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Integrated Plant Nutrient Management in Crop Production in the Central Ethiopian highlands

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Authorship statement

Balesh Tulema Bune: corresponding author, responsible for planning, designing and executing all the experiments, analysis and interpretation of results. Alone she has prepared the first draft of all the papers and wrote the final version in collaboration with the other authors.

Bishal Sitaula: assistant advisor (Paper 4).

Tor Arvid Breland: assistant adviser (Paper 2).

Bernard Vanlauwe:visited the experimental sites at Gare Arera, facilitated my training in Nairobi and assistant advisor (Paper 1)

Filipe Zapata: supervisor for the experimental work carried out at the FAO/IAEA Agriculture and Biotechnology Laboratory in Seibersdorf, Austria (Paper 3 & 4).

Fred Haakon Johnsen : co supervisor and advisor (Paper 5).

Jens Bernt Aune : overall supervisor of the Ph.D. studies of Balesh Tulema Bune.

Dedicated, primarily to God, Our Father.

LORD, ‘I know that you can do all things,

and that no purpose of yours can be thwarted’ (Job 42:2,NIV).

Secondly to my husband Botossa Kedida and my children Yisehak Botossa, Mihiret Botossa, Samuel Botossa and Zekarias Botossa.

Extended summary contents

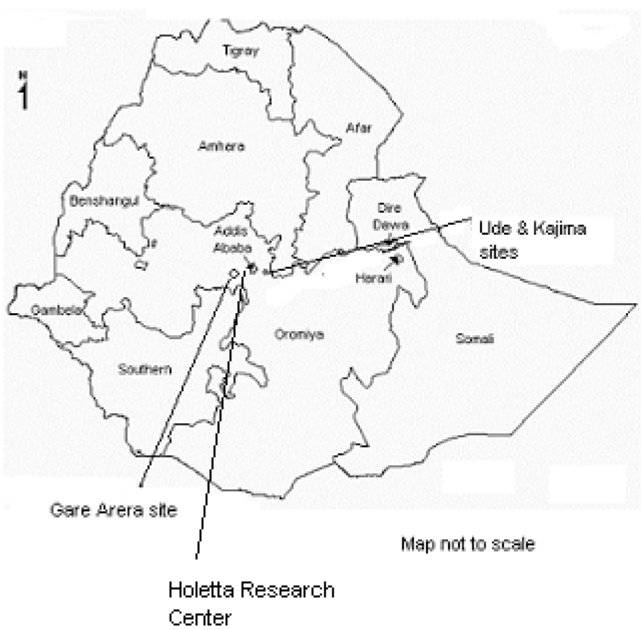
Integrated Plant Nutrient Management in crop production in the Central Ethiopian highlands.

Ethiopia is located in east Africa between 3^0 N and 15^0 N latitudes and 33^0 E and 48^0 E longitudes. The country covers an altitude range from 126 meters below sea level to 4620 m.a.s.l.. Ethiopia has an area of 1.13 million km^2 and occupies a huge landmass of Africa (FAO, 2003). Characteristically it has a rugged landscape, from a highland complex of mountains and bisected plateaux at the heart to torrid plains**.** Though the country is found in the tropics, the highlands enjoy temperate and tropical climates. The altitude modifies the temperatures and the annual average is seldom higher than 20^0C. Most of the highlands have rainfall in the range of 600 to 2700 mm.

The study site

The sites for this thesis work were in central Ethiopian highland, Oromiya Regional State, East and West Shawa zones, Ada Liban, Wolmera and Dendi districts (8°48' N, 39°38' E; $9^0$05' N, $38^0$30'E; $09^0$03' N, $38^0$30' E). The topography of the sites at Ada Liban district varied from flat land to gentle slope. Holetta station in Walmera district has a gentle sloping landscape whereas at Gare Area in Dendi district the landscape is more undulating than the other sites. The altitude of the site at East Shawa was about 1800 m. a. s. l., whereas, Holetta and Gare Arera were 2400 and 2200 m. a. s. l., respectively. The rainfall pattern at all

Fig. 1 Map of Ethiopia showing the study sites



locations was bimodal.

Justification of the study

The Ethiopian highlands are one of the hotspots on the African continent with regard to food production and in the struggle to preserve the natural resource base (FAO, 2003). The Ethiopian highlands cover 95% of the cropped area in Ethiopia and contain almost 85% of the Ethiopian population.

The cropped area is subject to severe losses of nutrients through soil erosion and by removal of dung and crop residue for fuel. Nutrient balance calculations for countries by Stoorvogel and Smaling (1990) showed that Ethiopia was among the countries with the highest rates of net nutrient losses. The annual nutrient deficit is estimated at -41 kg N, -6 kg P and -26 kg K ha^{-1}.

In the Ethiopian highland soil loss due to water erosion is about 1493 million ton per annum as estimated by Hurni (1993). Of this, nearly half is estimated to come from cultivated fields, which account for only about 13% of the country's total area. These losses will inevitably cause yield decreases unless appropriate measures are taken.

Population growth rate is high and by the year 2020 is expected to exceed 110 million, which is about a doubling of the current population. If present production trends remain unchanged, Ethiopia will face a food deficit. However, this negative trend can be reverted if appropriate measures are taken.

Most Ethiopian soils are deficit in nutrients, especially nitrogen and phosphorus and fertilizer application has significantly increased yields of crops (Asnakew et al., 1991, Tekalign et al., 2001).

However, despite the potential for increasing yields and farm income by the use of fertilizer, many small scale and poor farmers do not have the resources to make use of fertilizer for various reasons.

Moreover, though fertiliser use in Ethiopia has increased notably since 1990, there is no concomitant yield increase especially in tef [*Eragrostis tef* (Zucc.) Trotte]. Tef is a major staple crop in Ethiopia and cultivated on about two million hectares of land covering about 30% of the area under cereals. In the central highlands 70 to 80 % of the inorganic fertilizer purchased by the smallholders is known to be applied to tef. However, since the 1980, tef yields have almost stagnated, probably due to the occurrence of accelerated soil erosion and lack of appropriate cultural practices on farmers' fields (Fufa et al.2001, Mulat et al, 1998).

Hence, it is important to understand these constraints and develop low cost technologies that focus on development of appropriate Integrated Plant Nutrient Management (IPNM) for the Ethiopian highlands. Integrated Plant Nutrient Management is based on the principles i) optimising the use of organic fertiliser ii) supplementing with mineral fertiliser when needed and iii) minimising losses of nutrients. IPNM is not only concerned with good agronomy, but its success is highly dependent on economic, social and institutional issues (Dudal 2002; IFPRI 2000; Ragnar et al. 1999).

The objectives

The overall objective of this research was to understand the dynamics of soil nutrients and their management at farm level and to develop participatory plant nutrient management options for sustainable production.

Approach

The study employed different approaches: household survey with formal questionnaire, focus group discussion, interviews, household nutrient flow monitoring, participatory on farm experiments, on farm experiment, on-station field and greenhouse experiments.

Participatory nutrient flow monitoring

Quantitative analysis of nutrient-flow processes at farms of different socio economic levels was carried out to identify hotspots of soil nutrient depletion and suggest options for soil nutrient maintenance in Gare Arera farming systems.

Participatory on-farm experiments

Three participatory on-farm experiments were carried out. The first experiment was carried out to identify, characterize and evaluate the organic nutrient sources available in Gare Arera.
The second experiment evaluated the performance of conservation tillage in tef and wheat in Vertisol and Nitosol in Gare arera.
The third experiment was carried out to monitor the N use efficiency of urea fertilizer applied to tef under farmers' management in East Shawa zone.

On-station experiment

A field experiment was carried out to evaluate mustard meal as a source of N on tef at Holetta**.**

Greenhouse experiments

A series of greenhouse experiments was carried out to study the effect of key factors on fertilizer N use efficiency (FNUE) of tef.

Summary of findings

Nutrient balance at farm, soil fertility class and crop levels (paper 1)

The result of the nutrient flow and balance study showed significant difference in nutrient inputs outputs and balances between farms and within a farm. One important finding was that it matters at which scale nutrient balance is studied. The nutrient balance at the farm level was more positive than at the plot and crop levels. The reason was that nutrients accumulated in deposition sites in the vicinity of the homestead. The nutrient balance at farm level was –9 kg N, +11 kg P and +62 kg K ha^{-1} yr^{-1}. Among the farms, N was more depleted on poor households farms due to low input. The balance in different soil fertility group classes varied from –20 to –185 kg N ha^{-1}, from +11 to –83 kg P ha^{-1} and from +23 to –245 kg K ha^{-1} yr^{-1}.

The highest depletion was on very poor fertility soils as the land use of these soils was either a crop with low value or grazing land. Good and medium fertility soils are planted mostly with high value crops. Nevertheless the nutrient balance on all the crops, including tef was negative due to low nutrient input, high biomass removal and N losses. In all farms the most severe nutrient depletion was on grasslands.

There are options for increasing nutrient input from cheap nutrient sources such as farmyard and manure, compost, N fixation and bone meal application. Minimum tillage, safe removal of excess water from cropland and gully stabilization can reduce nutrient loses.

Comparative effect of urea and organic nutrient sources on tef (paper 2).

Major organic nutrient sources available at household level in the area were identified, characterised and evaluated. Application of organic material N at equivalent rate to tef on Nitosol and Vertisols resulted in the mean grain yield of 82 % and 99 % of urea treatment yield respectively. The apparent N recovery (% ANR) of urea and the organic materials was 27 and 21 respectively. The agronomic efficiency (AE) of the organic fertilizers was similar to urea on the Vertisol. The agro-ecological conditions in the study area appear favourable for the use of organic materials. ANR of urea was low, the surface broadcasting of urea and the high rainfall at time of application might have favoured N losses through different pathways. On Vertisol, tef was more responsive to FYM and on the Nitosol to compost. Compost enriched with ash could be a good choice on Nitosol while FYM performed well on Vertisol. Mustard meal can be applied on both soils in the vicinity of its production. The calculated average annual manure production per household varied from 2866 kg for poor farmers to 11653 kg for rich farmers. N calculated based on mustard seed production in Ethiopia in 2000 (CSA 2001) was about 580 Mg or 2.8 % of the total urea N consumption in Ethiopia (FAO 2004) during the same period.

Mustard meal N uptake by tef evaluated (paper 3)

When mustard meal was evaluated as a source of N for tef on Nitosol at Holetta the AE and the mustard meal N use efficiency (%mmNUE) obtained with the application of 31 kg N ha $^{-1}$ was 13 kg and 34 % respectively.

When N uptake from mustard meal and urea mixed in different ratios was studied with ^{15}N technique, the mean N use efficiency from urea was 40 % and was not affected by ratio of mustard meal. The mean % N use efficiency from mustard meal was 22.

NUE of tef monitored (paper 4)

When the fertiliser N use efficiency (FNUE) from urea applied to tef on Vertisol and Andosol was monitored under farmers' field management condition, the FNUE on Andosol was 33% compared to 22% on Vertisols. Higher uptake on Andosol was may be due to better soil drainage.

Urea and ammonium sulphate N use efficiency of four tef varieties studied under greenhouse conditions on typic Eutrocrept soil showed higher % FNUE for all the tested tef varieties when the N source was urea compared to ammonium sulphate. The mean % FNUE for urea and ammonium sulphate was 48 and 34% respectively. When the varieties were grown on a Nitosol or a Vertisol and ammonium sulphate was applied, the % FNUE of the tef varieties was 61% on the Nitosol and 28% on the Vertisol.

Option of zero and reduced tillage in tef and wheat production (paper 5)

The study assessed agronomic and economic effect of conventional tillage (four times ploughing), reduced tillage (one time pass with the plough), zero tillage and Broad Bed

Furrow (BBF). Farmers' perceptions on the methods were in addition assessed. The results showed that one time ploughing could be an option to conventional ploughing in tef, as there was no significant difference in yields and gross margin on the Vertisol. On the Nitosol, though there was no difference in the yield, the gross margin on minimum tillage was lower than the conventional. Nevertheless, the benefit of minimum tillage is not only the immediate economical benefit. BBF gave the highest yield of wheat on Vertisols followed by minimum tillage.

The willingness of farmers to adopt the zero/reduced tillage was low but varied with age and sex. Minimum tillage is an interesting option particularly for female headed households because it will reduce the need to rent oxen. Reduced tillage/zero tillage will also improve overall productivity of the farming system because it allows partly replacing oxen with cows and reduces the soil erosion.

Contribution of the study to Integrated Plant Nutrient Management (IPNM) in Ethiopia

IPNM seeks both increased agricultural production and preservation of the environment for future generations. IPNM relies on nutrient application and conservation, new technologies to increase nutrient availability to plants, and the dissemination of knowledge between farmers, researchers and other stakeholders (IFPRI 1999, World Bank 1999).

The nutrient flow analysis study in this work identified the unbalanced nutrient input and output and indicated the soil nutrient reserve was depleting. As reserves get depleted, crop growth and productivity could be compromised. The study showed that there is a scope for better management of organic nutrient sources.

Increased agricultural production through increased nutrient application is among IPNM strategies. In this work the possibility for increased nutrient input from locally available sources to the farming system were assessed in a survey and organic nutrient sources were identified. The identified nutrient sources were evaluated and their effect compared with mineral fertilizer. Composting was introduced as new technology to increase nutrient availability to plants and minimize constraints connected with manure use.

Conservation tillage that minimizes soil disturbance and soil erosion was studied and the possibility of sowing tef and wheat with minimum tillage was suggested.

The study showed that that there is no panacea to improved IPNM in the Ethiopian highlands. Choices of IPNM method depend on wealth and gender of farmers, position of the field, crops grown, soil type, access to manure and mineral fertilisers. All these factors vary between the farms.

Rich and medium wealth group farmers could afford to apply mineral fertilizers and increase nutrient inputs from organic sources as they have more access to manure and other organic materials for compost production. They can apply farmyard manure on Vertisols and ash enriched compost on Nitosol.

Poor farmers do not have many choices in the absence of a credit scheme. They have to increase nutrient input from cheap sources by incorporating more N fixing crops in the crop rotation and producing ash enriched compost.

Female farmers and poor male farmers without oxen have the option to use minimum tillage to reduce the ploughing cost. Similarly reduced tillage can be an alternative on soils prone to soil erosion. Advice to farmer with regard to IPNM must try to reflect this diversity in farmers' wealth and agro-ecological conditions.

This study sought to involve farmers strongly in the research and development process. Farmers were involved in nutrient monitoring, training and in discussion forums between government and non-governmental representatives, researchers and farmers. IPNM requires intensive knowledge dissemination between farmers and other stakeholders.

This study did not address the full range of factors that influence IPNM in the Ethiopian highlands. Further studies are needed to get a more comprehensive picture on the factors that influence agricultural practices and nutrient management in Ethiopia highlands. Nevertheless, I assume that this study should give a contribution to how future IPNM strategies could take into consideration local agronomic, social and economic issues.

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List of papers

This thesis is based on five papers referred to by their Roman numerals.

I. **Balesh Tulema Bune**, Jens Bernt Aune, Bernard Vanlauwe. Nutrient flows and balances among different groups of farmers in the smallholder farming system in Gare Arera, central Ethiopia. (to be submitted Agriculture, Ecosystem and Environment)

II. **Balesh Tulema ,** Jens Bernt Aune, Tor Arvid Breland. Availability of organic nutrient sources and their effects on yield and nutrient recovery of tef [*Eragrostis tef* (Zucc.) Trotter] and on soil properties (submitted to Journal of Plant Nutrition and Soil Science).

III. **Balesh Tulema Bune,** Filipe Zapata and Jens Aune (in press). Evaluation of mustard meal as organic fertilizer on tef **(*Eragrostis tef* (Zucc) Trotter** under field and greenhouse conditions. (Nutrient cycling in Agroecosystems)

IV. **Balesh Tulema Bune,** Felipe Zapata, Jens Aune and Bishal Sitaula (2005). N fertilization, soil type and cultivars effects on N use efficiency in tef [*Eragrostis tef* (Zucc.) Trotter. Nutrient cycling in Agroecosystems 71: 203-211.

V. **Balesh Tulema Bune,** Jens Bernt Aune and Fred Haakon Johnsen (unpub.). Agronomic, economic and cultural implications of zero/reduced tillage in Tef (*Eragrostis tef* Zucca) and Wheat (*Triticum aestivum*) production in Gare Arera, West Shawa Zone of Oromiya, Ethiopia (International Journal of Agricultural Sustainability)

Paper 1

Nutrient flows and balances among different groups of farmers in the smallholder farming system in Gare Arera, central Ethiopia.

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Abstract

There is a paucity of information on nutrient balances at farm and plot levels in Ethiopia. A nutrient balance study was undertaken on farms in Central Ethiopia in order to assess the balances and identify areas of intervention. The Nutmon computer toolbox was used to calculate the full nutrient balance at farm level, at different soil fertility classes and at crop level. Data were collected from nine farm households in three wealth categories (rich, medium, poor) from June 2001 to May 2002.

One important finding is that the scale of the nutrient balance studied is significant. The nutrient balance at the farm level is more positive than at the plot and crop level.

The nutrient balance at the farm level was –9 kg N, +11 kg P and +62 kg K ha^{-1} yr^{-1}. Among the farms, N was more depleted on poor household farms, whereas medium wealth group households had more P and K accumulation. The positive balances found are due to accumulation of organic inputs, such as manure and household waste at disposal sites in the homestead. The nutrient balance was in general more negative for the poor and very poor fertility soils as compared to the soils of good and medium soil fertility. Mean balance in different soil fertility group classes was –79 kg N ha^{-1}, -18 kg P ha^{-1} and –95 kg K ha^{-1} yr^{-1}. The highest depletion was in very poor fertility soils of the medium wealth households. Good and medium fertility soils are planted mostly with high value crops, such as tef and wheat that receive the highest nutrient input. Nutrient depletion varied between the crops. Nutrient depletion was most severe on grasslands. Maize and enset had a positive nutrient balance, with the highest nutrient accumulation on rich household farms. Crop removal was the primary contributor to nutrient depletion, followed by erosion. Wealthier households had less depletion due to more chemical fertiliser and feed inputs. The results show that there is an enormous variation in nutrient balance between different farm categories and among farms.

This variability has to be taken into consideration when developing future strategies for improved soil fertility management.

Improved manure management, incorporation of more legume crops in the cropping system, and green manure and fodder production during the short rains can increase nutrient inputs and reduce losses. Soil conservation measures and conservation tillage could be recommended for controlling losses through erosion.

Key words: crop-livestock farming, free livestock grazing, nutrient inputs and outputs, nutrient losses, organic fertiliser, soil fertility.

