and interaction effects of N and P levels were significant ($p < 0.05$) for grain and straw yield of wheat (Table 2), but stepwise multiple regression showed that main effect of P levels was not significant for grain and straw yields (Figure 2). Analysis of variance calculates main effects of P levels as averaged over N levels and hence unable to sort out the sole effects of P levels, whereas multiple regression analysis was robust enough to sort out the sole effects of P levels (Figure 2). Therefore, yield performance of bread wheat was not better than unfertilized control when P levels as high as 60 kg P ha^{-1} were applied alone. Results in Figure 2 also show that main effects of N significantly improved yield of bread wheat but the effects were significantly synergetic when N levels of 80-240 kg ha^{-1} were combined with P levels of 20-60 kg ha^{-1}.

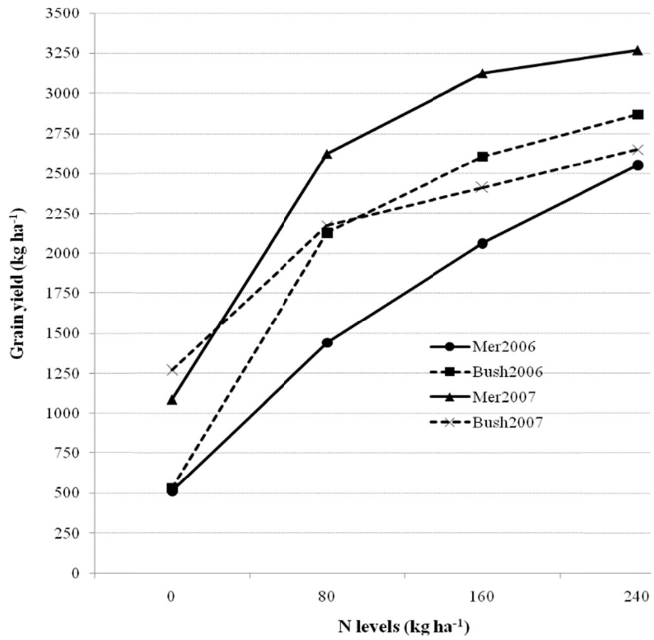

Figure 1. Grain yield response of bread wheat to N fertilizer levels, years and types of Vertisols in the first experiment

Note. Mer2006 = *Mererie* soil with wheat precursor, sown to experimental wheat on 10 July 2006; Mer2007 = *Mererie* soil with lentil precursor, sown to experimental wheat on 27 July 2007; Bush2006 = *Bushella* soil with tef precursor, sown to experimental wheat on 11 July 2006; Bush2007 = *Bushella* soil with lentil precursor, sown to experimental wheat on 23 July 2007.

Table 2. Mean square values and probabilities of main and interaction effects of year, types of Vertisols, nitrogen and phosphorus fertilizers on yield response of bread wheat in the first experiment, 2006-2007

Source of variation	DF	Mean squares (kg ha^{-1}) and probability levels for grain yield		Mean squares (t ha^{-1}) and probability levels for straw yield	
		Mean square	Probability	Mean square	Probability
Year (Y)	1	14 988 851	0.4645	55.920	0.4954
Types of Vertisols (S)	1	450	0.9958	21.692	0.6438
Y*S	1	10 188 585	0.0850	55.324	0.0022
Rep (Y*S)	12	95 693	0.0846	0.600	0.0005
Nitrogen levels (N)	3	48 858 590	0.0019	98.389	0.0113
Y*N	3	535 282	0.8066	3.640	0.1802
S*N	3	298 777	0.9025	7.256	0.0789
Y*S*N	3	1 644 132	0.0024	1.112	0.0534
Phosphorus levels (P)	3	3 781 282	0.0159	19.776	0.0030
Y*P	3	177 419	0.6910	0.291	0.8468
S*P	3	215 123	0.6480	1.384	0.3957
Y*S*P	3	347 061	0.1460	0.993	0.0692
N*P	9	527 278	0.0231	2.557	0.0052
Y*N*P	9	127 665	0.5964	0.396	0.3364
S*N*P	9	32 180	0.9846	0.239	0.6230
Y*S*N*P	9	150 923	0.0080	0.296	0.1405

