SOIL FERTILITY CHARACTERIZATION AND RESPONSE OF WHEAT (*Triticum aestivum)* AND TEFF (*Eragrostis tef*) TO DIFFERENT RATES OF SLOW RELEASE AND CONVENTIONAL UREA FERTILIZERS IN VERTISOLS OF OFLA DISTRICT, SOUTHERN TIGRAY, ETHIOPIA

MSc THESIS

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Soil Fertility Characterization and Response of Wheat (*Triticum aestivum)* and Teff (*Eragrostis tef*) to Different Rates of Slow Release and Conventional Urea Fertilizers in Vertisols of Ofla District, Southern Tigray, Ethiopia

A Thesis Submitted to the College of Agriculture and Environmental Sciences, School of Graduate Studies

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By

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As thesis research advisors, we hereby certify that we have read and evaluated the Thesis entitled "Soil Fertility Characterization and Response of Wheat (*Triticum aestivum)* and Teff (*Eragrostis tef*) to Different Rates of Slow Release and Conventional Urea Fertilizers in Vertisols of Ofla District, Southern Tigray, Ethiopia" prepared under my guidance by Okubay Giday, and recommend that it be submitted as fulfilling the thesis requirement.

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As members of the Board of Examiners of the MSc Thesis Open Defense Examination, we certify that we have read and evaluated the Thesis prepared by Okubay Giday and examined the candidate. We recommend that the Thesis be accepted as fulfilling the thesis requirement for the degree of Master of Science in Agriculture (Soil Science).

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DEDICATION

This thesis manuscript is dedicated to his love, Ms. Eyerusalem Egjgu, who paved the way toward this MSc. study.

STATEMENT OF THE AUTHOR

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BIOGRAPHICAL SKETCH

The author was born on November 20, 1985 in Adigrat, Eastern Zone of Tigray Region. He attended his elementary and junior secondary education at the Agaizi Elementary and Junior Secondary School in Adigrat and his senior secondary education at the Agaizi Secondary High School in the same place. After completing his secondary school education, he joined the Hawassa University in September 2006 and graduated with BSc degree in Natural Resource Management in July 2009.

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LIST OF ACRONYMS AND ABBREVIATIONS

AE	Agronomic efficiency
ANOVA	Analysis of variance
AR	Apparent N recovery
Apr.	April
Aug.	August
AP	Available phosphorus
BD	Bulk Density
ODOARD	Ofla District office of agriculture and rural development
CEC	Cation exchange capacity
CSA	Central Statistical Authority
CV	Coefficient of variation
CU	Conventional urea
ΔC	Cost of each rate subtracted from cost of the control
DH	Days to 50% heading
DM	Days to 90% physiological maturity
DZARC	Debre Zeit Agricultural Research Center
Dec.	December
Feb.	February
FAO	Food and Agriculture Organization
GN	Grain nitrogen
GY	Grain yield
Go	Grain yield of the unfertilized plot
Gn	Yield of the plot fertilized at ‘n’ fertilizer rate
HI	Harvest index
ha	Hectare
ΔI	Income of each rate subtracted from the income of the control
IPCC	Intergovernmental Panel for Climate Change
CIMMYT	International Center for Maize and Wheat Improvement
Jan.	January
LSD	Least significant difference
Mar.	March
MRR	Marginal rate of return
masl	Meters above sea level
NUE	Nitrogen use efficiency
Nov.	November
NFTP	Number of fertile tillers per plant
GP	Number of grains per spike
S/0.5m	Number of spikes per 0.5 m
NSP	Number of spikes per 0.5 m length
Un	Nutrient uptake at ‘n’ level of fertilizer nutrient
Uo	Nutrient uptake at the control plot
Oct.	October

OC	Organic carbon
OM	Organic matter
PL	Panicle length
PD	Particle Density
PBS	Percentage base saturation
PE	Physiological Efficiency
PH	Plant height
Sep.	September
SRU	Slow release urea
SL	Spicke length
S/S	Spikelets per spike
SE	Standard error
SN	Straw nitrogen
SY	Straw yield
SAS	System Analysis System
TGW	Thousand grains weight
TBY	Total biological yield
TNU	Total nitrogen uptake
TSP	Triple super-phosphate

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ABSTRACT

Nutrient losses due to leaching, volatilization , fixation and the activated risk of nitrate leaching after fertilizer addition to the soil may be reduced through the use of slow-release fertilizers. A fresh soil profile pit was opened and representative soil samples were collected from the profile and surface (0-15 cm) soil of the experimental area to characterize the fertility status of the soils of the study area on the base of selected physicochemical properties. Moreover, a field experiment was conducted during the main rainy season of the 2011 at Ofla testing site to determine the optimum rates and overall performance of slow release urea (SRU) fertilizer over conventional urea (CU) fertilizer for bread wheat and teff production. The field experiments comprised of 5 treatments for each experimental field, i.e three rates of slow release urea at 23, 46 and 69 kg N ha^{-1}, recommended rate 46 kg N ha^{-1} of conventional urea fertilizer and control (without any N fertilizer) laid down in a randomized complete block design with three replications. All experimental units were supplied with a uniform rate of 46 kg P ha^{-1}in the form of triple super phosphate (TSP) at planting time. At harvest, the crop were partitioned in to straw and grain for the determinations of N concentrations, uptakes and calculation of N fertilizer recoveries and use efficiencies. The soil textural class of the surface layer (0-25 cm) of the profile and the mean composite surface (0-15 cm) soil samples of the wheat and teff experimental plots were clay loam while it was clay for the subsurface (25-150^{+}cm) layers of the profile. The bulk and particle density values increased consistently with depth of the profile ranging from 1.18 to 1.32 and 2.51 to 2.85 g cm^{-3}, respectively. The OM (0.05 to 4.39%), available P (0.86 to 22.50 mg kg^{-1}) and total N (0.03 to 0.23%) of the soil profile decreased consistently with depth while pH (6.5 to 8.20) value increased with depth. Application of different rates and sources of N fertilizer significantly ($P \leq 0.01$) affected most the crop parameters tested. The significantly different and maximum plant height (109.67 and 112.33 cm), fertile tillers per plant (7.00 and 22.67), number spikes 0.5m (83.3), spikelets per spike (15.33) and spike or panicle length (9.67 and 52.00 cm) were obtained from application of the highest SRU rate (69 kg N ha^{-1}) whereas the lowest records were obtained from the control plot of wheat and teff crops, respectively. Similarly, the maximum grain yield (4720.00 and 3443.67 kg ha^{-1}), straw yield (7529.67 and 6208.33 kg ha^{-1}), total biomass (12249.67 and 9652.00 kg ha^{-1}) and 1000 grains weight (43.65 and 0.35 g) were obtained from the application of the highest SRU rate showing a decreasing trend with declining N rate with the lowest obtained from the control plots of wheat and teff, respectively. Application of SRU fertilizer has also affected the grain and straw N contents and uptakes of both crops. These showed increasing trend with increasing N rate where the maximum records in both crops were obtained at the highest rate of SRU (69 kg N ha^{-1}). In both crops, the application of 46 kg N ha^{-1} of SRU fertilizer has yield advantage of 497.67 and 462.00 kg ha^{-1} over the application of 46 kg N ha^{-1} of CU fertilizer for wheat and teff crops, respectively. This shows that SRU can reduce N losses by leaching in the form of NO_3^-, fixation as NH_4,volatilization as NH_3 and atmospheric emission in the form of N_2O or N_2. For both crops, the application of 46 kg N ha^{-1} SRU was the optimum rate.

1. INTRODUCTION

Declining soil fertility has continued to be a major constraint to food production in many parts of the tropical region. The low soil fertility in the tropics has been attributed to the low inherent soil fertility, loss of nutrients through erosion and crop harvests and little or no addition of external inputs in the form of organic or inorganic fertilizers (Mureithi *et al*., 2000). This is particularly evident in the intensively cultivated areas, traditionally called high potential areas that are mainly concentrated in the highlands of Ethiopia. These imply that the outflow of nutrients in most smallholder farms far exceeds inflows.

To address the problems of soil fertility, several technological interventions, especially those geared towards nutrient management and soil moisture conservation, have been suggested (Mureithi *et al*., 2000). Besides, the productivity of some soils is constrained by some other limiting factors eventhough they have high potential productivity or are naturally fertile. In this regard, Vertisols are important agricultural soils where primarily poor drainage and difficult workability limit nutrient availability and productivity, calling for proper soil fertility and water management practices (Desta, 1986).

In Ethiopia, Vertisols are widely and intensively utilized soil types covering 11% or 12.7 million hectares (ha) of the totarl land mass and is the fourth important major soil group (Mesfin, 1998). More than half (8.6 million ha) of the Vertisols are found in the central highlands with altitude of more than 1500 meters above sea level (masl). Generally, Vertisols have high montmorillonitic clay known for its shrink-swell properties in response to changes in soil moisture content. Vertisols produce large cracks that are closed only after prolonged rewetting and thus become hard when dry and very sticky and plastic when wet. These soils are also characterized by the presence of gilgai micro-relief or subsoil showing slickensides or spheroid structure due to contraction and expansion processes during drying and wetting (Probert *et al.*, 1987). Vertisols generally have weak horizon differentiation, low hydraulic conductivity, low infiltration rate and high moisture retention capacity ranging from 60 to 70% at field capacity because of their high clay content. The pH of Vertisols in some highland areas of the country vary from slightly acidic to strongly alkaline, of course depending on different factors (Eylachew, 2000).

Many soils in the highlands of Ethiopia are inherently poor in available plant nutrients and organic matter (OM) content (Tekalign *et al.,* 1988; Asnakew *et al.,* 1991). Tekalign *et al*. (1998) also reported that the Ethiopian highland Vertisols tend to exhibit low total nitrogen (N) and OM contents, and application of N fertilizer is considered essential to improve cereal crops production on these soils. However, cereal-dominated cropping systems, aimed at meeting farmers' subsistence requirements, coupled with low usage of chemical fertilizers have led to a widespread depletion of soil nutrients in the major cereal crops growing regions of the country. Heavy rains during the part of the main cropping season (June to August) also cause substantial soil nutrient losses due to intense leaching and erosion on Nitisols and denitrification on the frequently water-logged Vertisols (Asnakew *et al.,* 1991). Hence, series of experiments have been carried out on Vertisols to study the effects of N and phosphorus (P) fertilizers on crop yields and substantial yield increments have been recorded with proper management of these nutrient elements (Desta, 1986).

The crops that are commonly grown on Vertisols in Ethiopia are teff, barley, bread wheat, chickpea, lentil and noug (Desta, 1986). Wheat is one of the major cereal crops in the Ethiopian highlands that lie between latitude of 6^0 and 16^0 north and longitude of 35^0 and 42^0 east and is widely grown from 1500 to 3000 masl. The most suitable areas for wheat production, however, fall between 1900 and 2700 masl (Hailu, 1991). According to CSA (2011), the total wheat cultivated area in Ethiopia in the Meher (main rainy) season of the 2010/2011 was 1,553,240 ha. The total production for the same season was 2,855,686 tons, with national mean wheat yield of 1.84 tons ha^{-1} which is still considerably below the yield level obtained from experimental fields. Therefore, the yield gap suggests that there is a potential for increasing its total production and productivity per unit area through improved crop management practices, particularly by means of increased use of mineral and/or organic fertilizers .

Teff (*Eragrostis tef (Zucc*.) Trotter) is a small-grained cereal that has been grown as food crop in East Africa for thousands of years (D'Andrea, 2008). Teff is adapted to a large variety of environmental conditions and widely grown from sea level up to 2800 masl under various rainfall, temperature and soil conditions (Seyfu, 1997). According to CSA (2011), the total teff cultivated area in Ethiopia in the Meher (main rainy) season of the 2010/2011 was 2,761,190 ha. The national total production of teff for the same season was 3,483,488 tons, with national mean teff yield of 1.26 tons ha^{-1} which is still considerably below the yield level obtained from experimental fields. Therefore, the yield gap suggests that there is a potential for increasing its total production and productivity per unit area through improved crop and soil management practices, particularly by means of increased use of mineral and/or organic fertilizers.

Soil degradation and depletion of soil nutrients are among the major factors threatening sustainable cereal production in the Ethiopian highlands. Among the major plant nutrients, N is the most limiting factor calling for external inputs in the form of fertilizer for profitable cereal crop production in most agro-ecological zones. However, conventional N fertilizers are highly soluble and, once applied to the soil may be lost from the soil-plant system or made unavailable to the plants through the processes of leaching, NH_3 volatilization, denitrification, immobilization and fixed in the soil solids as NH_4-N form (Bock, 1984). The N recovery by crops from the soluble N fertilizers such as urea is often as low as 30–40%, with a potentially high environmental cost associated with N losses via NH_3 volatilization, NO_3^- leaching and N_2O emission to the atmosphere (Zhou *et al*., 2003).

In order to improve urea-N recovery and reduce its loss, many forms of slow-release urea fertilizers have been developed and applied to different plant species under a range of environmental conditions. The products may be coated, chemically and biochemically modified, or are granular (Jiao *et al*., 2004). Such slow release urea fertilizers can increase the efficiency of applied urea-N and are environmentally friendly because their N release is in synchrony with plant N uptake, and in a single application, can provide sufficient N to satisfy plant N requirements while maintaining very low concentrations of mineral N in soil throughout the growing season (Bacon, 1995).

The use of slow-release urea fertilizer sources is a common strategy to reduce N losses in horticultural crops, but its agronomic performance and cost-effectiveness for field crops has not been well established particularly in Ethiopia. Therefore, this study was conducted with the following specific objectives:

- To characterize the fertility status of the soils in the study area based on selected soil physiochemical properties,
- To evaluate the overall performance of applying slow-release urea fertilizer over the conventional urea fertilizer for wheat and teff production, and
- To determine optimum rates of slow-release urea fertilizer for wheat and teff productivity.

2. LITERATURE REVIEW

2.1. Soil Physical Properties

The physical properties of a soil have much to do with its suitability for the many uses to which it is allocated. The rigidity and supporting power, drainage and moisture storage capacity, plasticity, ease of penetration by roots, aeration and retention of plant nutrients are all intimately connected with the physical condition of the soil. It is, therefore, pertinent that those dealing with soils should know to what extent and by what means these soil properties can be altered and or managed for better productivity and profitability. This remains valid whether the soil is to be used as a medium for plant growth or as a structural material or any other functions (Brady and Weil, 2002).

2.1.1. Soil Texture and Structure

Soil texture is an inherent and relatively permanent property of a given soil. It is an important soil characteristic because it greatly modifies water intake rates (infiltration), water storage in the soil, the ease of tilling the soil, soil aeration and the availability of oxygen to plants, root penetration and growth and soil fertility (Brady and Weil, 2002). The nutrient holding ability of a given soil varies with the textural class and with the type of clay mineral in the colloidal fraction. In heavy clay soils such as Vertisols, oxygen availability to the crop is limited by excess water retained by these soils, as both water and air compete for the same space. Moreover, the rates of many important chemical reactions in soil are governed by soil texture because it determines the amount of surface area available for reaction (Brady and Weil, 2002).

Belay (1997) and Mohammed *et al.* (2005) reported that the soil textural class varied with positions of soils in the landscape where coarser materials were found in the upper slope positions and the finer materials in the lower part of the slope position. Belay (1996) revealed that Vertisols in the lower toe slopes were much heavier than those on the upper parts and this was mainly attributed to the relatively finer texture of the fresh alluvium reaching the lower slope positions and its more intense weathering due to higher moisture supply at the site.

Soil structure is one of the important physical properties of the soil, which is easily affected by land use/land cover and management practices. Consequently, changes in soil structure because of different management systems have pronounced effects on bulk density, porosity, aeration, infiltration, water storage capacity; the degree of resistance the soil has to erosion and formation of good seed bed to initiate plant growth (Sims, 2000; Wakene, 2001). Mishra *et al.* (2004) described that because of the presence of considerable amount of organic carbon in the surface layer; most of the soils of the Ethiopian highlands (under sub-humid climate) consist of granular structure with mollic properties. The subsurface horizons show sub-angular blocky followed by prismatic structures.

2.1.2. Particle and Bulk Densities

Soil particle density is the ratio of the mass to the volume of soil particles (soil solids). For many mineral soils, the particle density ranges from 2.60 to 2.75 g cm^{-3}. It does not vary a great deal for different soils unless there is considerable variation in OM content and mineralogical composition of the soil (Brady and Weil, 2002). Some mineral top soils which are high in OM (15-20%) may have a particle density as low as 2.40 g cm^{-3} or even less. Hence, particle density values indicate the rough level of OM content of the soil. However, for general calculations, the average arable mineral surface soils having 3-5% OM are assumed to have a particle density of about 2.65 g cm^{-3} (Brady and Weil, 2002).