1. Introduction

Soil fertility depletion is considered to be the fundamental biophysical root cause for declining per capita food production in Africa in smallholders' fields (Sanchez et al., 1997). Nutrient losses are high due to biomass removal, inadequate fertiliser application, erosion and other losses.

In sub-Sahara-Africa (SSA), nutrient depletion has been found to be intense in eastern Africa due to high outputs of nutrients in harvested products, erosion and relatively high inherent fertility of the soils (Smaling et al., 1997). In Ethiopia, soil erosion is a major cause of nutrient depletion. Soil loss due to water erosion is about 1,354 million Mg per annum (Hurni 1993) and of this, nearly half is estimated to come from cultivated fields.

The annual nutrient deficit in Ethiopia has been calculated to be -41 kg N, -6 kg P and -26 kg K ha^{-1} yr^{-1} (Stoorvogel and Smaling 1990).

However, a more diversified picture of nutrient mining appears when studying the nutrient balance at the farm and plot level as compared to the national level. For southern Ethiopia, the nutrient balance varied according to site and socio-economic characteristics of farmers (Elias el al. 1998).

It is obvious that the national figures are hard to relate to a specific farming system. This is particularly important for Ethiopia since the agricultural landscapes and production systems are variable with regard to topography, agro-ecological characteristics, ethno-history and culture that influence agricultural practices and nutrient management.

The nutrient balance may differ in accordance with household wealth because a household's wealth could influence fertiliser application, crop choice, fallowing duration, production and use of organic fertilisers (Swift et al., 1994). Wealth also influences the decision to invest in soil conservation measures. Hence, the assessments at the national level need to be complemented by data from farm and plot level.

This study focuses on nutrient balances within and between different wealth category farms to assess the nutrient redistribution that takes place at different levels such as farm level, soil fertility class level and crop level.

The objectives of this study were

(i) to asses how wealth category affects different soil characteristics and the nutrient balance;

(ii) to monitor nutrient inputs, outputs and balances at farm, soil fertility group and crop level and determine if the household wealth status has an effect on the measured parameters;

(iii) to assess the opportunities for increasing nutrient inputs and minimizing nutrient losses in order to improve nutrient management and increase crop productivity.

2. Material and methods

2.1. Study site

The study was carried out in Gare Arera (09^{0}03' N, 38^{0}30' E) Dendi District, West Shawa Zone of Oromiya Regional State, Ethiopia (Fig.1). The site is located 95 km west of Addis Ababa, on the Nekemt road. The topography is undulating land at mid altitude (2200 m.a s.l.). The soil in the area is predominantly Vertisol with Nitosols occurring in the uplands (Ethiopian Agricultural Research Organization (EARO), Gare Arera watershed data,unpublished). The area is located adjacent to Chilimmo natural forest. The area has a bimodal rainfall pattern, with the main rain from June to September and the short rain from February to April. The long-term average annual rainfall, maximum and minimum temperatures were 1,100 mm, 24^0 and 8^0 C, respectively (Weather data from Ginchi Research Centre).

2.2. Farming system

The farming system is mixed crop livestock. Tef is the main staple crop complemented by other cereals such as maize *(Zea mays)* and sorghum *(Sorghum bicolor)*. Other crops such as grass pea (*Grass pea Vetch*), wheat (*Triticum aestivum*), barley (*Hordium vulgarae*), peas (*Cicer arieinum*), lentils (Lens *culinaris* Medik.), faba beans (*Vicia faba*), niger seed (*Gizotia abissinca*) and linseed (*Linum usitaticimum*) are also grown.

2.3. Selection of farms for nutrient monitoring

At the beginning of the study, in June 2001, the aim of the study and the method of data collection were presented to the farmers in a meeting organised by Gare Arera Service Cooperative. After the meeting farmers who were willing to participate in the study were invited. Several farmers showed interest to participate in the study. From these, nine farmers representing three wealth groups, 'rich', 'medium' and 'poor' (according to the local criterion) were systematically selected for the year round nutrient flow and balance study.

The input data for Nutrient monitoring (NUTMON) were collected at two phases in accordance with the manual (Vlaming et al. 2001), farm inventory and farm monitoring.

2.4. Farm inventory

Farm inventory focused on identifying the resources available, their location and characterisation. The available resources (land, livestock,farm tools) were recorded by interviewing. The inventory was carried out at the beginning and at the end of the study.

2.5. Simple farm sketch preparation

To locate the plots each household head drew a simple farm map alone or assisted by family members. The location of each plot was indicated on the farm map.

2.6. Categorisation of plots according to the fertility category

The household head grouped the plots in fertility categories according to the plots' productivity as good, medium, poor and very poor. The soil around the residential home was called homestead soil.

2.7. Category of livestock

The animals owned by the household were categorised into cattle, small ruminants and equines.

2.8. Soil, plant and organic fertiliser sampling and characterisation

Three to five samples from the 0-30 cm soil depth were collected to make two composite samples per plot. Soil samples from different fields of the same soil fertility class for each farmer were sub-sampled and mixed to make three composite samples for each fertility class. Plant samples were collected at the crop harvest from each plot. Farmyard manure and ash samples were collected from each farm.

The samples were analysed at Holetta Agricultural Research Centre (HARC), Ethiopia. Prior to analysis, the samples were oven dried at 70^0 C for 72 hrs and ground to pass through a 500 µm sieve. The soil pH was measured by pH meter (Peech, 1965); soil texture was measured by the pipette method (Day, 1965); soil organic carbon (Allison, 1960), soil and plant N were measured according to Bremmer (1965); soil K was measured by methods described in Chapman (1965); and phosphorus was measured by the Bray 2 method (Bray and Kurz 1945). Plant P was measured by the procedures described by Murphy and Riley (1962) and Wantabe and Olsen (1965), and K was measured by methods described by Isaac and Kerber (1971).

2.9. Farm nutrient flow monitoring

Nutrient inflows and outflows in farms and plots were recorded according to the NUTMON manual (Vlaming et al. 2001). The list of inflows and outflows is given in Table 1 and Fig.1. Chemical and organic inputs (IN 1 and IN 2), and outputs as harvested products and residue (OUT 1 and OUT 2a) at different levels were measured, are directly based on the nutrient concentration. Nutrient concentration in enset leaves was adopted from previous work (Elias et al., 1998).

Manure from external grazing (IN 2b) and excretion of manure outside the farm (OUT 2b) were calculated by the Livestock uptake model "Dry matter" and Livestock excretion model, respectively (Vlaming et al., 2001).

Combined wet and dry atmospheric deposition (IN 3) was calculated according to the Nutmon model (Smaling, 1993).

Nitrogen fixation (IN 4): Chickpea, faba bean, grass pea and lentil provided the N input from biological nitrogen fixation. The % N fixation data for the study area was not available. Direct observation of the nodulation showed good nodulation of all the legume crops in the area. The work at other sites in Ethiopia also supported the observation (Tekalign and Asgelil, 1993) and it was assumed that 50% of the N requirements was derived from biological nitrogen fixation.

N loss through leaching (OUT 3) and gaseous loss (OUT 4) were estimated using transfer functions developed by Smaling (1993).

Soil erosion (OUT 5) was calculated using the simplified and adopted version of the Universal Soil Loss Equation (USLE). This equation predicts soil loss as a function of rainfall erosivity (R), soil erodibility (K), slope length (L), land cover (C) and land management (P). The R and K factors were calculated according to Vlaming et al., (2001). Different C factors were assigned to different fields, as the farmers grow pure stand crops in each plot. The management factor (P) for all the farms was considered the same.

Human excreta (OUT6) were calculated by default human excreta (Vlaming et al., 2001).

2.10. Limitations

Soil data on mineralization rate, soil erodibility, erosivity, enrichment factor and land cover factor was lacking for the study area.

The model has limitations when used in a system where croplands are freely grazed after crop harvest. The program assumes that the plot was out of use once the crop harvest was recorded. To account for animal grazing we had to assume the presence of crop on the field (plot) one to two months after harvest. In addition, the period of open grazing of the cultivated plots was not included as it resulted in over estimation of the output (OUT 2b).

Plots with local grass for grazing were continuously grazed, though the availability of biomass was limited. The extended presence of animals on the plot overestimates the output (OUT 2b). Hence, we expect overestimations of nutrient removal (OUT 2b) from the grazing plot.

It is difficult to draw a strong conclusion based on the results from this study as only three farmers represented each of the three wealth groups. However, we believe that the results will indicate the general trend in different wealth groups and soil fertility classes.

2.11. Statistical analyses

The data of processed nutrient flows and balances for individual farms were exported and analysed for variance using the MSTAT C computer package (Russell, D. Freed, Michigan State University, USA). The statistical analysis was based on analysis of variance. The means were separated using Fisher's protected Least Significance Difference test (LSD) at P= 0.05.

3. Results

The factors that defined wealth were land size, livestock number, family size, residential house type and number of houses owned.

Land and livestock resource availability varied significantly between the wealth groups (Table 2). The rich farmers had about 4 times as much livestock as the poor households. In addition the rich farmers had two and four times as much land as the medium and poor farmers, respectively. The same ranking was observed for the size of the cultivated land.

3.1. Characteristics of the soils in the different fertility categories

The farmers classified their soils into homestead soils and crop production soils. Homestead soils are the soils around residential homes, gardens and nearest crop production plots. The nearest crop production plot was planted for harvesting green maize and enset. Crop production plots were scattered over a large area in the watershed. Farmers classified the plots into soils of good, medium, poor and very poor fertility.

The homestead soils (Table 3) in all wealth groups were slightly acidic in reaction (pH) and high in N, P, K and OC. Soil N and P differed significantly between the wealth groups. Poor households had a significantly higher N content than rich and medium wealth groups. The P content was highest on the medium wealth household farms.

In good fertility soils the medium wealth group households had a significantly higher pH than the poor and rich households. The N, P, K and organic carbon contents also varied significantly between the households. The N and OC contents were highest on rich household farms, whereas the P and K contents were highest in medium wealth groups. Good fertility plots of poor households had the lowest content of N, P and OC.

The medium fertility soils varied significantly in the pH, N, OC and K contents and texture between the wealth groups. Soil N and OC content was lowest on poor household farms. The K content was lowest on rich household farms.

In poor and very poor fertility soils all the parameters varied significantly compared to the other wealth groups, with the exception of OC.

The general trend across soil fertility classes for the soil pH, P and K contents was: homestead > good fertility > medium fertility > poor and very poor fertility. For the N and OC contents, the trend was: homestead > poor and very poor fertility > good fertility > medium fertility.

3.2. Farm nutrient inputs, outputs and balances

The mean N input across the wealth groups was 47 kg ha^{-1} (Table 4). The medium wealth group farmers had 54 and 76% higher N input than the rich and poor households, respectively. On all farms, organic fertiliser as animal excreta made out 67-79% of the total N input. The mean mineral fertiliser N input was 7.5 kg ha^{-1} and accounted for 18% of the total N input. The poor households had a significantly lower N input from chemical fertilisers than the other wealth groups.

The mean N output was 56 kg ha^{-1} and varied between the medium and other wealth groups. Medium wealth households had 45 and 34% higher N output than the rich and poor households, respectively. The major N output was through animal excretion (OUT 2b) that comprised 32, 51 and 27% of the total in the rich, medium and poor households, respectively. The N output with harvested crops (OUT 1 + OUT 2a) constituted 4% of the total N output and varied between the poor and other households. The N output through leaching, gaseous loss and erosion constituted 59% of the overall total and varied between the poor and the other wealth households.

The mean N balance showed a deficit of 9 kg ha^{-1} and was most negative for the poor wealth group.

The mean farm P input was 18.7 kg ha^{-1}. The medium wealth group farmers had 37% higher P input than the rich and poor households. The major P input was organic source (IN 2a + IN

2b) that constituted 82% of the total and varied significantly between the wealth groups. The mineral P accounted for 15% of the P input.

The mean P output was 7.5 kg ha^{-1} and varied between the households. The highest P output was in the medium wealth group households. The rich and poor households had 34 and 44% less P output than the medium wealth group households, respectively. On all of the farms, the major P output was manure excreted outside the farm (OUT 2b).

The P balance was positive for all farms. The medium wealth households had the highest P accumulation.

The mean K input at farm level was 129 kg ha^{-1}. The major K input (97%) was organic fertilizer (IN 2a + IN 2b).

The mean K output was 67 kg ha^{-1} and was lowest for the medium wealth group and the mean K balance was 62 kg ha^{-1}. Medium wealth farms had the most positive balance.

3.3. Nutrient balance in soil fertility classes

The mean balance in different fertility group soils was –70 kg N ha^{-1}, -13 kg P ha^{-1} and –82 kg K ha^{-1} (Table 5). The N balance in all the soil fertility groups was negative. The balance in good fertility soils that also included homestead soils was –20 kg N ha^{-1} and was more negative for the poor household farms than for the other wealth groups. Similarly, in medium fertility soils, the N depletion was significantly higher on the poor household farms than the others.

In poor fertility soils the highest N depletion was on medium wealth group household farms. Rich and poor households had 73 and 35% less N depletion than the medium wealth group farms, respectively.

In very poor fertility soils, the N balance was very negative.

The P balance for good and medium fertility soils was positive (11 kg P ha^{-1}). The P balance was more positive for the rich households as compared to the poor households in all soil fertility classes.

Poor and very poor fertility soils had a negative mean P balance, but varied from depletion to accumulation between households. Medium wealth households had 17 and 30 kg ha^{-1} more P accumulation than the rich and poor households, respectively. Depletion of P was most intense in very poor fertility soils of the medium wealth households.

The K balance was negative in all fertility classes except the good fertility class. The K balance in good fertility soils was 23 kg K ha^{-1}. K depletion was particularly severe in the poor and very poor fertility soils. The medium wealth farmers had a very severe negative depletion (-251 kg ha^{-1}) in the poor and very poor fertility soils.

3.4. Nutrient balances for different crops and wealth groups

The N, P and K balances were assessed for the major agricultural crops in the district.

The mean N, P and K balances at crop level were –33, 1 and –19 kg ha $^{-1}$, respectively, and varied between farms and crops (Table 6 and Table 7). Tef is the major crop in the district and a detailed balance is therefore presented for this crop. The mean N input to tef was 15 kg ha $^{-1}$ and varied between the farms (Table 6). Rich and medium wealth households had 89 and 56% more N input than the poor households, respectively. The main N input on all farms was the chemical N that constituted 59-75% of the total N input. N input from organic nutrient sources constituted 8-16 % and varied between farms. The mean N output was 32.6 kg ha^{-1}. Rich and medium wealth group households had 12 and 14% more N output than the poor households, respectively. N output with harvest (OUT 1 + OUT 2) was 45, 24, and 22% of the total in the rich, medium and poor households, respectively. N output through gases, leaching and erosion amounted to 55 - 78% of the total.

The mean N balance in tef was –17 kg N ha^{-1} and varied between the rich and the other two wealth groups as the rich households had a lower negative balance.

The mean P input in tef was 10 kg P ha^{-1} and varied significantly between the wealth groups. Rich households had three and four times higher P inputs than the medium and poor households, respectively. The major P input was mineral fertiliser, which constituted 82 –90% of the total.

The mean P output in tef was 4 kg ha^{-1} and varied between the rich and other wealth groups. The rich households had about six times more P output in tef than the medium and the poor.

The mean P balance on tef was 6 kg ha^{-1} and significantly varied between the rich and other households. The rich households had 85 and 245% higher P in accumulation in tef fields compared to the medium and poor wealth group farmers.

The mean K input in tef was 4.6 kg ha^{-1} and rich households had 263 and 38% higher K input in tef than the medium and poor households, respectively. The K input from manure constituted 72, 16 and 26% in the rich, medium and poor households, respectively. Poor households had 36% K input from wood ash to tef. The other major K input in tef was dry and wet deposition (IN 3). Medium wealth households had 84% of K input in tef from deposition, whereas in rich and poor households it constituted 28 and 38%, respectively.

The mean K output was 23 kg and varied between wealth groups. Highest and lowest outputs were on the rich and medium wealth group farms, respectively. The K output with harvested products constituted 7.8% of the total K and varied from 3.6 to 13.7%. The highest K output was with erosion that made up 50% of the total output and followed by removal with animal excreta (OUT 2b), that was 35%. Erosion was highest on medium wealth group farms and lowest on rich household farms. Removal with animal excreta was highest in rich household tef fields.

The K balance of tef was negative on all farms and varied between medium wealth and other households.

For the other crops, the balance is presented according to wealth groups. Maize had a negative N balance and the depletion varied between wealth groups (Table 7). Highest depletion was on medium wealth group farms and lowest on poor household farms. The mean P balance was 35 kg ha^{-1} and was lowest for the medium soil fertility group. Rich and poor households had a 41 and 56 kg ha^{-1} higher P balance than the medium wealth group, respectively. The mean K balance in maize was 102 kg ha^{-1}. The K balance was highly variable. The most positive balance was in the poor households (161 kg ha^{-1})

The N balance in sorghum was – 41 kg ha^{-1}. Rich farmers had lowest depletion compared to the medium and the poor. The P balance in sorghum was –1 kg ha^{-1} and was lowest for the poor wealth category. The rich households had the lowest K balance.

The N balance in grass pea was –16 kg ha^{-1}. The P and K balances were also negative. Rich households had lowest depletion of P and highest depletion of K in grass pea. Poor households had lowest K depletion.

The N, P and K balances on the grazing plots were negative. The medium wealth group households had highest depletion of all three nutrients.

The N balance on wheat plots was negative but didn't vary between the farms. The mean P and K balances were positive, 9 and 3 kg ha $^{-1}$, respectively.

The N balance in enset was 22 kg ha^{-1}and was most positive in rich households. The rich households had 46 and 86 kg N ha^{-1} more accumulation compared to the medium and poor households, respectively. The P balance and particularly the K balance were most positive for the rich households.

4. Discussion

4.1. Wealth and nutrient balance

The rich and medium farmers in general had soils with a higher nitrogen and phosphorous content than the soils of the poor farmers**.**

This is in agreement with other studies that show that land and livestock holding are among the important factors that influence soil fertility management (Elias et al. 1998, Van den Bosch et al., 1998, Swift et al., 1994). In addition, in many parts of the tropics the size of fertile land a household owns is determined by the size of livestock ownership that produces manure (Elais et al., 1998; Scoones, 2001).

Wealthy farmers had higher input of N and P from mineral fertiliser. Wealth also positively influenced the nutrient balance of the good and medium soil fertility fields. This was contrary to the results in the highlands in southern Ethiopia (Elias et al., 1998) that showed more N depletion in rich farmers’ fields than in the poor farmers’ fields, but was in agreement with the results in the lowlands.