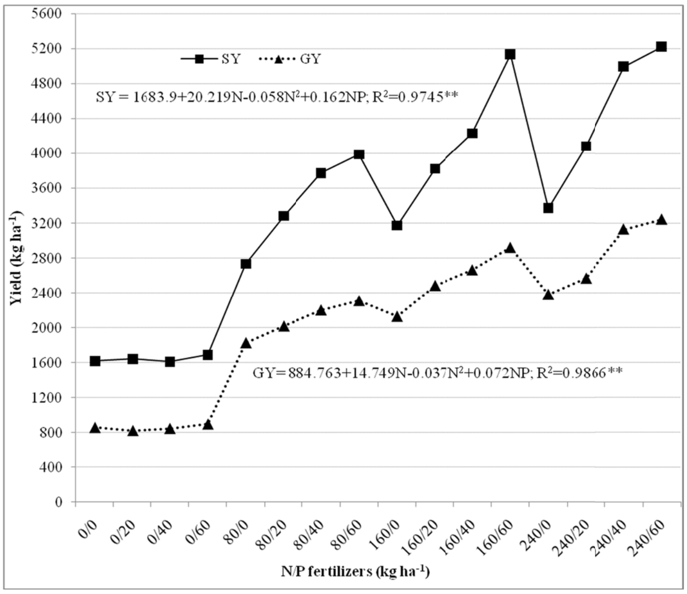

Figure 2. Yield response of bread wheat to N/P fertilizers levels; averaged over two years, two types of Vertisols, and four replications

Note. GY = grain yield; SY = straw yield; $^{**}p < 0.01$.

Results of economic analysis are presented in Table 3. This economic analysis was run on 155 combinations of N and P levels with the corresponding levels of grain and straw yields generated from the fitted response curves (Figure 2). Of these, 105 levels were dominated (data not shown for it is difficult to depict the wide spread sheet of economic analysis process of the full data set of 155 combinations of N and P levels), including the old recommendation of 87/20 kg ha^{-1} of N/P (150/100 kg ha^{-1} of urea/DAP) presented in Table 3.

Table 3. Summary of values selected from dominance, marginal rate of return (MRR) and sensitivity analyses results for each of 155 levels of N/P fertilizers and the corresponding predicted yield levels adjusted downward by 10%

	Deneba and Enewarie areas		
	Candidates for recommendation		Old recommendation
Urea/DAP	250/200	300/300	150/100
Adjusted grain yield (kg ha^{-1})	2433	2864	1812
Adjusted straw yield (kg ha^{-1})	3954	4765	2957
Fertilizer cost	6000.80	8095.50	3302
Net return	18 817.37	21 293.40	15 201.14
Marginal rate of return, MRR (%)	164.1	83.5	Dominated
Sensitivity analysis			
15% increase in fertilizer price	6900.92	9309.83	
Net return	17 917.25	20 079.07	
MRR (%)	129.6	59.6	

3.2 Second Experiment

Results of analysis of variance by assigning precursor crops, types of Vertisols and NP fertilizer in the respective main plots, sub-plots and sub-sub-plots are presented in Table 4. Main effects of NP levels, and interaction effects of types of Vertisols by precursors significantly ($p < 0.05$) affected grain and straw yield response of bread wheat. Precursors had no significant effect on wheat grain yield. However, their effect on wheat straw yield was marginally significant ($p < 0.0567$) and should be considered since the yield difference was 881.62 kg ha^{-1}. Types of Vertisols highly affected yield response of bread wheat on lentil precursor than on tef precursor

(Table 5). Grain and straw yields productivity responses of bread wheat to lentil precursor on *Mererie* were significantly higher than on *Bushella*.

