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Full Length Research Paper

Indigenous soil nutrient supply and effects of fertilizer application on yield, N, P and K uptake, recovery and use efficiency of barley in three soils of Teghane, the Northern Highlands of Ethiopia

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So far, application of fertilizer to mitigate problems of nutrient-limited yields in farmers' fields in the Highlands of Ethiopia has been based on conventional blanket fertilizer recommendations, without taking into account indigenous soil nutrient supply. In this study an attempt was made to take into account indigenous soil nutrient supply, internal nutrient use efficiency at maximum nutrient accumulation and dilution, and actual uptake and recovery fractions of applied fertilizers in order to parameterize the nutrient requirement of barley in the Northern Highlands of Ethiopia. For parameterization of fertilizer requirements, factorial field experiments have been carried out with different application rates, in soils identified as Cambisol, Luvisol-1 and Luvisol-2, characterized by different soil nutrient contents, in three replicates in four fields. Coefficients for estimation of potential supply of N, P and K, respectively, Nq = 6.0, Pr = 0.55, and Ks = 166, were estimated by using transfer functions calibrated for barley in the Northern Highlands of Ethiopia on the basis of soil OC content, exchangeable K, and P-Olsen. Yields at maximum accumulation and dilution, internal nutrient use efficiency and agronomic efficiency have been estimated for barley. The results show that different rates of fertilizer application are required for different soils with different indigenous soil nutrient supplies for different objectives, that is, either to attain maximum agronomic efficiency of a given nutrient or maximum yield. The coefficients used to quantify indigenous soil nutrient supply and parameterization of nutrient requirements of barley would help to consider different NPK combinations for different soils with different values of indigenous soil nutrient supply for targeted barley yields in the Northern Highlands of Ethiopia in stead of applying blanket fertilizer recommendation.

Key words: Agronomic efficiency, Internal nutrient use efficiency, maximum accumulation, maximum dilution, nutrient-limited yield.

INTRODUCTION

Barley is one of the most important food crops in the Highlands of Ethiopia, occupying about 12% of the total area of major cereal crops and accounting for 10% of the total annual cereal production in 1999 (ICARDA, 2003). In the Northern Highlands, barley grain is used for food, while its straw is used either for animal feed or for soil organic amendments. Barley yields are stagnant or declining in many parts of the highlands of Ethiopia (ICARDA, 2003), which could be the result of a decline in the natural supply of one or more crop nutrients. On the other hand, population is growing at an annual rate of 2.7% (IRIN, 2003) and land holdings in the area are less than 2 ha per household (Abegaz et al., 2007a). In general, there is a pressure on land use and hence use of marginal and fragile areas has become a common phenomenon which leads to soil nutrient decline. Another problem is less use of external inputs on blanket application. Consequently, for much of the last decade the people were food-insecure and dependent on external food aid (USAID, 2004). To increase production of cereal crops, increased use of chemical fertilizers has been suggested (Woldeab et al., 1991; Tarekegne et al., 1997), of which expensive imported N and P are the two most widely used (Ayele and Mamo, 1995).

Currently, 100 kg DAP (21 kg P and 18 kg N) and 100 kg urea (46 kg N) ha^{-1} are being used for barley and other cereal crops in the Northern Highlands of Ethiopia (Demeke et al., 1997). Such a blanket recommendation does not do justice to the differences in agro-ecological environments, indigenous soil nutrient supplies and crop specifications (Abegaz et al., 2006). Inefficient use of these expensive nutrients contributes to the depletion of scarce financial resources, increased production costs and potential environmental risks (Tarekegne and Tanner, 2001). There is therefore a need to refine fertilizer recommendation in Ethiopia considering farmers' scarce financial resources and potential environmental risks specific to local conditions. Farmers' practice is heavily biased towards one type of fertilizer, mainly DAP, and this may cause unbalanced nutrient supply and jeopardize the efficiency of utilization of fertilizers (Demeke et al., 1997). Moreover, most site-specific methods for evaluation of soil fertility and nutrient requirements address a single nutrient, without taking into account that uptake of one nutrient partly depends on the availability of other nutrients (Smaling, 1993). For example, uptake of N appears to be strongly affected by application of P fertilizer, especially in soils with low P-Olsen values (Penning de Vries and van Keulen, 1982; Janssen et al., 1990; Smaling et al., 1993; Janssen et al., 2001). At low P-availability, only a fraction of the potentially available N is taken up by the crop (Smaling, 1993). In soils characterized by low available N, uptake of P was stimulated by N-fertilizer application (Kamprath, 1987) through decreasing rhizosphere pH and increasing solubility of soil phosphates, stimulating root growth and root physiological capacity. Moreover, water use effi-ciency, that is, the amount of dry matter produced per unit of water consumed increases with increasing nitro-gen availability (van Keulen and Seligman, 1987). In general the N:P-ratio in plant tissue varies within a relatively narrow range, so that deficiency of one element may restrict uptake of the other (Penning de Vries and van Keulen, 1982). K application may increase yields considerably, particularly in fields where crop residues are removed under continuous cropping (Smaling, 1993). Conversely, optimal supply of moisture, N and P leads to increased yield responses to K fertilizer. Smaling (1993) criticized the attempts to link crop yields to the supply and uptake of a single nutrient, thus ignoring the evident interactions among nutrients. Therefore, formulating methods (equations) of balanced fertilizer application against traditional approaches is scientifically more interesting. The results can be applied in different regions, however with calibration of important parameters of equations.

To formulate more accurate fertilizer recommendations, a more generic nutrient evaluation method or model is required that considers both, site-specific indigenous soil nutrient supply and interactions of nutrients (Dobermann and White, 1999). For that purpose, equations for estimation of indigenous nutrient supply and some important parameters of nutrient requirements such as effects of fertilizer application on yield, N, P and K uptake, recovery and use efficiency of barley have been estimated in three soils of Teghane, the Northern Highlands of Ethiopia

MATERIALS AND METHODS

The study area

Location: The study site, Teghane, is located in Atsbi-Wonberta district, Tigray Regional State, Northern Highlands of Ethiopia, about 850 km north of Addis Ababa, the capital. It is situated between 13° 52' 53'' and 13° 53' 37'' N and between 39° 42' 05'' and 39° 43' 57'' E. The study area covers about 13.56 km^2 and its altitude ranges from 2710 to 2899 meter above mean sea level. The climate is temperate ("Dega" in Ethiopian context) (WBISPPO, 2002), with average annual monomodal rainfall from July to September of 541 mm for the period 1901 - 2002, at a location near Teghane (Viner, 2003). In the period 2000-2004, average annual rainfall was 532 mm (Atsbi World Vision, 2004).