4.2. Nutrient balance at the farm level

One important finding in this study is that the scale of the nutrient balance studied is significant. The nutrient balance at the farm level is more positive than at the plot and crop level. The aggregated farm nutrient balance obtained at the farm level showed a negative balance of 9 kg N ha $^{-1}$. The P and K balance was positive. The N depletion at the farm level was slight according to the classification by Stoorvogel and Smaling (1990).

The balance at the farm level is an aggregate of all the farm components and does not show internal flows and hence is less negative than the nutrient balances at other levels. The positive balances found are due to accumulation of organic inputs such as manure and household waste at disposal sites in the homestead. These sites were supposed to be a transitional place before recycling the nutrients to the fields. However, the farmers indicated that nutrients from these areas were seldom used as organic fertiliser due to distance to the field, lack of labour and lack of appreciation of the value of the accumulated material as organic fertiliser. The result of this study is in agreement with the results that found low utilisation of organic nutrient sources in western Oromiya (Legesse 1987; Dereje et al., 2001).

4.3. Nutrient balance for different soil fertility classes and crops

The nutrient balance for nitrogen, phosphorous and potassium was more negative when the balance was studied in different soil fertility classes instead of at the farm level. In general, the nutrient balance was more negative for the poor and very poor fertility soils as compared to the soils of good and medium soil fertility. Good and medium fertility soils are planted mostly with high value crops, such as tef and wheat that receive the highest nutrient input. In addition, land preparation for the crops starts early which restricts nutrient losses through grazing. The poor and very poor fertility soils had highest nutrient depletion. Most of the plots in this fertility group soil were grazing plots, plots for hay production that were grazed after harvesting of the hay and plots under crops such as nigerseed and linseed. Though the harvested yields were low, the plots were grazed for a longer period due to early harvest. In addition, areas around the home used for grazing livestock in the mornings and in the evenings were within this fertility soil. Grazing plots in the study area are grazed continuously throughout the year. In poor and very poor fertility soils, the depletion was highest in medium wealth household fields due to less grazing in the other fertility soils. The private grazing land per tropical livestock unit in the medium wealth households was 0.04 ha TLU^{-1} compared to 0.09 and 0.05 in the rich and poor households, respectively. In addition, this group had more daytime external confinement (outside farm) of livestock that resulted in higher excretion of manure outside the farm.

The result for the average N balances at the soil fertility level compared well with results obtained for out fields in the highlands of Kindo Koisha, Ethiopia (Elias et al., 1998).

This study shows that the hot spots of nutrient depletion are generally in poor and very poor fertility soils under grazing.

In the study area, fertility management at the plot level was more determined by the crop grown than by the soil fertility category. Tef is highly valued as a staple and cash crop in the farming system. It is also given priority in all crop management practices like land allocation and preparation, fertiliser application and weeding frequency regardless of the distance or the fertility class of the soil.

In Ethiopia in general, specifically in the central highlands, 70 to 80% of the fertiliser purchased by smallholders is known to be applied to tef fields (Kenea et al, 2001). Despite this, there was N depletion in tef fields due to inadequate input and high nutrient losses.

A cereal based cropping system is known to be more prone to nutrient losses due to accelerated erosion than root crop and perennial crops. Erosion on fields planted with small seed cereals such as tef was found to be high (Hurni, 1988) due to high land cover factor (C factor). Lack of soil conservation measures on sloping fields further accelerates nutrient losses due to erosion. N losses through leaching and gases were also high, which didn't support the general concept that leaching is higher on coarse textured soils compared to more fine textured soils (Færge and Magid 2004). There are no studies on N leaching in Ethiopia to compare the result. A loss of N in the form of N_2O can occur during the period with high soil moisture in clay soil (Davidson et al. 1993).

4.4. Option for improving nutrient inputs and minimising losses

Soil fertility management must address both the use of input and minimising the losses. The results show that there is an extreme variability between different farm categories and between farmers. Farmers and development agents will have to take this variability into consideration when developing future strategies for improved soil fertility management.

There appears to be a potential for improving the use of organic fertiliser in the area. Improved manure management practices such as roofed animal shelters, bedding materials and covering of manure piles are lacking. These practices are known to significantly reduce nutrient losses through leaching and gaseous forms (Briggs and Twomlow, 2002; Lekasi et al., 2002; Smaling, 1993). Nzuma and Murwira (2000) reported about 80% lower loss of ammonia from manure with crop residue added as bedding than manure without residues. In other parts of Ethiopia manure is highly valued and properly managed and also preferred to mineral fertiliser due to its long-term benefits (Atakilte et al., 2001; Elias et al., 1998).

The demand for manure for fuel in Gare Arera was low as it was also for western Oromiya (Wakene et al., 2001); however, the manure was not effectively managed and utilised for organic fertiliser. It is particularly the rich and medium farmers that can improve the management of organic fertilisers because they have access to more manure. However, as the plots are scattered over a large area it might be difficult to transport the manure directly to all fields. Hence, composting the manure will reduce the problem of transportation and application. An option is to apply the manure (compost) to the nearest fields and use mineral fertiliser on the distant fields.

The poor households have a lower NP in their soils in their good and medium fertility soils than the rich and medium households. Poor households have limited access to manure and inorganic fertilisers. These households therefore need to focus on ash-enriched compost and increasing the N input from fixation by incorporating more legume food crops in the cropping system.

The soils of different soil fertility classes will require different management. The homestead soils are fertile soils due to nutrient input through manure and other organic residues. These soils can sustain crop production without input for the near future. Good and medium fertility soils have a moderate N, P and K content and the depletion of nutrients was low. These soils can sustain the current crop production with low input and controlling nutrient losses. The poor and very poor fertility soils were not significantly inferior to the good and medium fertility soils in the N and organic carbon content, but the P and K contents were low. They need P fertilisation through manure with plants rich in phosphorous (Myers et al., 1994), application of bone meal and other organic sources or mineral fertilisation. The P content in poor/very poor fertility soils was about 50% of that in the good and medium fertility soil groups. Many studies in the past have shown P as the most yield-limiting nutrient, next to N on Vertisol (Desta, 1982; Tekalign et al, 1988). In addition, it was reported that the inorganic form of P in Vertisol has limited a capacity to act as a labile pool to supply available P to the plants (Duffera and Robarge, 1996; Piccolo and Huluka, 1986; Tekalign et al., 1988).

The main land use of poor fertility soils was production of crop with low management such as linseed, sorghum and nigerseed. Introduction of mixed cropping such as legume and oil seed or legume and cereal could benefit the cereal and the oilseed; increase the quality and quantity of the residue for fodder (Kassahun and Likelesh 2001). Very poor fertility soils are mainly under grazing, which resulted in severe nutrient depletion due to overgrazing. Hence, introduction of alternative land use such as forage legume production, multipurpose trees, and controlled grazing will increase the N input and reduce nutrient depletion and will ensure sustainable fodder production in both quantity and quality.

In all soil fertility classes it is possible to increase the N input through cultivating nitrogen fixing crops during the short rainy season.

Reducing undesired loss of nutrients is important for all soil fertility classes. The loss of N through erosion calculated by the model varied from 8 to 15 kg ha^{-1}. Erosion is visible as gully formations in the cultivated fields and as muddy water running after a rainstorm. There are no erosion control measures in the area. Measures that can control soil erosion in the area are reduced tillage (Balesh et al., unpublished), diverting flood water from the crop land and gully stabilisation (Worku and Hailu, 2001).

The fertiliser application time, which is in the middle of the peak rains, and the high clay content of the soil, can also increase the N loss. A loss of N in the form of N_2O can occur during the period with high soil moisture and poor drainage, that is a common characteristic of the Vertisols. Both denitrification and nitrification result in higher N_2O fluxes when the soil moisture content exceeds 70% water filled pore space (WFPS) (Davidson et al., 1993). Weier et al. (1993) reported that the total N loss due to denitrification greatly increased as soil texture becomes finer and WFPS increases. High loss of fertiliser N applied to tef in Vertisol has been reported from direct assessments in different places on Vertisol (Balesh et al., inpress). In addition, a lack of subsequent national yield increase with increased fertiliser application has been reported (Mulat et al., 1997) which supports the loss of the applied fertiliser from tef fields.

To feed the increasing population, the crop yields need to increase beyond the current level. This cannot be achieved without increasing the nutrient input. Both organic and mineral fertilisers have a role to play. Mineral fertilisers are expensive and future research should focus on increasing the efficiency of mineral fertiliser application.

Introducing improved soil fertility management will not happen unless training is given to farmers and development agents. In many studies educating farmers on the value of organic fertilisers, the use of such fertiliser has been reported as very important (Briggs and Twomlow, 2002; Ouedraogo et al., 2001). Dereje et al. (2001) also reported a correlation between manure and fertiliser use and literacy in Western Oromiya.

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Table 1.The monitored nutrient flow types.

Flow type	Flow label
Chemical fertiliser	IN 1
Imported organic fertilisers	IN 2a
Manure from external grazing	IN 2b
Wet and dry atmospheric deposition	IN 3
Symbiotic N fixation	IN 4
Harvested products	OUT 1
Exported crop residue and manure	OUT 2a
Excretion of manure outside the farm	OUT 2b
Leaching	OUT 3
Gaseous losses	OUT 4
Erosion	OUT 5
Human excreta	OUT 6 (farm level only)

Table 2. Land (ha) and livestock (TLU) possession of different wealth group households participated in the study in Gare Arera.

Wealth	Livestock (TLU)	Total land (ha)	Cultivated land (ha)
Rich	16.7	7.7	5.4
Medium	10.2	3.1	2.5
Poor	3.9	2.2	1.6
$LSD_{(0.05)}$	4.2	1.9	1.3

Table 3. Major physical and chemical characteristics of the homestead and different fertility category soils of different wealth group households.

SF class	Wealth	pH1:1	OC (%)	N (%)	P mg kg soil $^{-1}$	K cmol kg soil $^{-1}$	Clay%	Slit %	Sand%
Homestead	Rich	6.31	3.97	0.27	93.89	4.23	35.83	37.50	26.67
	Medium	6.46	3.80	0.27	131.50	3.08	41.88	35.76	22.36
	Poor	6.45	4.52	0.37	79.33	4.23	29.58	38.75	31.67
	LSD $_{(0.05)}$	0.06	0.25	0.04	17.59	0.43	4.02	0.98	3.04
Good	Rich	5.40	2.21	0.20	23.91	0.82	48.78	32.74	18.47
	Medium	6.12	2.05	0.19	52.46	1.78	48.79	31.47	20.07
	Poor	5.47	1.93	0.18	3.86	1.00	49.85	31.36	18.79
	LSD $_{(0.05)}$	0.21	0.08	0.01	13.03	0.27	0.33	0.41	0.45
Medium	Rich	5.29	1.97	0.17	13.47	0.73	53.31	29.63	17.06
	Medium	5.94	1.85	0.17	21.56	1.34	54.72	28.33	16.94
	Poor	5.72	1.43	0.13	17.86	1.36	53.14	26.86	20.00
	LSD $_{(0.05)}$	0.19	0.16	0.01	2.29	0.20	0.49	0.78	0.98
Poor & very poor	Rich	5.41	2.27	0.21	13.82	0.98	50.26	30.50	19.24
	Medium	5.37	2.46	0.23	4.78	0.62	56.21	26.77	17.02
	Poor	5.58	2.11	0.17	3.50	0.91	57.50	26.88	15.63
	LSD $_{(0.05)}$	0.07	ns	0.02	3.68	0.13	2.52	1.39	1.19

Table 4. Farm nutrient inputs and outputs (kg ha^{-1}) in different wealth groups in Gare Area.

Nutrient	Wealth	IN1	IN2a	IN2b	IN3	IN4	OUT1	OUT2a	OUT2b	OUT3	OUT4	OUT5	OUT6	Balance
N	Rich	8.6	1.7	27.2	3.3	0.0	0.6	0.6	18.1	11.3	6.0	8.7	1.7	-6.2
	Medium	9.5	0.4	50.0	3.4	0.0	1.5	0.5	28.3	13.4	7.7	15.1	1.6	-4.8
	Poor	4.4	0.7	25.5	3.1	1.9	2.0	1.4	15.3	9.9	5.2	15.2	2.3	-15.7
	$LSD_{(0.05)}$	3.1	0.8	15.5	0.2		0.8	0.6	7.7	2.0	1.4	4.2	0.4	6.7
P	Rich	2.7	5.4	6.8	0.5		0.1	0.2	5.8	0.0	0.0	0.1	0.5	8.7
	Medium	4.2	7.7	12.5	0.5		0.3	0.1	9.2	0.0	0.0	0.1	0.4	14.8
	Poor	1.8	7.2	6.4	0.5		0.2	0.3	4.4	0.0	0.0	0.2	0.6	10.2
	$LSD_{(0.05)}$	1.4	1.4	3.9			0.1	0.1	2.8			0.1	0.1	3.6
K	Rich	0.9	20.6	79.4	2.1		0.2	0.1	40.7	5.1	0.0	5.8	0.3	50.8
	Medium	0.8	30.6	145.7	2.2		1.0	0.1	67.6	8.9	0.0	13.7	0.3	87.7
	Poor	1.1	28.4	74.3	2.0		0.6	0.9	36.2	5.7	0.0	14.7	0.4	47.3
	$LSD_{(0.05)}$	0.2	5.9	45.1	0.1		0.5	0.5	19.2	2.3		5.5	0.1	25.3

Table 5. Nutrient balances (kg ha^{-1}) at different soil fertility levels.

Nutrient	Wealth	Good	Medium	Poor	V, P	LSD $_{(0,05)}$
	Rich	-18.1	-16.5	-37.5	-101.7	39.2
N	Medium	-19.6	-21.4	-136.4	-267.3	115.2
	Poor	-22.7	-38.7	-88.3	-	42.4
	LSD $_{(0.05)}$	2.7	13.2	56.0	152.7	
	Rich	17.7	1.0	-4.2	-27.8	18.4
P	Medium	0.2	6.0	12.8	-138.0	70.9
	Poor	14.1	-3.4	-17.4		17.9
	LSD $_{(0.05)}$	10.5	5.3	17.1	88.2	
	Rich	60.8	-22.9	-34.0	-238.1	124.4
K	Medium	-29.7	-40.7	-251.6	-246.9	121.2
	Poor	37.2	-50.7	-82.2	-	60.0
	LSD $_{(0.05)}$	53.1	15.9	129.3	158.5	

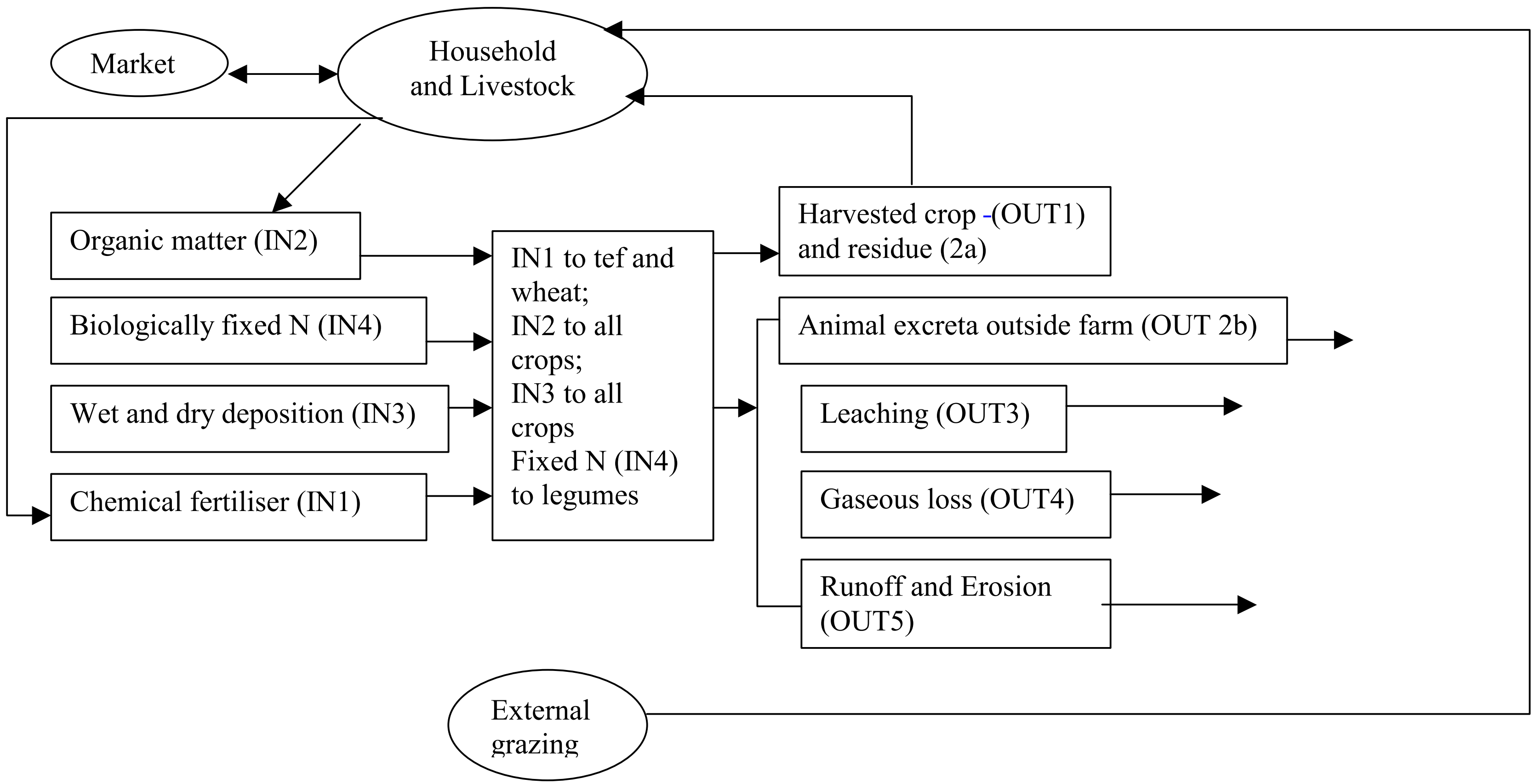
Table 6. Nutrient inputs, outputs and balances (kg ha^{-1}) in tef in different wealth group households in Gare Arera.