Table 4. Mean square values and probabilities of main and interaction effects of precursor crops, types of Vertisols and NP fertilizer levels on yield response of bread wheat in the second experiment, 2012-2013

Sources of variation	DF	Mean squares (kg ha^{-1}) and probability levels for grain yield		Mean squares (kg ha^{-1}) and probability levels for straw yield	
		Mean square	Probability	Mean square	Probability
Precursors (P)	1	1 716 805	0.4299	25 098 613	0.0567
Rep (P)	14	2 597 928	0.3327	5 821 111	0.2907
Types of Vertisols (S)	1	35 866 215	0.0009	52 127 155	0.0037
P*S	1	15 529 165	0.0156	31 686 770	0.0169
S*Rep (P)	14	2 052 668	<0.0001	4 309 679	<0.0001
NP	3	13 054 902	<0.0001	48 152 937	<0.0001
P*NP	3	86 248	0.5122	875 369	0.1912
S*NP	3	76 939	0.5609	502 692	0.4302
P*S*NP	3	131 476	0.3229	499 231	0.4334

Note. NP = combined nitrogen and phosphorus fertilizer levels.

Table 5. Yield of bread wheat as affected by interaction of precursor crops and types of Vertisols in the second experiment

Precursor crops	Grain yield (kg ha^{-1})			Straw yield (kg ha^{-1})		
	Types of Vertisols		Difference	Types of Vertsisols		Difference
	Mererie	*Bushella*		*Mererie*	*Bushella*	
Lentil	4848.87	3093.56	1755.31	7325.09	5053.69	2271.40
Tef	3920.63	3558.56	362.07	5444.38	5163.16	281.22
Difference	928.25	-465.0		1880.71	-109.47	

Appropriate selection of sowing dates and precursor crops in the second experiment highly improved productivity of NP levels when compared to their productivity in the first experiment in which yield was depressed by early sowing dates and wheat precursor (Table 6). Mean separation of yield in the second experiment showed that all NP levels were significantly ($p < 0.05$) different and yield of bread wheat increased with increased NP levels (Table 6). Even though analysis of variance did not detect interaction effects of NP levels with types of Vertisols and precursor crops, regression analysis showed that grain yield responses of bread wheat to applied NP levels on both precursors were significantly ($p < 0.05$) linear on both types of Vertisols except that of lentil precursor on *Mererie* which gave quadratic response (Figure 3). Bread wheat straw yield response to applied NP fertilizer on tef precursor was significantly ($p < 0.05$) cubic on *Mererie* while all other NP by precursor crop by types of Vertisols combinations effects were significantly ($p < 0.05$) linear (Figure 4).

Table 6. Productivity of NP levels in the first and second experiments

NP levels (kg ha^{-1})†	Predicted yield (kg ha^{-1}) in the first experiment*		Observed yield (kg ha^{-1}) in the second experiment$^{\#}$	
	Grain yield	Straw yield	Grain yield	Straw yield
107	2013	3286	3040	4193
191	2703	4393	3684	5396
252	3182	5294	4204	6412
336	Not tested	Not tested	4494	6986

Note. † 107NP = 87N + 20P; 191NP = 151N + 40P; and 252NP = 192N + 60P; 336NP = 256N + 80P. # average yield over 32 sites for each of grain and straw yield.

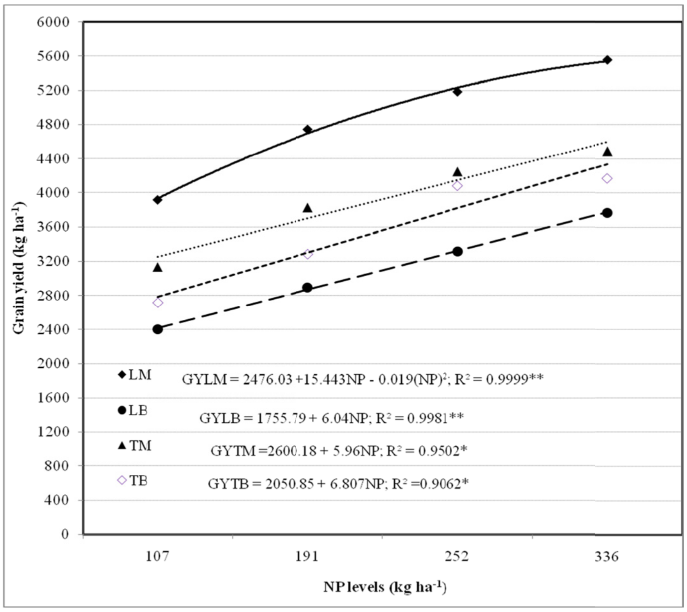

Figure 3. Grain yield of bread wheat as affected by NP levels, precursor crops and types of Vertisols

Note. LM = lentil precursor on *Mererie*; LB = lentil precursor on *Bushella*; TM = tef precursor on *Mererie*; TB = tef precursor on *Bushella*; GY = grain yield; *p < 0.05, **p < 0.01.