Soil data

In February 2003, soils of Teghane were surveyed to determine their characteristics for biophysical modelling work. Following the toposequence survey method, nine representative soil pits have been opened and described following the FAO-UNESCO (1990) guidelines. From each profile, samples were taken for laboratory determination of physico-chemical properties. The samples were bulked for each soil type and analysed either at the National Soil Research Center (NSRC), Addis Ababa or the International Livestock Research Institute (ILRI), Addis Ababa.

Soils of the study area were identified as Cambisols, Luvisols and Leptosols (FAO-UNESCO, 1990). Cambisols, covering 26% of the area, are intensively cultivated. They are located on the colluvial terrace slopes. Their depth is between 50 - 150 cm from the top surface. These soils were under cultivation since long ago. Luvisols, also covering 26% of the area, are located in the valley bottom or flood plain. They are relatively deep, with favourable physical and chemical characteristics. Traditionally, these soils were under grassland, but in recent years a significant proportion has been transformed to arable land in response to the shortage of land for food crop production. Leptosols, covering 46% of the area, are located on the elevated plateau and on hill slopes, crests and ridges, interspersed with rock outcrops and patches of Luvisols. They are limited in depth to about 25 cm by underlying continuous hard sedimentary rock, or contain less than 20 percent fine particles to a depth of 75 cm (FAO-UNESCO, 1990). These soils are degraded and eroded and characterized by coarse textures, low nutrient contents and low moisture holding capacity and therefore hardly used for crop production.

Farming systems

Mixed crop-livestock farming is the dominant agricultural system in Teghane. In the 2002-2003 cropping season, barley (*Hordeum* spp.) and wheat (*Triticum* spp.) were the two major crops, grown respectively on about 69 and 16% of the cultivated fields (Abegaz et al., 2007a). "Gunaza" (six row barley), "Sasa" and "Brguda" are the most common varieties of barley. Field pea (*Pisum* spp.) and faba bean (*Vicia* spp.) are the next important crops. Most of the

Table 1. Chemical characteristics of experiment fields (2003) in Teghane, Northern Highlands of Ethiopia.

Soil unit	OC (g kg^{-1})	P-Olsen (mg kg^{-1})	Exch. K (mmol kg^{-1})	pH (H_20)
Cambisol	11.0	7.0	15.0	6.4
Luvisol-1	19.0	5.0	2.0	6.5
Luvisol-2	37.0	6.0	15.4	6.4

grazing lands are on Luvisols in the valley bottom, where temporary water logging is a serious problem for cultivation of food crops in the rainy cropping season. Marginal fields on rock outcrops with patches of Leptosols are either under open woodland or in use as homestead.

Crop data

For establishment of the correlation between soil parameters and yield in a given locality, it is important to investigate relevant chemical parameters of a variety of soils and associated grain yields. For this end, four fields, two each on Cambisols and Luvisols, designated Cambisol-1, Cambisol-2, Luvisol-1 and Luvisol-2, have been selected for field experimentation in the 2003 cropping season (Abegaz and van Keulen, 2008). The two Cambisol fields and Luvisol-1 had been under continuous cultivation for over 50 years, while the Luvisol-2 field had been under grazing until seven years ago. In early July 2003 just before sowing, composite soil samples from the 0-20 cm surface layer of each field as well as from 22 farm fields were collected for laboratory analyses. From these samples; Organic Carbon (Walkley and Black, 1947), available P (Olsen et al., 1954), exchangeable K (Thomas, 1982), and soil pH-H_2O (1:2 soil:water ratio) have been analyzed. Soil chemical characteristics of the experimental fields are presented in Table 1.

The trials were planted on a gross plot size of 2.75 m x 2.75 m. Host farmers prepared the trial plots using the traditional ox-plowing practice. The treatments were laid out in a complete randomized design, replicated three times with three nutrients (three rates for N and K (0, 25, 50 kg ha^{-1}) and four rates for P (0, 25, 50 and 75 kg ha^{-1})). These rates (for N and P) are selected on the basis of common practices of fertilizer application in the Northern Highlands of Ethiopia. All P (triple superphosphate) and K (potassium chloride) were applied as basal dressing at sowing, while the N (urea) was split: one-half applied at sowing and the other half at early booting. Topdressing of N was combined with supplementary irrigation. In all fields, the local barley variety "Gunaza" was sown at a rate of 120 kg ha^{-1} on July 18 and harvested on November 17.

Hand weeding was used to control weeds. At physiological maturity, a net area of 2.5 m x 2.5 m was harvested at ground level with a sickle. The harvested plants were air-dried and weighed to determine aboveground dry matter. Grain was separated from straw manually and weighed to determine grain yield. Harvest index was calculated by dividing grain yield by total aboveground biomass. Cambisol-2 was excluded from the analysis, because it was affected by erosion. From the 22 farmers' fields, yields were estimated in the same way and included in the analysis. Samples (both grain and straw) were analyzed for N, P and K.

From the experiment, N, P and K mass fractions were determined in 216 (3 x 72) grain samples (GN, GP and GK, respectively) and 108 (36 x 3) composite (from identical treatments) straw samples (NSt, PSt and KSt, respectively). Nutrient contents in grain (NGU, PGU and KGU) and straw (NStU, PStU and KStU) were calculated by multiplying grain and straw yields by their respective N, P and K concentrations and total uptake (TNU, TPU and TKU) calculated. N (NHI), P (PHI) and K (KHI) harvest indices were calculated as the ratios NGU/TNU, PGU/TPU and KGU/TKU, respectively, and expressed as percentages. Also, has been estimated. Grain yields, total nutrient uptake, internal efficiency, agronomic efficiency and grain yield at maximum accumulation and maximum dilution were subjected to analysis of variance (ANOVA).

Parameterization and calibration of transfer coefficient

Transfer coefficient refers to coefficient established somewhere else at one time and to be used in different location and/or condition. Thus, coefficients established for estimation of supply of N, P and K for maize in Kenya (Janssen et al., 1990) have been calibrated for barley in the Northern Highland of Ethiopia. Calibration here is regarded as adjustment of already established indices for estimation of supply of N, P and K to agree with the supply of the same for barley in the Northern Highlands of Ethiopia, based on experiment values.

Thus, for calibration of those coefficients for estimation of SN, SP and SK, kg ha^{-1}, and parameterization of nutrient requirement of barley for the northern highlands of Ethiopia, the following has been carried out: i) soil chemical analyses (OC, total nitrogen, P-Olsen and exchangeable K), ii) factorial experiments by considering the range of current fertilizer application practices in the Northern Highlands of Ethiopia, iii) estimation of maximum recovery fraction of applied fertilizer and, iv) estimated grain yield per kg N, P and K at maximum accumulation (YNA, YPA, YKA) and maximum dilution (YND, YPD, YKD) for the fertilizer rates under consideration.