Nutrient	Wealth	IN1	IN2a	IN2b	IN3	OUT1	OUT2a	OUT2b	OUT3	OUT4	OUT5	Balance
N	Rich	13.8	1.2	1.9	2.8	6.6	2.4	6.2	8	3.7	6.8	-14.0
	Medium	12.1	1.3	0	2.8	6.8	1.3	0	8.1	3.6	14.4	-17.9
	Poor	6.1	0.9	0.3	3.1	3.5	1.5	1.6	9.7	4.3	9.4	-19.5
	LSD $_{(0.05)}$	4.6	0.2	1.2	0.2	2.1	0.7	3.6	1.1	0.4	4.4	3.4
P	Rich	15.6	0.5	1.6	1.2	3.8	0.6	4.5	0.0	0.0	0.1	10.0
	Medium	6.3	0.3	0.0	0.4	1.3	0.2	0.0	0.0	0.0	0.1	5.4
	Poor	3.6	0.2	0.1	0.5	0.7	0.2	0.4	0.0	0.0	0.1	2.9
	LSD $_{(0.05)}$	7.1	0.2	1.0	0.5	1.9	0.3	2.8				4.1
K	Rich	0.0	0.2	4.8	1.9	1.8	1.4	19.6	0.0	0.0	6.8	-22.8
	Medium	0.0	0.3	0.0	1.6	1.8	1.4	0.0	0.0	0.0	9.9	-11.2
	Poor	1.8	0.2	1.1	1.9	0.9	1.6	9.4	0.0	0.0	12.9	-19.9
	LSD $_{(0.05)}$	1.2	0.1	2.8	0.2	0.6	0.1	11.1			3.5	6.8

Table 7. Nutrient balance (kg ha $^{-1}$) for different crop in Gare Arera.

Crop	Wealth	N	P	K
Maize	Rich	-18.3	43.8	153.3
Maize	Medium	-20.1	3.0	-7.8
Maize	Poor	-16.6	59.1	160.5
LSD $_{(0.05)}$		2.0	32.8	107.7
Sorghum	Rich	-9.2	1.2	-2.0
Sorghum	Medium	-53.2	0.0	-32.0
Sorghum	Poor	-61.3	-4.1	-55.3
LSD $_{(0.05)}$		31.7	3.1	30.2
Grass pea	Rich	-15.3	-0.4	-17.1
Grass pea	Medium	-20.1	-1.5	-8.4
Grass pea	Poor	-13.9	-0.8	-0.8
LSD $_{(0.05)}$		3.7	0.6	9.2
Grass	Rich	-146.7	-58.7	-217.5
Grass	Medium	-245.5	-95.1	-709.6
Grass	Poor	-140.6	-66.4	-83.6
LSD $_{(0.05)}$		66.6	21.7	373.0
Wheat	Rich	-15.9	3.4	-14.8
Wheat	Medium	-2.0	15.6	21.2
LSD $_{(0.05)}$		61.2	12.9	297.0
Faba bean	Rich	-18.4	0.5	-14.9
Faba bean	Medium	-34.8	-3.6	-12.0
Faba bean	Poor	-53.3	-5.0	-16.7
LSD $_{(0.05)}$		19.8	3.2	2.7
Chick pea	Rich	-7.9	-0.1	-7.6
Chick pea	Medium	-7.9	0.0	-5.1
Chick pea	Poor	-37.7	-0.8	-22.9
LSD $_{(0.05)}$		19.5	0.5	10.9
Lentil	Rich	-10.4	0.0	-2.8
Lentil	Medium	-8.0	0.0	-3.2
LSD $_{(0.05)}$		18.8	0.3	9.1
Enset	Rich	65.8	110.8	420.7
Enset	Medium	20.0	9.6	1.5
Enset	Poor	-20.0	0.0	1.3
LSD $_{(0.05)}$		48.6	69.5	273.9

Fig. 1. General farm level nutrient flow model in Gare Arera, West Shawa zone Dendi district central Ethiopia



Paper 2

Availability of organic nutrient sources and their effects on yield and nutrient recovery of tef [*Eragrostis tef* (Zucc.) Trotter] and on soil properties.

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Short title: availability and effect

Abstract

Inadequate nutrient and organic matter supply constitutes the principal cause for declining soil fertility and productivity in much of sub-Saharan Africa (SSA). Organic fertilisers constitute important sources of nutrients and decomposable organic matter for increasing yield and improving soil fertility. In a survey in Gare Arera, the central Ethiopian highland, farmyard manure (FYM) and compost enriched with ash were identified as under-utilised organic nutrient sources. Mustard meal, a by-product of mustard seed, was included for comparison. On-farm experiments were carried out on two major soil types (Nitosol and Vertisol) to study the effect of organic fertiliser on the yield and yield components of tef **[*Eragrostis tef* (Zucc) Trotter]** and selected soil properties. Mustard meal FYM and compost enriched with ash were compared with synthetic fertiliser (urea + triple super phosphate) and an unfertilised control. In the field experiments, application of organic fertilisers on Nitosol and Vertisols at an N rate equivalent to that of urea produced grain yields of 82% and 99% of that produced with urea, respectively. The apparent N recovery from urea, mustard meal, FYM and compost was 31, 25, 16 and 28% on Nitosol, respectively, and 23, 17, 26 and 21% on Vertisol, respectively. The mean agronomic efficiency for the organic and synthetic fertilisers on Nitosol was 20 and 24 kg grain kg^{-1} N applied, respectively, whereas on the Vertisol it was 13 kg grain kg^{-1} N for both. On Vertisol, tef was most responsive to FYM and on the Nitosol it was most responsive to compost. Soil N and P contents were increased due to organic fertiliser application. The results showed compost enriched with ash is a good choice on Nitosol while FYM performs well on Vertisol. Mustard meal can be applied on both soils.

Keywords: Compost, farmyard manure, mustard meal, Nitosol, nutrient loss, urea, Vertisol.

Introduction

Increasing food production and sustaining soil fertility in the smallholder farms is an enormous challenge in sub-Saharan Africa (SSA). Soil nutrient status is widely constrained by the limited use of mineral and organic fertilisers and nutrient loss mainly due to erosion and leaching. Many smallholder farmers do not have access to mineral fertilisers for reasons such as high price of fertilisers, lack of credit facilities, poor distribution and other socio-economic factors. Consequently, crop yields are low, in fact decreasing in many areas, and the sustainability of the current farming system is at risk (Stangel, 1995; UNDP, 1992).

Ethiopia is one of the 14 sub-Saharan countries with highest rates of nutrient depletion (Stoorvogel and Smaling, 1990) due to lack of adequate mineral fertiliser input, limited return of organic residues and manure, high biomass removal, erosion and leaching. The annual nutrient deficit is estimated at -41 kg N, -6 kg P and -26 kg K ha^{-1} yr^{-1} (Stoorvogel and Smaling, 1990). There is an urgent need to improve nutrient management.

Farmyard manure is a potential source of organic fertiliser as the country has the highest livestock number in Africa (Zinash, 2001). The annual dry manure production is estimated at 22.7 million Mg. Annual crop residue production is estimated at 12.7 million Mg. Moreover, there are various other unexploited organic by-products or wastes from processing animal and plant products such as mustard meal, coffee husk, sugar cane straw and abbatory by-products.

Use of farmyard manure and other locally available organic materials is important for improving soil quality. Organic fertilisers, in addition to supplying nutrients, improve the physico-chemical condition of soils, enhance nutrient cycling and build the soil organic matter (SOM) capital (Palm, 1995; Reeves, 1997). Some materials, such as brassica green manure, mustard meal, and neem cake also have the capacity to suppress weed, pests, diseases and pathogens (Boydston and Hang, 1995; Brown and Morra, 1997).

The decomposition and nutrient release patterns of organic materials are determined by the quality of the material. Concentration of N, lignin and polyphenols, C, P and ratios between these factors are known to regulate or correlate with nutrient mineralisation (Giller and Cadisch, 1995 Murwira et al., 2002; Palm and Sanchez, 1991). In addition, decomposition and N mineralisation depend on soil properties and other environmental factors (Muller, 1988; Azam et al., 1993). The N recovery from organic fertilisers also depends on the synchrony between N release and the N requirement by the plant (Hood et al., 1999).

The limited research that has been carried out in Ethiopia on organic fertilisers suggested high yield response in areas where there was no moisture limitation (EARO 1998, Hailu et al., 1992; Leggese, 1992; Kelsa, 1992). However, no systematic research has been carried out on the efficient use of the available organic sources. The objectives of this study were to identify and characterise organic nutrient sources that are available to farmers in the study area, compare their effects to those of commercial fertiliser on the crop yield and nutrient contents of tef [*Eragrostis tef* (Zucc.) Trotter] and assess the effects of fertiliser application on selected characteristics of Nitosol and Vertisol.

Material and methods

The study site

The study was undertaken in Gare Arera, Dendi district ($09^{0}03'$ N, $38^{0}30'$ E) West Shawa Zone of Oromiya Regional State, Ethiopia. The site is located 95 km south west of Addis Ababa, on Nekemt road (Figure 1). The topography is undulating and the altitude is 2200 m. a. s. l.

The area has a bimodal rainfall pattern, with the main rainy season from June to September and the short rain from February to April. The monthly distribution of the year 2002 and the last decade is shown in Fig. 2.

The dominant soils are Vertisols and Nitosols (Ethiopian Agricultural Research Organization (EARO), Gare Arera watershed data, unpublished). The Vertisols are relatively fertile soils and used for growing a wide variety of crops.

Agriculture is rain-fed and can be characterised as a mixed crop livestock subsistence farming. The cropping system is cereal based and tef is the most widely grown crop. The most dominant cropping rotation is characterised by three years of cereal crops followed by one year of a leguminous or oil crop.

The livestock population is comprised of cattle, sheep, goats, equines and poultry. Oxen are mainly used for ploughing and threshing, equines for transport and small ruminants and poultry for income generation (Yosef and Aster, 2002).

Organic fertiliser identification and compost production

The data on identification of available organic fertiliser, cropland and livestock holding and other supportive information were collected as part of a survey with formal questionnaire. The survey involved 110 households representing three wealth groups: ‘rich’, ‘medium’ and ‘poor’ (according to the local criterion). The households were selected randomly from a record of classified households by Gare Arera Service Cooperative. During the interviews, which were carried out at the farmers’ homes, observations were also made on the presence of organic waste materials in the homestead.

Data on management practices of organic fertilisers and opinion of the farmers’ on value of organic nutrient sources were gathered through discussion in a focus group composed of male and female farmers. Gender distribution in the group was about three to one, as women headed households were not many.

Farmyard manure (FYM), crop residues, tree litter and household refuses were identified as sources.

Following the identification, FYM was sampled from 28 households for characterisation as a major potential nutrient source. The storage duration of the sampled farmyard manure varied from 8 to 37 months.

Compost production was rare in the study area; hence, training was given to willing farmers before the start of the study. Nine farmers (one female and eight male) were selected for compost production. The composting materials were FYM, crop residues, household refuse and ash. Forest litter and soil were added to increase the quantity of the compost and to ensure adequate presence of decomposer microbes. The organic materials were collected depending on their availability in the household. The compost was produced during the off-season of 2002. Pit composting was preferred to surface composting by the farmers. The pit size varied, but most farmers had a pit which measured 1.5 m × 2.4 wide by 0.5 m deep. The layers were built with successive strata of decomposing materials with fresh and woody materials constituting the bottom layer. Optimum moisture content was monitored by checking with a stick inserted in the compost. The part of the stick which is in the compost layer must be moist, but not wet or dry. The compost was turned into another pit every three weeks. The compost was mature at the end of the fourth turning (after three months). The mature compost from eight pits was sampled for the analysis of major nutrients, lignin and total extractable polyphenolics (TEP).

Composts from two households were selected for use in the field experiments. Mustard meal for the experiments was obtained from Addis-Modjo Oil Complex. One farmer supplied the FYM for the experiments. The FYM was a mix collected from cattle, donkeys, sheep and goats and without bedding material.

Soil and organic material characterisation

Soil samples for initial characterisation of the experimental fields were collected from the surface (0-30 cm) at random across the field to make composite samples before installing the experiments on 3 and 4 July 2002 on Vertisol and Nitosol, respectively. Soon after harvesting tef on 3 and 4 December 2002, soil was sampled from each plot.

The laboratory analyses were carried out at Holetta Agricultural Research Centre (HARC), Ethiopia. Prior to analysis, the samples were oven dried at 70^0 C for 72 hrs and ground to pass through a 500 μm sieve. The soil pH was measured by pH meter (Peech, M., 1965), soil organic carbon was measured according to Allison (1960), soil and plant N were measured according to Bremmer (1965), soil K was measured by methods described by Chapman (1965) and P was measured by the Bray 2 method (Bray and Kurz, 1945). Plant P was determined by the procedures described by Murphy and Riley (1962) and Wantabe and Olsen (1965) and K was determined by procedures according to Isaac and Kerber (1971). Lignin was analysed by the Acid Detergent Fibre method and the TEP was analysed by the Folin-Denis method (Anderson and Ingram, 1993). The N and P contents of FYM and compost were analysed in May 2002. Mustard meal had been previously characterised for the purpose of another experiment (Balesh et al., inpress).

Design and management of the field experiments

On-farm experiments were conducted according to a randomised block design with three replications at two sites. Plot size was 3 m × 3 m. Data were collected in 2002. Effects of N from organic fertilisers on the yield and yield components of tef were compared with the recommended rate of N from commercial fertiliser and a control without fertiliser. The organic fertilisers included were mustard meal (a by product of mustard seed (*Brassica carinata* L. from the pressing industry), farmyard manure and compost. The commercial N source used was urea, and P was applied as triple super phosphate (TSP). The P deficit in the organic fertilisers was compensated by TSP.

Two fields were selected, one on Vertisol and the other on Nitosol. The experimental fields were oxen ploughed in May, mid June and end of June before the start of the experiment. The manure and mustard meal were applied and incorporated in the soil on July 3 and 4, 2002 on Vertisol and Nitosol, respectively. The organic fertilisers were broadcasted on the plots and then worked manually into the soil by hoe at planting. The N and P rates used were in accordance with the recommendations, 60/26 and 40/26 kg ha^{-1} for Vertisols and Nitosols, respectively. Land preparation prior to sowing was as practiced by farmers. The fields were trampled by livestock or humans to make seedbed and to control weed growth. After trampling, urea and TSP were hand broadcasted, followed by seeding. The experiment was seeded with tef variety DZ-01-354 on 24 and 25 July 2002 on Nitosol and Vertisol, respectively. Tef is traditionally sown during the peak of the rain. At the time of sowing, the soil was fully saturated and the fields were partially flooded with water. Shallow drainage ditches were dug around the field and between the blocks to control runoff water coming from upper fields. Weeding was carried out three and six weeks after sowing.

The crop was harvested at physiological maturity. Plant height was measured taking 10 randomly selected samples from each plot. The whole plot was harvested without leaving borders. Plant samples were taken for moisture determination and seed nutrient analysis. The samples for biomass moisture determination were dried in an oven at 70^0 C for 24 hrs. Threshing was done manually. The grain yield was adjusted to 12% moisture content.

Data calculations were done as follows.

The livestock number was converted to tropical livestock unit (TLU). A Tropical Livestock Unit (TLU) is an animal unit used to aggregate different classes of livestock. One TLU equals an animal of 250 kg live weight (Jahanke, 1982). To convert different animals to TLU, the numbers of different animals were multiplied by the corresponding conversion factors as follows: bull (oxen) = 1.4, cow = 1.0, calf, sheep/goat = 0.1, equines = 0.25.

Daily FYM production was calculated as 0.8% of animal body weight (Fernandez-Rivera et al., 1995).

Nutrient contents in the manure were calculated by multiplying the total dry matter (DM) by corresponding nutrient concentration.

Nutrient available ha $^{-1}$ cropland was calculated as total nutrient in the manure produced at night in the kraal divided by the cropland area. According to Fernandez-Rivera et al.(1995), animals produce 43% of their manure during night.

N yield of tef,

N yield = Grain yield X % N (equation 1)

Agronomic efficiency (AE) of fertiliser,

$$\text{AE} = \frac{Grain\ yield\ of\ treatment - Grain\ yield\ of\ control}{N\ rate\ applied} \qquad \text{(equation 2)}$$

Apparent recovery of fertiliser N (ANR),

$$\%\ \text{ANR} = \frac{N\ yield\ of\ treatment - N\ yield\ of\ control}{N\ rate\ applied}\ X\ 100 \qquad \text{(equation 4)}$$

Apparent recovery of fertiliser P (APR),

$$\%\ \text{APR} = \frac{P\ yield\ of\ treatment - P\ yield\ of\ control}{P\ rate\ applied}\ X\ 100 \qquad \text{(equation 5).}$$

Data analysis

The data were analysed for variance using the MSTAT C computer package (Russell, D. Freed, Michigan State University, USA). Where the F test indicated significance, the means were separated using Fisher's protected Least Significance Difference test (LSD) at P = 0.05.

Results

Availability of organic fertiliser and its utilisation

In the study area animals graze freely inside or outside the farm during the daytime and are confined to kraals during the night.

The calculated manure production suggested manure was available in significant quantities in the area. The average annual manure production per household varied from 2866 kg for poor farmers to 11653 kg for rich farmers (Table 1). This corresponded to 24 and 12 kg N ha $^{-1}$ for rich and poor farmers, respectively.

The survey indicated that the manure is not well utilised. It was common to see mounds of manure accumulated over time in the homesteads. According to the farmers, the main reason for not applying manure to croplands was lack of confidence in the effect of manure. In addition, female farmers mentioned labour shortage for manure collection from the kraal to the storage location during the rainy season and increased weed problems. Elderly farmers said they knew of the value of manure but lacked capacity to take the manure to the fields. The farmers who participated in the compost production and use explained that composting was the solution to the weed problem.

There are two types of manure management and use. The manure produced during the dry season in the kraal is collected and made into dung cakes for fuel or sold for cash income. Manure produced during the main rain season is partially stored in one or several piles nearest to the kraal. The dry manure is distributed to the garden area planted with vegetables and maize for green harvest. The garden is a disposal area both for manure and household refuse, except ash. Ash from burning dung, wood and crop residue is mostly disposed of in pits, based on the experience that concentrated application causes wilting of plants.

The unawareness concerning use of the accessible manure cannot be explained by lack of interest from local stakeholders. Both the Dendi District Rural Development Bureau (RDB) and Community Development Promotion Organization (CDPO) underlined the importance of organic fertilisers in increasing food production and alleviating poverty and encouraged the participating farmers to disseminate the technology.

Nutrient composition of the organic fertilisers

The nutrient concentrations in the manure (Table 2), with the exception of Ca, negatively correlated with manure age (Fig. 3). The FYM contained more N than compost but less P and K (Table 2). Mustard meal had highest nutrient concentrations.