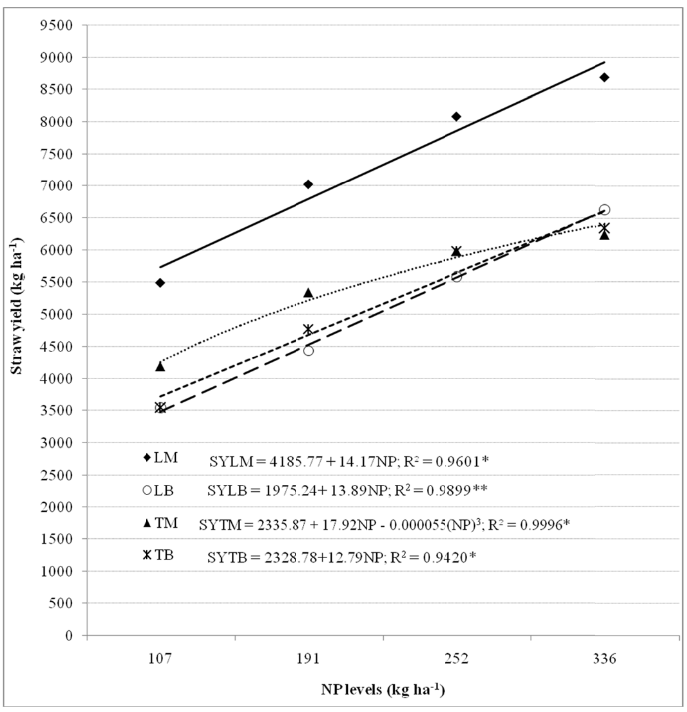

Figure 4. Straw yield of bread wheat as affected by NP levels, precursor crops and types of Vertisols

Note. LM = lentil precursor on *Mererie*; LB = lentil precursor on *Bushella*; TM = tef precursor on *Mererie*; TB = tef precursor on *Bushella*; SY = straw yield; *p < 0.05, **p < 0.01.

Economic analysis using predicted yields (based on equations in Figures 3 and 4) from four tested NP levels and 17 NP levels additionally selected within the range of tested levels (Table 7) showed that higher NP rates were more profitable on *Bushella* than on *Mererie* (Table 8).

Table 7. Four tested NP levels and 17 NP levels selected for economic analyses

No.	NP levels (kg ha^{-1})	Urea (kg ha^{-1})	DAP (kg ha^{-1})	N to P ratio
1	107.0	150.0	100.0	4.35:1
2	115.9	162.5	108.3	4.35:1
3	124.8	175.0	116.7	4.35:1
4	133.8	187.5	125.0	4.35:1
5	142.7	200.0	133.3	4.35:1
6	151.6	212.5	141.7	4.35:1
7	160.5	225.0	150.0	4.35:1
8	169.4	237.5	158.3	4.35:1
9	191.0	250.0	200.0	3.78:1
10	200.6	262.5	210.0	3.78:1
11	210.1	275.0	220.0	3.78:1
12	219.7	287.5	230.0	3.78:1
13	252.0	300.0	300.0	3.20:1
14	262.5	312.5	312.5	3.20:1
15	273.0	325.0	325.0	3.20:1
16	283.5	337.5	337.5	3.20:1
17	294.0	350.0	350.0	3.20:1
18	304.5	362.5	362.5	3.20:1
19	315.0	375.0	375.0	3.20:1
20	325.5	387.5	387.5	3.20:1
21	336.0	400.0	400.0	3.20:1

Table 8. Predicted grain and straw yields (10% downward adjusted), marginal rate of return (MRR) and sensitivity analyses results of four NP levels selected out of 21