Calibration of transfer coefficients for estimation of SN, SP and SK

Soil chemical data were related to total nutrient uptake in the aboveground plant dry matter to calculate the coefficients of Nq, Pr and Ks for estimation of SN, SP and SK, respectively.

Coefficient to estimate potential indigenous soil N supply (Nq) calculated as:

$$Nq = \frac{1}{m}\sum_{y=1}^{m}\frac{1}{OC_m}\left(\frac{1}{n}\sum_{x=1}^{n}TNU_{yx}\right) \quad (1)$$

Where,

Nq: Coefficient to estimate potential indigenous soil N supply.
TNU: Total N uptake (kg ha^{-1}) in aboveground plant DM at maturity in treatments $P_{50}K_{25}$, $P_{50}K_{50}$, $P_{75}K_{25}$, $P_{75}K_{50}$ without N fertilizer.
OC: organic carbon contents of the soil (g kg^{-1})
y: soil type 1, …, m
x: treatment 1, …, n

Coefficient to estimate potential indigenous soil P supply (Pr) calculated as:

$$\Pr = \frac{1}{m}\sum_{y=1}^{m}\frac{1}{P-Olsen_m}\left(\frac{1}{n}\sum_{x=1}^{n}(TPU - PSOC)_{yx}\right) \quad (2)$$

Where,
Pr : coefficient to estimate potential indigenous soil P supply

PSOC : potential supply of P from organic carbon and defined as O.35*OC (Janssen et al., 1990)

TPU : total P uptake (kg ha^{-1}) in aboveground plant DM at maturity in treatments $N_{25}K_{25}$, $N_{25}K_{50}$, $N_{50}K_{25}$, $N_{50}K_{50}$ without P fertilizer. In this analysis data of Luvisol-1 and Luvisol-2 were used because in these soils P-Olsen is relatively lower than that of Cambisol, so that P is supposed to be maximally diluted in these soils with the application of the other nutrients. $N_{50}K_{25}$ of Luvisol-2 is excluded because its value was higher compared to the other treatments under consideration, may be due to micro-heterogeneity of treatments.

Coefficient to estimate potential indigenous soil K supply (Ks) calculated as:

$$Ks = \frac{1}{m}\sum_{y=1}^{m}\frac{1}{v_m}\left(\frac{1}{n}\sum_{x=1}^{n}TKU_{yx}\right) \qquad (3)$$

where,
Ks: coefficient to estimate potential indigenous soil K supply
v: exch.K/(2+0.9*OC) (Janssen et al., 1990).
TKU: Total K uptake (kg ha^{-1}) in aboveground plant DM at maturity in treatments $N_{25}P_{25}$, $N_{25}P_{50}$, $N_{25}P_{75}$, $N_{50}P_{25}$, $N_{50}P_{50}$, $N_{50}P_{75}$ without K fertilizer.
Exch.K: soil exchangeable K (mmol kg^{-1})

Estimation of recovery fraction of applied nutrients

Recovery fraction of applied nutrient ($Nre_{(x)}$) is the ratio between nutrient uptake from applied fertilizer and the rate of fertilizer application. It is calculated as:

$$Nre_{(x)} = (TU_{(xf)} - TU_{(x0)})/ Fr_{(x)} \qquad (4)$$

Where,
$TU_{(xf)}$: average total nutrient uptake (kg ha^{-1}) from treatments receiving a dose $Fr_{(x)}$
$TU_{(x0)}$: average total nutrient uptake (kg ha^{-1}) from the control (zero-fertilizer) treatments
$Fr_{(x)}$: Rate of fertilizer application (kg ha^{-1})
$_{(x)}$: nutrient under consideration (N, P or K)

Grain yield at maximum accumulation and maximum dilution

Grain yield at maximum accumulation of nutrient occurs when increasing that nutrient rate doesn't increase uptake and yield. Thus, grain yield per unit nutrient (x) uptake at maximum accumulation of that nutrient ($Y_{(x)}A$, kg kg^{-1}(x)) is the ratio between grain yield (kg ha^{-1}) at maximum application rate of nutrient (x) and omission of the other two nutrients, and total nutrient uptake in aboveground plant DM (kg ha^{-1}) at maximum application rate of nutrient (x) and omission of the other two nutrients. It is calculated as:

$$Y_{(x)}A = GY_{(x)}A/TU_{(x)}a \qquad (5)$$

Where,
$GY_{(x)}A$: grain yield (kg ha^{-1}) at maximum application rate of nutrient (x) and omission of the other two nutrients

$TU_{(x)}a$: total nutrient uptake in aboveground plant DM (kg ha^{-1}) at maximum application rate of nutrient (x) and omission of the other two nutrients Grain yield at maximum dilution of a nutrient occurs when that nutrient is the only limiting factor and growth doesn't respond to application of other nutrients. Grain yield per unitnutrient (x) uptake at maximum dilution of that nutrient ($Y_{(x)}D$, kg kg^{-1} (x)) was calculated as:

$$Y_{(x)}D = GY_{(x)}D/TU_{(x)}d \qquad (6)$$

Where,
$GY_{(x)}D$: grain yield (kg ha^{-1}) from treatments receiving no nutrient (x) (and the maximum rates of the other two nutrients)
$TU_{(x)}d$: total nutrient uptake in aboveground plant DM (kg ha^{-1}) from treatments receiving no nutrient (x) (and the maximum rates of the other two nutrients).

Internal nutrient use and agronomic efficiencies

Internal nutrient use efficiencies (INue, kg grain kg^{-1} nutrient) were calculated as:

$$INue = GY/ TU \qquad (7)$$

where,
GY : grain yield (kg ha^{-1})

TU : total nutrient uptake (kg ha-1) in aboveground plant DM at maturity Agronomic efficiency (AE, kg grain kg^{-1} applied fertilizer) was calculated as:

$$AE = (GY_{(xr)} - GY_{(c)})/R_{(xr)} \qquad (8)$$

where,

$GY_{(xr)}$: grain yield (kg ha^{-1}) of treatment receiving fertilizer nutrient x at rate r
$GY_{(c)}$: grain yield (kg ha^{-1}) of the control treatment
$R_{(xr)}$: rate of fertilizer (x) application (kg ha^{-1})

RESULTS and DISCUSSION

Potential Indigenous Soil N, P and K Supply

Equations for estimation of potential indigenous soil N, P and K supply (Janssen et al., 1990) for barley in the Northern highlands of Ethiopia are:

$$SN = Nq^* \text{ organic carbon (g kg}^{-1}) \qquad (9a)$$

$$SP = 0.35 * OC \text{ (g kg}^{-1}) + Pr * \text{P-Olsen (mg kg}^{-1}) \qquad (9b)$$

$$SK = (Ks * \text{exch. K (mmol kg}^{-1}))/ (2+ 0.9 * OC \text{ (g kg}^{-1})) \qquad (9c)$$

Where Nq, Pr and Ks are 6.0, 0.55 and 166, respectively, computed by eqns. 1-3 and data of Table 2.