Bulk density value is expressed as the ratio of oven dried soil to its total volume as it exists naturally including any air space and organic materials in the soil volume. It can be used to determine if the soil is too compacted to prevent root penetration and adequate aeration or porous enough to allow it. It is also needed for calculation of total soil water storage capacity per soil volume (Brady and Weil, 2002). Bulk densities of soil horizons are inversely related to the amount of pore space and soil OM content. Textural variations also influence the value of bulk density. For example, clay, clay loam and silt loam surface soils show low bulk density values (1.0 to 1.6 g cm^{-3}) as compared to sands and sandy loam soils which show high bulk density values (1.2 to 1.8 g cm^{-3}) (Landon, 1991).

Eylachew (2000) reported that the bulk density values of Vertisols described at Ginchi, Sheno and Alemaya areas ranged from 0.96 to 1.70 g cm^{-3} and they showed an increasing trend down the profile with the exception of the soil at Ginchi which exhibited decreasing pattern with soil depth. In another study, Abayneh (2001) also revealed that the bulk densities of the surface layers of Vertisols profiles described at the valley bottom of the Raya Valley ranged from 1.00 to 1.13 g cm^{-3}.

2.1.3. Total Porosity

Soil porosity is the part of the soil volume, which is not occupied by solid particles, but filled with water and air. The size distribution of the individual pores gives valuable information about soil aeration and soil moisture characteristics. For instance, the percentage volume occupied by small (micro) pores in sandy soils is low, which accounts for their low water holding capacity but good aeration due to high percentage of the micro pores.. In contrast, fine textured surface soils have more total pore space, and relatively large proportion of micro pores. Therefore, such soils have high water holding capacity but both water and air pass through these soils with difficulty because of very few large pores (Brady and Weil, 2002).

Total porosity of soils usually lies between 30 to 70% and may also be used as a very general indication of the degree of compaction where management exerts a decisive influence on it as in the case with bulk density (Brady and Weil, 2002). Sands with a total pore space of less than about 40% and clay soils with less than 50% are liable to restrict root growth due to excessive strength (Landon, 1991).

2.2. Soil Chemical Properties

Soil chemical properties encompasses these properties which are responsible and take part in the chemical reactions and processes of the soil. These are the results of weathering of their mineral components, decomposition of organic materials and the activity of plants and animals pertaining to plant and animal growth and human development (Sims, 2000). Some of these soil chemical properties are soil reaction (pH), soil OM content, total N, phosphorus, cation exchange capacity (CEC) and exchangeable cations (Ca, Mg, K, Na, H and Al). A generalized statement of the chemical properties of Ethiopian Vertisols is that they have low organic carbon and total N contents, near neutral to alkaline soil reaction, high CEC and high exchangeable bases, Ca and Mg being the most dominant cations (Eylachew, 2000).

2.2.1. Soil Reaction (pH)

Soil reaction (pH) is probably the most commonly measured soil chemical property and is also one of the most informative. Soil pH indicates the state of weathering of a given soil. In slightly weathered soil, the surface soil pH is neutral to slightly alkaline (Tisdale *et al.,* 1997). However, the pH of soil also depends on the parent material from which the soil is derived. Globally most Vertisols, being derived from basic rocks such as basalts and limestone, are usually slightly acidic to neutral and alkaline in reaction. The most important factors for alkalinity are the weathering processes of basic element rich minerals and irrigation water of high salt mainly bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) ions. According to Eylachew (2000), Vertisols characterized in different parts of the country have shown pH ranges of 6.3 to 7.6 on the surface layer and 6.8 to 8.5 in the underlying layers.

In general, soil pH has significant importance in soil plant relationships as it determines the solubility and availability of plant nutrients, lime requirement of soils, root activity of higher plants and the performance (population and activity) of beneficial soil microorganisms. Particularly, the activity of N fixers and nitrifires are seriously depressed in strongly acidic and strongly alkaline soils (Tisdale *et al.,* 1997).

2.2.2. Soil Organic Matter

Kapkiyai *et al.* (1998) indicated that soil organic matter (OM) content is a critical component of soil productivity and its maintenance is a sound approach to maintaining productivity of continuously cropped soils. The same publication showed that changes in soil OM results from imbalances between organic inputs and losses, and declining soil OM are frequently observed when lands are converted from natural vegetation to agriculture. Tisdale *et al.* (1997) pointed out that had it not been for soil OM, there would hardly be life in soil. Management of crop residues and returning farm wastes to cultivated fields form essential components of soil OM and thus, soil fertility management for sustainable agriculture. Besides serving as a major natural source of plant nutrients in the soil, organic matter acts as a soil conditioner. Consequently, it increases the cation exchange capacity, moisture holding capacity, porosity and aeration (Berhanu, 1978). In addition, it has a large contribution to the kind and degree of structure development, structure stability and consequently to the resistance of soils to erosion.

Soil OM, in the highlands of Ethiopia is susceptible to form a complex with smectite caly mineral, resulting in its further decomposition and thus the formation of humus remains arrested (Mishra *et al*., 2004). The same authors showed that the rate of organic matter decomposition is also slow due to the presence of volcanic ash materials as well as low mean soil temperature (below 30 ^{o}C), where in microbial activities are restricted. The decomposing crop residues maintain soil fertility by releasing the essential nutrients absorbed by the plants except the amount translocated to the seeds. However, retention of crop residues in the highlands of the country is unthinkable owing to the current imbalanced demand and supply of livestock fodder (Selamyihun, 2004).

Organic matter levels of Vertisols are usually low particularly when they are continuously cultivated. According to Mohammed (2003), the amount of soil OM showed great variability as a result of differences in land use/land cover conditions, and altitude and slope positions. The same author reported that OM content of Vertisols varied from low in the surface layers to very low in the underlying horizons. On the other hand, Yihenew (2002) reported that OM contents of Vertisols of Bichena and Woreta Research testing sites were 4.65 and 5.00%, respectively, which were rated as medium. Eylachew (1999) in his study of the major soils of the Chercher Highlands also revealed that the Typic Pellustert (calcic Vertisols) have also medium OM content (4.88%).

2.2.3. Total Nitrogen

Nitrogen is the most limiting nutrient in the tropics and critical shortage of this nutrient brings significant grain/biomass yield reduction (Yihenew, 2002). Most Ethiopian black or dark grey soils are N-depleted and more than 50% of cultivated lands are N-responsive soils (Mishra *et al*., 2004). Variation in contents of total N is closely related to the contents of OM, which is its major source, and thus, the source of its variability (Mohammed *et al*., 2005). In general, in surface soil layers, OM and total N content increase with increasing elevations while in the subsoil horizons the contents of these parameters do not reveal consistent relationship with elevation in the soils at the western slopes of mount Chilalo (Ahmed, 2002).

Total N content in the top 15 to 20 cm of surface soils ranges from 0.01% (or even less in desert soils) to more than 2.5% in peats (Tisdale *et al.,* 1997). The same authors also indicated that N content in the subsurface of any soil is generally less than its content in the surface layer since most organic residues are deposited on the soil surface.

According to Berhanu (1978), total N contents of Vertisols of the Central highlands and Eastern lowlands of Ethiopia varied from 0.08 to 0.22% and the C: N ratio was about 11-18. The wide range in C: N ratio was attributed to low N content that might be caused by microbial immobilization, denitrification losses resulting from poor drainage, leaching losses and less OM input. Furthermore, other research works (Tekalign *et al.,* 1988; Mesfin, 1998; Eylachew, 2000; Mohammed, 2003) conducted in Ethiopia on Vertisols also indicate that N is the most deficient nutrient element than any other essential element in these soils and has called for the application of inorganic fertilizers and need for a sound management of soil OM.

2.2.4. Available Phosphorus

Phosphorus (P) is a critical element in natural and agricultural ecosystems and its management need is second only to the need for the management of N for the production of healthy plants and profitable yields (Brady and Weil, 2002). However, the forms of P that occur in soil parent materials are generally of low availability to plants (Tamirat, 1992). This low available P infertility is recognised as one of the most limiting factors in plant growth and productivity on a worldwide basis in general and remains to be one of the major nutrient constraints in the rainfed upland farming systems throughout the tropics (Birru and Heluf, 2003). As a result, P has become to be known as the master key to agriculture because lack of available P in soils has limited the growth of both cultivated and uncultivated plants of considerable areas worldwide (Tisdale *et al.,* 1997).

The association of available P with that of the total soil P is controlled by different soil factors and chemical environments (Mishra *et al.*, 2004). The most labile soil P that is the immediate source of P for crop uptake is largely influenced by the initial P concentration, sorbing capacity of the soils and exposure time of the applied P to the adsorbing minerals (Birru and Heluf, 2003). According to Mishra *et al.* (2004), P in the Ethiopian soils poses different scenario wherein only a very low fraction of total P is available to plants. Eylachew (1987) reported that the average total P content for soils of the eastern highlands of the country revealed 0.05%. On the other hand, Ahmed (2002) showed that the average available P contents in the topsoil's of the western slopes of mount Chilalo) areas increased with increasing elevation.

Phosphate is strongly adsorbed on the surfaces of clay by replacement of OH^- from clays (Tisdale *et al.,* 1997). Available P was high at the upper most horizon of soil profile and decreased further with depth (Mulugeta, 2000) due to fixation by clay and Ca, which were found to increase with profile depth in vertisol under lowland conition of Fogera plain, northern Ethiopia . Soils containing large quantities of clay fix more P than soils with low clay content. In other words, the more surface area exposed with a given type of clay, the greater is the tendency to absorb P (Tisdale *et al.,* 1997). However, for the Vertisols, the effect of clay on phosphate is not ascribed to a direct relation between clay and phosphate but to the swelling nature of the clay. Increasing clay content is likely to be associated with the development of severe and prolonged anaerobic conditions which severely restrict P uptake by the plant.

2.2.5. Cation Exchange Capacity

Next to photosynthesis and respiration, no process in nature is more vital to plant and animal life than the exchange of ions between soil particles and plant roots via the soil solution (Brady and Weil, 2002). Tisdale *et al.* (1997) have stated that ion exchange in soils occurs on surfaces of clay minerals, inorganic compounds, OM, and plant roots. Cation exchange capacity (CEC) is the sum of the exchangeable cations that a soil or other material can absorb at a specific pH (Foth and Ellis, 1997) and CEC is commonly expressed as centimole of positive charge per kilogram (coml(+) kg^{-1}). Cation exchange capacity is important for both soil fertility and recent nutrition studies and for soil genesis and thus widely used in soil classification (Tisdale *et al.*, 1997).

Generally, the type and texture of a soil developed on a given region is largely governed by the predominant clay mineral contained in it. Therefore, the CEC of soils varies with its texture, mineralogy and OM contents. Thus, sandy soils have lower CEC values than clayey soils because the coarse-textured soils are commonly lower in both clay and humus that are electrically charged (usually negatively) and these attract positively charged ions in the soil solution. Likewise, a clay soil dominated by 1:1 type silicate clays and Fe and Al oxides have much lower CEC than the one with similar humus content but dominated by smectite clays (Brady and Weil, 2002). In this regard, Vertisols typically have high clay contents and dominated by smectite clay mineralogy, so that the exchange capacity is usually high (20 to 80 coml(+) kg^{-1}). According to Eylachew (2000), the Vertisols identified at Wonji, Ginchi, Sheno and Alemaya areas were found to have high CEC values commonly ranging from 37 to 67 coml(+) kg^{-1}).

2.2.6. Exchangeable Bases

The levels of exchangeable cations in a soil are usually of more immediate value in advisory work than the CEC because they not only indicate existing nutrient status, but can also be used to assess balances amongst cations. This is of great importance because many effects, for example on soil structure and on nutrient uptake by crops, are influenced by the relative concentrations of cations as well as their absolute levels (Landon, 1991).

Different land use systems, intensive cultivation and soil depth have been reported to affect exchangeable bases. Accordingly, Wakene (2001) reported that the surface horizons of soils in baco area contained the highest exchangeable Ca in the intensively cultivated and virgin land than the currently abandoned and land left fallow for fifteen years as compared to their respective subsurface horizons. Similarly, exchangeable Mg was the highest in the surface soil on the intensively cultivated research field, virgin land and the land under fallow for twelve years. Tamirat (1992) also reported that exchangeable K was higher in the surfaces or the upper sub-surface layers of the soils than in the deep soils.

In general, soils under continuous cultivation, application of inorganic N containing fertilizers, high exchangeable and extractable Al and low pH are characterized by low contents of Ca and Mg nutrient containing minerals and Ca and Mg deficiency due to excessive leaching. However, virgin and/or grazing lands and areas under long year of fallow practices Vertisols (Tamirat, 1992; Eylachew, 2001) retain more basic cations, which are mainly dominated by exchangeable Ca and Mg.

2.3. Nitrogen Nutrition, Crop Growth and Yield Response to N Fertilization

2.3.1. Nitrogen Nutrition and Importance in Plants

Nitrogen (N) plays a vital role in all living tissues of the plant and in increasing crop yield. No other element has such an effective role on promoting vigorous plant growth. Abundant protein tends to increase the size of the leaves, and accordingly, to bring about an increase in carbohydrate synthesis (Peter *et al.,* 1988). High N supply favors the conversion of carbohydrates into proteins, which in turn promotes the formation of protoplasm (Arnon, 1972; Gooding and Davies, 1997; Brady and Weil, 2002). Nitrogen making up 1 to 4% of plant dry matter and being the essential consistent of protein; it is involved in all major processes of plant development and yield formation (Arnon, 1972; Gooding and Davies, 1997).

Nitrogen exerts its influence on crop growth in various ways. In small cereal crops, leaf area is usually increased by N application (Langer and Liew, 1973). Similarly, Hay and Walker (1989) explained that the primary effect of additional N on wheat is to increase crop photosynthesis by increasing leaf area index and leaf area duration. This is due to an increase in the number of tillers, the total number of leaves and also increased leaf expansion.

According to Langer and Liew (1973), cereal crops require sufficient N throughout all developmental stages of growth to ensure maximum leaf area index and leaf area duration to attain maximum grain yields. Generally, early N application promotes leaf area index while late application prolongs leaf area duration i.e. delay leaf senescence and the potential hotosynthetic capacity of crop is raised. Besides to these, good supply of N to crop stimulates root growth and developments as well as the uptake of other nutrients (Brady and Weil, 2002). Similarly, Gooding and Davies (1997), making more N available to deficient plants increases chlorophyll contents and leaf greener particularly the older leaves, increase leaf size, delay senescence, stimulates tillering and increase height.

When plants are deficient in N, they become stunted and yellow in appearance. The loss of protein N from chloroplasts in older leaves produces the yellowing or chlorsis indicative of N deficiency. Chlorosis usually appears first on lower leaves, the upper leaves remain green while under severe N deficiency, lower leaves will turn brown and die. This necrosis begins at the leaf tip and progresses along the mid rib until the entire leaf is dead (Tisdale *et al.*, 1997). The younger leaves retain their N and in addition, obtain N translocated from older leaves (Devlin and Witham, 1996). According to Bruggs (1978), N deficiency reduces tillering due to retarded appearance of lateral bud, limited root growth and small and weak shoots whose leaves contain reduced levels of chlorophyll and carotenoids. In general, deficiency of N during the early stages of tiller development is detrimental (Devlin and Witham, 1996).

2.3.2. Effects of N on Wheat and Teff Growth Parameters

The positive responses of cereal crops to increasing N have been among others associated with increase in number of tillers (Power and Alessi, 1978). Hussain *et al*. (1993) reported that increasing N application increased the number of fertile tillers per unit area of bread wheat. Similarly, Power and Alessi (1978) indicated that N promotes rapid growth and increases tiller production of the same crop. Consequently, an increase in grain yield with N application is resulted from increased tiller number. Ejaz *et al*. (2002) have also confirmed that the number of tillers per plant of wheat increased with increasing rate of applied N.

Moreover, Evans (1975) and Baethgen and Alley (1989) indicated that lower N rates resulted in reduced number of tillers, and lower tillers number of wheat was associated with reduced yield. For this reason, N availability at tillering is important for development of plant density that is sufficiently large to utilize moisture, light, and nutrient efficiently during grain filling. Tillering of wheat has been reported to increase with increasing light and N availability during vegetative phase depending on varieties in which the stimulation effect of N on tillering may be due to its effect on cytoknin synthesis (Mengel and Kirkby, 1996).

According to Mengel and Kirkby (1996), N fertilization of cereal crops causes increment in tiller population density and tiller fertility, with overall effect determined by the rate and the time of application. Consequently, with few exceptions, increased N application gives increased head population density at harvest. The same authors have also indicated that accurately timed application of fertilizer reduces mortality of tillers, presumably because terminal spikelets mark the beginning of the most rapid phase of crop growth, when intra-plant competition for N is not greatest.

El-Karamity (1998) elaborated that applied N rates significantly affected the number of bread wheat plants per meter square which increased from 189.8 in the control (plot without N fertilizer) to a maximum of 351.4 with the application of 200 kg ha^{-1} of N. Similarly, Ejaz *et al*. (2002) observed higher productive tillers of wheat with 160 kg N ha^{-1} than in the control. This is attributed to proper vegetative and reproductive growth which ultimately resulted in increased number of productive tillers per m^2.