NP rate (kg ha^{-1})	Urea/DAP (kg ha^{-1})	GY (kg ha^{-1})	SY (kg ha^{-1})	Fertilizer cost (Birr/ha)	Net income (Birr/ha)	MRR (%)	MRR (%) at 15% fertilizer price increment
Productivity and MRR of NP fertilizer and lentil precursor on Mererie							
107	150/100	3523	5132	3302.30	31 707.30	-	-
191	250/200	4270	6204	6000.80	36 403.28	123.6	94.4
210.1	275/220	4407	6447	6600.88	37 231.31	134.1	103.5
252	300/300	4663	6982	8095.50	38 540.82	77.9	54.7
273	325/325	4770	7250	8770.13	39 101.72	78.9	55.6
336	400/400	5001	8053	10 794.00	40 103.82	28.5	11.7
Productivity and MRR of NP fertilizer and lentil precursor on Bushella							
107	150/100	2162	3116	3302.30	18 128.80	-	-
191	250/200	2619	4167	6000.80	20 573.50	71.2	48.8
210.1	275/220	2722	4406	6600.88	21 142.89	94.9	69.4
252	300/300	2950	4930	8095.50	22 213.75	65.8	44.1
273	325/325	3064	5193	8770.13	22 824.92	90.6	65.7
336	400/400	3407	5981	10794.00	24 658.45	90.6	65.7
Productivity and MRR of NP fertilizer and tef precursor on Mererie							
107	150/100	2914	3767	3302.30	24 904.78	-	-
191	250/200	3365	4835	6000.80	27 330.93	64.1	42.7
210.1	275/220	3467	5028	6600.88	27 817.83	79.7	56.2
252	300/300	3692	5368	8095.50	28 577.16	44.3	25.4
273	325/325	3805	5491	8770.13	28 956.24	54.2	34.0
336	400/400	4143	5630	10 794.00	29 737.08	26.6	10.1
Productivity and MRR of NP fertilizer and tef precursor on Bushella							
107	150/100	2501	3328	3302.30	21 057.45	-	-
191	250/200	3016	4296	6000.80	23 814.32	81.5	57.8
210.1	275/220	3133	4516	6600.88	24 454.69	106.7	79.7
252	300/300	3389	4998	8095.50	25 681.25	75.9	52.9
273	325/325	3518	5240	8770.13	26 370.48	102.2	75.8
336	400/400	3904	5966	10794.00	28 438.14	102.2	75.8

Note. GY = grain yield; SY = straw yield.

4. Discussion

4.1 First Experiment

The significant interaction of year by type of Vertisols and N levels showed that productivity of *Mererie* on unfertilized plots and on plots fertilized with the highest rate of 240 kg N ha^{-1} was about 96 and 89%, respectively, of that of *Bushella* in 2006 (Figure 1). This shows that *Busshella* was more productive than *Mererie* but the difference was higher on plots fertilized with 240 kg N ha^{-1}. Similar trend was observed in 2007 but the difference was much wider for wheat productivity on *Mererie* being 86 and 123% of that of *Bushella* under the respective unfertilized plots and plots fertilized with 240 kg N ha^{-1}. However, wheat was more responsive to fertilizer application on *Mererie* than on *Bushela* in 2007 since *Mererie* out-yielded *Bushella* with the application of 240 kg N ha^{-1}. This interaction effect could mainly be attributed to different sowing dates used in 2006 and 2007. The respective sowing dates for *Bushella* and *Mererie* were 10 and 11 July in 2006, while it was adjusted to 22 and 28 July in 2007 based on farmers experience. As the soil is not saturated at early sowing, it continues to sip in more water in the succeeding rainy days and swells, but after saturation it discharges excess water and the soil settles down that effectively reduces the depth of drainage furrows, hampering free movement of drainable excess water in the furrows. Thus, early sown wheat even if it is provided with drainage borad bed and furrows, faces waterlogging that enhances root disease and eventually reduces yield. The results of a sowing date experiment that was conducted in 2007 and 2008 main rainy season on *Mererie* and *Bushella* soils at Deneba, Enewarie and Goshebado areas in the central highlands of Ethiopia also support this justification in which grain yield of bread wheat linearly increased with each day delay of sowing from 10 to 31 July on *Mererie* soil while the response was quadratic for *Bushella* soil (Molla, 2014). This testifies to the fact that early sowing in 2006 highly depressed bread wheat productivity on *Mererie* soil. Relatively higher clay content of *Mererie* soil implies higher water holding capacity that aggravates the depressive effect of waterlogging in early sowing which exposes the wheat crop to a longer waterlogging duration (Molla, 2014). This long duration waterlogging stress also exposes the wheat crop to dry wilting caused by *Fusarium* sp., *Sclerotium* sp., and *Gaeumannomyces* sp. All these stresses could be attributed to the low yield of early sown wheat on Vertisols in general and in *Mererie* soil in particular. Another research report also showed that late sowing dates (early August sowing) produced 30% higher grain yields than that of early sowing dates (sowing in late June through July) on Vertisols at Ginchi (with the altitude of 2200 m.a.s.l), without disaggregating Vertisols into *Mererie* and *Bushella* (Tanner, Gorfu, & Zewdie, 1991). Moreover, lentil precursor crop in 2007 improved productivity on both soil types as compared to cereal precursor crops (wheat on *Mererie* and tef on *Bushella* soils) in 2006; the yield increment especially on unfertilized control of lentil precursor in 2007 was about 125% over the unfertilized control of cereal precursors in 2006, averaged over the two types of Vertisols (Figure 1).