Grain yield and actual uptake of N, P and K

Grain yield

Cambisol: In the Cambisol, GY varied between 2.61 ($N_0P_0K_{25}$) (Figure 1) and 4.87 ($N_{50}P_{75}K_{50}$) Mg ha^{-1}. Yields for all treatments differ from that of the control (P<0.05), except for $N_0P_0K_{25}$, $N_0P_0K_{50}$ and $N_{25}P_0K_{25}$. Yields at N_{25} and N_{50} were not significantly different at P_{25}, P_{50} and P_{75} (Figure 2). Moreover, yields at K_{25} and K_{50} were not signi-

Table 2. Calculation of coefficients of Nq, Pr and Ks for estimation of indigenous nutrient supply.

Nutrients	Fertilization rate	Cambisol	Luvisol-1	Lunisol-2	Average		
					Nq	Pr	Ks
N							
	N0P50K25	90.4	76.1	179.5			
	N0P50K50	86.6	78.3	173.9			
	N0P75K25	93.6	65.2	175.8			
	N0P75K50	83.2	66.7	154.2			
	Average TNU	88.5	71.6	170.9			
	OC	11.0	19.0	37.0			
	Nq	8.0	3.8	4.6	6*		
P							
	N25P0K25		8.4	17.4			
	N25P0K50		8.0	16.2			
	N50P0K25		9.4				
	N50P0K50		9.1	17.8			
	average TPU		8.7	17.1			
	P-Olsen		5.0	6.0			
	PSOC		6.7	13.0			
	TPU-PSOC		2.1	4.2			
	Pr		0.4	0.7		0.55	
K							
	N25P25K0	58.6	27.1	107.7			
	N25P50K0	58.8	23.7	120.0			
	N25P75K0	72.0	23.6	126.5			
	N50P25K0	54.7	24.7	79.2			
	N50P50K0	66.1	23.3	93.1			
	N50P75K0	51.7	16.3	73.4			
	Average TKU	60.3	23.1	100.0			
	Exch.K	15.0	2.0	15.4			
	Exch.K/(2+0.9*OC)	1.3	0.1	0.4			
	Ks	47.9	220.8	229.2			166*

* rounded

significantly different at N_{25} and N_{50} and at P_{25}, P_{50} and P_{75} ($P<0.05$) (Figure 3). This implies that in the unfertilized situation, barley yield is not limited by indigenous K-supply. Mean yield of treatment $N_0P_{50}K_0$ (4.1 Mg ha^{-1}) is higher than that of treatment $N_{50}P_0K_0$ (3.3 Mg ha^{-1}) ($P < 0.05$) (Figure 1), suggesting that for Cambisol P is the most limiting nutrient, followed by N. The 'best' (in terms of grain yield) combinations in the experimental treatments were (but not significantly different at $P<0.05$) $N_{50}P_{75}K_{25}$ (4.78 Mg ha^{-1}) and $N_{50}P_{75}K_{50}$ (4.87 Mg ha^{-1}).

Luvisol-1

In Luvisol-1, GY varied between 1.82 (control) and 4.52 ($N_{50}P_{75}K_{50}$) Mg ha^{-1}. Yields for all treatments are different from that of the control ($P < 0.05$), except for $N_{25}P_0K_0$, $N_0P_{25}K_0$ and $N_{50}P_0K_0$ (Figure 1). Yield response is increasing with increasing rates of K fertilizer. Yields do respond to N and P fertilizers, though less than to K fertilizer (Figures 1 - 3). The response to P fertilization is stronger than to N fertilization. Thus, in this soil the most limiting nutrient is K, followed by P. The 'best' combinations for this soil were (but not significantly different at $P<0.05$) $N_{25}P_{50}K_{50}$ (4.42 Mg ha^{-1}) and $N_{50}P_{75}K_{50}$ (4.52 Mg ha^{-1}).

Luvisol-2

In Luvisol-2, GY varied between 5.22 (at $N_{25}P_0K_0$) (Figure 1) and 8.00 (at $N_{50}P_{50}K_0$) Mg ha^{-1} (Figure 2). The yield at $N_{25}P_0K_0$ was lower than that of the control because of lodging. Only yields of the P_{50} and P_{75} treatments are higher than the control yield ($P<0.05$). This implies that in this soil, barley yield in the unfertilized situation is not