Effects of synthetic and organic fertilisers on the yield and yield components of tef in different soil types

Plant height was significantly lower in the control compared to the plots receiving fertiliser both on Nitosol and Vertisol (Table 3). The effect of soil type on plant height was significant for the control and urea treatments.

There was a strong grain yield response to fertiliser on Nitosols. The increase, as compared to the control, was fourfold for urea and compost and threefold for mustard meal and FYM. On Vertisol the organic fertilisers produced the same yield result as urea, and the grain yield doubled, compared to the control, with the application of the fertilisers.

The agronomic efficiency of fertiliser (AE) was higher on Nitosols than on Vertisols (Table 4). On Nitosols, urea and compost had the highest AE, whereas on Vertisols urea, mustard meal and FYM gave a higher value than compost.

The N concentration in grain was higher in the urea and mustard meal treatments than FYM and compost on Nitosol. On Vertisol N concentration was highest in the FYM treatment. Very low N concentration was found in the mustard meal treatment on Vertisol. The P and K concentrations were highest for mustard meal and lowest for urea on the Nitosol, whereas on the Vertisol these values were highest for compost.

Urea, mustard meal and compost produced similar N yields, which were significantly greater than those on the FYM and the control plots on the Nitosol (Table 5). On the Vertisol, mustard meal produced lower N yield than FYM, urea and compost. All fertiliser treatments increased P and K yields both on Nitosol and Vertisol. P and K yields were higher on Vertisol than on Nitosol for all of the treatments.

The apparent N recovery (% ANR) varied between treatments and soil type (Table 6). On Nitosol, the treatment ranking was: urea > compost > mustard meal > FYM. On Vertisol it was in the order of FYM > urea > compost > mustard meal. ANR was significantly lower on Vertisol than on Nitosol.

Apparent P recovery was lower on Vertisol than on Nitosol. On Nitosol, P recovery was higher for mustard meal and compost than for urea and FYM. On Vertisol, no clear effect of treatment was found. Though the seed N and P contents and the N and P yields were higher on Vertisol, the ANR and APR were higher on the Nitosol mainly because of the higher N application rate and the high control yield on Vertisol.

Effect of fertiliser application on selected properties of the experimental soil

On Nitosol, the pH of the soil sampled soon after crop harvest was higher than the pH of the soil samples collected at planting (Table 7). Application of urea and mustard meal resulted in a significant decrease of the soil pH compared to the control. On the contrary, compost increased the pH. On Nitosol, mustard meal and compost application resulted in increased soil N compared to the control. Increase in soil P due to application of organic fertilisers varied from 8 to 64% with the highest increase on the FYM treatment

On Vertisol, the effects of the treatments on pH were small. The soil N content increased on all fertiliser treatments and the highest increase (0.03%) was with the application of compost and FYM. FYM application also resulted in 125 % increase in the soil P compared to the control. The K content in the soil at crop harvest time was significantly lower than at planting on all plots with fertiliser application. Decrease in K content of the soil might be due to the increased K removal with the increased yield.

Discussion

Availability and possible use of organic fertiliser

Farmyard manure was not efficiently utilised due to lack of confidence in the effect of manure, labour shortage for manure management and weed problems. The distance between croplands and homesteads (kraal location) was also another important constraint as the fields were scattered over a large area in the watershed. These problems have resulted in negligence of this important fertiliser resource at the farmers' disposal. Previous studies have also suggested the distance of fields from kraal as a major problem in manure utilisation (Hailu et al., 1992; Dereje et al., 2001). In addition, there appears to be a lack of knowledge among farmers as the research and the extension services in the past focused on promotion of mineral fertilisers, often ignoring the organic fertiliser that is more easily available (Teklu et al., 2004; Corbeels et al., 2000). In line with the results of this study, earlier studies in western Oromiya indicated rare use of FYM for soil fertility maintenance, despite the availability of the resource and of labour to handle it (Legesse, 1987; Wakene et al., 2001). However, in other parts of Ethiopia manure is a highly valued resource in soil fertility maintenance, preferred to inorganic fertilisers due to its long-term benefit (Elias, 2000; Atakilte et al., 2001).

Composting was a new technology introduced in the area by this study. However, the technology was highly valued by the farmers who participated in the training. These farmers understood the value of compost as organic fertiliser. Moreover, already after their first year of experience, they were confident that composting could solve problems associated with manure application such as increased weed infestation. Hence, compost could be an important organic fertiliser that all farmers produce and use, as materials such as household wastes, ash from burning biomass and water were available for composting. Compost promotion was an important extension service package in southern Ethiopia where organic and inorganic fertiliser application was differentiated by the distances of the fields from the homestead (Elias, 2000; Scoones, 2001). In other African countries, such as Kenya, composting was taught in schools as part of Rural Science (Nandwa et al., 2000). In the study area, however, no attempt had been made, neither by extension services nor by other organisations, to encourage farmers to promote organic matter management.

Mustard meal is a by-product from oil seed pressing industries, as it constitutes about 70% of the initial mustard seed material (Balesh and Salema, 2000). The availability of mustard meal is location specific. Hence, farmers in the vicinity of its production area can use it, as transporting bulky material might be difficult and costly. Currently, use of mustard meal for the farmers in Gare Arera area might not be feasible.

Agronomic and N recovery efficiencies of the fertilisers used

Despite the fact that the FYM and the compost used in this study had lower N concentrations than the 2.5% threshold level for immediate mineralisation (Palm et al., 1997), the yield response to the organic fertilisers applied alone at the recommended N rate of mineral fertiliser was equivalent to the response to urea N. The effect of mustard meal, categorised as a high-quality material according to the preliminary decision tree (Palm et al., 1997), was similar to that of compost and FYM.

In this study, stunted growth of the plants that received organic fertilisers at the early stage was observed, but it is impossible to know whether it was caused by the delay in mineralisation or initial immobilisation.

The response to the fertilisers was not in line with predictors of N mineralisation such as lignin + ployphenol/N (Fox et al., 1990), N, lignin and polyphenol concentration or the preliminary decision tree on the use of organic materials for N management (Melillo et al., 1982; Palm et al., 1997). Rather, the results of this study agreed with studies suggesting that polyphenol/N controls or correlates with N materialisation (Palm and Sanchez, 1991) and a C/N ratio of 15 is the critical limit for net mineralisation from the FYM (Kirchman, 1985; Kihanda, 1996). However, the mineralisation measured indirectly as the crop N uptake is a less reliable indicator than N measured directly. Other nutrients present in the organic fertilisers and effects on physical factors can influence N uptake and use efficiency (van Noordwijk and van de Geijn, 1996).

The apparent N recovery (ANR) of high quality organic fertilisers is generally reported to be below 20 (Haggar et al., 1993; Myers et al., 1994; Vanlauwe et al., 1996), but in this study all of the organic fertilisers had an average ANR above that level. ANR for urea fertiliser was lower than the reported worldwide average mineral fertiliser N recovery of about 33% for cereal production (Raun and Johnson, 1999) but in closer agreement with the value reported for humid tropics, which is less than 25% (Myers et al., 1994).

These results show that the agro-ecological conditions in the study area are favourable for the use of organic fertiliser, but the timing and method of application may be unfavourable for urea. The organic fertiliser releases the N more slowly than mineral fertiliser, which may make it less exposed to leaching and gaseous losses than urea. This might explain the relatively high ANR and agronomic efficiency (AE) of organic fertiliser as compared to urea in this study. Similarly, Sisworo et al. (1990) reported higher N use efficiency from cowpea residue compared to inorganic fertiliser in the humid tropics. The efficiency of organic fertilisers could also be due to supply of micronutrients and improvements in the soil's physical properties not associated with synthetic fertiliser. Nitosols and Vertisols in Ethiopia are suspected to be deficient in one or more micronutrients (Desta, 1983). However, stunted growth at the beginning of the season with organic fertilisers suggests that there is a need for improving the synchrony between N supply and demand (Myers et al., 1994). Wakene et al. (2001) emphasised the importance of integrating organic and inorganic nutrients to increase the yield of maize.

The AE of the fertilisers was higher on Nitosol than on Vertisol. On Nitosol, the ANR of urea was comparable to the reported worldwide average mineral fertiliser N recovery of about 33% for cereal production (Raun and Johnson, 1999) but on Vertisol it was lower. In a previous study with ^{15}N, the N use efficiency of urea applied to tef at two sites on Vertisols was 17 and 27 % (Balesh et al., 2005). The low ANR on Vertisol is probably due to gaseous losses of N.

Urea was surface applied by broadcasting during the peak of rain (Fig.1). During the period with high soil moisture and poor drainage, which is a common characteristic of Vertisols, N can be lost in the form of N_2O. Both denitrification and nitrification result in substantial losses when soil moisture content is high (Davidson et al., 1993; Myers et al., 1994). Weier et al. (1993) reported that total N loss due to denitrification greatly increased as soil texture became finer and water filled pore space increased.

FYM had lower efficiency than the other fertilisers on Nitosols but similar levels of efficiency to the others on Vertisols. The prolonged water logging in Vertisols might have delayed the N mineralisation, hence protected the N from loss and increased its availability in the later growth stages.

On Nitosol, however, the strongly acid soil characteristics might have impaired microbial activity as near to neutral soil pH is known to be optimum for most decomposers (Rosswall and Paustian 1984). The N utilisation from manure is in a broader agreement with the study that found 15-35% N recovery by the first crop after manure application (Kirchman, 1985).

Efficiency of compost was high on Nitosol, comparable to ANR of urea even though the N content in compost was below the minimum threshold content required for immediate mineralisation. The high ANR and APR observed after compost application might be due to the increased soil pH that increased the N and P releases both from the compost and the soil. The pH of the Nitosol was less than 5, which is categorised as low (Landon, 1984). This effect was probably less pronounced in Vertisol since this soil had a higher initial pH than Nitosol. The ash material in the compost was assumed to be the major reason for the increased pH. Ash is an important material both as nutrient source and as ameliorant material due to its alkaline reaction, especially on acid soils (Lerner and Utzinger, 1986).

The ANR of mustard meal on Nitosol was low (25%) as compared to a previous study on Nitosol at Holetta Research Centre (34%) (Balesh et al., in press).

On Vertisol, the ANR of mustard meal was lower than expected for this high-quality organic fertiliser. Early application of mustard meal to avoid toxicity on seed germination (Balesh and Salema, 2000) and the high soil moisture at planting might have led to losses of the N released in excess of the plant demand (Anderson and Swift, 1983). In a previous study that evaluated response of bread wheat to mustard meal application for three years, the response on Vertisol was higher than on the Nitosol (Balesh and Salema, 2000). However, unlike tef, bread wheat was planted early in the rainy season to avoid water logging at early stage. The probability of N loss can further be explained by the fact that tef seed N concentration and N yield were low, which suggests that the crop suffered N deficiency.

Tef traders and consumers consider tef grown on Vertisol as the best quality which is also reflected in the price. This might be related to the higher N and P contents of tef grown on Vertisols as shown in this study.

Conclusion

This study shows that potentially a considerable amount of FYM and other organic materials for composting are at the farmer's disposal, but it is not properly made use of. There was a lack of awareness regarding the agronomic value of organic fertilisers and this has to be addressed through appropriate policies and facilitation.

With the application of organic fertilisers at the recommended N rate it was possible to significantly increase tef crop yield on Nitosol and Vertisol. The result showed that compost enriched with ash is a good choice for organic fertiliser on Nitosol, while FYM performed well on Vertisol. Mustard meal can be used on both soil types. The effects of organic fertilisers partly exceeded the effects of fertilisers of equivalent amount of N given as urea together with triple super phosphate, suggesting that organic fertilisers provided qualities not associated with synthetic fertilisers.

The use of organic fertilisers is a sound technology to combat soil nutrient depletion and for alleviating food shortage and poverty. However, continuous on-farm experimentation with the farmers is important to evaluate the technical and economic efficiencies under different ecological conditions and to alleviate constraints that arise from organic fertiliser technology adoption.

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Table 1. Mean cropland and livestock holding, annual farmyard manure (FYM) production and potential NPK available to cropland in different wealth category households Gare Arera.

Wealth group	Cropland, ha	Livestock TLU	Dry FYM * Kg per household yr^{-1}	Manure nutrient available, kg ha^{-1} N	P	K
Rich	2.8	16.0	11653	24	10	15
Medium	1.7	8.0	5840	20	8	12
Poor	1.4	3.9	2866	12	5	7
Mean	2.0	9.3	6782	18	7	11
$L.S.D._{(0.05)}$	0.7	4.0	2612	2	1	1

* Calculated according to Fernandez-Rivera et al. (1995)

Table 2. Major nutrient content (g kg $^{-1}$) in FYM, mustard meal the compost

	FYM (18)		Mustard meal (4)		Compost (8)	
Nutrient	Mean	SD	Mean	SD	Mean	SD
C	136	24	880.0		128.0	3.47
N	13.3	6.0	62.5	0.29	7.3	2.6
P	5.4	2.1	7.4	0.37	2.5	1.7
K	8.3	4.0	10.3	0.11	14.1	4.2
Ca	11.7	2.3	10.0			
Mg	4.8	3.0	10.0			
Lignin	85.0		63.5		58.2	22.1
TEP	5.0		20.5		1.46	0.7
C:N	11.5		13.8		17.5	
Lignin : N	7.1		1.1		8.0	
Lignin +TEP: N	7.5		1.3		8.2	

Numbers in parenthesis indicate sample size

Table 3. Plant height, biomass and grain yield of tef on Nitosol and Vertisol for the mineral and organic nutrient sources at Gare Arera

Treatment	Plant height (cm)		Biomass yield (kg ha^{-1})		Grain yield (kg ha^{-1})	
	Nitosol	Vertisol	Nitosol	Vertisol	Nitosol	Vertisol
Control	57	54	1438	2649	354	891
Urea	72	73	3846	6728	1320	1667
Mustard meal	70	69	3370	5846	1113	1688
FYM	69	69	2570	4909	990	1685
Compost	67	67	3058	4866	1306	1563
Mean			2856	5000	1136	1645
L.S.D.$_{(0.05)}$	5	7	800	1487	348	305

Table 4. Agronomic efficiency (AE), N, P and K content of tef for mineral and organic fertilisers in Nitosol and Vertisol in Gare Arera

Treatment	AE (kg grain kg $^{-1}$N)		%N		%P		%K	
	Nitosol	Vertisol	Nitosol	Vertisol	Nitosol	Vertisol	Nitosol	Vertisol
Control			1.44	1.65	0.32	0.38	0.43	0.39
Urea	24	13	1.45	1.58	0.30	0.38	0.40	0.39
Mustard meal	19	13	1.46	1.15	0.37	0.36	0.47	0.37
FYM	16	13	1.24	1.79	0.35	0.39	0.43	0.38
Compost	24	11	1.36	1.53	0.32	0.44	0.44	0.48
Mean	21	13	1.39	1.54	0.33	0.39	0.43	0.40
L.S.D.$_{(0.05)}$	4	1	0.08	0.21	0.02	0.02	0.02	0.04

Table 5. N, P and K yields for mineral and organic fertilisers applied to tef in Nitosol and Vertisol in Gare Arera

Treatment	N (kg ha $^{-1}$)		P (kg ha $^{-1}$)		K (kg ha $^{-1}$)	
	Nitosol	Vertisol	Nitosol	Vertisol	Nitosol	Vertisol
Control	4.3	13.0	1.0	3.0	1.4	3.1
Urea	16.6	23.2	3.6	5.5	4.8	5.7
Mustard meal	14.3	17.1	3.7	5.4	4.7	5.5
FYM	10.6	26.5	3.1	5.8	3.8	5.6
Compost	15.6	21.1	3.7	6.0	5.1	6.6
Mean	12.3	20.2	3.0	5.2	3.9	5.3
L.S.D.$_{(0.05)}$	4.4	4.6	1.0	1.1	1.3	1.2

Table 6. Apparent N recovery (ANR) and apparent P recovery (APR) of mineral and organic fertilisers applied to tef in Nitosol and Vertisol in Gare Arera

Treatments	%ANR		% APR	
	Nitosol	Vertisol	Nitosol	Vertisol
Urea	30.7	23.0	10.0	5.4
Mustard meal	24.8	16.9	10.3	5.3
FYM	15.8	26.3	8.0	5.7
Compost	28.2	20.8	10.5	5.9
Mean	28.9	21.8	9.7	5.6
L.S.D.$_{(0.05)}$	6.4	3.9	1.14	0.3

Table 7. Effect of organic fertiliser application on selected properties of Verisols and Nitosl 2002

Treatment	Nitosol				Vertisol			
	pH in H_2O	N (%)	P mg kg^{-1} soil	K cmol kg^{-1}	pH in H_2O	N (%)	P mg kg^{-1} soil	K cmol kg^{-1}
Initial	4.87	0.17	2.50	0.66	5.38	0.16	2.50	0.88
Control	4.97	0.19	1.20	0.73	5.42	0.16	2.50	0.82
Urea	4.92	0.20	1.80	0.88	5.47	0.17	2.40	0.70
Mustard meal	4.94	0.23	3.10	0.75	5.41	0.17	2.40	0.81
FYM	4.97	0.20	4.10	0.78	5.42	0.19	5.50	0.70
Compost	5.07	0.24	2.70	1.10	5.43	0.19	2.50	0.61
Mean	4.96	0.21	2.57	0.82	5.42	0.17	2.97	0.75
L.S.D.$_{(0.05)}$	0.05	0.02	0.99	0.13	0.02	0.01	1.20	0.08

Fig. 1 Map of Ethiopia showing the study site.