With regards to the effect of applied N on plant height, El-Karamity (1998) reported the tallest (82.2 cm) plants of wheat at the highest N rate (200 kg N ha^{-1}) and the shortest (65.6 cm) was recorded at the control plots. Nitrogen fertilizer applied at 80 kg N ha^{-1} resulted in taller plant of the some crop than the lower N rates (Amanuel *et al*., 2002).

Sufficient N results in rapid growth and hastens maturity, too little N slows growth and delays maturity, whereas excess N encourages continued vegetative growth of cereals which results in delayed flowering and maturity (Cook and Ellis, 1992). An adequate supply of N is associated with high photosynthetic activity; vigorous vegetative growth and dark green color. An excess of N in relation to other nutrients such as P, K and S can delay maturity. If N is used properly in conjunction with other needed soil fertility inputs, it can speed up the maturity of crops such as corn and small grains (Tisdale *et al*., 1997).

2.3.3. Effects of N Fertilizer on Wheat and Teff Yield Components

2.3.3.1. Tillers, number of spikes, spikelet per spike, spike and panicle length

Tilahun *et al*. (1995) reported that grain yield is closely related to the number of spikes per unit area. Fertilized plots of wheat produced more spikes than the control. Such response can be attributed to the adequate N availability which might have facilitated the tillering ability of the plants resulting in a greater spike population. Ayoub *et al*. (1994) also reported that spike population of bread wheat increased with increase in the level of applied N fertilizer. Similarly, Hay and Walker (1989) explained that N fertilization increases spike density of wheat at harvest because of increased fertile tillers.

Power and Alessi (1978) observed that for wheat crop no more than one spike is produced per stem and the number of heads per unit area is highly dependent on the use of higher N rate to promote the initiation, survival and development of secondary tillers. Application of N resulted in more grain production per spike as compared to the control (Ayoub *et al*., 1994). However, at higher doses of N grain production per spike of wheat did not differ significantly from that of the non-fertilized plots. Ejaz *et al*. (2002) elaborated that when N becomes low, spikelet per spike decreased due to unavailability of the required amount of N for vegetative growth and reproductive growth of plants. Similarly, the findings of a study conducted by Whing and Kemp (1980) revealed that spikelet numbers of wheat increased with increasing applied N rate, due to increased spikelet primordial production.

According to Ejaz *et al*. (2002), at higher dose of N, spike length becomes higher due to the available N in significant quantity to keep the plant health, which ultimately resulted in increased spike length corresponding to the amount of fertilizer used when compared to the non fertilized wheat crops. Maximum spike length of wheat which was obtained at higher dose of N, gives raise to high number of spikelets and more number of grains per spike indicating that better partioning of assimilates during the vegetative phase (El-Karamity, 1998). Tilahun *et al*. (1995) reported that both spike numbers and grain weight of wheat were increased with increasing levels of N fertilizer. Frederick and Marshal (1985) elaborated that at some point; the N efficiency tends to decrease with increasing rate of N and such inefficient use of N is apparently associated with decreased kernel weight.

Tilahun *et al*. (1995) found that fertilized plots of bread wheat produced higher tillers and more spikes than the control and stressed that grain yield is closely related to the number of spikes per unit area. Ayoub *et al*. (1994) also reported that spike population of wheat increased with increased N fertilization which is mainly because of increased fertile tillers. El-Karamity (1998) found maximum spike length of wheat which gives rise to more spikelets and grains per spike indicating better partitioning of assimilates during the vegetative phase on plots supplied with higher doses of N fertilizer.

Application of higher rates of N fertilizer increases the number of panicles per unit area of teff by increasing the number of productive tillers (Legesse, 2004). Among the yield components of teff, panicle length is highly correlated with grain yield and it is the most important factor that causes variation in grain yield (Mulugeta, 2003). Likewise, tillers are another yield attributes (components) of teff that are associated with grain yield. Application of excessive amount of N has a detrimental effect on panicle length growth which in turn reduce grain yield of teff (Tekalign *et al*., 2000; Mulugeta, 2003). In general, plant height, panicle length and number of tillers per plant are the most responsive yield components to N rate in teff (Tekalign *et al*., 2000).

2.3.3.2. Influence of N on dry biomass and harvest index of wheat and teff crops

The total dry matter produced by a plant as the result of photosynthesis and nutrient uptake, minus that lost by respiration is called biological yield (Ayoub *et al*., 1994). The biological yield of wheat increases as amount of N applied was increased from the control level to highest rate. Similarly, Hussins and Pan (1993) observed that dry matter production of wheat increased with increased N levels. El-Karamity (1998) also indicated that straw yield ha^{-1} was significantly increased at highest nitrogen levels compared with those at lowest levels and such increase in straw yield at higher N rates is probably due to increased height and tillering capacity of this crop.

Increasing N fertilizer rates to an optimum level for cereal crops commonly increases biological yield. Biological yield, which is the total dry matter produced by a plant as the result of photosynthesis and nutrient uptake minus that lost by respiration, usually responds positively to increasing levels of applied N. El-Karamity (1998) indicated that straw yield of wheat was significantly increased at highest N level compared with those at lower levels. According to Sorour *et al*. (1998), increased grain yield of wheat with increased N application was resulted from an increase in one or more of the important yield components. According to Ejaz *et al.* (2002), the beneficial effects of N on grain yield of wheat could be seen through more fertile spikes, spike lengths, number of productive spikelets, grains per spike and 1000 grain weight .

Sorour *et al*. (1998) ascribed that poor grain yield of wheat was recorded, at the lowest spike length, number of spikes per spike, number of grains per spike, number of spikes per m^2 and lowest protein percentage. Moreover, application of high levels of N to wheat crop on Vertisols and Nitisols in the Central Highlands of Ethiopia had significantly increased grain and biomass yields (Amsal *et al.*, 2000) and grain and straw N contents (Amsal and Tanner 2001).

Similarly, An increase in nitrogen fertilizer rate was reported to increase dry matter accumulation in teff. Straw yield and total above ground biomass yield were significantly affected by nitrogen rate (Tilahun, 1995; Mulugeta, 2003). High straw, total above ground biomass and grain yields of teff were recorded when high (90 kg ha^{-1}) amount of nitrogen fertilizers was applied (Tekalign *et al.,* 2000). Nitrogen is important factors in determining of teff grain yield (Tekalign, *et al.*, 2000). Increasing N fertilizer increases dry matter accumulation in teff which is ascribed to an increase in length of leaves and elongation of stem and panicles (Legesse, 2004; Mulugeta, 2003).

Results of several studies have shown that application of N tends to increase the biomass of different crops. Successive increase in N levels increased dry matter accumulation and straw yield of teff (Tekalign, *et al.*, 2000; Mulugeta, 2003). It is quite natural that increasing levels of applied N increased grain yield (Tekalign *et al.*, 2000) due to an increase in yield components. The increase in yield components was the result of better nutrition or N uptake of crop (Rathore *et al*., 1991; Tekalign *et al*, 2000) which led to greater dry matter production and its translocation to the sink (Dala and Dixit, 1987; Tekalign, *et al.*, 2000). However, increasing N supply beyond the optimum requirement of crops resulted in a decline of grain yield (Singh *et al.*, 1994; Tekalign *et al.*, 2000).

The report of DZARC (1989) indicated that the response of teff grain and straw yield to N fertilizer application on a Vertisols was highly significant. Accordingly, the highest mean grain yield of teff was obtained under the application of 92 kg N ha^{-1} which was not significantly different from the yield obtained with the application of 69 kg N ha^{-1}. The highest mean straw yield of the same crop was also obtained by applying 92 kg N ha^{-1} which was significantly different from the immediate lower rate (69 kg N ha^{-1}) of N applied (DZARC, 1989).

The term harvest index (HI) is defined as the ratio of grain yield (dry basis) to aerial dry matter yield (Hussins and Pan, 1993). Moreover, Donald and Hamblin (1976) reported that grain yield of wheat was proportional to harvest index while biomass yield and HI are uncorrelated. Further, they stated that factors which make up grain yields such as grain weight and grains per spikelete have a relatively higher effect on HI. Hussins and Pan (1993) reported that the HI of wheat is around 0.34 in traditional cultivars and about 0.44 in improved new varieties.

2.3.4. Effect of N Fertilization on Wheat and Teff Grain Yield

The highest grain yield of any crop is the result of all positive relationships of the yield components (Sorour *et al*., 1998). Some yield components may decrease due to N supply but the decline is usually more than off-set through its increase in other components, therefore, the total grin yield increases (Donald and Hamblin, 1976). The beneficial effects of N on grain yield of wheat could be seen through more fertile spikes, spike lengths, number of productive spikelets, grains per spike and 1000 grain weight (Ejaz *et al.,* 2002). In addition to that, grain yield can be increased by increasing floret survival by avoiding carbon-water and nutrient (particularly N) limitation (Mengel and Kirkby, 1996). On the other hand, the poorest grain yield of wheat recorded can be ascribed to lowest spike length, number of spikelet/spike, number of grains/spike, number of spikes/m^2 and lowest protein percentage (Sorour *et al*., 1998). According to Asnakew *et al*. (1991) grain yield of bread wheat was significantly increased with application of N up to 90 kg N ha^{-1} and still showed that an increasing trend with N rate up to 180 kg N ha^{-1}.

The effects of N on grain and dry matter yields were found to be significant and increased as applied N levels raised up to 200 kg N ha^{-1} for durum wheat (Samuel, 1981). He revealed that as N levels increased from 0 to 200 kg N ha^{-1}, the corresponding grain yields were increased from 800 to 2300 kg ha^{-1}. In another study conducted by Tilahun (1995), application of 120 kg N ha^{-1} gave the highest durum wheat yield of 2284 kg ha^{-1}. The same author reported that the highest yield of teff often resulted from higher N rate and it had significant effects on grain number such that high N rate gave greater number of grains per meter square. The application of high rate of N fertilizer increased the number fertile panicle of teff (Mulugeta, 2003). The responses to N rate was highly dependent on seasonal conditions especially rainfall amount and distribution. This may be due to reduced efficiency in N uptake from the soil caused by different losses especially through denitrification (Troeh *et al*., 1993).

The high yield of teff under N application is the result of better nutrition and utilization or N uptake (Tekalign *et al*., 2000; Mulugeta, 2003). This leads to greater dry matter production, accumulation and its translocation to the sink organ (Dalal and Dixit, 1987). However, increasing N beyond the maximum nutrient requirement level of the crop resulted in marginally increasing or declining grain yield (Singh and Pillai, 1994).

2.4. Nitrogen Uptake, Recovery and Use Efficiency

Apparent recovery is a measure of the ability of the crop to extract N from the soil. Agronomic efficiency measures the dry matter assimilated in the grain in response to applied fertilizer while physiological efficiency can be termed as utilization efficiency (grain yield per total N in the plant) and measures the capacity of the plant to convert the already absorbed N in the plant in to grain yield (Moll *et al*., 1982).

Nitrogen use efficiency (NUE) can be defined as the product of uptake efficiency (total N uptake per applied N through fertilizer) and utilization efficiency (yield per total N uptake) (Moll *et al*,. 1982; Ortiz-Monasterio *et al*., 1997). According to Wuest and Cassman (1992), N uptake is rapid from stage 2 to 4 (tillering to booting) and 80% of total accumulation occurs by the seventh stage (anthesis complete). Over 70% of the total N uptake will be translocated to grain at maturity. The NUE is a useful index for evaluating the impact of fertilizer management practices (timing, placement, source and rate) and cropping systems on the percentage of applied N taken up by the crop. This parameter is especially useful for comparing management practices that may affect N availability to plants and/or soil N losses or additions.

Ortiz-Monasterio *et al*. (1997) explained that NUE of 45% or lower generally reflect limited plant growth associated with plant diseases, poor soil drainage, or some other limiting factors. The amount of N applied depends upon the yield level of the crop and apparent N recovery. Hobbs *et al*. (1997) envisage that a wheat crop yielding 7.0 tons (t) ha^{-1} might require 330, 254 and 206 kg N ha^{-1} provided it shows 50, 65 and 80% apparent N recovery, respectively. Wuest and Cassman (1992) found recovery of N applied at planting ranged from 30 to 55%, while recovery of N applied at anthesis ranged from 55 to 80% in irrigated wheat. According to the same authors, the amount of fertilizer N applied at anthesis had the greatest influence on post-anthesis N uptake, which ranged from 17 to 77 kg N ha^{-1}. This shows that late N application can be efficiently taken up by plants. Grain protein levels of wheat may increase with late-season N applications (Wuest and Cassman, 1992).

Nitrogen compounds for grain growth are mainly supplied by the vegetative aerial parts (65–80%); the remainder originating from uptake and reallocation by the roots after anthesis (Hobbs *et al*., 1997). Peter *et al.* (1988) also explained that N concentrations in grain and straw of wheat increased with added N and reached their highest levels at recommended rates of N fertilizer. Applying more fertilizer N than recommended increased neither wheat crop N uptake nor grain yield.

2.5. Slow Release Urea Fertilizer as a Strategy to Reduce N Loss

Inefficient fertilizer use may contribute to environmental degradation, particularly in intensive agricultural systems where the recovery or use efficiency of nutrients by crops is relatively low. For example, it is estimated that NUE for cereal production worldwide is only 33% (Raun and Johnson, 1999). A portion of the N not used by the crop is presumed to be lost to the environment through denitrification, runoff, volatilization, leaching, fixation as NH_4-N in soil solids and gaseous plant emissions. Such losses raise concerns about surface and groundwater contamination, and greenhouse gas emissions.

Slow release urea (SRU) fertilizers are fertilizers designed to slowly release nutrients at a rate that matches the demand of the crop plants. Such products can be used to maximize fertilizer use efficiency and minimize potential losses to the environment. Increased nutrient use efficiency may also increase yield and quality of crop products, thus providing an increased economic benefit for growers. There have been a limited number of published findings of studies that investigated the benefits of SRU on large acreage agricultural crops. The publications that exist generally indicate that there is significant additional value in using SRU under most conditions. For example, N fertilizer application rates on cotton may be reduced by 40% if controlled release fertilizers rather than the conventional N fertilizers are used (Howard and Oosterhuis, 1997).

Nitrous oxide (N_2O) has been identified as a major greenhouse gas and also as an ozone depleting substance. Within the North and Central America, about 54% of N_2O–N emitted is attributed to fertilizer additions (IPCC, 1996). The processes by which N_2O is produced in soil are transient, and quantification and management thereof are complicated. The Intergovernmental Panel on Climate Change (IPCC) has proposed various strategies for reducing N_2O emissions from fertilizer applications (IPCC, 1996). One proposed approach is to adopt advanced fertilizer technologies such as the use of nitrification inhibitors and controlled release fertilizers (Mc Taggart *et al.,* 1994). Slow release fertilizers can reduce N_2O emissions by releasing N closer to the time of plant uptake and therefore limiting the amount of N exposed to denitrifying conditions.

3. MATERIALS AND METHODS

3.1. General Description of the Study Area

The field experiment was conducted during the 2011 main cropping season under rainfed conditions at farmer's training center in Ofla District, Southern Zone of Tigray Regional State (Figure 1). Ofla District, one of the six districts of the Southern Zone, is located about 620 km north of Addis Ababa and about 150 km south of Mekelle city. The study District has about 133,296 ha of land area and the altitude varies between 1700 and 2800 masl whilst the slope ranges from 2 to 35% (ODOARD, 2011).

The study area is characterized by a bimodal rainfall pattern with the main wet season (*kiremt*) extending from July to September and the small wet season (*Belg*) which extends from March to May. The area is characterized by heavy and erratic rainfall distribution. The ten years (2002-2011) mean annual rainfall is 980.5 while the annual rainfall in 2011 was 1050 mm (Appendix Table 1). Similarly, the mean maximum and minimum temperatures were 22.28 and 7.69 ^{0}C, respectively (Appendix Tables 2 and 3). Vertisols, are the dominant soil types in the area. The area has crop-dominated mixed crop-livestock farming system. The dominant crops growing around the experimental area are wheat (*Triticum aestivum* L.), maize (*Zea mays* L.), barley (*Hordeum vulgare*), teff (*Eragrostis tef*) and some species of legume crops (ODOARD, 2011).