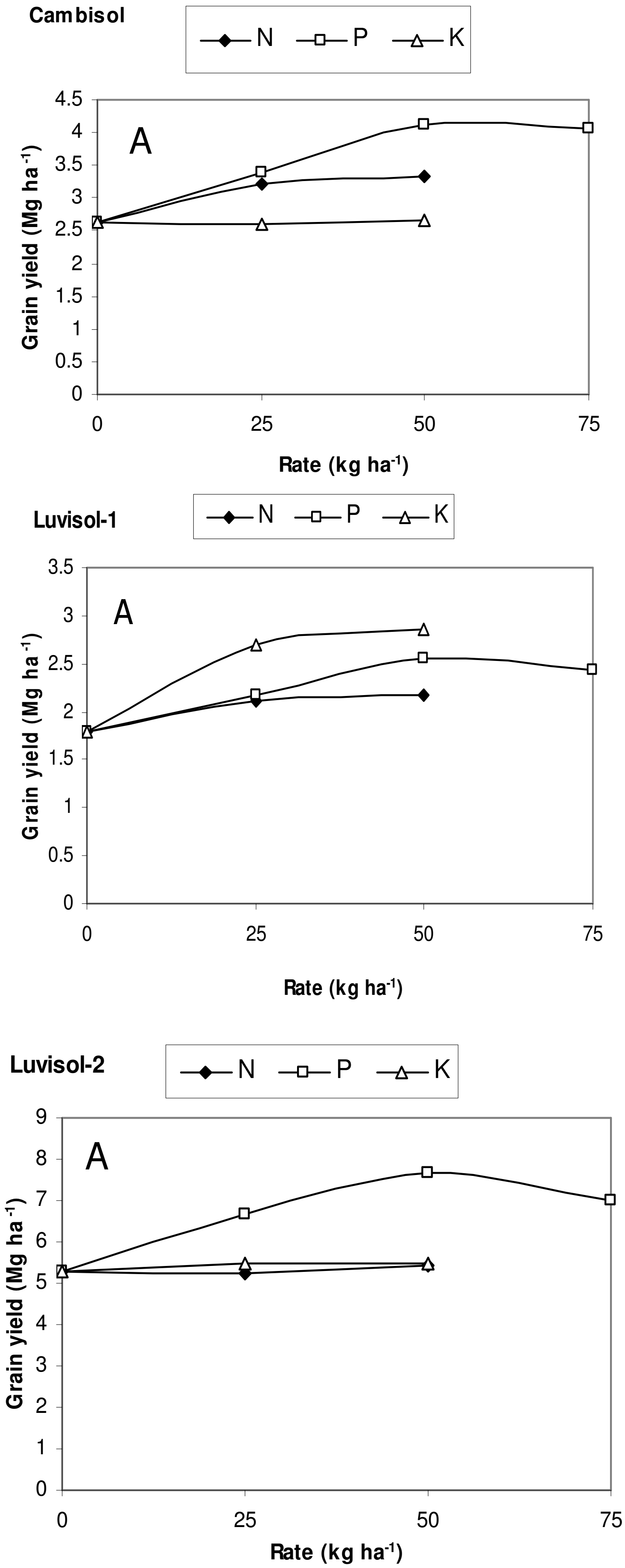

Figure 1. Grain yield in relation to fertilization rate of N, P and K.

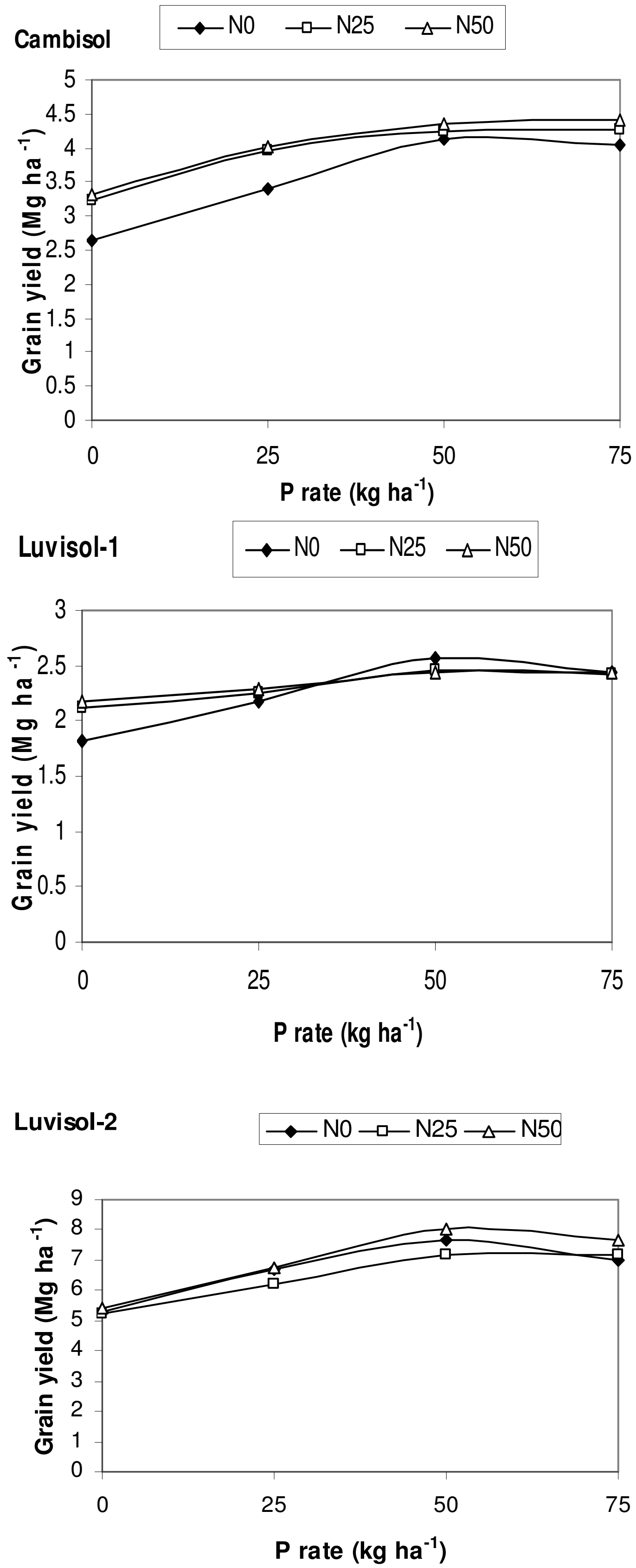

Figure 2. Grain yield in relation to fertilizer P for three levels of N fertilizer.