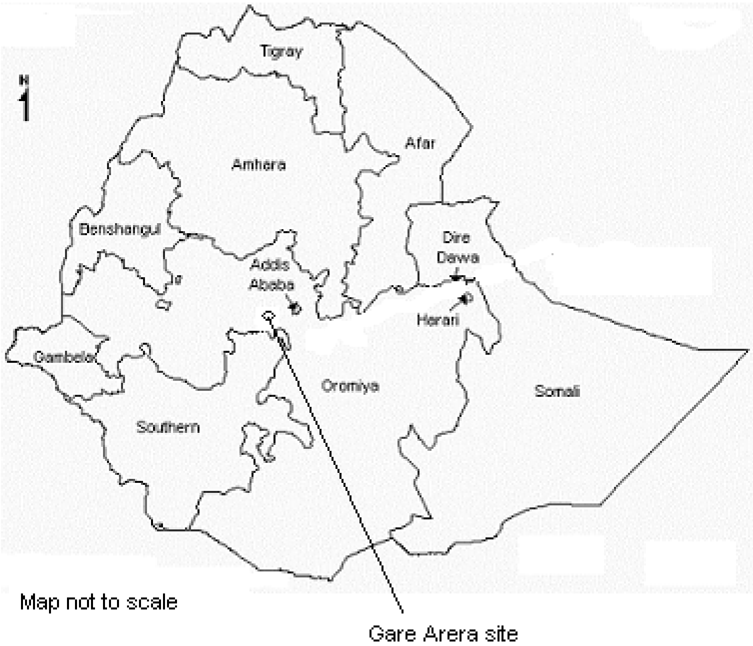


Fig. 2. Monthly rainfall during 2002 and the monthly mean of longterm (1990-2001) in the study area

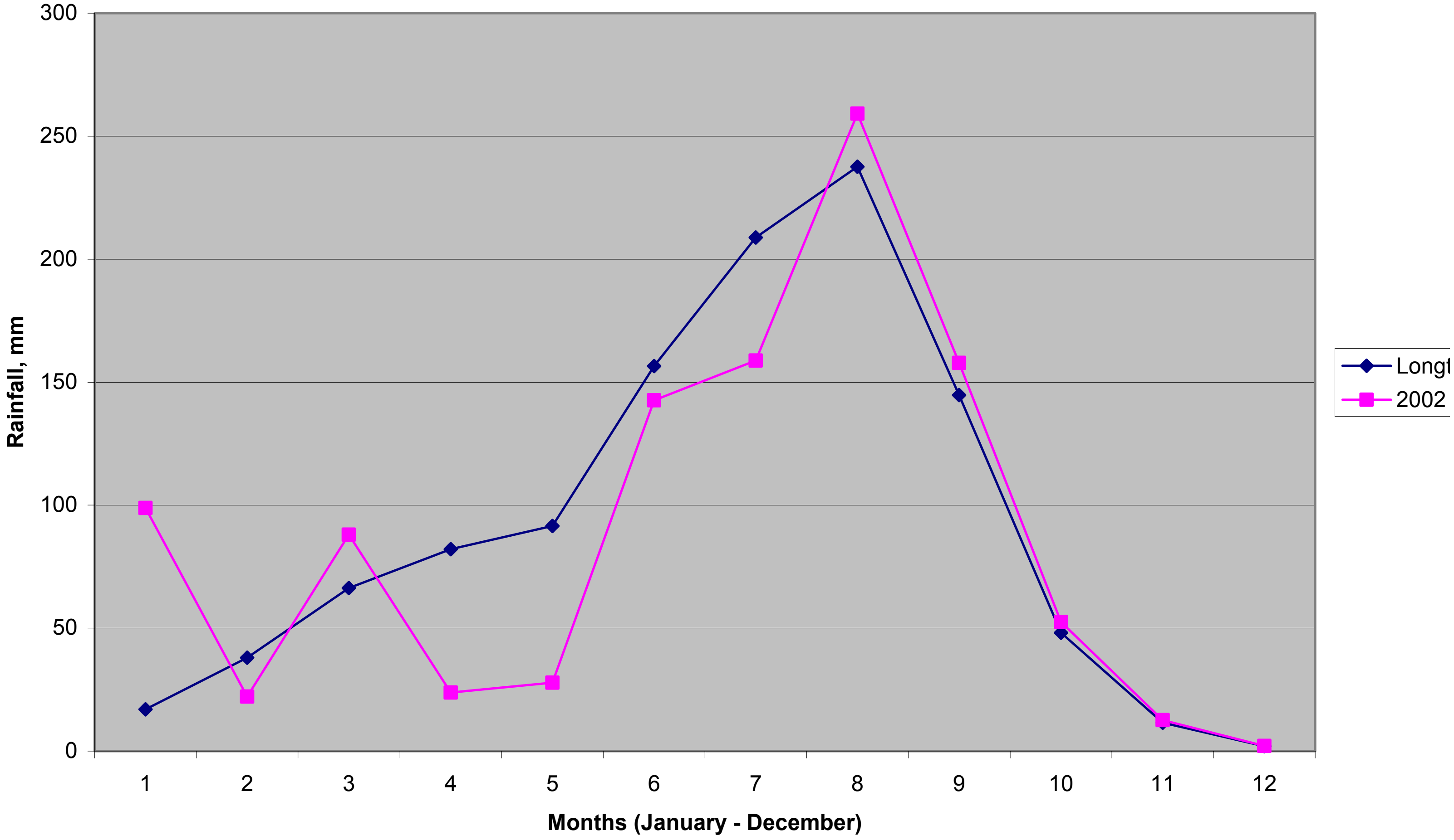
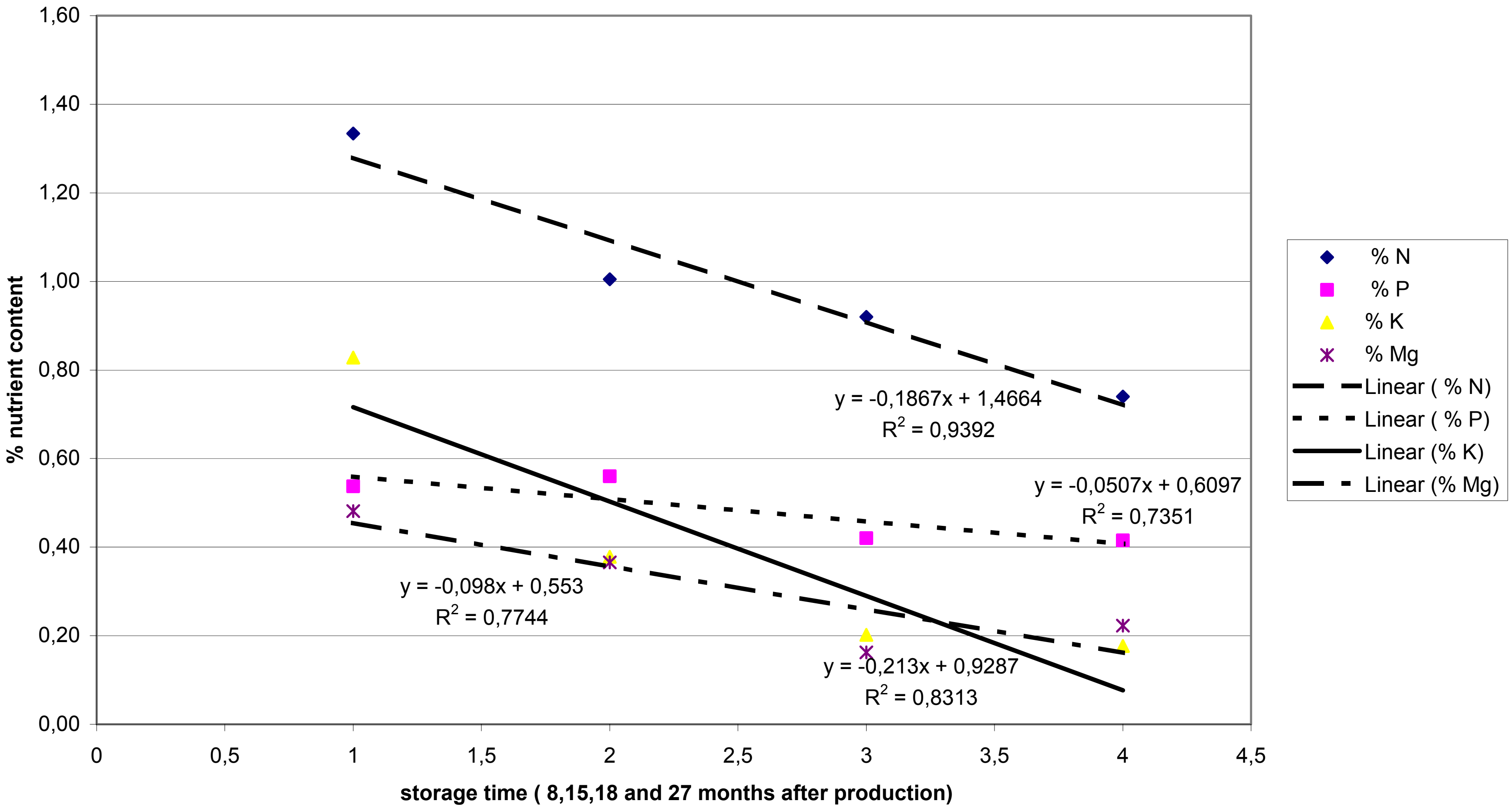


Fig. 3. Major nutrient content in manure as affected by storage period



Paper 3

Evaluation of mustard meal as organic fertiliser on tef (*Eragrostis tef* (Zucc) Trotter under field and greenhouse conditions.

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Key words /phrases: difference method, Ethiopia, isotope dilution, Nitosol, nitrogen use efficiency, organic and mineral fertiliser combination.

Abstract

Experiments were conducted to evaluate the potential use of mustard meal as organic fertiliser on tef **(*Eragrostis tef* (Zucc) Trotter.** Mustard meal is a high quality nutrient source with 6.35 % lignin, 2.1% total extractable polyphenol, C to N ratio of 14 and lignin to N ratio of 1.1. Under field conditions the effect of tef on Nitosol was studied in a split plot design with three replications. Grain yield increases due to increased mustard meal N rate varied from 2 to 116 % over the control. The agronomic efficiency was 3.0, 8.3 and 13.5 kg when N was applied at 15, 23 and 31 kg ha^{-1}, respectively. The mustard meal N use efficiency was 7.6, 20.6 and 33.7 % for the above-indicated N rates. Application of mustard meal in powder form was more effective than granular. In the greenhouse, the effect of mustard meal and urea N mixed in different quantity was studied with ^{15}N technique. The N derived from fertiliser was lowest (3.5%) when 20 mg N pot $^{-1}$ from urea was combined with 100 mg N pot $^{-1}$ from mustard meal and highest (11%) when 67 and 33 mg N pot^{-1} as urea and mustard meal were combined, respectively. The N derived from mustard meal was lowest (3.3%) when mustard meal and urea N were combined at 50 mg N pot $^{-1}$ each, and highest (8.9%) when combined at 20 and 100 mg N pot $^{-1}$, respectively. The urea and mustard meal N yields significantly varied between the treatments. The N use efficiency from urea (FNUE) varied from 38.4 to 43%. Combining urea and mustard meal N at 50 mg N pot $^{-1}$ each has decreased FNUE to 4.4% compared to the urea N applied alone at 50 mg N pot^{-1}. N use efficiency from mustard meal was highest (38.4 %) when mustard meal and urea N were combined at 33 and 67 mg N pot $^{-1}$, respectively, and lowest when it was combined at 67 and 33 mg N pot $^{-1}$.

Introduction

Soil fertility is the principal constraint for increasing crop production in the Ethiopian highland (Paulos and Sahlemedhin 2001). Several factors such as intensive cultivation, lack of sufficient fallow period for fertility restoration, high soil erosion and lack of adequate nutrient input have resulted in soil nutrient depletion and crop yield decline. Adoption and consumption of mineral fertilisers is constrained by high cost, lack of access to credit and other deficiencies. Availability of organic nutrient sources such as farmyard manure and crop residues for nutrient recycling are limited due to other competitive uses.

In the recent past, there has been increased interest in the use of available nutrient sources that have been neglected due to lack of knowledge and access. Various organic sources of plant nutrients such as by-products or wastes from processing animal and plant products are potentially good nutrient sources (Cooke 1982; Sharama and Deb 1988). Incorporating organic materials such as mustard meal, coffee husk, sugar cane straw, and abbatory by-products into the soil enhances nutrient cycling and builds the soil's organic nitrogen pool (Palm 1995; Reeves 1997).

Mustard seed (*Brassica carinata **(l)***), locally called 'gomenzer', is one of the important edible oilseed crops in Ethiopia and it has many better qualities compared to the other oilseeds. It is higher in grain and oil yield and has a higher resistance to pests and diseases than the other oilseeds (Balesh et al 1991). It also plays an important role in bridging the seasonal food shortage between planting and crop harvest since the green leaves are consumed as a vegetable. Due to its high biofumigative effect, it is also a preferred precursor for cereals (Angus et al. 1994; Kirkegaard et al. 1994; Sarwar et al. 1998).

However, brassica meals are known to contain high amounts of erucic acid and glucosinates, which are harmful to animal as a feed (Joseffson 1970; Tangtaweewipat et al. 2004). These substances can be hydrolysed by the myrosinase enzyme (present endogenously in *Brassica* tissues) to release a range of hydrolysis products that are toxic to germinating seeds and seedlings as well as to animals, causing for example goitre in non-ruminants (Kirkegaard et al. 1994; Kirkegaard et al. 1995; 1996; Rosa et al. 1997; Sarwar et al. 1998).

In Ethiopia, the effort to use the meal as a fuel source was impracticable as the smoke during burning caused respiratory organ irritation. Hence, the residue after solvent extraction was disposed as a waste product.

Lack of value for the meal has been one of the factors for its small acreage and low production. During 1997 –1999 for instance, it occupied only 4% of the area under oilseeds and contributed 6% to the total oilseed production (CSA 2001).

Nevertheless, mustard meal, which makes about 70% of the seed material, is rich in organic N (5.8-6.1% N or over 30% crude protein) and also has a good content of P (0.7-0.8%), K (0.8-1.1 %) and other essential plant nutrients such as Ca, Mg, Na, S and organic carbon (Balesh and Salema 2000).

Limited research has so far been carried out in Ethiopia on its potential use as a protein supplement in the diet of sheep (Teshome and Goshu 1990), and as a source of nitrogen for bread wheat on Vertisol (Balesh and Salema 2000).

The use of mustard meal organic fertiliser on tef [*Eragrostis tef* (Zucc.) Trotte] is very important, as tef is a major staple crop and in most areas the only source of cash income for the smallholders in Ethiopia. Moreover, compared to other cereals, tef is the only crop grown by all wealth category farmers under various agro climates and in different soils (Hailu and Seyefu 2001; Tekalign et al. 2001). Accordingly, utilisations of mustard meal on tef will definitely increase its demand and solve the problems associated with its transportation as it can be used in the localities of its production.

The objectives of this study were therefore to:

determine the effect of mustard meal N application rate on the yield, the agronomic efficiency (AE) and N use efficiency (NUE) in Nitosol with the difference method under field conditions.

determine the effect of selected combinations of mustard meal and urea N on the dry matter production and NUE with ^{15}N technique under greenhouse conditions.

Material and methods

A field and a greenhouse experiment were carried out at the station at Holetta Agricultural Research Centre (HRC) in Ethiopia and in the greenhouse at the FAO/IAEA Agriculture and Biotechnology Laboratory in Seibersdorf, Austria.

Field experiment

The experiment was carried out on Nitosol (Table 1) during the 1994 and 1995 crop seasons.

The experimental design was a split plot with 3 replications. The main plots consisted of the texture of mustard meal, viz., powder and granular mustard meal and the sub plots included three levels of N derived from mustard meal, 15; 23 and 31 kg N ha^{-1} and a control. The recommended N rate for tef on Nitosol was 31 kg ha^{-1}. To all treatments, 11 kg P ha^{-1} was applied. P content in the mustard meal (Table 2) was taken into account when calculating the P applied per treatment.

Before mustard meal application, composite soil samples were collected from the experimental field from the surface 20 cm soil depth to characterise the major chemical and physical properties. Mustard meal was applied and incorporated in the soil twenty days before planting to avoid the toxicity on germinating seed. The mustard meal was hand broadcasted on the plots and then worked into the soil by hoe, manually.

At the recommended planting time (18th and 20th July 1994 and 1995, respectively), the plots were levelled manually using hoes and digging forks and trampled by humans. Triple super phosphate was surface broadcasted manually, followed by seed sowing with the variety DZ-01-35 at the rate of 35 kg ha^{-1}. Tef is traditionally planted in the middle of the rainy season (Table 3). Shallow drainage ditches were dug around the field and between the blocks to control runoff water. Three to four hand weedings were carried out during the growth period. At crop maturity, mid November, the whole plot was harvested using sickles. Threshing was done manually. The grain yield was adjusted to 12% moisture content.

Laboratory analysis of the soil, mustard meal and tef seed was carried out at HRC.

Agronomic efficiency (AE) of mustard meal nitrogen was calculated by:

$$AE = \left(\frac{Ymm - Y0}{mmN rate} \right) \quad (1)$$

Ymm = Grain yield of mustard meal N treatment

Y0 = grain yield of control treatment.

The NUE was measured by the difference method (Harmsen and Moraghan 1988). NUE was calculated from the N yield of the crop in the unfertilised (N0) and the fertilised (*Nmm*) plots and the amount of mm meal N applied (*mmN rate)*.

$$\% \text{ mm NUE} = \left(\frac{Nmm - N0}{mmN rate} \right) X\, 100 \quad (2)$$

N yield was calculated:

N yield = grain yield X % N content in grain (3)

The data were analysed for variance using the MSTATC computer package (Russell, D. Freed, Michigan State University, USA). Where the "F" statistics indicated significance, the means were separated using Duncan's Multiple Range Test at P= 0.05.

Greenhouse experiment

The greenhouse experiment was conducted at the FAO/IAEA Agriculture and Biotechnology Laboratory in Seibersdorf, Austria. The work investigated the N uptake from mustard meal combined with ^{15}N labelled urea at different proportions. The method employed was the isotope dilution where the N uptake from the unlabelled source was measured indirectly in a pair of treatments, a standard treatment (with ^{15}N labelled urea alone) for each corresponding combination treatment (IAEA1990). The outline of the treatments was as follows:

Treatment i (standard treatment) = Soil + ^{15}N labelled urea solution

Treatment ii = Soil + ^{15}N labelled urea solution + mustard meal. A complete list of the treatments is shown in Table 4.

The experimental soil was typic Eutrocrept (Seibersdorf soil). Selected physico-chemical characteristic of the soil is given in Table 1. The mustard meal was applied in a powder form. Each treatment was applied to a 3 kg air-dry soil in a bucket, thoroughly mixed and then filled into plastic pots. The soil moisture was brought to 60 % field capacity. A week before planting the labelled urea with 3.5 atom % ^{15} N excess was applied in a solution to all treatments, except treatment 2, where the labelled urea was applied at 10 atom % ^{15} N excess. The procedure of mixing was similar to the mustard meal. The soil in each pot was transferred to a bucket and thoroughly mixed. The labelled urea solution was applied to the soil, mixed carefully, transferred to the original pot and left undisturbed for one week. The condition in the greenhouse was as follows: mean day and night temperatures were 28 and 20

^{0}C, respectively; light regime ranged from 220 to 860 μ moles $m^{-2}s^{-1}$ for 12-h photoperiod; and the relative humidity varied between 60 and 70% (day and night amplitude).