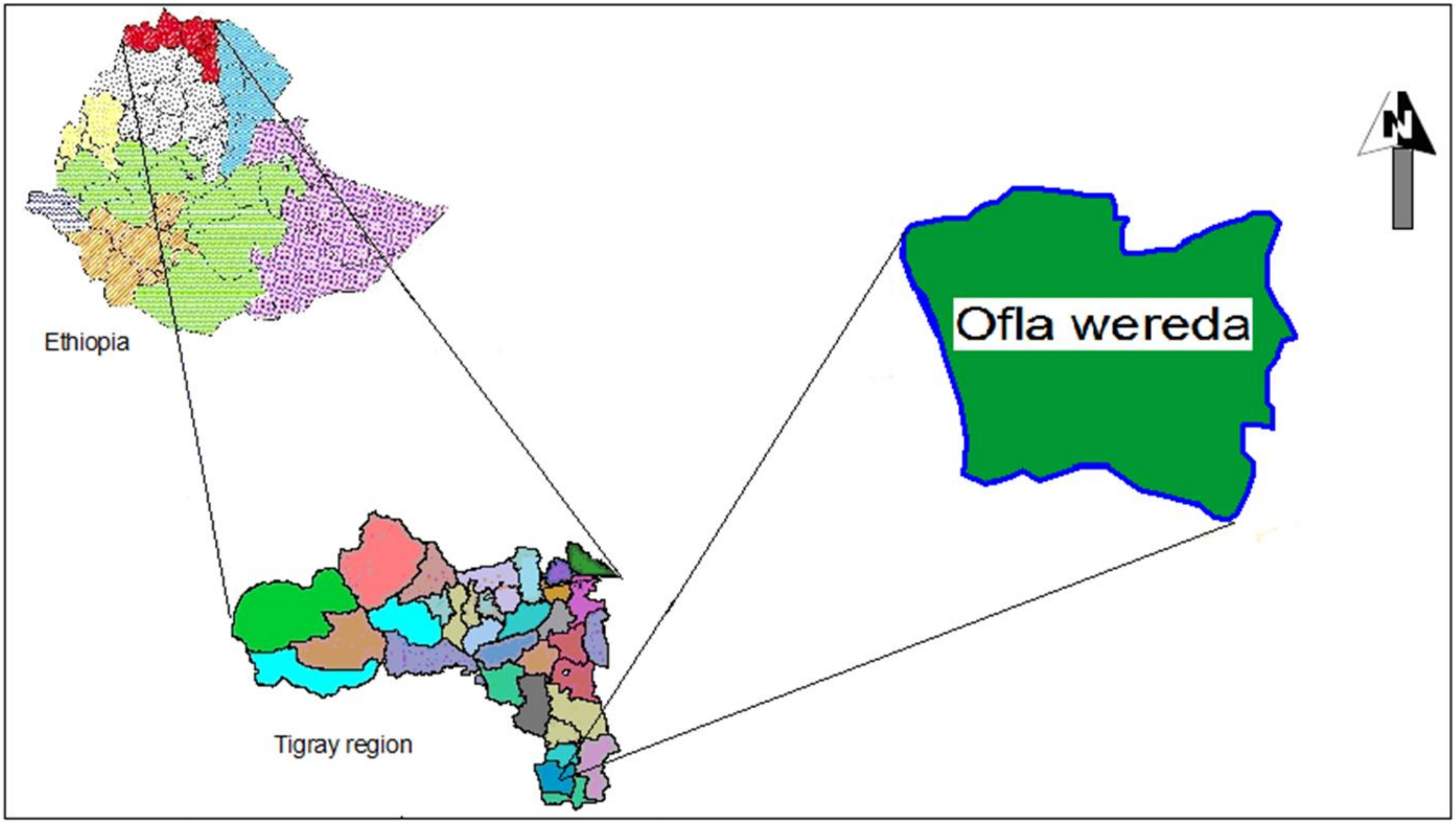

Figure1. Location map of the study area

3.2. Experimental Materials, Treatments and Design

The field experiment comprised of 5 treatments for each experimental plots (wheat and teff), i.e. three rates of slow release urea fertilizer at 50 kg (23 kg N ha^{-1}), 100 kg (46 kg N ha^{-1}) and 150 kg (69 kg N ha^{-1}) kg ha^{-1}, recommended N rate at 100 (46 kg N ha^{-1}) from conventional urea fertilizer and control (without any N fertilizer). The field experiments were laid down in a randomized complete block design with three replications. All experimental unites were treated with a uniform rate of 46 kg P_2O_5 ha^{-1}in the form of triple super phosphate (TSP) at planting time. An improved wheat crop variety known as HAR-1685 and teff variety known as DZ-cr-387 (kuncho teff) were sown by hand drilling at a rate of 150 and 5 kg seed ha^{-1}, respectively, and were used as test crops.

3.3. Experimental Procedures and Field Management

The experimental plot was prepared using local plow (maresha) pulled by oxen according to farmers' conventional practice. Accordingly, the field was plowed three times before sowing. The plot size was 4 m x 3 m (12 m^2) each containing 15 planting rows of 4 m length at a spacing between rows of 20 cm for both crops. The plots within a block were separated by 0.5 m whereas the blocks were separated by 1 m wide open space area. The net plot size was 3 m x 2.6 m (7.8 m^2) leaving one outer row on both sides of each plot and 0.5 m row length at both ends of the rows to avoid possible border effects. The slow release urea fertilizer was incorporated 3-4 cm deep into the soil with 5 cm distance from the planting raw at the time of sowing while the conventional urea fertilizer was applied in two equal splits, the first half at the time of sowing and the second half was top-dressed at the mid tillering stage of the crops. Furthermore, during the different growth stages of the crops, all the necessary agronomic practices were carried out accordingly.

3.4. Soil Sampling, Sample Preparation and Analysis

3.4.1. Surface Soil and Profile Sampling and Sample Preparation

A fresh soil profile pit with 1 m width, 2 m length and 1.5 m depth was excavated at a point representative for the adjacent experimental plots of wheat and teff. The soil profile was described morphologically under field condition and sampled depth-wise (layers) for characterization of some selected physicochemical properties. Moreover, before sowing, surface soil samples (0-15 cm depth) were collected using Auger from eight to ten spots from each block to form one composite soil sample per block for soil fertility evaluation. Undisturbed (core) soil samples were also collected using core samplers for soil bulk density determination.

The composite surface soil and soil profile samples collected were air dried in wooden material, ground and sieved to pass through a 2 mm sieve in preparation for laboratory analysis. Finally, the samples (surface and profile) were analyzed in the laboratory (National Soil Testing Center) for texture, particle density, bulk density and total porosity (physical properties), and for pH, OM, total N, available P, CEC and exchangeable bases (Ca, Ma, K and Na) among the soil chemical properties.

3.4.2. Analysis of Soil Physical and Chemical Properties

Soil particle size distribution (texture) was analyzed by the Bouyoucos hydrometer method following the procedure described by Bouyoucos (1962). Bulk density was determined from the undisturbed (core) soil samples collected using core samplers, weighed at field moisture content and then dried in an oven at 105 ^{0}C (Baruah and Barthakur, 1997). Similarly, particle density was measured by the Pycnometer method. Finally, soil total porosity was estimated from the bulk density (BD) and particle density (PD) values as:

$$Total\,porosity\,(\%) = \left(1 - \frac{BD}{PD}\right) \times 100$$

Soil pH was measured potentiometrically using a pH meter with combined glass electrode in 1: 2.5 soils: water ratio suspension as described by Carter (1993). The Walkley and Black (1934) wet digestion method was used to determine soil organic carbon content and percent soil OM was obtained by multiplying percent soil organic carbon by a factor of 1.724. Similarly, total N was analyzed using the Kjeldahl digestion and distillation method as described Jackson (1958) by oxidizing the OM in concentrated sulfuric acid solution (0.1N H_2SO_4) and converting the nitrogen into NH_4^+ as ammonium sulfate. Determination of available P was carried out by the Olsen method using sodium bicarbonate as extracting solution (Olsen *et al.*, 1954).

The exchangeable bases (Ca, Mg, K and Na) in the soil were determined from the leachate of 1 molar ammonium acetate (NH_4OAc) solution at pH 7.0. Exchangeable Ca and Mg in the extract were measured by atomic absorption spectrophotometer whilst K and Na were read using flame photometer from the same extract (Rowell, 1994). Similarly, CEC was measured after leaching the ammonium acetate extracted soil samples with 10% NaCl solution and determining the amount of ammonium ion in the percolate by the Kjeldahl procedure and reported as CEC (Hesse, 1972).

Finally, the fertility status of the soil of the experimental field (study area) was evaluated based on the concentrations of the respective parameters (both physical and chemical properties) obtained from the laboratory analyses. In other words, the results of the soil analysis were compared with established ratings and/or critical levels or limits for different classes of the respective plant nutrient elements in evaluating the fertility status of the soils studied.

3.5. Crop Data Collection

Days to 50% seedling emergence, days to 50% heading and to 90% physiological maturity were recorded when the plants in each plot reached the respective phonological stages. Numbers of fertile and non fertile tillers per plant were counted from 10 main stands which were tagged before tillers appeared, at the period of heading and at maturity, respectively. Average heights of main stems of wheat were measured from ten main plants by measuring from the ground level to the tip of the spike excluding the awns at harvest while the average height of main stems of teff was measured at heading and physiological maturity by measuring using measuring tape from the ground level to the tip of the panicle.

The number of spikes per 0.5 m length of wheat was obtained by counting the total number of spikes in four 0.5 m row length. Number of spikelets per spike of wheat was taken as the average from 10 random plants by counting the spikelet per spike and dividing by the spikes sampled. Numbers of kernels was taken as average number of grain per spike of 10 random wheat plants and expressed as average number per plant. The weight of thousand kernels was determined by measuring the weight of 1000 kernels randomly taken from the total grains harvested from each experimental plot and it was adjusted at 12.5% moisture content by using Dicky John hand moisture tester instrument.

Grain yield was determined by harvesting the crop of the entire net plot area (inclusive of plant sample for yield components and laboratory analysis) and was adjusted to 12.5% moisture content. The total above ground biomass was determined by weighing the straw and grain yields for each plot. Harvest index was calculated as a ratio of grain yield to the total above ground biomass multiplied by 100% at 12.5% moisture content (singa, 1977).

3.6. Plant Tissue Sampling and Analysis for Nitrogen Content

Plant samples were collected from each plot at harvest and partitioned into vegetative and grain for the determinations of N concentrations in grain and straw and calculation of N fertilizer recoveries and use efficiencies. The samples collected from each replication of a treatment were bulked to give one composite plant tissue sample per treatment. The straw samples were washed with distilled water to clean the samples from contaminants such as dust. Then the samples were oven dried at 70 ^{0}C for 24 hours or to constant weight and ground and sieved through 0.1 mm size sieve and saved for laboratory analysis. The N contents of the grain and straw samples were determined following the wet digestion method, which involves the decomposition of the plant tissues and grain using various combinations of HNO_3, H_2SO_4 and $HClO_4$. From the digest, N was measured using the Kjeldahl procedure.

Total N uptakes in straw and grains were calculated by multiplying the N contents by the respective straw and grain yields per hectare. Total N uptakes by the whole plant were determined by summing up the respective grain and straw N uptakes on hectare basis. Finally, apparent fertilizer N recoveries (AR) were calculated by the procedure described by Pal (1991) as:

$$AR = \left(\frac{U_n - U_0}{n}\right) * 100$$

where U_n stands for nutrient uptake at 'n' level of fertilizer nutrient and U_o stands for nutrient uptake at the control or 'no fertilizer' case. Similarly, agronomic use efficiencies (AE) and physiological use efficiencies (PE) of N fertilizers were calculated using the procedures described by Mengel and Kirkby (1996) and Woldeyesus *et al.* (2004) as follows:

$$AE = \left(\frac{G_n - G_0}{n}\right)$$

$$PE = \left(\frac{G_n - G_0}{U_n - U_0}\right)$$

where G_n stands for grain yield of the plot fertilized at 'n' fertilizer rate and G_o for grain yield of the unfertilized plot. The notations U_n and U_o stand for the N nutrient uptake in the two fertilization cases as described earlier.

3.7. Partial Budget Analysis

Variable cost of N fertilizer was used for the partial budget analysis**.** Marginal rate of return, which refers to net income obtained by incurring a unit cost of fertilizer, was calculated by dividing the net increase in yield of wheat and teff crops, due to the application of each rate to the total cost of N fertilizer applied. This enables to identify the optimum rate of N fertilizer for wheat and teff crops production. The marginal rate of return (MRR) for both crops were calculated as follows:

$$Marginal\ Rate\ of\ Return\ (MRR) = \left(\frac{\Delta I}{\Delta C}\right) * (100)$$

Where ΔC stands for cost of each rate subtracted from cost of the control and ΔI for income of each rate (Birr/ha) subtracted from the income of the control.

3.8. Statistical Analysis

The yield and other crop data were subjected to analysis of variance (ANOVA) appropriate to randomized complete block design using SAS software program (SAS Institute, 2000). The analysis results of the soil and tissue samples were interpreted using descriptive statistics. Comparisons of means were performed using the least significant difference (LSD). Pearson's simple linear correlation coefficient (r) values were computed to examine the magnitude and direction of relationships between the different crop yield and yield components.

4. RESULTS AND DISCUSSION

4.1. Characterization of the Soil of the Study Area

4.1.1. Physical Properties of the Soil

4.1.1.1. Texture

Apparently, particle size distribution has important bearing in soil water movement, aeration, root extension, oxidation-reduction processes and nutrient and OM contents as well as composition. In the present study, the texture of the surface layer (0-25 cm) of the profile and the average of the composite surface (0-15 cm) soil samples of both wheat and teff experimental plots were clay loam (Table 1). However, the texture changed to clay in the subsurface layers of the soil profile opened adjacent to the experimental plots. Generally, the soil profile contained more than 30% clay throughout (> 50% clay below the plow layer) and had intersecting slickenside's and cracks (Appendix Table 4) which open and close periodically suggesting the presence of Vertic horizon. The proportions of clay and silt within the profile ranged from 32 to 52% and from 23 to 35%, respectively, whereby the silt fraction and the silt to clay ratio decreased consistently with increasing soil depth (Table 1). On the other hand, the sand content at the surface layer of the soil profile was the highest (33%) followed by the bottom layer, which contained 27% sand.

The silt to clay ratio of the soil ranged from 0.46 to 1.09 for the profile and from 0.38 to 1.16 and 1.43 to 1.56 for the composite surface soil samples of the wheat and teff experimental plots, respectively (Table 1). This ratio is one of the indices used to assess the rate of weathering and determine the relative stage of development of a given soil. According to Young (1976), a ratio of silt to clay below 0.15 is considered as low and indicative of an advanced stage of weathering and/or soil development while greater than 0.15 indicates that the soil is young containing easily weatherable minerals. Hence, the silt to clay ratio of the soil observed in the present study is generally high (greater than 0.15) both for the profile and the composite surface soils (Table 1) suggesting low degree of weathering and young soil development stage.

4.1.1.2. Particle and bulk density

The bulk density values of the layers in the profile varied consistently with depth ranging from 1.18 g cm^{-3} at the surface layer to 1.32 g cm^{-3} at the bottom layer while the average bulk densities of the wheat and teff experimental plots were 1.19 and 1.20 g cm^{-3}, respectively (Table 1). These values are closer to the average range of bulk density for mineral soils which is 1.30-1.40 g cm^{-3} as indicated by Bohn *et al.* (2001). The relatively lower bulk density values observed at the surface layer could be due to the relatively high OM contents (Table 2) which resulted in high total porosity (> 52%). On the other hand, the relatively high bulk density values in the layers below the plow depth (0-25) could be due to the rapid decline in OM content as well as reduced root penetration (Appendix Table 4) and compaction caused by the weight of the overlying soil material.

Table 1. Selected physical properties of the profile and composite surface soil samples of the wheat and teff experimental plots

Depth	Particle size (%)			Textural	Silt/clay	BD	PD	
(cm)	Sand	Silt	Clay	class	ratio	(g cm^{-3})	(g cm^{-3})	TP (%)
0–25	33	35	32	Clay loam	1.09	1.18	2.51	52.99
25–98	23	25	52	Clay	0.48	1.29	2.61	50.57
98–150^{+}	27	23	50	Clay	0.46	1.32	2.85	49.43
Composite surface (0-15) soil samples before planting of wheat								
Block 1	31	19	50	Clay	0.38	1.17	2.52	53.57
Block 2	31	37	32	Clay loam	1.16	1.16	2.46	52.85
Block 3	31	37	32	Clay loam	1.16	1.23	2.57	52.14
Mean	31	31	38	Clay loam	0.90	1.19	2.52	52.85
Composite surface (0-15) soil samples before planting of teff								
Block 1	23	47	30	Clay loam	1.56	1.24	2.56	51.56
Block 2	27	43	30	Clay loam	1.43	1.19	2.50	52.40
Block 3	25	45	30	Clay loam	1.50	1.17	2.52	53.57
Mean	25	45	30	Clay loam	1.50	1.20	2.53	52.51

BD = Bulk density; PD = Particle density; TP = Total porosity

The particle density values of the layers in the profile increased consistently with depth ranging from 2.51 g cm^{-3} at the surface (0-25 cm) layer to 2.85 g cm^{-3} at the bottom layer ($98\text{-}150^{+}$ cm) while the average particle density of the wheat and teff experimental plots were 2.52 and 2.53 g cm^{-3}, respectively (Table 1). For many mineral soils, the particle density ranges from 2.60 to 2.70 g cm^{-3} and it does not vary a great deal for different soils unless there is considerable variation in OM content and mineralogical composition of the soil (Brady and Weil, 2002). Therefore, the particle densities of the soils where the current study was conducted are closer to the average range of particle density for mineral soils. However, the particle density values of the surface layers of the profile and the mean of the composite surface soil samples of the wheat and teff experimental fields were relatively lower than the underlying subsurface layers of the profile. This is probably attributed to the rapid decline in OM with increasing soil depth from 4.39% at the plow depth to 0.05% at the bottom of the subsoil (Table 2).