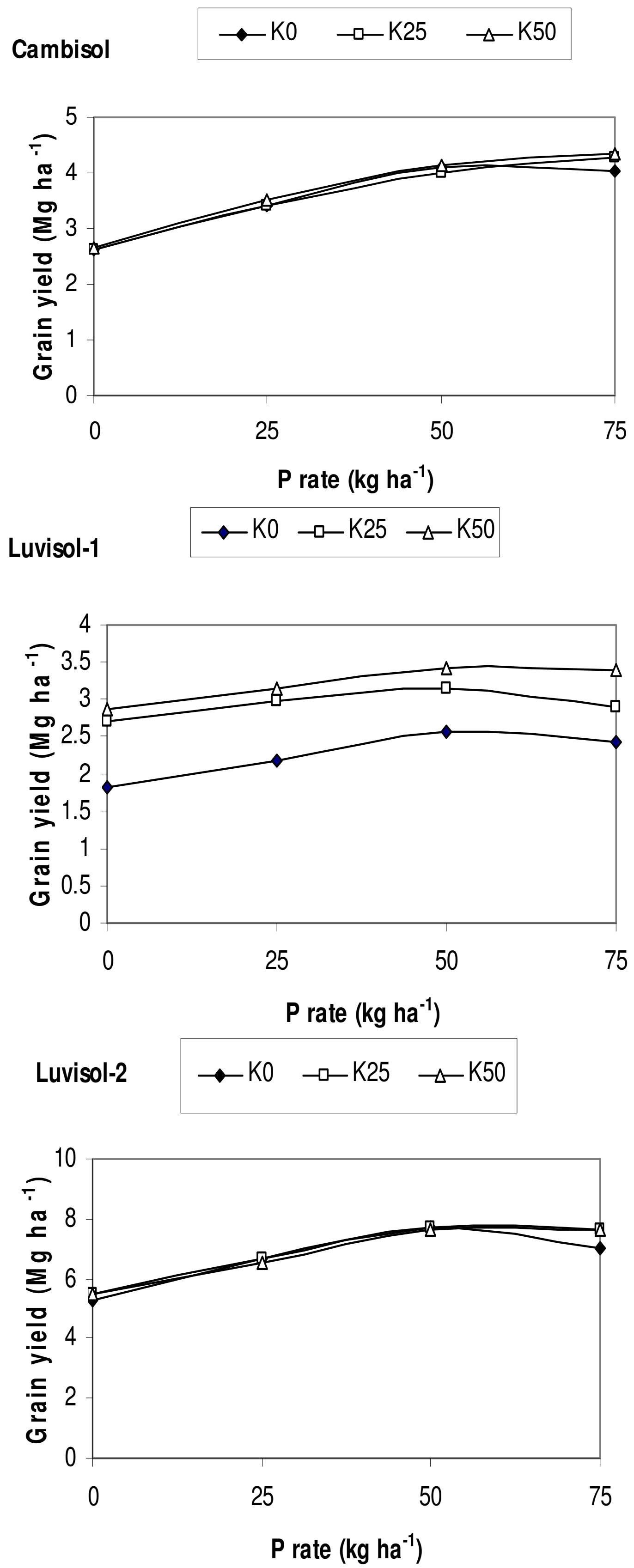

Figure 3. Grain yield in relation to fertilizer P for three levels of K fertilizer

limited by indigenous N and K supplies.

Recovery fraction

The N-recovery fraction varied between 0.39 in Luvisol-2 and 0.49 in Cambisol. The recovery fraction of P was between 0.08 in Luvisol-1 and 0.20 in Luvisol-2. The recovery fraction of K was between 0.57 in Luvisol-1 and 1.0 in Luvisol-2. Therefore, for barley in the Northern Highlands of Ethiopia, maximum recovery fractions of 0.5, 0.2 and 1.0 can be used for N, P and K, respectively.

Internal efficiency, agronomic efficiency and grain yield at maximum accumulation and maximum dilution

Internal efficiency

Average internal nitrogen use efficiency (Table 3) was higher in the Cambisol (43) than in Luvisol-1 (41) and Luvisol-2 (40) ($P<0.05$). Average internal phosphorus use efficiency was higher in Luvisol-1 (268) than in Luvisol-2 (254) and in the Cambisol (243) ($P<0.05$). Average internal potassium use efficiency was much higher in Luvisol-1 (89) than in Cambisol and Luvisol-2 (each 63) ($P<0.05$). For all of the three nutrients, average internal use efficiency was the highest in soil characterized by low indigenous contents of the respective nutrients (Table 3).

Agronomic efficiency

Average agronomic nitrogen efficiency (Table 4) was higher in the Cambisol (57) than in Luvisol-2 (44) and Luvisol-1 (35) ($P<0.05$). Average phosphorous agronomic efficiency was higher in Luvisol-2 (43) than in the Cambisol (35) and in Luvisol-1 (28) ($P<0.05$). Average agronomic potassium efficiency was higher in Luvisol-1 (58) than in the Cambisol (39) and in Luvisol-2 (40) ($P<0.05$). For all of the three nutrients, average agronomic efficiency was highest in soil characterized by low indigenous contents of the respective nutrients (Table 4).

Grain yield at maximum accumulation and maximum dilution

Average YNA (on Cambisol and Luvisol-1) in the 50 kg N treatments, without P and K fertilizers (Table 3), was 34 ('a'), whereas average YND (on Cambisol and Luvisol-1) was 52 ('d') both in kg kg^{-1} total N uptake in the above-ground plant DM in the treatments receiving 75 kg P and 50 kg K ha^{-1} without N fertilizer. Therefore, equations for YNA and YND (Figure 4A) for barley were defined as:

$$YNA = 34 \quad (10a)$$
$$YND = 52 \quad (10b)$$

Average YPA (on Cambisol and Luvisol-2) in the 75 kg P

Table 3. Internal nutrient use efficiency in three soils of Teghane, Northern Highlands of Ethiopia.

	Internal N use efficiency			Internal P use efficiency			Internal K use efficiency		
Application rate	**Cambisol**	**Luvisol-1**	**Luvisol-2**	**Cambisol**	**Luvisol-1**	**Luvisol-2**	**Cambisol**	**Luvisol-1**	**Luvisol-2**
N0,P0,K0	39	40	41	250	246	265	57	83	78
N0,P0,k25	38	38	40	278	277	243	71	77	65
N0,P0,K50	41	44	42	282	265	261	53	66	59
N0,P25,K0	45	36	42	262	198	272	69	81	58
N0,P25,K25	43	41	41	267	284	253	56	93	50
N0,P25,K50	43	43	39	217	321	305	68	86	ND
N0,P50,K0	47	46	44	206	208	283	67	144	92
N0,P50,K25	44	41	43	233	232	225	54	72	**44**
N0,P50,K50	48	44	44	257	289	265	62	98	51
N0,P75,K0	50	38	39	**175**	197	**190**	76	78	67
N0,P75,K25	46	44	44	221	275	245	59	84	72
N0,P75,K50	**52**	**51**	50	201	309	271	56	81	68
N25,P0,K0	41	39	37	304	274	265	69	78	81
N25,P0,K25	43	36	40	257	324	323	73	96	58
N25,P0,K50	38	46	35	294	**393**	**336**	60	101	86
N25,P25,K0	44	40	38	218	247	242	68	83	57
N25,P25, K25	44	40	39	189	250	246	63	71	45
N25,P25, K50	43	42	38	271	288	272	68	100	58
N25,P50,K0	41	37	40	214	247	257	70	103	60
N25,P50, K25	46	41	40	216	248	228	77	75	58
N25,P50,K50	48	40	41	205	223	246	57	65	76
N25,P75,K0	48	44	44	217	275	246	59	103	57
N25,P75, K25	45	41	37	211	270	259	55	92	75
N25,P75, K50	42	40	42	184	247	225	51	81	61
N50,P0,K0	**33**	**34**	35	274	299	323	76	118	39
N50,P0,K25	41	39	36	303	317	215	57	98	46
N50,P0,K50	36	37	38	299	330	310	63	91	54
N50,P25,K0	39	43	39	253	283	240	73	93	85
N50, P25, K25	44	37	44	257	258	225	76	64	48
N50, P25, K50	40	38	43	273	318	244	61	64	49
N50,P50,K0	42	39	42	295	248	245	66	104	86
N50, P50, K25	41	37	44	241	249	247	59	82	58
N50, P50, K50	40	44	40	243	222	221	38	79	51
N50,P75,K0	39	43	37	267	262	225	85	**150**	**104**
N50, P75, K25	41	39	38	209	255	245	48	77	68
N50, P75, K50	42	39	39	201	235	190	57	77	53
Average	43	41	40	243	268	254	63	89	63

Note: Bold figures are values used for grain yields at maximum accumulation and dilution

treatments without N and K fertilizers was 182 (‘a’), whereas average YPD (on Luvisol-1 and Luvisol-2) was 365 (‘d’),both in kg kg^{-1} total P uptake in the aboveground plant DM in the treatments receiving N25 and K50 kg ha^{1}. The equations for YPA and YPD (Figure 4B) were defined as:

Table 4. Agronomic efficiency (AE) of applied fertilizer in three soils of Teghane, Northern Highlands of Ethiopia.