Twenty days after the mustard meal application and seven days after labelling the soil with ^{15}N of urea, tef was planted in each pot. To all pots, a blanket basal application of 60 mg P pot^{-1} as triple super phosphate ($Ca(H_2PO_4)_2$ and 150 mg K pot^{-1} as potassium chloride (KCl) was made.

At germination, the seedlings were thinned to 10 plants pot^{-1}. The soil moisture was kept between 50 and 60% of field capacity during the growth period by weighing and watering daily.

Harvest was done at an early grain-filling stage. All above ground plant material was gathered, chopped and sub-sampled by quartering. Samples were oven-dried for 72 hours at 70 ^{0}C and weighed. The dry samples were ground to 200 μm and analysed for total N and atom % ^{15}N excess using an automatic N analyser coupled to a SIRA mass spectrometer (IAEA 1990).

N yield of the dry matter was calculated as indicated for the field experiment.

The % Nitrogen derived from urea (% Ndff) was calculated:

$$\% \text{ Ndff} = \frac{atom\,\%^{15}N\,excess\;\;in\;plant\,sample}{atom\,\%^{15}N\,excess\;\;in\,fertilizer} \times 100 \qquad (4)$$

% N derived from mustard meal (%Ndfmm) was calculated:

$$\% \text{ Ndfmm} = \left(1 - \frac{atom\,\%\;\,^{15}N\;\,excess\;treatment\;\,ii}{atom\;\%\;\,^{15}N\;\,excess\;treatment\;\,i}\right) X\,100 \qquad (5)$$

Where,

Treatment ii = plant grown with labelled urea and mustard meal application.

Treatment i = plant grown with labelled urea.

% N derived from the soil (%Ndfs) was calculated:

$$\%\ Ndfs = 100 - \%\ Ndff \quad (Treatment\ i)\ or\ \ 100 - \ (\%Ndff\ + \%Ndfmm\ )\ \ (Treatment\ ii) \qquad (6)$$

Fertiliser N yield was calculate:

$$Ndff,\ (mg\ pot^{-1}) = N\ yield \times \%Ndff \qquad (7)$$

Mustard meal N yield was calculated:

$$Ndfmm,\ (mg\ pot^{-1}) = \%Ndfmm\ X\ N\ yield \qquad (8)$$

Soil N yield was calculated:

$$Ndfs,\ (mg\ pot^{-1}) = \%NdfsX\ N\ yield \qquad (9)$$

Fertiliser N use efficiency was calculated:

$$\%\ FNUE = \frac{Ndff\ (mg\ \ pot^{-1})}{urea\ \ N\ rate\ pot^{-1}} \times 100 \qquad (10)$$

Mustard meal NUE was calculated:

$$\%\ MmNUE\ \ = \frac{mm\,N\ yield, (mg\ pot^{-1})}{mm\,N\ rate\ pot^{-1}}\ X100 \qquad (11)$$

The data were analysed for variance as described for the field experiment.

Results

Field experiment

There was significant treatment effect both years (Table 5). Mean grain yield in 1994 and 1995 were 480 and 562 kg ha $^{-1}$. The grain yield was 39 and 5 % higher in 1994 and 1995, respectively, when the N was applied in powder mustard meal compared to the granular.

In 1994 grain yield increase due to mustard meal application in powder form at 15, 23, and 31 kg N ha^{-1} was 23, 107 and 207% compared to the control, respectively. For the mustard meal applied in the granular form these values were 12, 77 and 138%, respectively.

In 1995 the yield increase due to powder mustard meal application at 15, 23 and 31 kg N ha $^{-1}$ was 5, 32 and 68 % compared to the control, respectively. When N was applied in the granular mustard meal the increase was 14, 26 and 96 % for the N rates indicated above, respectively.

Agronomic efficiency followed similar response as the yield and varied significantly between mustard meal type and mustard meal N rates (Table 6). The mean AE for powder meal was 69% higher than the granular meal in 1994. In 1995 the AE was 20% higher when the N was applied in granular mustard meal. Mean AE during 1994 and 1995 was 10.2 and 6.3 kg, respectively. The AE for the recommended N rate in 1994 and 1995 was 16 and 11 kg tef grain per kg N applied with mustard meal.

Mean N use efficiency (%NUE) of mustard meal was 25 and 16 % in 1994 and 1995, respectively, and significantly varied between the powder and granular mustard meal and the N treatments (Table 7).

The mean NUE was 32 and 19 % for the powder and granular mustard meal in 1994, respectively. For all N rates NUE was higher when mustard meal was applied in powder and the increase in NUE was 88, 58 and 71% with the N applied at 15, 23 and 31 kg ha $^{-1}$, respectively, compared to the granular. The NUE obtained with the application of the recommended N rate in powder and granular mustard meal was 57 and 54 % higher than the means, respectively.

In 1995 the NUE for both mustard types was low but 20 % higher for the powder meal than the granular. However, when the recommended N rate (31 kg N ha $^{-1}$) was applied, the NUE was 23% higher for granular mustard meal than the powder.

Greenhouse experiment

There was significant variation in dry matter yield between the treatments, except between 33-0 and 67-0 (Table 8). There was no yield difference between the treatments 20 -100 and 67 - 33 and between 33 - 67 and 50 - 50.

N yield significantly differed between treatments. Lowest N yield was obtained when 33 mg N pot^{-1} was applied as urea alone. Applying N either at 50 mg or 100 mg per pot as urea alone resulted in similar N yields. Highest N yield was obtained with the treatment 67 – 33.

N derived from fertiliser (%Ndff) varied from 4 to 16%, and increased as the urea N rate increased both in sol and combined treatments. Combining urea and mustard meal N did not significantly affect %Ndff.

N derived from mustard meal (%Ndfmm) varied between mustard meal N combined with urea N at a 50 to 50 mg N pot^{-1}and other combinations. %Ndfmm was similar for the treatments 67 - 33 and 33 – 67.

N derived from soil (%Ndfs) varied between all treatments when urea was applied alone. When the urea and mustard meal N were combined the variation was significant between the treatment 67- 33 and the other treatments.

Fertiliser N yield (Ndff) has varied between the treatments with 100 mg N pot $^{-1}$ sol urea and other treatments, between urea N applied alone at different rates and the urea and mustard meal N combined. Among the treatments in the pair, fertiliser N yield was different between 100-0 and 20 -100 treatments.

Mustard meal N yield varied significantly between the treatments. Combining urea and mustard meal at 20 - 100 mg N pot^{-1} gave 56% higher mustard meal N yield than the mean, whereas at 33 - 67, 50 - 50 and 67 - 33 produced 16, 43 and 2 % less N yield than the mean, respectively.

Fertiliser N use efficiency (%FNUE) varied from 38 to 43% when urea was applied alone and in combination. Highest and lowest % FNUE were obtained when urea was applied 50-0 and 33-0, respectively. Combining urea and mustard meal N at a 50-50 resulted in significant FNUE decrease (4.4%) compared to 50-0.

Mustard meal N use efficiency (%MmNUE) varied from 15 to 38%. Highest MmNUE was obtained when the N of mustard meal and urea was combined at 33- 67 and lowest when it was applied either at 67 -33 or 50 - 50 combinations.

Discussion

Mustard meal is a material with high N content, low C to N ratio (14), 6.4 % lignin and 2.1 % total extractable polyphenol categorized as a high quality organic material with a high mineralisation rate (Palm et al. 1997; Murwira et al. 2002).

According to the preliminary decision tree on the uses of organic materials of different quality for N management (Palm et al. 1997), the organic material was to be incorporated directly with the annual crop at planting. However, early incorporation into the soil was needed as mustard meal contains erucic acid and glucosinolates (Mojtahedi et al.1991; Bhardwaj et al.1996; Tangtaweewipat et al. 2004) that are toxic to germinating seeds (Joseffson 1970, Kirkegaadr et al. 1996). This practice, however, might have negative effects due to the lack of the synchrony between N released from the organic fertiliser and the N uptake by the plant (Hood et al.1999).

The mean yield over the two years was 65% of the national average yield of tef, which was about 800 kg (Mulat et al. 1998). However, when the N was applied at the recommended rate (31 kg N ha $^{-1}$) the yield obtained was the same as the national average yield. The mean agronomic efficiency was 8 kg per kg N, but at the then recommended N rate it was 86 % higher.

The mustard meal N use efficiency over the two years was 21 % and is consistent with what is generally reported. NUE for high quality organic nutrient sources is frequently less than 20 % (Haggar et al. 1993; Vanlauwe et al. 1996). However, the NUE obtained, when N was applied at 31 kg ha $^{-1}$, was 34%, which was high for organic nutrient sources and comparable to mineral fertiliser (Raun and Johnson 1999).

Higher efficiency of mustard meal applied in powder form, compared to the granular form, might be due to the uniform distribution of the powder during application, which facilitated better availability and the uptake of N by the crop.

The granular mustard meal is solid and has variable size. Hence, it might need more time to disperse. In addition, the granule mustard meal might create high concentration areas that could have negatively impacted the growth of the plant. This can be supported by the observed localised stunted growth on the plots with granular mustard meal application.

The difference in NUE between the N rates might be due to the immobilisation of the N applied at low rate. Though mustard meal is a high quality material, the low N rate might have resulted in N immobilisation. Nhamo et al. (2001) had reported an initial net N immobilisation from manure applied at low N rate at high soil moisture content under laboratory conditions.

In the greenhouse study, combining urea with mustard meal did not affect the FNUE as the means with and with out combination were about 40%. However, the range of the %FNUE obtained in this experiment was lower than the reported 50% for another study with the same variety and soil type (Balesh et al. 2005). We assume that this was because of the N loss during the time of equilibrium.

The NUE of mustard meal obtained for the greenhouse uptake was 22.5 % and was influenced by the quantity of combination with urea N. However, the trend was too irregular to identify either the synergetic or the priming effect.

The chemical composition of the greenhouse and field experiment results showed the role neglected organic nutrient sources can play in crop production and soil nutrient management.

Moreover, the contribution of mustard meal to the total fertiliser consumption in Ethiopia might be more evident if we illustrate it with basic data. During the 2000 crop season, about 13,905 metric tons of mustard seed were produced by the smallholder farmers in Ethiopia (CSA 2001) with a potential of 584 metric tons N available in the mustard meal after pressing the oil. According to FAO statistics (FAO 2004) this quantity was about 2.8 % of the total urea N consumption in Ethiopia during the same period.

Besides the nutrient added to the soil system, brassica crops are well known for the suppression of cereal pathogens by the release of biocidal compounds. Isothiocyanates produced during the breakdown of glucosinolates reduce disease infection in the following crops (Angus et al.1991; Kirkegaard et al. 1994; Boydston and Hang 1995; Brown and Morra 1997). The high nutrient content, low lignin to N ratio, low lignin and total extractable polyphenol to N ratios and the suppression of parasitic nematodes position mustard meal among high quality rare organic fertilisers.

There is evidence that mustard meal has been used against household and storage pests in Ethiopia. For instance, the farmers in the vicinity of the edible oil processing industry in Bahir Dar Ethiopia use mustard meal for controlling wood lice and termites in their home and grain stores. In addition, they apply mustard meal to vegetables and maize grown in the garden to control nematodes. .

Conclusions

The laboratory characterisation of the material, the N use efficiency measured with the difference method under field conditions and with ^{15}N technique under greenhouse conditions, proved that mustard meal is a high quality organic fertiliser.

The feasibility of using mustard meal as organic fertiliser for increasing tef yield is high. However, further field evaluation is necessary with more rates of mustard meal N and in combination with mineral N sources.

The indigenous and scientific knowledge of biocide value of mustard meal needs to be developed in Ethiopia, as the meal can play several roles such as best organic fertiliser, feed supplement and pest controller.

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Table 1. Some selected physico-chemical characteristics of the experimental soils

Soil property	Unit	Holetta (Nitosol)	Seibersdorf (Eutrocrept)*
Texture	class	Clay	Clay loam
**Field capacity	g kg^{-1}soil.	263	370
Organic Carbon	g kg^{-1}soil	19.5	32
pH 1:1 (Soil:H_2O)		5.5	8.2
Total N	g kg^{-1}soil	1.5	2.3
P	mg kg^{-1}soil	7.83	176
K	cmol kg^{-1} soil	1.5	1.0

*Hood et al., 2000 ** Data from Holetta Soil Research program and Seibersdorf laboratory.

Table 2. Composition of mustard meal

Nutrient type	% (dry matter)
Organic Carbon	88
N	6.1
P	0.6
K	1.1
S	0.6
Lignin	6.3
Total extractable polyphenolics (TEP)	2.1

Table 3. Rainfall, maximum and minimum temperatures of Holetta Research Centre, Ethiopia.

Months	Rainfall, mm		Max. temp., ^{0}C		Min. temp., ^{0}C	
	1994	1995	1994	1995	1994	1995
Jan	0.0	0.0	24.1	24.0	2.1	1.4
Feb	2.3	84.6	25.1	24.3	4.4	5.7
Mar	86.7	41.9	24.6	24.5	8.3	7.0
Apr	45.9	123.8	24.1	22.5	7.7	9.8
May	29.8	80.7	25.1	24.0	7.3	7.6
Jun	107.3	91.6	21.4	23.6	8.1	6.5
July	216.4	191.9	19.0	19.4	9.8	8.6
Aug	209.3	262.7	19.3	19.7	9.1	9.1
Sep	149.7	82.1	20.6	20.6	6.6	6.3
Oct	0.0	15.5	22.4	22.6	2.5	3.5
Nov	36.6	0.0	21.8	23.4	2.9	2.0
Dec	0.0	34.0	23.1	22.8	1.6	3.3

Data from Ethiopian Agricultural Research Organization.

Table 4. Treatments in the greenhouse experiment

Treatment	Treatment pair	Labelled urea, mg N pot^{-1}	Atom % ^{15}N excess	Mustard meal, mg N pot^{-1}	Pot content
100*-0	Standard treatment	100	3.5	0	Soil + ^{15}N labelled urea solution
20*-100	Treatment with mustard meal	20	10	100	Soil + ^{15}N labelled urea solution + mustard meal
33*-0	Standard treatment	33	3.5	0	Soil + ^{15}N labelled urea solution
33*-67	Treatment with mustard meal	33	3.5	67	Soil + ^{15}N labelled urea solution + mustard meal
50*-0	Standard treatment	50	3.5	0	Soil + ^{15}N labelled urea solution
50*-50	Treatment with mustard meal	50	3.5	50	Soil + ^{15}N labelled urea solution + mustard meal
67*-0	Standard treatment	67	3.5	0	Soil + ^{15}N labelled urea solution
67*-33	Treatment with mustard meal	67	3.5	33	Soil + ^{15}N labelled urea solution + mustard meal

N* = labelled urea N; N= unlabelled mustard meal N

Table 5. Effect of mustard meal on the grain yield of tef (kg ha^{-1}) grown on eutric Nitosol at Holetta Research Centre, Ethiopia.

Treatment	1994		1995	
	Powder meal	Granular meal	Powder meal	Granular meal
N0	300c	260c	440c	430c
N15	370c	290c	460c	490c
N23	620b	460b	580b	540b
N31	920a	620a	740a	820a

Means with the same letter in the same column are not significantly different at Duncan's Multiple Range Test at P= 0.05

Table 6. Agronomic efficiency (kg grain kg^{-1} N) of mustard meal application on tef on a Eutric Nitosol at Holetta (Ethiopia).

	1994		1995	
Treatments	Powder meal	Granular meal	Powder meal	Granular meal
N15	4.5c	2.4c	1.5c	3.7b
N23	13.8b	8.6b	5.8b	4.8b
N31	20.1a	11.7a	9.5a	12.5a

Means with the same letter in the same column are not significantly different at Duncan's Multiple Range Test at P= 0.05

Table 7. N use efficiency (%) of mustard meal application on tef on a Eutric Nitosol at Holetta (Ethiopia)

	1994		1995	
Treatment	Powder meal	Granular meal	Powder meal	Granular meal
N15	11.3c	6.0c	3.7c	9.3b
N23	34.2b	21.6b	14.5b	12.0b
N31	50.2a	29.3a	24.0a	31.2a

Means with the same letter in the same column are not significantly different at Duncan's Multiple Range Test at P= 0.05

Table 8. Shoot dry matter, N yield, N derived from fertiliser, N derived from mustard meal and N from soil, fertiliser and mustard meal N yield, soil N yield, N utilisation efficiency from urea and mustard meal in tef under greenhouse conditions.

Treatment	DM, g pot^{-1}	N yield, mg pot^{-1}	% Ndff	% Ndfm	% Ndfs	Ndff, mg pot^{-1}	Ndmm, mg pot^{-1}	Ndfs, mg pot^{-1}	% FNUE	% MmNUE
100*-0	25.2c	241.7b	16.4a		83.6d	39.6a		202.1c	39.6bc	
20*-100	26.5b	228.2d	3.5e	8.9a	87.6c	8.0e	20.3a	199.9d	40.0bc	20.3b
33*-0	26.2b	204.2e	6.2d		93.8a	12.7d		191.5e	38.4c	
33*-67	28.4a	227.3d	5.9d	4.8c	89.3bc	13.4d	10.9c	203.0c	40.6bc	16.3c
50*-0	28.4a	241.5b	8.9c		91.1b	21.0c		220.0a	43.0a	
50*-50	28.4a	224.7d	8.6c	3.3d	88.1c	19.3c	7.4d	198.0d	38.6c	14.8c
67*-0	25.9c	235.7c	11.7b		88.3c	27.6b		208.1b	41.2b	
67*-33	27.3b	248.7a	11.1b	5.1b	83.8d	27.6b	12.7b	208.4b	41.2b	38.4a

Means with the same letter in the same column are not significantly different at Duncan's Multiple Range Test at P= 0.05

Paper 4

N fertilization, soil type and cultivars effects on N use efficiency in tef [*Eragrostis tef* (Zucc.) Trotte]

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Key words: fertilisers N use efficiency, N derived from fertilisers, N fertilisers, Nitosol, tef [***Eragrostis tef (Zucc.) Trotte***] varieties, Vertisol.