4.1.1.3. Total porosity

Total porosity of the soil profile decreased consistently with depth from 52.99% at the surface layer to 49.43% at the bottom layer. In accordance with the total porosity of the surface layer of the profile characterized representing both experimental fields the average volumes of total soil porosity of the fields under wheat and teff experimental plots were 52.85 and 52.51%, respectively (Table 1). The relatively higher values of total porosity observed at the surface layer of the profile and the composite surface soil samples across the blocks of both experimental fields correspond to the higher OM content and the resultant lower bulk density values (Tables 1 and 2). The range of total porosity observed in the soils considered in this study falls within the range of 46 to 64% reported by Abayneh (2001) for the soils of the Raya valley.

4.1.2. Chemical Properties of the Soil

4.1.2.1. Soil reaction (pH)

The data in Table 2 in indicates that the soil pH value within the soil profile linearly increased with increasing profile depth. According to the soil pH rating (Appendix Table 5) established by Tekalign (1991), the results of soil analysis in this study showed that the pH of the soil profile varied from slightly acidic (pH = 6.3) at the surface layer (0-25 cm depth) to strongly alkaline (pH = 8.2) at the bottom ($98\text{-}150^{+}$ cm) layer. Similarly, the mean pH values of the composite surface soil samples from the wheat (6.5) and teff (6.6) experimental plots were categorized under the slightly acidic soil reaction class as per the same rating provided in Appendix Table 5 (Table 2).

According to Eylachew (2000), the pH of Vertisols characterized in different parts of the country was within the range of 6.3 to 7.6 on the surface layer and within 6.8 to 8.5 in the underlying layers. Therefore, the soil pH values recorded for the profile and the composite surface soil samples of the wheat and teff experimental fields of the present study fully agree with these findings. The increase in pH consistently with increasing soil profile depth may be due to the marked increase observed in the basic cations particularly exchangeable Ca and Mg with depth (Table 2). The increase in basic cation concentrations with soil depth, in turn, may suggest the existence of downward movement of these constituents from the surface layer to the subsurface layers within the profile.

4.1.2.2. Organic matter

The organic matter (OM) content of the profile decreased consistently with depth ranging from 4.39% at the surface layer (0-25 cm) to 0.05% at the bottom ($98\text{-}150^{+}$ cm) layer (Table 2). On the other hand, the composite surface soil samples collected from the experimental plots of wheat and teff had mean OM contents of 3.71 and 2.26%, respectively. According to the rating of soil OM content (Appendix Table 6) established by Tekalign (1991), the surface layer of the profile had medium while the composite surface soil samples of the wheat and teff experimental plots had medium and low OM contents, respectively.

The reasons for the low to medium OM levels observed in the soils of the present study areas could be intensive cultivation of the land which encourages oxidation reaction and the total removal of crop residues for animal feed and source of energy. Moreover, there is no practice of organic fertilizers addition, such as animal (farmyard) manure and/or green manure that could have contributed to the soil OM pool in the study area. In other soils of Ethiopia, variability of soil OM has also been related to land use history and the associated management practices. Accordingly, OM content is generally low in cultivated soils than soils under grazing lands and in soils of grazing land soils compared to soils of forest land (Eylachew, 1999). Moreover, medium OM content of 3.07 and 2.07% were reported for soil samples collected from the plow layer of cultivated lands from Gojjam and Amaressa areas, respectively (Mesfin, 1998).

4.1.2.3. Total nitrogen

The total N contents of the soil profile varied from 0.03% at the bottom layer (98-150^{+} cm) to 0.23% at the surface (0-25 cm) layer (Table 2). The total N content of the surface layer of the profile (0.23%) and the mean total N contents of the composite surface soil samples of wheat (0.17%) and teff (0.13%) experimental plots of the study area are rated as medium based on its classification provided by Berhanu (1980) and presented in Appendix Table 6. Apparently, the highest value of total N (0.23%) corresponds to the layer of the profile containing the highest OM content (4.39%) and the lowest amount of total N (0.03%) was recorded in the bottom layer which contained the lowest OM content (0.05%) (Table 2).

In line with the OM contents of the profile, the contents of the total N also decreased consistently with depth suggesting the strong correlation between the two soil parameters. The medium total N contents indicate that the soils of the study area are deficient in N to support proper growth and development of crops for expressing their genetic yield potential which suggest that the soils require fertilization with external N inputs and gradual build of its OM levels to ensure sustainable productivity.

4.1.2.4. Available soil phosphorus

The available P content of the profile ranged from 0.86 mg kg^{-1} at the bottom layer to 20.50 mg kg^{-1} at the surface layer. Similarly, the mean available P contents of the composite surface soil samples of the wheat and teff experimental plots were 21.14 and 14.33 mg kg^{-1}, respectively (Table 2). According to Olsen *et al.* (1954) rating (Appendix Table 6), the average available P contents of the composite surface soil samples of both experimental plots and the surface layer of the profile fall under the high P status implying that response of crops to P fertilization at such P level may not be very high.

On the other hand, Tekalign and Haque (1991) reported that 8.5 mg P kg^{-1} of was the critical level for some crops such as faba bean on major and/or agriculturally important soils of Ethiopia when assessed by the Olsen P extraction method. Finck and Vendateswarlu (1982) also revealed that for cereals, the critical limit below which responses to applied P could be expected on Vertisols is about 8 mg kg^{-1} soil of Olsen extractable P. Considering these critical levels of soil P, the amount of available P observed in the soils of the present study remains to be high.

The content of P showed a decreasing trend with soil depth (Table 2). This is in agreement with the findings of Tekalign *et al.* (1988) who reported that topsoil available P is usually greater than that in the subsoil due to sorption of the artificially added P on the soil surface and its gradual desorption, greater biological activity and higher addition and accumulation of organic materials on the surface soil than in the subsoils. Mulugeta (2000) also indicated a decrease in P content with increasing depth due to its fixation by clay and Ca in the subsurface soil which were found to increase with profile depth.

Table 2. Selected chemical properties of the profile and composite surface samples of wheat and teff experimental area

Depth (cm)	pH (H_2O)	OM (%)	Total N (%)	AP (mg kg^{-1})	Exchangeable bases and CEC (coml(+) kg-1) Na	K	Mg	Ca	CEC	PBS
0–25	6.3	4.39	0.23	20.50	0.26	0.73	9.14	29.14	41.42	94.81
25–98	7.5	0.10	0.06	2.20	0.43	0.42	10.99	35.44	50.37	93.87
98–150$^+$	8.2	0.05	0.03	0.86	0.76	0.51	11.48	31.89	49.33	90.49
Composite surface (0-15) soil samples before planting of wheat										
Block 1	6.6	3.56	0.16	22.30	0.20	0.58	10.80	22.14	40.19	83.90
Block 2	6.4	3.72	0.18	19.34	0.17	0.58	9.41	22.57	42.77	81.44
Block 3	6.4	3.86	0.17	21.78	0.22	0.58	11.78	21.00	41.44	81.03
Mean	6.5	3.71	0.17	21.14	0.19	0.58	10.66	21.90	41.47	82.12
Composite surface (0-15) soil samples before planting of teff										
Block 1	6.6	2.20	0.19	13.68	0.18	0.57	10.00	22.00	41.20	79.49
Block 2	6.5	2.33	0.10	13.52	0.22	0.75	12.00	21.71	40.45	85.74
Block 3	6.6	2.24	0.10	15.80	0.19	0.59	11.00	22.54	42.80	80.19
Mean	6.6	2.26	0.13	14.33	0.19	0.64	11.00	22.08	41.48	81.81

OM = Organic matter; AP = Available phosphorus; CEC = Cation exchange capacity; PBS = Percentage base saturation

On the other hand, Mohammed *et al.* (2005) observed low levels of available P in the surface horizons of the cultivated soils of the Chercher highlands in Eastern Ethiopia. In general, existence of low contents of available P is a common characteristic of most of the soils in Ethiopia (Tekalign and Haque, 1991; Yihenew, 2002; Wakene and Heluf, 2003) which is contrary to the P content observed in the soils of the present study area.

4.1.2.5. Exchangeable bases

Exchangeable Ca followed by Mg was the predominant cation in the exchange sites of both the profile and the composite surface soil colloidal materials (Table 2). The mean exchangeable Ca and Mg contents of the composite surface soil samples of the wheat and teff experimental plots were 21.90 and 10.66 and 22.08 and 11.00 cmol(+) kg^{-1} while that of exchangeable Na and K were 0.19 and 0.58 and 0.19 and 0.64 cmol(+) kg^{-1}, respectively. Exchangeable Ca content varied from 29.14 coml(+) kg^{-1}) at the surface layer to 35.44 cmol(+) kg^{-1} at the middle layer and did not show any clear pattern of variability among the layers of the profile, whereas exchangeable Mg increased with soil depth consistently from 9.14 cmol(+) kg^{-1} at the surface layer to 11.48 coml(+) kg^{-1}) at the bottom layer.

The high contents of exchangeable Ca and Mg show that the soil parent material primarily rich in basic cations and the divalent cations are retained in higher concentrations and for longer periods by the soil colloidal particles because of their higher selectivity cofficient over the monovalent cations. A high content of these two cations has also been reported in Vertisols of Bichena and Woreta areas (Yihenew, 2002) and in soils of Jelo micro-catchment (Mohammed *et al.*, 2005). According to the rating of FAO (2006), the concentrations of these two cations are rated as very high (Appendix Table 7 and Table 2) where they saturated 88 to 92% of the soil exchange complex.

In the surface soil of study area, the proportions of the cations were in the order of Ca > Mg > K > Na. This might be related to the parent material from which the soils have been developed *i.e.* basalt rock and their differential attraction to the soils' exchange complex which is approximately in that order. Generally, exchangeable Na and K contributed very small proportion to the CEC. Nevertheless, according to the FAO (2006), the observed exchangeable K value was high for the surface horizon where it generally decreases inconsistently with increasing soil profile depth (Table 2). This indicates that the potential supply of K for crop growth largely lies in the surface layer and hence calls for protection and maintenance of the surface soil to secure sustainable crop production without any external addition of K fertilizers. The content of exchangeable Na in the soil relative to the CEC was below the critical value to cause soil sodicity and, hence, Na toxicity on crops and/or adverse effect on soil physical properties are unlikely to occur. Yet, the content of exchangeable Na showed a consistent increase trend with soil depth from 0.26 cmol(+) kg^{-1}at the plow depth to 0.76 cmol(+) kg^{-1} at the bottom subsurface layers (Table 2).

4.1.2.6. Cation exchange capacity and percent base saturation (PBS)

According to the rating (Appendix Table 7) suggested by landon (1991), the CEC values of the surface soil layer fall under the very high rate. As indicated in Table 2, CEC did not show any clear pattern of variability among the layers of the profile although the surface layer had the lowest CEC (41.42) cmol(+) kg^{-1} while the highest (50.37 cmol(+) kg^{-1}) was obtained at the upper subsoil layers of the profile (Table 2). Similarly, the mean CEC values of the composite surface soil samples from wheat and teff experimental fields were also rated as very high (Appendix Table 7) and was 41.47 and 41.48 cmol(+) kg^{-1}, respectively (Table 2). Although the OM content of the soil is low to mediume, the amount and type of clay might have been very important in contributing to the CEC values. The type of clay could most probably be montmorillonite with a shrinking and swelling behavior with extensive internal and external surfaces that can attract or adsorb many cations. This is in line with the findings of Mebit (2006) who reported very high CEC on Eutric Vertisols and that varied with soil depth.

The CEC to clay ratios were over 0.97 reaching 1.29 in the surface horizon. Therefore, the range suggests the presence of 2:1 clay minerals and can be expected to have more nutrient reserves (Landon, 1991). Mohammed *et al.* (2005) also indicated that the CEC to clay ratios of the soils of Jelo catchment were over 0.67 reaching 2.05 in some horizons which predicted the presence of smectite (montmorillonite) clay mineralogy of high inherent CEC in all of the soil horizons. This shows that inorganic material (colloidal clay) is the predominant contributing factor to the very high CEC observed in the soils. Moreover, the high CEC values imply that the soil has high buffering capacity against the induced changes.

According to the rating (Appendix Table 7) by Hazelton and Murphy (2007), the percent base saturation (PBS) of the surface layer of the soil profile was rated as very high. Similarly, the mean values of the composite surface soil sample from wheat and teff experimental plots were also very high ranging from 81.03 to 83.90 in the wheat field and from 79.49 to 85.74% in the teff field (Table 2). Unlike CEC and some of the exchangeable cations (Mg and Na) which increased with soil depth, PBS decreased consistently with depth (Table 2).

4.2. Response of Wheat and Teff to Applied N Fertilizers

4.2.1. Effects of N on Phonology of Wheat and Teff Crops

More than 90% crop emergence occurred in all plots regardless of the treatments. Crop emergence up to 50% was recorded in all plots within seven and four days for wheat and teff crops, respectively. The days to 50% heading recorded significant difference for wheat ($P \leq 0.05$) and teff ($P \leq 0.01$) crops due to the application of different rates and sources of N fertilizer (Appendix Table 8). Days to 50% heading in both crops were responded similarly to the application of 23 kg N ha^{-1} of slow release urea (SRU) and 46 kg N ha^{-1} of conventional urea (CU) fertilizers in both crops. This shows SRU fertilizer can reduce N loss (leaching, volatilization and erosion) since it releases the N slowly over the growing season so that it can be taken up by the crop.

As the N level of the SRU fertilizer increased from 23 to 69 kg N ha^{-1}, 50% heading of wheat and teff plants were increased by 4.34 and 3.67 days, respectively (Table 3). This result is supported by Legesse (2004) who reported that N fertilization at the rate of 23 and 46 kg N ha^{-1} significantly delayed the heading stage of teff by five days as compared to the control. Fertilizer N is reported to promote leaf growth and leaf area thereby increasing the amount of radiation intercepted and dry matter production (Russel, 1988). This might have promoted greater vegetative development for longer period of time before reproductive phase begins and hence might have caused delay in heading.

The highest dose of N (69 kg N ha^{-1} of SRU) delayed physiological maturity of both teff and wheat crops significantly ($P \leq 0.05$) over all other treatments except for application of 46 kg N ha^{-1} . It increased the days to 90% maturity of wheat and teff from 119.33 to 123.67 and 85.67 to 91.67 days, respectively (Table 3). In a similar study, Gurmessa (2002) indicated that fertilizer N beyond 46 kg ha^{-1} delayed the physiological maturity of wheat and Legesse (2004) has reported that N fertilization delayed the physiological maturity of teff. This delay might be due to extended vegetative growth instead of reproductive growth in response to the adequate supply of such an important growth promoting mineral nutrient.

Table 3. Effect of N on wheat and teff phenological parameters

	Wheat		Teff	
N rates (kg ha^{-1})	Days to 50% heading	Days to 90% maturity	Days to 50% heading	Days to 90% maturity
0 (Control)	68.67c	119.33d	56.33c	85.67c
23 (SRU)	71.33b	121.33c	58.00b	88.33b
46 (SRU)	74.33a	123.33ab	60.67a	91.00a
69 (SRU)	75.67a	123.67a	61.67a	91.67a
46 (CU)	72.00b	122.33bc	57.33 bc	88.67b
LSD (0.05)	1.88	1.14	1.09	0.88
SE (±)	1.23	0.99	0.26	0.26
CV (%)	1.37	0.50	0.98	0.52

Means within a column sharing common letter(s) are not significantly different at $P > 0.05$; SRU = Slow release urea; CU = Conventional urea; LSD = Least significant difference; SE = Standard error; CV = Coefficient of variation

Plants treated with N, particularly with the highest level of N, remained slightly green for longer duration while those plants without N showed yellowish spikes, leaves and stems indicating early physiological maturity in the later case which might have been due to depression of cytokinin synthesis or increased production of abscisic acid under low N supply (Marschner, 1995). According to the same author, amino acids are required for the synthesis of cytokinins so that cytokinin metabolism is low at low N status of the soil. The coefficients of correlation for days to heading and maturity of both crops with applied N were also found positive and significant suggesting that with increasing the rates of N fertilizer, the plants of both crops took longer period to initiate heading and to attain maturity than the experimental units and/or plants receiving either no or lower rates of N (Table 6).

4.2.2. Effects of N Fertilization on Wheat and Teff Growth Parameters

4.2.2.1. Plant height

Application of different rates and sources of N fertilizer affected wheat and teff plant heights significantly ($P \leq 0.05$) and highly significantly ($P \leq 0.01$), respectively (Appendix Table 8). Regardless of the rate of application, the plants of both crops on the plots which received N fertilizer were taller significantly as compared to their respective plant heights on the control plots (Table 4). Generally, plant height of both crops increased consistently with increasing rates of N where the maximum plant heights of 109.67 and 112.33 cm were obtained from the application of the highest N rate (69 kg N ha^{-1} SRU) and the lowest of 81.00 and 85.67 cm were obtained from the control plot of wheat and teff crops, respectively. In accordance with the response observed for the phenological parameters, the plant heights of both wheat and teff crops recorded due to application of 23 kg N ha^{-1} from SRU and 46 kg N ha^{-1} from CU were statistically similar while there were significant differences between plots which received 46 kg N ha^{-1} of SRU and 46 kg N ha^{-1} of CU in both crops.