AE of N				AE of P				AE of K			
Rates	**Cambisol**	**Luvisol-1**	**Luvisol-2**	**Rates**	**Cambisol**	**Luvisol-1**	**Luvisol 2**	**Rates**	**Cambisol**	**Luvisol-1**	**Luvisol-2**
N25,P0,K0	24	19	15	N0,P25,K0	31	14	56	N0,P0,k25	1	35	8
N25,P0,K25	22	28	19	N0,P25,K25	32	46	55	N0,P0,K50	0	39	4
N25,P0,K50	34	77	16	N0,P25,K50	35	53	50	N0,P25,K25	32	46	55
N25,P25,K0	53	23	35	N0,P50,K0	30	15	48	N0,P25,K50	18	63	Nd
N25,P25, K25	69	61	50	N0,P50,K25	28	27	49	N0,P50,K25	55	53	73
N25,P25, K50	54	34	61	N0,P50,K50	30	32	47	N0,P50,K50	30	68	47
N25,P50,K0	60	48	75	N0,P75,K0	19	8	28	N0,P75,K25	66	43	34
N25,P50, K25	69	46	78	N0,P75,K25	22	14	31	N0,P75,K50	34	64	47
N25,P50,K50	61	63	70	N0,P75,K50	23	18	31	N25,P0,K25	22	36	13
N25,P75,K0	65	35	76	N25,P25,K0	53	17	35	N25,P0,K50	17	63	3
N25,P75, K25	67	52	78	N25,P25, K25	69	38	50	N25,P25, K25	69	38	50
N25,P75, K50	69	63	67	N25,P25, K50	54	53	61	N25,P25, K50	27	63	30
N50,P0,K0	28	12	7	N25,P50,K0	30	13	37	N25,P50, K25	69	62	78
N50,P0,K25	35	19	20	N25,P50, K25	35	31	47	N25,P50,K50	30	88	47
N50,P0,K50	41	32	4	N25,P50,K50	30	52	47	N25,P75, K25	67	43	39
N50,P25,K0	56	26	29	N25,P75,K0	22	8	25	N25,P75, K50	35	73	47
N50, P25, K25	46	20	27	N25,P75, K25	22	14	31	N50,P0,K25	35	46	17
N50, P25, K50	64	37	25	N25,P75, K50	23	25	31	N50,P0,K50	20	60	4
N50,P50,K0	69	8	54	N50,P25,K0	56	19	58	N50, P25, K25	46	37	54
N50, P50, K25	74	26	47	N50, P25, K25	46	37	54	N50, P25, K50	32	71	25
N50, P50, K50	72	25	47	N50, P25, K50	64	68	49	N50, P50, K25	74	76	69
N50,P75,K0	71	18	47	N50,P50,K0	35	12	54	N50, P50, K50	36	60	47
N50, P75, K25	86	26	53	N50, P50, K25	37	38	47	N50, P75, K25	86	79	89
N50, P75, K50	90	38	47	N50, P50, K50	36	24	47	N50, P75, K50	45	90	47
				N50,P75,K0	16	8	31				
				N50, P75, K25	29	26	35				
				N50, P75, K50	30	36	31				
Average	57	35	44		35	28	43		39	58	40

Nd = no data

YPA = 182 (10c)
YPD = 365 (10d)

Average YKA (on Luvisol-2) in the 25 kg K and 50 kg P treatments without N fertilizers was 44 (‘a’), whereas average YKD (on Luvisol-1 and Luvisol-2) was 127 (‘d’), both in kg kg^{-1} total K uptake in the above ground plant DM in the treatments receiving 75 kg P and 50 kg N ha^{-1}. Thus, the equations for YKA and YKD (Figure 4C) were defined as:

YKA = 44 (10e)
YKD = 127 (10f)

The ranges for barley in this study between maximum accumulation and maximum dilution are relatively narrow compared to reported values for other cereals, for example maize (YNA-YND, YPA-YPD and YKA-YKD, respectively 30-70, 200-600 and 30-120 (Janssen et al., 1990)) and wheat (YNA-YND and YPA-YPD, respectively 26.8-59.8 and 161.7-390.5 (Pathak et al., 2003)), possibly because the genetic potential of the local land races is too low (Demeke et al., 1997) to respond well to the two extremes.

Grain Yield and Actual Uptake

Average grain yields (Mg ha^{-1}) varied from 2.93 on Luvisol-1 via 3.91 on the Cambisol to 6.82 on Luvisol-2 ($P<0.05$). TNU (kg ha^{-1}) in aboveground plant DM varied between 67.0 (control) and 115.4 ($N_{50}P_{75}K_{25}$) on the