Stepwise multiple regressions clearly showed that P fertilizer alone had little effect on yield response (Figure 2). This little response is not due to the Olsen extraction method that was used in soil sample analysis of this experiment (Table 1). Previous study on ten Ethiopian Vertisols showed the highest correlation between wheat P uptake and Olsen extraction method (Mamo, Richter, & Heiligtag, 2002). Other studies also concluded that even though most Ethiopian Vertisols are deficient in P, field crop responses to applied P fertilizer alone was little that was also confirmed on wheat even under improved drainage conditions (Haque, Abebe, Mamo, & Dibabe, 1993; Woldeab, Mamo, Bekele, & Ajema, 1991). However, the recent on-farm research conducted in the central highlands of Ethiopia in 2005 to 2006 indicated that yield of bread wheat significantly increased with increasing P levels on the relatively fertile black soil containing 1.47 % organic carbon, 0.15% total N, 9.08 ppm available P, and 152.39 ppm available K; but there was no response to applied P levels on relatively infertile black soil containing 0.90% organic carbon, 0.09% total N, 2.92 ppm available P, and 103.47 ppm available K (Molla, 2013). Soil fertility status indicated in Table 1 with the same methods of analysis to those reported by Molla (2013) is similar to values of the relatively infertile black soil. This result implies that response to applied P alone could be expected at least when soil nutrient content of total N is medium to high level. It has already been established elsewhere that crop utilization of P is significantly enhanced when the appropriate balance of nutrients like N is available: N enhances P uptake by increasing top and root growth, altering the plant metabolism and increasing the solubility and availability of P (FAO, 1999; Tisdale, Nelson, & Beaton, 1985).

Figure 2 showed that both grain and straw yield response of bread wheat to applied N fertilizer reached a plateau at N_{160}. Thus, to raise productivity level beyond the level attained by the application of N_{160} alone, it seems a necessity to apply P fertilizer to have synergetic effect of NP fertilizers. Unless it is a question of optimizing economically benefiting ratio of N and P fertilizers application levels, application of N levels higher than zero together with their matching P fertilizer levels higher than zero was always higher yielding than application of N fertilizer levels alone. For example, grain and straw yields of $N_{80}P_{20}$, $N_{80}P_{40}$ and $N_{80}P_{60}$ were higher than that of $N_{80}P_0$.

Economic analysis carried out on 155 combinations of N and P levels with the corresponding levels of grain and straw yields showed that about 68% of the rates were dominated (data not shown), including the previous recommendation of 87/20 kg ha^{-1} of N/P (150/100 kg ha^{-1} of urea/DAP presented in Table 3). Each of these dominated levels had increased cost but not net income when compared to the immediate preceding level of each. Since lower rates have penalties in terms of yield and net income, only those rates which have higher productivity with narrow differences in net income are selected for further evaluation. Moreover, sensitivity analysis at 15% increment of fertilizer price also shows that the selected higher rates still have more than 50% marginal rate of return. Thus, the agronomic and economic evaluation results of the first experiment suggest that application rates of 151/40 kg ha^{-1} of N/P (250/200 kg ha^{-1} of urea/DAP), and 192/60 kg ha^{-1} of N/P (300/300 kg ha^{-1} of urea/DAP) are recommended for further evaluation as compared to previous low recommendation and the latest higher application rate of farmers. Other adjustments recommended to be made for further evaluation are to include dominant precursor crops, types of Vertisols, and appropriate sowing dates.