Simple correlation coefficient also showed that N was strongly and positively correlated ($r = 0.99^{**}$ and $r = 0.98^{**}$) with plant height of wheat and teff crops, respectively (Table 6). In agreement with this result, Amsal *et al.* (2000) reported a positive and linear response of plant height of wheat to increasing N fertilizer application in the central highlands of Ethiopia. Several other studies (Zewdu *et al.,* 1992; Tilahun *et al.,* 1996a; Minale *et al.,* 2004) have also revealed remarkable plant height enhancement in reaction to each incremental dose of N fertilizer. Moreover, plant height of teff was significantly increased by N application on Vertisols on farmer's fields (Minale *et al.,* 2004).

4.2.2.2. Number of tillers per plant

The effects of application of different rates and sources of N fertilizer on the number of productive tillers were statistically significant for wheat ($P \leq 0.05$) and teff ($P \leq 0.01$) crops, respectively (Appendix Table 8). Number of fertile tillers per plant increased linearly with increasing rate of applied SRU from 4.33 and 9 in the plots without N (control) to 7.00 and 22.67 in the plots supplied with 69 kg N ha^{-1} for wheat and teff crops, respectively (Table 4). The number of fertile tillers per plant for those plots supplied with 46 kg N ha^{-1} of SRU were 6.67 and 20 while it was 6 and 15 for those plots supplied with 46 kg N ha^{-1} of CU, respectively. The differences in mean number of fertile tillers obtained due to the application of different rates of applied N were significant ($P \leq 0.05$) between each other for teff crop. It can also be observed from the highly significant and positive correlation coefficient that the increasing N rate had enhanced the development and growth of new productive tillers.

Table 4. Effect of N on wheat and teff growth parameters

N rates	Wheat			Teff		
	Plant	Number of tillers $plant^{-1}$		Plant	Number of tillers $plant^{-1}$	
(kg ha^{-1})	height (cm)	Fertile	Non Fertile	height (cm)	Fertile	Non Fertile
0 (Control)	81.00c	4.33c	1.00	85.67c	9.00e	1.33
23 (SRU)	91.00b	5.67b	0.67	103.67b	13.00d	1.33
46 (SRU)	109.00a	6.67ab	0.67	112.33a	20.00b	1.00
69 (SRU)	109.67a	7.00a	2.00	112.33a	22.67a	1.67
46 (CU)	91.67b	6.00ab	1.00	104.00b	15.00c	1.67
LSD (0.05)	2.89	1.31	NS	3.08	1.65	NS
SE (±)	0.70	0.31	0.20	0.89	0.53	0.26
CV (%)	1.59	11.72	11.72	1.58	5.50	5.48

Means of the respective crop within a column sharing common letter(s) are not significantly different at $P > 0.05$;SRU = Slow release urea; CU = Conventional urea; LSD = Least significant difference; SE = Standard error; CV = Coefficient of variation

Marschner (1995) reported that N stimulates tillering probably due to its effect on cytokinin synthesis. Batey (1984), Archer (1988) and Mossedaq and Smith (1994) revealed that tillering is enhanced by increased light and N availability during the vegetative growing period and wheat reacts to N application by producing more tillers per plant and by exhibiting a higher percentage survival of tillers. Ayoub *et al*. (1994) also reported that the spike population of wheat increased with increasing level of N fertilization which is mainly because of increased fertile tillers than the control plots.

4.2.3. Effects of N Fertilizer on Wheat and Teff Yield and Yield Components

4.2.3.1. Number of spikes, spikelets per spike, grains per spike, spike and panicle length

The number of spikes 0.5 m^{-1} row of wheat showed significant response ($P \leq 0.01$) to the application of different rates and sources of N fertilization (Appendix Table 8). In this case, the maximum number of spikes (83.30) in wheat was recorded from the application of 69 kg N ha^{-1} followed by 78.00 and 56.33 due to applications of 46 kg N ha^{-1} of SRU and CU fertilizers, respectively, while the minimum number of spike (34.67) was recorded from the control plots (Table 5). There was no significant ($P > 0.05$) difference in spike count of wheat at 23 kg N ha^{-1} of SRU and 46 kg N ha^{-1} of CU fertilizers. However, the spike count obtained due to the application of different rates and sources of N fertilizer were significantly different from the spike count at the control plot and between each other except that of 23 kg N ha^{-1} of SRU and 46 kg N ha^{-1} of CU.

Several researchers (Zewdu *et al.*, 1992; Tilahun *et al.*, 1996a) also reported the enhancement of spikes per unit area with increasing rates of N fertilizer. Power and Alessi (1978) also reported that for wheat, one spike is produced per main stem; thus, the number of heads per unit area is highly dependent on the use of high N rates to promote the initiation, survival, and development of secondary tillers. Similarly, Alcoz *et al.* (1993) reported that N fertilization doubled grain yield as compared with the yield on the control plots due to the production of significantly more and heavier spikes in the fertilized ones. High and positive correlation coefficient observed between applied N and spike number (Table 6) also suggests that N fertilization affected the development and growth of spike in wheat crop.

Spike length of wheat was significantly ($P \leq 0.01$) affected by the application of different rates and sources of N fertilization (Appendix Table 8). However, except for the control plot, there was no significant difference in spike length among the different rates of SRU and CU fertilizers. Accordingly, the highest number of spike length (9.00 cm) was obtained with the application of the highest rate of SRU (69 kg N ha^{-1}) while the lowest spike length (7.33) was recorded from the control plots (Table 5).

Spikelets per spike of wheat was significantly ($P \leq 0.01$) affected by the application of different rates and sources of N fertilizer (Appendix Table 8) and the maximum (15.33) and the minimum (11.67) records were obtained at the highest and the lowest N rates, respectively. with regard to the response of spikelets per spike of wheat, the application of 23 kg N ha^{-1} of SRU and 46 kg N ha^{-1} of CU were similar while the application of 46 kg N ha^{-1} of SRU was significantly different from 46 kg N ha^{-1} of CU fertilizer.

Table 5. Effect of N fertilization on yield components of wheat and teff

	Wheat				Teff
N rates (kg ha^{-1})	Spikes 0.5 m^{-1}	Spike length (cm)	Spikelets $spike^{-1}$	Grains $spike^{-1}$	Panicle length (cm)
0 (Control)	34.67d	7.33b	11.67c	27.33d	29.67c
23 (SRU)	54.67c	8.67a	13.67b	31.00c	42.00b
46 (SRU)	78.00b	9.33a	14.33ab	34.67b	49.67a
69 (SRU)	83.33a	9.67a	15.33a	38. 67a	52.00a
46 (CU)	56.33c	9.00a	13.33b	31.33c	43.33b
LSD (0.05)	2.81	1.00	1.11	1.24	2.65
SE (±)	0.97	0.26	0.33	0.38	0.72
CV (%)	2.43	6.05	4.33	2.02	3.25

Means within a column sharing common letter(s) are not significantly different at $P > 0.05$ SRU = Slow release urea; CU = Conventional urea; LSD = Least significant difference; SE = Standard error; CV = Coefficient of variation

The number of grains per spike of wheat also responded significantly ($P \leq 0.01$) to the application of different rates and sources of N fertilization (Appendix Table 8). Accordingly, the highest number of grains per spike (38.67) was obtained with the application of the highest rate of SRU (69 kg N ha^{-1}) while the lowest grains per spike (27.33) was recorded from the control plots (Table 5). The number of grains per spike increased with increasing N rate. However, there was no significant ($P > 0.05$) difference between the number of grains per spikes, spikelets per spike and spike length responded similarly to the application of 23 kg N ha^{-1} of SRU and 46 kg N ha^{-1} of CU fertilizers (Tables 5).

Panicle length of teff was significantly ($P \leq 0.01$) affected by the application of different rates and sources of N fertilization (Appendix Table 8). The highest and lowest panicle length of teff (52.00 and 29.67 cm) were recorded at the highest rate of SRU and the control plots, respectively. In line with the other parameters, there was no significant differences in panicle length due to the application of 23 kg N ha^{-1} of SRU and 46 kg N ha^{-1} of CU fertilizers (Table 5). Panicle length is one of the yield attributes of teff which could lead to high increment of grain, straw and biomass yields.

Panicle length exhibits positive and highly significant correlation with culm length, plant height, number of internodes and grain (Mulugeta, 2000; legesse, 2004). Thus, crops with high panicle length could have higher grain, straw and biomass yields. Application of higher amount and efficient utilization of N leads to high photosynthetic efficiency and accumulation of high dry matter which ultimately increases yield. Highly significant and positive coefficient of correlation ($r = 0.98^{**}$) was observed between panicle length of teff and applied N rate indicating an increase in the rate of N resulted in a longer panicle length (Table 6). Similarly, spikelets per spike ($r = 0.89^{**}$) and spike length ($r = 0.82^{**}$) of wheat were positively and significantly correlated with applied N rate (Table 6).

4.2.3.2. Thousand grains weight

Thousand grains weight responded significantly ($P \leq 0.01$) to the application of different rates and sources of N fertilizer (Appendix Table 8) and increased consistently with the increase in applied N rate like most of the other crop parameters, there was no significant differences in 1000 grain weight in both crops between the applications of 23 kg N ha^{-1} of SRU and 46 kg N ha^{-1} of CU fertilizers for both crops. The maximum and minimum thousand grains weight of wheat (43.13 and 39.13 g) and teff (0.35 and 0.25 g) were obtained at the application of 69 kg N ha^{-1} of SRU and control plots, respectively (Table 7).

Significant and positive correlations ($r = 0.96^{**}$ and $r = 0.98^{**}$) were observed between thousand grains weight and applied N rate for wheat and teff crops, respectively (Table 6) indicating an increase in the rate of N resulted in a more weight of wheat and teff grains. This result is in line with the findings of Tilahun *et al*. (1996a) who indicated that 2.2 to 10.0% higher grain weights were obtained from 120 over 60 kg N ha^{-1} depending on the location and climatic condition of the growing season. Amsal *et al.* (2000) also reported a positive and linear response of thousand grains weight to N fertilization where the subsequent decline in grains weight was attributed to sub-optimal assimilation of nutrients and, hence, shriveled seeds of wheat. In contrast, Gooding and Davis (1997) have shown either no improvement or reduced kerenel weight due to N fertilization even when yields increased. Zewdu *et al.* (1992) has also reported nonsignificant response of 1000 grains weight to application of N fertilizer in the highlands of Ethiopia.

4.2.3.3. Grain yield

Grain yield of both crops responded significantly ($P \leq 0.01$) to the application of different rates (SRU) and sources (SRU and CU) of N fertilizer (Appendix Table 8). The highest mean grain yield of wheat (4720 kg ha^{-1}) was obtained from 69 kg N ha^{-1} of SRU with an increment of 2336.33 kg ha^{-1} over the yield obtained from the control plot (Table 7). The next highest mean grain yield (4685 kg ha^{-1}) was obtained from 46 kg N ha^{-1} of SRU with no significant difference ($P > 0.05$) compared to the application of 69 kg N ha^{-1} of SRU and the least yield (2383.67 kg ha^{-1}) was obtained from the control plot.

Similarly, the highest mean grain yield of teff (3443.67 kg ha^{-1}) was obtained from 69 kg N ha^{-1} of SRU with 1332.34 kg ha^{-1} yield advantage over and the control plot (Table 7). The next highest mean grain yield (3379.67 kg ha^{-1}) was obtained from 46 kg N ha^{-1} SRU with no statistically significant difference ($P > 0.05$) compared to the yield obtained with the application of 69 kg N ha^{-1} of SRU and the least teff grain yield (2111.33 kg ha^{-1}) was obtained from the control plot (Table 7). Generally, grain yield exhibited a linear increase with increasing rate of application of N fertilizer in both wheat and teff crops.

Table 6. Correlation matrix among N fertilizers, growth parameters, yield and yield components of wheat (above the diagonal line) and teff (below the diagonal line)

	N	DH	DM	FT	SL/ PL	S/0.5m	TGW	S/S	PH	GY	SY	TBY	HI
N		0.92**	0.93**	0.77**	0.82**	0.99**	0.96**	0.89**	0.99**	0.99**	0.99**	0.99**	0.97**
DH	0.96**		0.81**	0.86**	0.83**	0.94**	0.91**	0.82**	0.92**	0.86**	0.93**	0.91**	0.58**
DM	0.98**	0.92**		0.57*	0.59*	0.74**	0.75**	0.55*	0.68**	0.68**	0.70**	0.70**	0.47ns
FT	0.98**	0.92**	0.92**		0.81**	0.86**	0.83**	0.71**	0.83**	0.85**	0.86**	0.89**	0.66**
SL/ PL	0.98**	0.85**	0.95**	0.94**		0.82**	0.83**	0.85**	0.80**	0.86**	0.87**	0.88**	0.71**
S/0.5m	-	-	-	-	-		0.93**	0.88**	0.88**	0.92**	0.97**	0.95**	0.64*
TGW	0.98**	0.92**	0.93**	0.94**	0.87**	-		0.89**	0.91**	0.90**	0.96**	0.94**	0.63*
S/S	-	-	-	-	-	-	-		0.87**	0.87**	0.93**	0.91**	0.61*
PH	0.98**	0.82**	0.93**	0.90**	0.98**	-	0.80**	-		0.87**	0.93**	0.91**	0.60*
GY	0.99**	0.89**	0.97**	0.95**	0.98**	-	0.89**	-	0.98**		0.96**	0.99**	0.87**
SY	0.99**	0.90**	0.98**	0.94**	0.97**	-	0.88**	-	0.97**	0.99**		0.99**	0.70**
TBY	0.99**	0.89**	0.98**	0.95**	0.98**	-	0.88**	-	0.98**	0.99**	0.99**		0.79**
HI	0.96**	0.48ns	0.64*	0.56*	0.75**	-	0.88**	-	0.83**	0.75**	0.75**	0.76**	

DH = Day to 50% heading; DM = Days to 90% maturity; FT = Fertile tiller; SL = Spicke length; PL = Panicle length; S/0.5m = Number of spikes per 0.5m row length; TGW = 1000 grain weight; S/S = Spikelets per spike; PH = Plant height; GY = Grain yield; SY = Straw yield; TBY = Total biomass yield; HI = Harvest index; - = Parameters not considered in teff crop

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In both crops, the application of 46 kg N ha^{-1} of SRU fertilizer has yield advantage of 497.67 and 462.00 kg ha^{-1} over the application of 46 kg N ha^{-1} of CU fertilizer for wheat and teff crops, respectively (Table 7). This shows that SRU can reduce N losses by leaching in the form of NO_3^-, fixation as NH_4,volatilization as NH_3 and atmospheric emission in the form of N_2O or N_2. Similarly, it is reported that N fertilizer application rates on cotton have reduced by 40% if controlled release rather than conventional fertilizers are used (Howard and Oosterhuis, 1997).

The partial budget analysis (Appendix Table 9) done by considering only grain yield of the respective crop indicates that high marginal rates of return (1681.00 and 1003. 40%) were obtained by applying 46 kg N ha^{-1} SRU for wheat and teff crops, respectively. This means that the income obtained by applying 46 kg N ha^{-1} SRU fertilizer were more than 17 and 10 times a unit total SRU fertilizer cost for wheat and teff crops, respectively. Accordingly, the application of 46 kg N ha^{-1} of SRU was the optimum rate for both crops.

Highly significant and positive correlation of N fertilizer with grain yield and other yield components of wheat and teff crops (Table 6) also indicates that N is the principal factor that controls the growth and development of the crop. Moreover, grain yield of wheat was highly and positively correlated with most of the growth parameters and yield components such as straw yield (r = 0.96**), total biomass yield (r = 0.99**), thousand grains weight (r = 0.90**), plant height (r = 0.87**), fertile tillers (r = 0.85), spike number (r = 0.92**), spike length (r = 0.86**) and spikelet per spike (r = 0.87**) (Table 6). Similarly, grain yield of teff was highly and positively correlated with most of the growth parameters and yield components such as straw yield (r = 0.99**), total biomass yield (r = 0.99**), thousand grains weight (r = 0.89**), plant height (r = 0.98**), fertile tillers (r = 0.95) and panicle length (r = 0.98**) (Table 6).

Several other studies also indicated positive and linear responses of grain yield to increasing levels of N fertilizer (Tilahun *et al.*, 1996a; Amsal *et al.*, 2000). Tilahun *et al.* (1996a) reported that application of 120 kg N ha^{-1} showed yield advantage ranging from 19 to 49% over the yield obtained from 60 kg N ha^{-1} depending on the inherent N status of the soil and the amount and distribution of rainfall during the growing season of the respective locations. Similar to the present results, Mulugeta (2003) reported that grain yield of teff was affected significantly by N fertilization. According to the DZARC (1989) report, application of N fertilizer beyond 60 kg ha^{-1} produced the highest yield of teff.