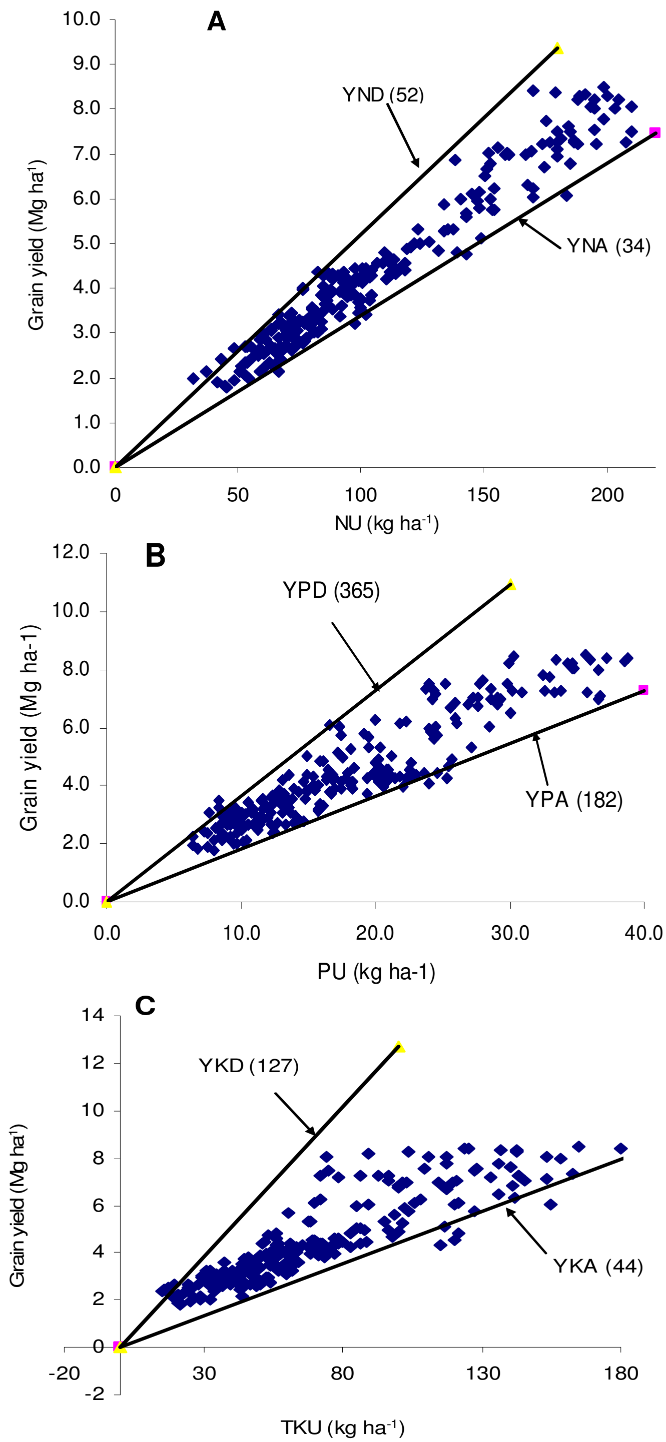

Figure 4. Relationship between grain yield (GY) of barley and total uptake of nitrogen (A), phosphorus (B) and potassium (C) in aboveground DM. YND, YPD and YKD = slope of the relation at maximum N, P and K dilution, respectively and YNA, YPA and YKA = slope of the relation at maximum N, P and K accumulation, respectively.

Cambisol, 45.0 (control) and 114.7 ($N_{50}P_{75}K_{50}$) on the Luvisol-1 and 129.1 (control) and 208.9 ($N_{50}P_{75}K_{25}$ and $N_{25}P_{75}K_{25}$) on Luvisol-2. Mean TNU (kg ha^{-1}) was much higher on Luvisol-2 (169.0) than on the Cambisol (92.0) and Luvisol-1 (72.5) (P<0.05).

TPU (kg ha^{-1}) varied between 9.4 ($N_0P_0K_{25\&50}$) and 24.2 ($N_{50}P_{75}K_{50}$) on the Cambisol, 7.4 (control) and 19.8 ($N_{25}P_{50}K_{50}$) on Luvisol-1 and 16.2 ($N_{25}P_0K_{50}$) and 40.3 ($N_{50}P_{75}K_{50}$) on Luvisol-2. Average TPU varied from 11.1 on Luvisol-1 via 16.7 on the Cambisol to 27.4 on Luvisol-2 (P<0.05).

TKU (kg ha^{-1}) varied between 36.7 ($N_0P_0K_{25}$) and 117.8 ($N_{50}P_{50}K_{50}$) on the Cambisol, 17.8 ($N_0P_{50}K_0$) and 67.9 ($N_{25}P_{50}K_{50}$) on Luvisol-1 and 68.2 (control) and 174.2 ($N_0P_{50}K_{25}$) on Luvisol-2. Average TKU varied from 35.0 on Luvisol-1, via 63.2 on the Cambisol to 112.9 on Luvisol-2 (P<0.05).

Conclusion

In this study, equations have been established to estimate indigenous soil nutrient supply from soil chemical properties for barley in the Northern Highlands of Ethiopia. Also some important parameters, such as effects of fertilizer application on yield, N, P and K uptake and recovery and use efficiency of barley in the Northern Highlands of Ethiopia have been estimated. OC-content of Luvisol-1 is 1.7 times that of the Cambisol (Table 1); while TNU of Luvisol-1 is only 67% of that of the Cambisol, as a result of its substantially lower value of exchangeable K, which negatively affects the uptake of other elements (Fitzpatrick, 1986). Similarly, the recovery fractions of applied N and P fertilizers are lower in Luvisol-1. In the Cambisol and Luvisol-2, indigenous exchangeable K is about 15 mmol kg^{-1} and TNU, TPU and TKU, and GY in treatments $N_0P_0K_{25}$ and $N_0P_0K_{50}$ are not different from those in the control treatments (P<0.05). On the other hand, in Luvisol-1, TNU, TKU and GY in treatments $N_0P_0K_{25}$ and $N_0P_0K_{50}$ are significantly higher than those in the control treatments (P<0.05). In this soil, application of 25 and 50 kg K ha^{-1} resulted in an increase of about 50% in TNU and GY, compared to the average of the control treatments, whereas application of K fertilizer in the Cambisol and Luvisol-2 gave no yield response, however, TKU has increased. In Luvisol-1, TNU, TPU and TKU in treatments receiving only N or P fertilizer were not different from those in the control (P<0.5).

Agronomic efficiencies of applied nutrients were different for different values of indigenous soil nutrient supply and different NPK combinations. Average agronomic efficiency of N was highest in the Cambisol, in which indigenous N, P and K supply are balanced, and was lowest in Luvisol-1 with low exchangeable K. The best combinations for maximum agronomic efficiency of N were $N_{50}P_{75}K_{50}$, $N_{25}P_0K_{50}$ and $N_{25}P_{50\&75}K_{25}$ in the Cambisol, Luvisol-1 and Luvisol-2, respectively. Average agronomic efficiency of P was highest in Luvisol-2, which is characterized by high OC and exchangeable K contents. The best combinations for maximum agronomic efficiency of P were $N_{25}P_{25}K_{25}$, $N_{50}P_{25}K_{50}$ and $N_{25}P_{25}K_{50}$ in the Cambisol, Luvisol-1 and Luvisol-2, respectively. Average agronomic efficiency of K was generally high in the Luvisol-1, characterized by low exchangeable K. The best combinations for maximum agronomic efficiency of K were $N_{50}P_{75}K_{25}$, $N_{50}P_{75}K_{50}$ and $N_{50}P_{75}K_{25}$ in the Cambisol, Luvisol-1 and Luvisol-2, respectively. Similarly, the best fertilizer combinations for maximum yield appeared different for soils with different indigenous nutrient supplies.

The results show that different rates of fertilizer application are required for different soils with different indigenous soil nutrient supplies for different objectives, i.e. either to attain maximum agronomic efficiency of a given nutrient or maximum yield. The coefficients used to quantify indigenous soil nutrient supply and parameterization of nutrient requirements of barley would help to consider different NPK combinations for different soils with differrent values of indigenous soil nutrient supply for targeted barley yields in the Northern Highlands of Ethiopia in stead of applying blanket fertilizer recommendation.

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