4.2 Second Experiment

The experience gained in the first experiment with regard to sowing dates, precursor crops and types of Vertisols that were supported by farmers' knowledge and the results of on-farm sowing date experiment in 2007-2008 (Molla, 2014) highly improved bread wheat productivity in the second experiment. Thus, bread wheat productivity in the second experiment was higher than the first experiment by about 32-51% for grain yield, and 21-28% for straw yield (Table 6). It was also documented elsewhere in the highlands of central Ethiopia that the use of farmers' knowledge improved bread wheat productivity and this information helped in making site specific fertilizer recommendations (Molla, 2013). Reviews of research works have also established that the attributes of crop rotation in improving productivity could be due to benefits such as increased nitrogen supply from legume precursor crops, soil nutrient availability, soil structure, soil microbial activity and the presence of growth-promoting substances originating from crop residues in the rotation (Karlen, Varvel, Bullock, & Cruse, 1994; Malik, 2010). Legume precursors are also reported to improve nitrogen use efficiency of wheat (Badaruddin & Meyer, 1994; Rahimizadeh, Kashani, Zare-Feizabadi, Koocheki, & Nassiri-Mahallati, 2010).

The second experiment revealed significant interaction between the types of Vertisols and precursor crops included. Thus, lentil precursor on *Mererie* gave about 57% more grain yield of bread wheat over that of lentil precursor on *Bushella*. Differential effect of types of Vertisols on bread wheat grain yield productivity following tef precursor was small and *Mererie* gave about 10% more grain yield than *Bushella*. The interaction effect showed that lentil precursor gave about 24% more grain yield of bread wheat over that of tef precursor on *Mererie*, but it gave about 13% lower yield than that of tef precursor on *Bushella*. The trend was also similar for straw yield productivity on *Mererie* while the productivity gap was negligible on *Bushella*, where straw yield of bread wheat on lentil precursor was about 2% lower than that of tef precursor. This trend could also be explained by soil characteristics presented in Table 1 and N to P ratios of NP rates presented in Table 7. *Mererie* had relatively lower values of organic carbon and total nitrogen than *Bushella* and hence was more responsive to lower NP rates having higher ratio of N. Relatively lower content of available P and K in *Bushella* resulted in a response to application of higher NP rates for the reason that these higher NP rates had higher ratio of P. In other words, P ratio in NP rates increased with increasing NP rates (Table 7). This result shows that the ratio of N to P is critical and affects productivity (Tahir, Ali, Iqbal, & Yamin, 2004).

Higher positive effect of tef precursor on bread wheat productivity on *Bushella* is difficult to explain but might be attributed to soil compaction resulting from practice of farmers' during tef sowing that might form firm structure to improve drainage on *Bushella*. Research results elsewhere also showed that even though tef is a cereal crop, it improves productivity of cereal crops when it is used as a precursor crop. For instance, a two rotation cycle experiment comprising tef-maize, climbing type haricot bean-maize, and soybean inoculated with rhyzobium-maize gave the respective maize grain yield of 8.2, 8.6 and 7.8 tones ha^{-1} at Bako, western Ethiopia (Zerihun, Abera, Dedefo, & Fred, 2013). This shows that grain yield of maize following a cereal crop, tef, was comparable to those of legume precursors. Such effects of tef should draw the attention of research so as to explain its attributes.