Table 7. Effect of N fertilization on yield and harvest index of wheat and teff

N rates	Wheat				
(kg ha^{-1})	TGW (gm)	GY (kg ha^{-1})	SY (kg ha^{-1})	TBY (kg ha^{-1})	HI (%)
0 (Control)	39.13d	2383.67d	4646.00d	6963.00e	34.23c
23 (SRU)	40.83c	4065.67c	6157.33c	10223.00d	39.83b
46 (SRU)	42.20b	4685.00a	6861.33b	11581.33b	40.57a
69 (SRU)	43.13a	4720.00a	7529.67a	12214.67a	38.53b
46 (CU)	41.05c	4187.33b	6246.33c	10463.67c	40.03ab
LSD (0.05)	0.74	107.24	127.76	197.88	1.15
SE (±)	0.27	38.47	49.9	70.39	0.28
CV (%)	0.94	1.42	1.08	1.02	1.55
			Teff		
0 (Control)	0.25d	2111.33d	3607.67d	6239.00c	33.83b
23 (SRU)	0.27c	2830.67c	5072.67c	7903.33b	36.13a
46 (SRU)	0.31b	3379.67a	6011.67b	9391.33b	36.00a
69 (SRU)	0.35a	3443.67a	6208.33a	9652.00a	35.78a
46 (CU)	0.28c	2917.67b	5119.67c	8037.33b	36.27a
LSD (0.05)	0.01	78.05	192.51	212.77	1.13
SE (±)	0.003	26.40	63.70	76.93	0.29
CV (%)	1.88	1.41	1.96	1.37	1.55

Means of the respective crop within a column sharing common letter(s) are not significantly different at $P > 0.05$; TGW = Thousand grain weight; GY = Grain yield; SY = Straw yield; TBY = Total biomass yield; HI = Harvest index; SRU = Slow release urea; CU = Conventional urea; LSD = Least significant difference; SE = Standard error; CV = Coefficient of variation

4.2.3.4. Straw and total biomass yields

The application of different rates and sources of N fertilizer on the straw yield was significant at $P \leq 0.01$ for both crops (Appendix Table 8). The highest mean straw yield of wheat (7529.67 kg ha^{-1}) was obtained from the application of 69 kg N ha^{-1} of SRU with an increment of 1372.34 and 2883.67 kg ha^{-1} straw yield advantage over the application of 23 kg N ha^{-1} and the control plot, respectively (Table 7). The next highest mean straw yield (6861.33 kg ha^{-1}) was obtained from 46 kg N ha^{-1} of SRU and the least yield (2383.67 kg ha^{-1}) was obtained from the control plot.

Similarly, the highest mean straw yield of teff (6208.33 kg ha^{-1}) was obtained from the application of 69 kg N ha^{-1} of SRU with an increment of 1135.66 and 2600.66 kg ha^{-1} straw yield advantage over the application of 23 kg N ha^{-1} and the control plot, respectively (Table 7). The next highest mean straw yield (6011.67 kg ha^{-1}) was obtained from 46 kg N ha^{-1} of SRU and the least straw yield (3607.67 kg ha^{-1}) was obtained from the control plot. In both crops, the response of straw yield for the application of 23 kg N ha^{-1} of SRU was not significantly different ($P > 0.05$) from the application of 46 kg N ha^{-1} of CU responded while the application of 46 kg N ha^{-1} of SRU were significantly different from 46 kg N ha^{-1} of CU with a straw yield advantage of 615 and 892 kg ha^{-1} for wheat and teff, respectively. Generally, straw yield of both crops showed a sharp increase with increasing the rates of N fertilizer, following the same trend as grain yield (Table 7).

Highly significant and positive relationships were also observed among straw yield of wheat and growth parameters and yield components such as plant height (r = 0.93**), fertile tillers (r = 0.86**), spike number (r = 0. 97**) and spike length (r = 0.87**) (Table 6). Similarly, Highly significant positive relationships were also observed among straw yield teff and growth parameters and yield components such as plant height (r = 0.97**), fertile tillers (r = 0.94**), and panicle length (r = 0.97**) (Table 6). Application of 69 kg N ha^{-1} of SRU gave the highest straw yield (7529.67 and 6208.33 kg ha^{-1}) which were superior by (22.30 and 22.40%) and (62 and 72.00%) as compared to the control and application 23 kg N ha^{-1} of SRU for wheat and teff crops, respectively (Table 7).

In agreement with this result, Tilahun *et al.* (1996a) showed straw yield increments of 24 to 29% for 120 over 60 kg N ha^{-1} from experiments conducted in the central and southeastern Ethiopia. Moreover, the result from the experiment done on Vertisols of the central highlands of Ethiopia by Selamyihun *et al.* (1999) showed that straw yield of durum wheat increased significantly with each incremental dose of N.

In accordance with the grain and straw yields, total biomass yield of both crops were also significantly ($P \leq 0.01$) affected by the application of different rates and sources of N fertilizer (Appendix Table 8). The highest total biomass yield (12214.67 and 9652.00 kg ha^{-1}) were obtained from the application of the highest rate of SRU (69 kg N ha^{-1}), with 1991.67 and 1748.67 kg ha^{-1} total biomass yield advantage over the lowest N rate (23 kg N ha^{-1}) of wheat and teff crops, respectively (Table 7). The next highest mean biomass yield were obtained from 46 kg N ha^{-1} of SRU with a difference of (1358.33 and 4618.33) and (1448.00 and 3152.33) kg ha^{-1} yield advantages over the application of 23 kg N ha^{-1} SRU and the control plots of wheat and teff crops, respectively. The application of 46 kg N ha^{-1} of SRU had 1117.66 and 1354 kg ha^{-1} biomass yield advantage over 46 kg N ha^{-1} of CU for wheat and teff crops, respectively (Table 7).

Generally, in both crops total biomass yield increased with increasing rate of N which is also expressed by the positive and highly significant correlation (r = 0.99**) (Table 6). Other essential relationships were also observed between biomass yield of wheat and pertinent yield and yield components such as grain yield (r = 0.99**), straw yield (r = 0.99**), plant height (r = 0.91**), fertile tillers (r = 0.89**) and spike length (r = 0.88**) (Table 6). Similarly, essential relationships were also observed between biomass yield of teff and pertinent yield and yield components such as grain yield (r = 0.99**), straw yield (r = 0.99**), plant height (r = 0.98**), fertile tillers (r = 0.95**) and panicle length (r = 0.98**) (Table 6).

4.2.3.5. Harvest Index

The application of different rates and sources of N fertilizer on wheat and teff harvest index (HI) were highly significant ($P \leq 0.01$) (Appendix Table 8). Harvest indices of wheat and teff for all N rates were higher and significantly different from control plots (Table 7). Except for the control, the lowest harvest indices were recorded from plots which receive 69 kg ha^{-1} of SRU for both crops, and this could be due to higher straw yield obtained from highest N fertilization (69 kg ha^{-1}). The mean HI values varied from 38.53 to 40.57% and 33.83 to 36.27% for the effect of N on wheat and teff, respectively (Table 7).

Mengel and Kirkby (1996) also reported that harvest indices of modern wheat cultivars normally range from 35.0 to 40.0%, whereas older cultivars have indices in the range of 23.0 to 30.0%, which agreed with the present observation. Similar to the present results, Mulugeta

(2003) also found the lowest harvest index when the highest N rate was applied as compared to the control treatment in tef. Moreover, it is also in agreement with the results of Marschner (1995) and Mulugeta (2000) that excess nitrogen application resulted in a reduction of harvest index in cereal crops.

4.3. Nitrogen Uptake and Utilization of Wheat and Teff Crops

4.3.1. Grain and Straw N Contents and Uptakes of Wheat and Teff

The grain and straw N contents and their uptakes were affected by the application of different rates and sources of N fertilizer for both wheat and teff crops. Both the grain and straw N contents increased with each successive addition of N fertilizer. Accordingly, the highest grain N (2.69 and 2.68%) and straw N (1.28 and 1.83%) contents of wheat and teff were obtained at the rate of 69 kg N ha^{-1} of SRU while the least were obtained from the control plots (Table 8). Furthermore, grain N, straw N and total N uptake parameters linearly increased in response to the increased N fertilization where the maximum uptakes were recorded at the highest N rate (69 kg N ha^{-1} of SRU) and the minimum were at the control plots for both crops (Table 8). The grain N and straw N uptakes of wheat were increased by 173% and 351%, respectively while total N uptakes increased by 229 in response to 69 kg N ha^{-1} of SRU relative to the control.

Similarly, The grain N and straw N uptakes of teff were increased by 273% and 148%, respectively and while total N uptake increased by 168% in response to 69 kg N ha^{-1} of SRU relative to the control. The result clearly showed the positive effects of N on wheat and teff grain and straw yields and the improvement of grain and straw N contents by application of SRU fertilizer. The grain N uptake of all N rates were much higher than that of the straw uptake due to higher grain N content than the straw. The total N uptake recorded in the current study due to N fertilization is much higher compared with results of the previous studies in Ethiopia, (Tilahun *et al.*, 1996b; Selamyihun *et al.,* 1999; Amsal and Tanner, 2001) which showed total N uptakes of wheat ranging from 23.3 to 83.4 kg N ha^{-1} for Vertisols. Moreover, the results are in line with the findings of Tekalign *et al*. (2000) that grain nitrogen content increased with an increase in the rate of nitrogen fertilization in teff. Similarly, Genene (2003) reported a positive correlation between nitrogen fertilization and grain and straw nitrogen contents in wheat.

Table 8. Effects of applied N on grain and straw N content and uptake parameters of wheat and teff

N rates (kg ha^{-1})	GN (%)	SN (%)	GN uptake (kg ha^{-1})	SN uptake (kg ha^{-1})	TNU (kg ha^{-1})
			Wheat		
0 (Control)	1.95	0.46	46.48	21.37	67.85
23 (SRU)	2.28	0.89	92.68	54.80	147.48
46 (SRU)	2.48	1.12	116.19	76.85	193.04
69 (SRU)	2.69	1.28	126.97	96.38	223.34
46 (CU)	2.30	0.93	96.32	59.96	156.28
			Teff		
0 (Control)	2.17	0.86	24.70	45.81	76.83
23 (SRU)	2.25	1.10	63.69	55.79	119.48
46 (SRU)	2.58	1.33	87.19	79.95	167.14
69 (SRU)	2.68	1.83	92.29	113.61	205.90
46 (CU)	2.42	1.19	70.60	60.92	131.52

GN = Grain nitrogen; SN = Straw nitrogen; TNU = Total nitrogen uptake; SRU = Slow release urea; CU = Conventional urea

The application of 46 kg N ha^{-1} of SRU has improved the grain, straw and total N uptakes of the fertilizer nitrogen by 20.63, 28.17, 23.52% and 23.50, 31.24, 27.08% over application of 46 kg N ha^{-1} of CU for wheat and teff crops, respectively (Table 8). The results indicated that grain, straw and total N uptake of the fertilizer nitrogen were significantly enhanced by the application of SRU than CU fertilizer.

4.3.2. Apparent Recovery, Agronomic and Physiological Efficiencies of N

The mean apparent fertilizer recovery (nutrient use efficiency) of SRU recorded was 286 and 191% for wheat and teff crops, respectively. Apparent recoveries of N decreased with increasing rate of SRU application in wheat crop. Accordingly, the maximum (346%) and the minimum (225%) apparent recoveries of N fertilizer were obtained at 69 and 23 kg N ha^{-1} of SRU fertilizer for wheat crop (Table 9). In contrast to this, apparent recoveries of N increased inconsistently with increasing rate of SRU application in teff crop (Table 9). The application of 23 kg N ha^{-1} of SRU has improved the apparent recovery of the fertilizer nitrogen by 80.20 and

56.78 % over 46 kg N ha^{-1} of CU for wheat and teff crops, respectively. Such low AR of N in CU might be attributed to the susceptibility of N to different losses through leaching or denitrification, and, hence, exhibits low recovery under conditions of high rainfall or impeded drainage.

In contrast to the current result, Wuest and Cassman (1992) found recovery of N applied at planting ranged from 30 to 55%, while the recovery of N applied at anthesis ranged from 55 to 80% in irrigated wheat. In the present study, an average of agronomic efficiency of SRU obtained was 53.50 and 25.29 kg grain per kg of N for wheat and teff crops, respectively. Maximum agronomic efficiency of N (73.13 and 31.27) were obtained at application rate of 23 kg N ha^{-1} of SRU fertilizer. Meanwhile the minimum value of 33.86 and 19.31 were recorded at the rate of 69 kg N ha^{-1} of SRU for wheat and teff crops, respectively (Table 9).

Table 9. Effects of N fertilizer application on N apparent recovery, agronomic and physiological efficiencies of wheat and teff

	wheat			Teff		
N rates N kg ha^{-1}	AR (%)	AE (kg kg^{-1} N)	PE (kg grain kg^{-1} N)	AR (%)	AE (kg kg^{-1} N)	PE (kg grain kg^{-1} N)
0 (control)	-	-	-	-	-	-
23 (SRU)	346	73.13	21.12	185	31.27	16.86
46 (SRU)	272	50.05	18.38	196	27.57	14.04
69 (SRU)	225	33.86	15.03	187	19.31	10.32
46 (CU)	192	39.21	20.40	118	17.51	14.74

AR = Apparent recovery; AE = Agronomic efficiency; PE = Physiological efficiency

The application of 23 kg N ha^{-1} of SRU has improved the agronomic efficiency of the fertilizer nitrogen by 80.21 and 78.58% over 46 kg N ha^{-1} of CU for wheat and teff crops, respectively. The AE of both crops were too high compared with the results of previous studies in the country *i.e.* 22.48 and 20.68 kg grain per kg applied N for the Vertisol and Nitisol zones, respectively (Amsal and Tanner, 2001) and 9.5 to 18.3 kg grain per kg applied N on waterlogged Vertisols in central Ethiopia (Tilahun *et al.*, 1996b).

The physiological efficiency (PE) of both crops responded to the application of SRU with an apparent decreasing trend *i.e.* the efficiency declined with each successive addition of SRU fertilizer rates (Table 9). Thus, the maximum and minimum physiological efficiencies of N for wheat (21.12 and 16.86) and teff (15.03 and 10.32) kg grain per kg total N uptake were recorded at the lowest and highest SRU rates, respectively. Genene (2003), in the study conducted on bread wheat in southeastern Ethiopia, reported mean PE of N as low as 2.74. On the other hand, Amasl and Tanner (2001) reported 47.33 kg grain per kg total N for bread wheat grown on Vertisols in central Ethiopia.

The application of 23 kg N ha^{-1} of SRU has improved the apparent recovery, agronomic efficiency and physiological efficiency of the fertilizer nitrogen by 80.21, 86.51, 3.53% and 56.78, 78.58, 14.38% over 46 kg N ha^{-1} of CU for wheat and teff crops, respectively (Table 9). Generally, the results indicated that agronomic efficiency, apparent recovery and physiological efficiency were significantly enhanced by the application of SRU fertilizer than CU fertilizer. Moreover, the application of 23 kg N ha^{-1} of SRU improved the agronomic efficiency and physiological efficiency of the fertilizer nitrogen than 46 and 69 kg N ha^{-1} of SRU for both crops. However, effectiveness of fertilizers in increasing crop yields and optimizing farmer profitability should not be sacrificed for the sake of efficiency alone. There must be a balance between optimal nutrient use efficiency and optimal crop productivity.

The partial budget analysis (Appendix Table 8) done by considering only grain yield of the respective crop indicates that high marginal rates of return (1681.00 and 1003. 40%) were obtained by applying 46 kg N ha^{-1} of SRU for wheat and teff crops, respectively. This means that the income obtained by applying 46 kg N ha^{-1} SRU fertilizer was more than 17 and 10 times a unit total SRU fertilizer cost for wheat and teff crops, respectively. Accordingly, the application of 46 kg N ha^{-1} of SRU was the optimum rate for both crops.

5. SUMMARY AND CONCLUSIONS

Soil degradation and depletion of soil nutrients are among the major factor threatening sustainable cereal production in the Ethiopian highlands. Among the major plant nutrients, N is the most limiting factor calling for external inputs in the form of fertilizer. However, conventional N fertilizers are highly soluble and may be lost through the processes of leaching, NH_3 volatilization, denitrification, immobilization and fixed in the soil solids as NH_4-N form. Therefore, the use of slow-release urea fertilizer is a common strategy to reduce N losses.

A fresh soil profile pit was opened and described, and samples were collected depth-wise Moreover, composite surface soil (0-15 cm) samples were collected from the wheat and teff experimental field (one composite sample per block) to characterize the fertility status of the soils of the study area on the bases of selected physicochemical properties. Furthermore, a field experiment was conducted to determine the optimum rates and the overall performance of slow release urea fertilizer over conventional urea fertilizer for bread wheat and teff crops production.

The soil profile opened was 150^+ cm deep and had very dark grayish brown (10YR 3/2) color when moist at the surface horizon. The moist color characteristic of the soil surface changed to very dark gray (10Y 3/1) at the underlying subsurface (25-98 and 98-150^+ cm) layers of the profile. The soil textural class of the surface layer (0-25 cm) of the profile and the mean composite surface (0-15 cm) soil samples of the wheat and teff experimental plots were clay loam while it was clay for the underlying subsurface layers of the profile. The bulk and particle density values of the layers in the profile varied consistently with depth ranging from 1.18 and 2.51 g cm^{-3} at the surface layer to 1.32 and 2.85 g cm^{-3} at the bottom layer of the profile, respectively.

The pH of the soil profile decreased consistently with increasing soil depth from 6.3 (slightly acidic) at the surface horizon to 8.2 (strongly acidic) at the bottom of the subsoil. The total N and OM contents of the surface layer of the profile and the mean total N content of the composite surface soil samples of the wheat and teff crops experimental fields were rated as medium while the composite surface soil samples of wheat and teff experimental plots had medium and low OM levels, respectively. The available P content of the soil profile at the surface layer (20.5 mg P kg^{-1} soil) and the composite surface soil samples of the wheat (21.14 mg P kg^{-1} soil) and teff (14.33 mg P kg^{-1} soil) were in the range of the high available P status. In other words, the soil test P values observed indicates that crops grown on the soils of the study area are unlikely to respond to P fertilization significantly as the current amount of soil available P is adequate for optimum crop production.

The soil exchange complex of both the profile and composite surface soil samples of the wheat and teff experimental plots were predominantly occupied by divalent basic cations (exchangeable Ca followed by Mg).The CEC values of the plow layer of the soils in the study area as determined in the profile and the composite surface soil samples of the experimental fields were rated as very high. The CEC values of the profile increased inconsistently with increasing soil profile depth from 41.42 cmol(+) kg^{-1} at the surface horizon to 50.37 cmol(+) kg^{-1} at the upper subsurface (25-98 cm) depth of the profile which was also rated as very high throughout its depth. Among the exchangeable cations, all except Na were rated as high to very high and all except K increased with depth consistently.

Application of different rates and source of N fertilizer significantly ($P \leq 0.01$) affected most of the crop parameters tested such as spikes per 0.5 m raw length, spike or panicle length, spikelet per spike, grains per spike, 1000 grains weight, grain yield, straw, biomass and harvest index of the respective crop. Accordingly, the highest mean grain yield of wheat (4720 kg ha^{-1}) was obtained at the highest SRU rate (69 kg N ha^{-1}) with an increment of 654.33 and 2336.33 kg ha^{-1} over 23 kg N ha^{-1} of SRU and the control treatments, respectively. This highest yield was followed by the yield obtained with 46 kg N $ha^{-1}$of SRU which had 619.33 and 2301.33 kg ha^{-1} yield advantage over the 23 kg N ha^{-1} and the control treatments, respectively.

Similarly, the maximum mean grain yield of teff (3443.67 kg ha^{-1}) was obtained at the highest rate of SRU (69 kg N ha^{-1}) with a yield advantage of 613 and 2332.34 kg ha^{-1} over the 23 kg N ha^{-1} of SRU and the control plots, respectively, followed with SRU rate of 46 kg N ha^{-1} and a yield advantage of 549 and 1268.34 kg ha^{-1} over the 23 kg N ha^{-1} and the control plots, respectively. This response was mainly attributed to the medium and low OM and total N contents of the soils of the study area which demand for external N input to support proper growth and development of crops in the short run and improvements of soil OM for sustainable and/or long term productivity.

In both crops, the application of 46 kg N ha^{-1} of SRU fertilizer has yield advantage of 497.67 and 462.00 kg ha^{-1} over the application of 46 kg N ha^{-1} of CU fertilizer for wheat and teff crops, respectively (Table 7). This shows that SRU can reduce N losses by leaching in the form of NO_3^-, fixation as NH_4, volatilization as NH_3 and atmospheric emission in the form of N_2O or N_2. Similarly, it is reported that N fertilizer application rates on cotton have reduced by 40% if controlled release rather than conventional fertilizers are used.

The partial budget analysis indicates that high marginal rates of return (1681.00 and 1003. 40%) were obtained by applying 46 kg N ha^{-1} for wheat and teff crops, respectively which means that the income obtained by applying 46 kg N ha^{-1} SRU fertilizer was more than 17 and 10 times a unit total SRU fertilizer cost for wheat and teff crops, respectively. Accordingly, the application of 46 kg N ha^{-1} of SRU was the optimum rate for both crops.

The plant total N content and uptakes were linearly increased in response to the application of different rates of SRU fertilizer where the maximum values for grain and straw N contents and uptakes were obtained at the highest N rate for both crops. It was also apparent that much of the nutrients applied were assimilated by the grain than that achieved by the straw. Nitrogen apparent recovery and Physiological efficiency were decreased in response to applied SRU rates where the maximum records were observed at the lowest rate of SRU.

Generally, inefficient fertilizer use may contribute to environmental degradation, particularly in intensive agricultural systems where much fertilizer applied and the recovery or use efficiency of nutrients by crops is relatively low. It is commonly estimated that N use efficiency for cereal production worldwide is only 33%. A portion of the N not used by the crop is presumed to be lost to the environment through denitrification, runoff, volatilization, leaching, and gaseous plant emissions. Such losses raise concerns about surface and groundwater contamination, and greenhouse gas emissions. Therefore, slow release fertilizers are fertilizers designed to slowly release nutrients. Such products can be used to maximize fertilizer use efficiency and minimize potential losses to the environment. Increased nutrient-use efficiency may also increase yield and quality of crops, thus providing an economic benefit for growers.

As a general conclusive remark, the results of the current study provide a significant indication as the application of SRU can influence yield and quality of crop residues on wheat and teff. Despite the need for verification of this study results over several locations and soil types, direct application of the findings by farmers at the study area will remain beneficial than the application of CU fertilizer provided that this SRU fertilizer is available.

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7. APPENDIX

Appendix Table 1. Monthly distribution of rainfall (mm) of Ofla District from 2002 to 2010

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
2002	65.3	0.7	34.1	107.7	15.6	3.0	137.2	228.6	90.2	8.0	0.0	92.6	783.0
2003	13.0	24.0	74.2	74.8	23.7	20.1	168.0	377.1	77.5	1.8	3.9	30.1	888.2
2004	13.9	6.0	40.9	56.0	1.9	54.0	143.6	249.1	65.5	4.1	25.7	9.9	670.6
2005	8.3	0.0	34.5	223.4	163.4	28.1	253.0	297.6	39.7	36.5	48.1	0.0	1132.6
2006	0.0	1.0	182.2	96.2	44.6	6.9	149.0	307.4	51.7	60.1	10.2	172.2	1081.5
2007	58.1	21	68.8	152.6	13.2	76.6	313.4	389	32.6	29.4	27.5	0.0	1181.7
2008	64.2	0.0	0.0	16.6	70.4	42.6	187.1	143	103.4	29.5	137	0.0	794.1
2009	2.2	0.0	44.2	49.3	4.7	6.5	330.6	176	32.2	66.9	38.6	55.1	806.5
2010	0.6	5.3	42.0	111.7	61.6	11.0	311.7	428	64.1	7.7	0.0	27.0	1070.3
2011	14.2	0.0	67.1	9.3	89.7	0.0	263.3	199	45.8	7.5	253.2	100.9	1050.0
Mean	27.9	5.3	44.4	67.9	47.9	27.3	281.2	267.0	278.1	28.2	91.3	36.6	980.5

Source: National Meteorological Agency, Mekelle Branch

Appendix Table 2. Monthly maximum temperature (^{o}C) of Ofla District from 2002 to 2011

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
2002	17.8	20.5	21.8	22.5	25.6	26.2	25.2	22.4	21.8	22.1	21.7	20.1	22.3
2003	20.3	22.4	22.3	22.6	24.4	25.5	22.4	21.7	22.3	21.4	20.9	19.4	22.1
2004	21.1	20.8	22.2	22.8	26.1	25.1	23.1	22.3	23.0	21.4	20.9	19.5	20.6
2005	19.9	23.3	22.7	22.8	23.0	25.3	22.8	23.2	23.2	22.1	21.1	20.3	20.8
2006	21.0	22.4	22.0	21.4	24.3	25.9	23.2	22.6	23.0	22.5	21.3	20.0	22.5
2007	18.5	21.4	23.5	23.5	24.1	24.1	23.2	22.8	23.4	22.6	22.3	19.6	22.4
2008	20.1	20.0	23.1	23.8	24.1	24.5	22.8	22.0	22.2	18.8	19.7	18.9	21.7
2009	20.3	20.9	22.2	22.7	24.5	26.9	22.6	22.4	23.3	21.9	22.3	20.8	22.6
2010	20.4	21.3	21.8	22.6	23.9	25.9	23.1	21.4	21.8	22.0	22.2	21.6	22.3
2011	20.1	20.5	22.9	23.5	24.2	25.7	22.4	22.9	23.1	21	22.1	20.6	22.4
Mean	19.88	20.82	22.7	23.22	24.16	25.42	22.82	22.3	22.42	21.26	21.72	20.30	22.28

Source: National Meteorological Agency, Mekelle Branch

Appendix Table 3. Monthly minimum temperature (^{o}C) of Ofla District from 2002 to 2011

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
2002	6.3	4.5	8.3	8.6	7.1	11.0	11.7	11.1	8.3	4.5	3.0	7.2	7.6
2003	4.3	2.0	3.8	10.1	9.8	11.0	13.1	12.1	9.9	4.1	4.5	2.8	7.3
2004	6.7	5.8	7.4	10.6	7.8	11.3	12.5	12.1	8.0	6.0	5.0	6.2	8.3
2005	7.3	5.4	9.9	9.8	10.5	10.4	12.6	11.8	9.9	5.1	3.8	6.9	8.6
2006	4.1	6.9	8.8	9.9	10.0	11.2	12.7	11.9	9.4	8.2	5.8	9.1	9.0
2007	8.3	9.3	7.0	10.3	10.9	12.4	12.5	11.9	10.0	5.6	6.6	2.6	9.0
2008	5.2	3.2	3.4	8.5	10.1	11.0	12.4	11.8	9.1	8.2	4.9	2.6	7.5
2009	3.8	4.4	7.4	8.0	7.1	9.3	11.5	11.2	6.7	3.8	1.7	6.2	6.8
2010	4.8	6.3	7.5	9.9	10.3	11.8	12.3	12.1	9.5	5.4	2.6	4.8	8.1
2011	7.0	5.5	7.1	9.0	6.6	6.6	7.3	8.5	10.4	7.0	5.5	4.2	7.06
Mean	5.82	5.74	6.48	9.14	9.00	10.22	11.2	55.50	9.14	6.00	4.26	4.08	7.69

Source: National Meteorological Agency, Mekelle Branch

Appendix Table 4. Description of the soil profile opened at Ofla Testing site

Date of description	8 November 2011
Author	Okubay Giday
Location	Ofla District, Southern Zone of Tigray Region
Coordinates	12^{0} 31' 58" N; 39^{0} 30' 13" E
Altitude	2450 masl
Topography	Flat
Surrounding landform	Steep slope
Slope gradient at site	2%
Land use/cover	Crop land
Moisture condition	Moist throughout
Drainage class	Well drained
Erosion status at site	Slight sheet
Erosion at surrounding	Medium rill
Parent material	Basalt
Rocky outcrops	None
Soil type	Vertisols
Depth (cm)	**Description**
0-25	Very dark gray to dark gray (10YR 3.5/1) dry, very dark grayish brown (10YR 3/2) moist; clay loam; hard, firm, very sticky and very plastic; medium common cracks; many fine roots; clear and smooth boundary; pH 6.3.
25-98	Very dark gray (10YR 3/1) moist; clay; strong, firm, very sticky and very plastic; medium common cracks; many distinct slickensides; few $CaCO_3$ concretions; common fine roots; gradual and smooth boundary, pH 7.5.
$98\text{-}150^{+}$	Very dark gray (10YR 3/1) moist; clay; strong, very coarse angular blocky; firm; very sticky and very plastic wet consistence; medium common cracks; many distinct slickenside's; high $CaCO_3$ concretions; few very fine roots; pH 8.2.

Appendix Table 5. Soil pH rating for 1: 2.5 soil to water ratio suspension

pH	Ratings
< 4.5	Very strongly acid
4.5-5.2	Strongly acid
5.3-5.9	Moderately acid
6.0-6.6	Slightly acid
6.7-7.3	Neutral
7.4-8.0	Moderately alkaline
> 8.0	Strongly alkaline

Source: Tekalign (1991)

Appendix Table 6. Ratings for organic matter (OM), total N and available phosphorus

OM (%)[a]	Total N (%)[b]	Available P (mg kg^{-1})[c]	Rating
> 5.17	> 0.25	> 10	High
2.59-5.17	0.12-0.25	5-10	Medium
0.86-2.59	0.01-0.12	< 5	Low
< 0.86	< 0.01	Not Given	Very Low

Source: [a]Tekalign (1991), [b]Berhanu (1980), [c]Olsen *et al*. (1954)

Appendix Table 7. Ratings for exchangeable basic cations, cation exchange capacity (CEC) and percentage base saturation (PBS)

Ca (cmol (+) kg^{-1})[a]	Mg (cmol (+) kg^{-1})[a]	K (cmol (+) kg^{-1})[a]	Na (cmol (+) kg^{-1})[a]	CEC (cmol (+) kg^{-1})[a]	PBS	Rating
> 20	> 8	> 1.2	> 2	> 40	> 80	Very high
10-20	3-8	0.6-1.2	0.7-2	25-40	60-80	High
5-10	1-3	0.3-0.6	0.3-0.7	12-25	40-60	Medium
2-5	0.3-1	0.2-0.3	0.1-0.3	6-12	20-40	Low
< 2	< 0.3	< 0.2	< 0.1	< 6	< 20	Very Low

Source: [a]FAO (2006) , [b]Hazelton and Murphy (2007)

Appendix 8. Mean square estimates for crop phonological, growth parameters and yield and yield components of wheat and teff for one factor randomized complete block design

	Mean squares for source of variation		
Plant parameter	Treatment (N)	Error	CV (%)
	Wheat		
Emergence	0.00^{ns}	0.00	0.00
Days to 50% heading	22.33*	0.98	1.37
Days to 90% maturity	9.17^{ns}	0.37	0.50
Plant height	467.60*	2.35	1.57
No. of spikes 0.5 m^{-1}	1156.73**	2.23	2.43
Spike length	2.43**	0.28	6.05
Spikelets $spike^{-1}$	5.50**	0.35	4.33
Grains per spike	54.73**	0.43	2.02
No. of fertile tillers	3.23*	0.48	11.72
No. of nonfertile tillers	0.50^{ns}	0.20	11.72
1000 grain weight	6.94**	0.15	0.94
Grain yield	2729412.83**	3243.98	1.42
Straw yield	3439065.77**	4604.57	1.08
Biomass yield	12437285.70**	11044.73	1.02
Harvest index	19.88**	0.36	1.55
	Teff		
Emergence	0.00^{ns}	0.00	0.00
Days to 50% heading	15.43**	0.33	2.20
Days to 90% maturity	17.07**	0.22	0.52
Plant height	355.73**	2.68	1.58
Panicle length	227.83**	1.98	3.25
1000 grain weight	0.01**	0.00	1.88
No. of fertile tillers	89.57**	0.77	5.50
No. of nonfertile tillers	0.23^{ns}	0.18	5.48
Grain yield	859552.52**	1718.57	1.42
Straw yield	3175238.67**	10453.47	1.96
Biomass yield	5608219.40**	12770.55	1.37
Harvest index	2.81**	0.32	1.60
Harvest index	2.81**	0.32	1.60

* = Significant at $P \leq 0.05$; ** = Significant at $P \leq 0.01$; ns = Not significant at $P > 0.05$; CV = Coefficient of variation

Appendix 9. Partial budget analysis for SRU fertilizer rates for wheat and teff crops

Wheat				
Cost (Ethiopian Birr)				
	0 kg N ha^{-1}	23 kg N ha^{-1}	46 kg N ha^{-1}	69 kg N ha^{-1}
Weighing and transport	0.00	30.00	30.00	30.00
Fertilizer application	0.00	60.00	120.00	180.00
Fertilizer cost	0.00	800.00	1000.00	1200.00
Total cost	0.00	890.00	1150.00	1410.00
Income (Ethiopian Birr)				
Income ha^{-1}	20,022.00	34,146.00	39,354.00	39,648.00
Change in cost	0.00	890.00	1150.00	1410.00
Change in income	0.00	14,124.00	19332.00	19626.00
Marginal rate of return (%)	0.00	1586.90	1681.00	1391.90
Teff				
Cost (Ethiopian Birr)				
Weighing and transport	0.00	30.00	30.00	30.00
Fertilizer application	0.00	60.00	120.00	180.00
Fertilizer cost	0.00	800.00	1000.00	1200.00
Total cost	0.00	890.00	1150.00	1410.00
Income (Ethiopian Birr)				
Income ha^{-1}	19210.10	25,753.00	30748.90	31331.30
Change in cost	0.00	890.00	1150.00	1410.00
Change in income	0.00	6542.90	11538.80	12121.20
Marginal rate of return (%)	0.00	735.20	1003.40	859.70