Economic analysis by using predicted yields (based on equations in Figures 3 and 4) from four tested NP levels and 17 NP levels additionally selected within the range of tested levels (Table 7) showed that NP rates higher than 252 kg ha^{-1} were more profitable on *Bushella* than on *Mererie* (Table 8). For instance, the highest NP rate, 336 kg ha^{-1}, gave marginal rate of return (MRR) values less than 50% on *Mererie* while it gave about 91-102%

MRR on *Bushella*. As compared to higher rates, lower NP rates such as 191 and 210.1 kg ha^{-1} gave MRR values higher than 50% in all types of Vertisols and precursor crops. For instance, application of 191 and 210.1 kg NP ha^{-1} gave about 64-134% MRR, the lowest value being for 191 kg NP ha^{-1} with tef precursor on *Mererie.* Sensitivity analysis at 15% price increment of fertilizer also showed that application of 210.1 kg NP ha^{-1} could be the only rate having MRR of higher than 50% in all types of Vertisols and precursors tested (Table 8). Therefore, regardless of differences in agronomic productivity over precursor crops and types of Vertisols, application of 210.1 kg NP ha^{-1} or more appropriately for packaging purpose application of 212 kg NP ha^{-1} (167 kg N ha^{-1} plus 45 kg P ha^{-1}) is recommended to be promoted for bread wheat production on tested precursors and types of Vertisols at Deneba and Enewarie, and similar areas. This recommendation may seem a high rate but, recent on-farm research on N and P fertilizer application rates for bread wheat production in the highland areas at 2425-2600 m.a.s.l in northwestern Ethiopia recommended 276/20 kg N/P ha^{-1} to get maximum yield and economic advantage having about 362% MRR (Asargew, Bitew, & Beshir, 2014).

5. Conclusions

The agronomic and economic evaluation results of the first experiment suggested application rates of 151/40 kg ha^{-1} of N/P (250/200 kg ha^{-1} of urea/DAP), and 192/60 kg ha^{-1} of N/P (300/300 kg ha^{-1} of urea/DAP) for further evaluation as compared to previous old recommendation and the latest high application rate of farmers; with the adjustment of sowing dates to types of Vertisols under dominant precursor crops. It was also established that application of P fertilizer alone made little contribution to yield increment and therefore, use of the right N/P fertilizers combination should be given attention in advising farmers. Yield response attained plateau at N_{160} but it increased further when P was applied. No yield plateau was attained for NP levels tested (N/P combinations as high as 240/60).

The second experiment revealed that the agronomic yield response of bread wheat to types of Vertisols was significantly affected by precursor crops. Bread wheat following lentil precursor was best performing on *Mererie* (relatively heavy Vertisols) while it was the least on *Bushella* (relatively light Vertisols). Differences due to the effects of the types of Vertisols on bread wheat productivity following tef precursor was negligible.

Grain yield response of bread wheat to N/P rates following lentil precursor on *Mererie* was significantly quadratic while responses following lentil precursor on *Bushella*, and tef precursor on both types of Vertisols were significantly linear. Application of the highest rate (256/80 kg N/P ha^{-1}) on wheat following lentil precursor gave grain yield of 5001 and 3407 kg ha^{-1} on *Mererie* and *Bushella* Vertisols, respectively. The same rate on wheat following tef precursor gave grain yield of 4143 and 3904 kg ha^{-1} on *Mererie* and *Bushella* Vertisols, respectively. However, application of 167/45 kg N/P ha^{-1} was more economical (79.7-134.1% marginal return).

6. Recommendations

The stepwise execution of data from the two experiments, agronomic and economic yield response analysis eventually led to the conclusive recommendation of application of 210.1 kg NP ha^{-1} or more appropriately for packaging purpose application of 212 kg NP ha^{-1} (167 kg N ha^{-1} plus 45 kg P ha^{-1}) for bread wheat production on all types of Vertisols and precursor crops tested in Deneba, Enawarie and similar areas. However, the recommended fertilizer rate should be revised whenever there is significant input and output price change so as to deliver the contemporary economically applicable rate by using the generated response curve equation. Such high rate recommendations could be environmentally inadvisable even though it is lower than the farmers' rate being used currently. Therefore, to improve fertilizer use efficiency and minimize the rate, studies on nitrogen fertilizer application timing, macro and micro-nutrient imbalances, long-term crop rotation and NP rate options, herbicidal control of grassy weeds that are similar to wheat at early stage, and development of waterlogging tolerant bread wheat varieties are suggested.

The comparable or higher performance of the cereal precursor crop, tef, to that of the legume precursor, lentil, in improving productivity of bread wheat on *Bushella* needs attention of research to understand the mechanism.

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