Abstract

Tef [*Eragrostis tef* (Zucc.) Trotte] is a major staple crop in Ethiopia and a large proportion of the imported fertiliser are being applied to tef fields. However, since 1980s the yield on farmers' fields has stagnated. Response of the crop to applied fertiliser is influenced by several factors. We aimed to study the fertiliser N use efficiency (FNUE) of four tef varieties from ammonium sulphate and urea on different soil types with the help of ^{15}N isotopic dilution technique. Three experiments were conducted under greenhouse and field conditions. On a typic Eutrocrept soil, higher percent N derived from fertiliser (% Ndff) and % FNUE were obtained for all the tested tef varieties when the N source was urea, while percent N derived from soil (% Ndfs) was higher for ammonium sulphate. The mean % FNUE for urea and ammonium sulphate was 49 and 34% respectively. When the varieties were grown on a Nitosol or a Vertisol and ammonium sulphate was applied, the % Ndff, the total and fertiliser N yield and % FNUE of the tef varieties were higher on a eutric Nitosol compared to the Vertisol. The mean % FNUE was 61.3 for the Nitosol and 27.8 for the Vertisol. In an 'on farm' experiment, relatively higher FNUE (33.3%) was obtained on an Andosol compared to Vertisols (17 and 27%). The tested varieties showed no difference in FNUE. As tef is the most important crop grown on Vertisols in Ethiopia low FNUE has a direct negative implication on the livelihood of the farmers and the environment.

Introduction

Tef is a cereal crop that belongs to the grass family, Poaceae (Gramineae), sub-family *Eragrostideae.* It is the only cultivated cereal in the genus *Eragrostis*, which contains about 350 species (Abebe 2001). Ethiopia is both the centre of origin and diversity for tef (Vavilov 1951). Tef is a major staple crop in Ethiopia and Eritrea and hardly grown anywhere outside these countries. In Ethiopia, it is cultivated on about two million hectares of land covering about 30% of the area under cereals (Kenea et al. 2001). The average tef grain yield is low, only about 800 kg ha^{-1}.

As soil nitrogen and phosphorus deficiencies are main factors limiting its production in Ethiopia, response of tef to N and P fertiliser application is common in the main growing areas of the country (Tekalign et al. 2001; Teshome and Verheye 1993). Improved tef varieties that are adequately fertilized can produce up to 2.5 t grain ha^{-1} in "on station" field experiments.

The fertiliser use in Ethiopia has increased notably since 1990. In 1995/96 crop season 111884 metric tons or 46.3 % of the total fertiliser used in the country was applied to tef fields **(**Anonymous 1997**)** with a national average rate of 46 kg N-P ha^{-1} for the users only. This application rate is relatively high compared to past experiences in Ethiopia.

However, there is no concomitant yield increase, because, since the 1980s, tef yields have almost stagnated probably due to the occurrence of accelerated soil erosion and lack of appropriate cultural practices on farmers' fields (Fufa et al 2001).
In addition, in Vertisols, low yield of tef might be due to problems associated with water logging or poor drainage that impairs availability and uptake of fertilizer N. The low water infiltration rate in Vertisol influences losses of applied N through processes such as denitrification, ammonia volatilisation and bypass flows (Sigunga 1997). Water logging, runoff and erosion are not problems on 'on station fields' as they are fully controlled at field, block and plot levels.

Because of the absence of alternative options to sustain yield, farmers have no choice but continue to invest in chemical fertilizer, although they know that the return may be inadequate to cover the risk involved (Mulat et al. 1998). Under the prevailing conditions of high fertiliser costs and low agriculture-based incomes, fertiliser recommendations to correct nutrient deficiencies and increase production must take into account the fertiliser N use efficiency (FNUE) by the crop and the factors/conditions that influence the crop response to the N fertilisation. To improve FNUE, it is necessary to evaluate soil, crop and fertilizer management options such as fertiliser sources, method and time of application, soil properties, crop genotype (variety) and cultural practices under the prevailing socio-economic conditions. In general, recovery of fertiliser N by annual crops is low, rarely greater than 50-60% of that applied (Bowen and Zapata 1991; Isfan et al.1994).

Little information on FNUE by tef is available. Therefore, it is necessary to investigate means to increase the efficiency of this expensive (and imported) agricultural input to achieve sustainable tef production. First step in this direction would be to evaluate the key factors that influence FNUE. This study addresses plant factors (varieties), fertiliser N sources, and soil types. We determined the FNUE of different tef varieties as influenced by these factors alone and in combination under greenhouse and field conditions using ^{15}N isotope technique.

Materials and methods

A series of greenhouse and field experiments was carried out to study the effect of key factors on FNUE of different tef varieties. The first experiment conducted in the greenhouse at the FAO/IAEA Agriculture and Biotechnology Laboratory in Seibersdorf, Austria, investigated tef genotypic differences in fertiliser N recovery. The greenhouse experiment, carried out at Holetta Agricultural Research Centre in Ethiopia, assessed the response of tef varieties to ammonium sulphate as an N source on station's two main soil types. A third experiment was conducted under farmers' field management practices to evaluate the NUE from urea, the only fertiliser N source applied in Ethiopia, by a widely grown, improved variety, DZ-01-354 in two tef growing areas.

Experiment 1

This greenhouse experiment examined the response of four tef varieties to urea and ammonium sulphate. The conditions in the greenhouse were as follows: mean day and night temperatures were 28 and 20^{O} C, respectively; light regime ranged from 220 to 860 μ moles $m^{-2}s^{-1}$ for 12-h photoperiod; and the relative humidity varied between 60 and 70% (day and night amplitude).

The experimental soil was typic Eutrocrept (Seibersdorf), (Table 1). The soil was ground and passed through a 4-mm sieve. Ten tef plants were grown in plastic pots, each containing 3 kg soil. To all pots, a blanket basal application of 20 mg P kg^{-1} soil as triple super phosphate (TSP) and 50 mg K kg^{-1} soil as potassium chloride (KCl) was made. The experimental design was a factorial of two fertiliser N sources and four tef varieties arranged in a complete randomised design with 3 replications.

Three improved tef varieties (DZ-01-354, DZ-01-196, DZ-Cr-37) and one local (Dabbi) were included in the study. DZ-01-354 and DZ-01-196 were varieties with late and intermediate-maturity periods, respectively. DZ-Cr-37 and Dabbi were early maturing varieties.

The ^{15}N-labelled fertiliser N sources were urea and ammonium sulphate with 1.95 and 2.62 atom % ^{15}N excess, respectively, and both were applied at the rate of 13 mg N kg $soil^{-1}$**.** All the ^{15}N-labelled chemical fertilisers were applied in solution immediately after germination.
Moisture content at field capacity was determined using a pressure plate, and soil moisture content in the pots was kept at 50 and 60% of field capacity during the growth period by weighing and watering daily.

The varieties were sensitive to sunlight hours and had prolonged vegetative growth. Harvest was done at grain-filling stage. All aboveground plant material was gathered, chopped and sub-sampled by quartering. Samples were oven-dried for 72 hours at 70^{O} C and weighed. The dry samples were ground to 200 μm and analysed for total N and atom % ^{15}N excess using an automatic N analyser coupled to a SIRA mass spectrometer (IAEA1990).

Commonly used methods for estimating FNUE are the isotopic dilution, difference method and regression analysis (Roberts and Janzen 1990). According to the ^{15}N isotopic dilution method that was used in this experiment, the amount of fertiliser N taken up by the plant is calculated from the total N uptake and isotopic ratio analysis of plant samples fertilized with ^{15}N fertilisers (Harmsen and Moraghan 1988; Roberts and Janzen 1990).
Experiment 2

Two soil types predominant in major tef growing areas in Ethiopia, an eutric Nitosol and a pellic Vertisol (Anonymous 1986) were collected from unfertilised fields in Holetta and Ginchi Research Centres, respectively. (Table 1). The same pots and amount of soil as described in experiment 1 were used. A factorial experiment of two soil types and four tef genotypes arranged in complete randomised design with four replications was used. ^{15}N

labelled ammonium sulphate with 10.03 atom % ^{15}N excess was applied in solution to all pots at a rate of 18 mg N kg^{-1} soil. A blanket basal application of 20 mg P kg^{-1} soil as TSP and 50 mg K kg^{-1} soil as KCl was made to all pots. The amount of N and P applied was established according to the recommended rates for tef by the new Extension Program of the Ministry of Agriculture. Soil moisture was kept between 50 and 60 % field capacity during the growth period by daily weighing and watering.

Plants were harvested and prepared for analysis as previously described for Experiment 1. The soil and plant analyses for the experiments carried out in Ethiopia were done at Soil and Plant Analysis Laboratory, Holetta Research Centre. Total N and ^{15}N content in the plant material were analysed by the Kjeldahl method and emission spectrometry using the NOI-6 PC Emission Spectrometer, respectively (IAEA 1990). The soil pH (1:1 H_2O) was measured by pH meter; soil texture measured by the pipette method (Day 1965); organic carbon (Allison 1960); total N (Bremner 1965); cation exchange capacity by methods described in (Black et al. 1965) and phosphorus by the Bray 2 method (Bray and Kurz 1945)

Experiment 3

An “on farm” field experiment on FNUE by tef was conducted in 1997 in three sites of the Ada area (8°48' N, 39°38' E), east Shawa zone of the Oromiya Regional State, Ethiopia (Figure 1). This area is well known for its tef production, seed quality and relative production profitability because of tef-straw market value. The altitude of the area varied from about 1800 m.a.s.l. at Ude 1 and Ude 2 to 1920 m.a.s.l. at Kajima. The landscape of Ude 1 (Site-1) and Ude 2 (Site-2) was almost flat whereas that of Kajima (site-3) was gently sloping. The soils were classified as Vertisols at Ude1 and Ude2 and Andosol at Kajima (Murphy 1959). Selected soil properties are given in Table 1. The area has a bimodal rainfall pattern, with the main rain from June to September and the short rain (‘Belg’) from February to April. Monthly rainfall, monthly maximum and minimum temperatures in 1997 are given in figure 2 (Anonymous 1997).

Experimental plots were laid down adjacent to farmer's tef fields and the farmers themselves managed the experiments. In the year prior to the experiment, the plots were cropped with tef at Ude 1, sunflower at Ude 2 and wheat at Kajima without fertiliser or manure inputs. The main yield plot size was 16 m^2 (4 m x 4 m) and the ^{15}N subplot (1m^2) was located in the middle of the main plot. The design was one factor (site) randomised complete block with four replications. Before planting, soil samples were collected from 0-20 cm depth to characterize the soil fertility status in the sites. Prior to sowing, traditional trampling was used to prepare fine seedbed for tef germination and to reduce weed growth. Seeding with variety DZ-01-354 was performed manually on July 22 and 23, 1997.

Recommended fertiliser rates (64 and 20 kg ha^{-1} for N and P, respectively) were surface broadcasted as urea and diammonium phosphate (DAP) on the yield plots. On the ^{15}N subplots the fertiliser was applied as ^{15}N labelled urea with 10.03 atom %^{15}N excess and TSP as source of P as it was not possible to get labelled DAP. A hand weeding was done at 7 weeks after planting at Ude 2. At the two other sites two hand weeding were done at 4 and 7 weeks after planting, depending on the farmer's judgment.

Before harvest, plant samples were taken from the ^{15}N subplots for total and ^{15}N analysis. At crop maturity, the whole plot was harvested on November 22 and 28, 1997 in Ude and Kajima, respectively, and threshed manually.

Chemical and isotopic analyses were made as described for Experiment 2. The calculations for the % Ndff, % Ndfs and % NUE were performed according to the direct labelling method (IAEA, 1990).

N yield = yield × % N (1)

% Nitrogen derived from fertiliser (% Ndff) was calculated

$$\%\ \text{Ndff} = \frac{atom\ \%^{15}N\ excess\ in\ plant\ sample}{atom\ \%^{15}N\ excess\ in\ labelled\ fertiliser} \times 100 \quad (2)$$

% N derived from the soil (%Ndfs)

% Ndfs = 100 − %Ndff (3)

Fertiliser N yield = N yield × %Ndff (4)

% NUE was calculated:

$$\%\ \text{NUE} = \frac{Fertiliser\ N\ yield}{N\ rate\ applied} \times 100 \quad (5)$$

The experimental data were subjected to analysis of variance using statistical computer program MSTAT-C. To compare treatment means, the least significant difference (LSD) at 5% levels was utilised.

Results and discussion

Experiment 1

There was significant variety and interaction effect on dry matter yield (Table 2). The early maturing variety DZ-Cr-37 produced 5-9 and 4-5 % higher dry matter yield than the other varieties. The N derived from the fertiliser (% Ndff) was low for both fertiliser N sources; yet it was higher for urea than ammonium sulphate. The % Ndff varied from 7.6 to 8.2 % when the N source was urea and from 5.7 to 6.1 % when it was ammonium sulphate. Wider variation (10-50 mg N pot^{-1}) in fertiliser N yield was observed among the varieties when the N source was ammonium sulphate. The NUE was significantly different due to the fertiliser N sources and the interaction of fertiliser N sources and varieties. The mean NUE for urea was 14.7 % higher than that of the ammonium sulphate. The differences in % FNUE between the urea and ammonium sulphate sources were 19.2, 16.8, 14.3 and 8.7 for the varieties DZ-01-354, DZ-01-196, DZ-Cr-37 and Dabbi, respectively. The FNUE observed was low for greenhouse experiments. We assume that the soil property, calcareous (14.3% $CaCO_3$), clay loam texture, high pH, application of the fertilizer on the surface, the temperature in the greenhouse and the moisture had favoured loss of fertiliser N through ammonia volatilisation and oxidation (Cai et al 2002; Raun and Johnson 1999; Sigunga et al. 2002). Higher N utilisation from urea compared to ammonium sulphate by all varieties may be due to higher N loss from ammonium sulphate than urea through volatilisation. The ammonium fertiliser provides ammonium ions instantly available for volatilisation (Cai et al. 2002; Zhu et al. 1989), while when urea was applied the ammoniacal N concentration depended on the rate of hydrolysis of urea. Fertiliser type and especially the interaction between fertilizer type and soil type, is known to influence NH_3 loss from inorganic fertilizers (Hargrove et al. 1977; Whitehead and Raistrick 1990).

Experiment 2

The tef varieties produced lower dry matter yield (on the average 45% less) in the Vertisol than in the Nitosol (Table 3). No significant differences were found between varieties on dry matter yields. The % Ndff values were 7 % higher on the average in the Nitosol than in the Vertisol. No significant differences between the varieties were found in total and fertiliser N yields. However, mean total and fertiliser N yields were higher in the Nitosol and there were significant interactions between soil type and variety. Highest total and fertilizer N yield was obtained for Dabbi grown in the Nitosol.

The mean % NUE in the Nitosol was 34 % higher than in the Vertisol. Consequently, the NUE values in the Nitosol were superior over the Vertisol by 34, 25, 28 and 43 % for the varieties DZ-354, DZ-01-196, DZ- Cr-37 and Dabbi, respectively.

Higher NUE in the eutric Nitosol compared to the pellic Vertisol could be due to better drainage and higher organic matter content that improved soil water and air balances that resulted in higher fertiliser N uptake and yield. The % FNUE values reported for the Nitosol are adequate (above 50%). Vertisols are generally regarded as problematic soils in Ethiopia due to their distinctive hydro-physical properties, which lead to a high incidence of prolonged water-logging and limitation of nutrient availability and plant growth (Astatke 2003; Asgelil et al. 2001; Syers et al. 2001).

Experiment 3

The dry matter, grain and total N yields significantly varied across sites and all the parameters were highest at Kajima on Andosol (Table 4). The FNUE obtained was well below the reported average N use efficiencies of 50% reported for annual crops (Newbould 1989), but the result in Andosol agrees well with the reported worldwide average FNUE for cereal production of about 33% (Raun and Johnson 1999). The Andosols have better drainage than the Vertisols and the tef growth was more profuse at this site than at the other two sites. The mean FNUE in the Vertisols was much lower (11.5%) than on the Andosol, however it was in line with results obtained under the greenhouse conditions on the same soil type.

This differential response of tef to N fertilisation is possibly due to physical property of the soil, moisture regime and crop management practice.

Tef is sown and the fertiliser was surface applied during the wettest time of the rainy season, when the Vertisols have swelled sufficiently to close the cracks and only a small proportion of the intense rainfall enters the soil. Hence, the major portions of the rainfall flood on the surface and eventually run down the slope as surface runoff. Hence, it was obvious that the fertiliser can be washed away with runoff. This situation was common at all sites, though, the field at Kajima was well drained. Runoff was more intensive at Kajima because of the slope and runoff from upper fields as the traditional furrow opening practice to drain excess water from the field is along the slope.

A loss of N in the form of N_2O can occur during the period with high soil moisture and poor drainage, that is a common characteristic of the Vertisols. Both denitrification and nitrification result in higher N_2O fluxes when soil moisture content exceeds 70 % water filled pore space (WFPS) (Davidson et al. 1993). Weier et al. 1993 reported that total N loss due to denitrification greatly increased as soil texture becomes finer and WFPS increased.

Broadcast application of urea with no cover might have also favoured the losses of the applied N fertiliser through ammonia volatilisation (Sommer et al. 2004).

The other factor that indirectly affects the nitrogen-use efficiency of the tef crop might be the unfavourable root growth condition and the root morphology of the crop. Tef has a fibrous type of root system with fine roots and a shallow rooting depth of only 4-8 cm (Tadesse 1975). The high moisture in Vertisols obviously creates poor aeration that affects normal root development, impairs nutrient availability and uptake. In Kenyan Vertisols, lower yield was obtained on un drained plots due to unfavourable root growth condition created by high moisture content compared to the drained plots (Sigunga 1997).

A further possible explanation for the low FNUE and the low yield in farmers fields could be poor weed control. This hypothesis is partially supported by the observed higher FNUE in greenhouse experiment for similar soil type and variety.

$$\frac{\%FNUE\ in\ greenhouse}{\%FNUE\ in\ field} = 1.4$$

Rezene and Zerihun (2001) have also reported tef grain yield losses as high as 54 % countrywide and 45-55 % for the study area due to weed infestation. Better weed control at Ude1 resulted in higher FNUE compared to Ude 2 where the farmer only under took one hand weeding at a late growth stage. Although not in all areas, proper weeding time and frequency are not considered as critical as planting or harvesting calendars in tef production. Many research findings clearly indicated the importance of weed management in cereal production in the tropics (Balasubramanian 1999; Becker and Johnson 2001).

Conclusion.

The FNUE obtained in these studies was variable and low. The general trend was that N nutrition in tef production was affected by nutrient sources and soil type. Accordingly, the % NUE of urea fertiliser was higher than ammonium sulphate for all the tested varieties.

When tef was grown on Vertisol and Nitosol and ammonium sulphate was applied as N source, higher FNUE was recorded on Nitosol for all the varieties.

Safe removal of excess water from tef field, control of runoff and timely weeding can improve NUE on Vertisols. The tested varieties showed no pronounced difference in the FNUE.

There is a need for further research to identify significant factors contributing to low FNUE and developing proper management strategies to increase tef yield and NUE.

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Table 1. Some selected physico-chemical characteristics of the experimental soils.

Soil property	Holetta (Nitosol)	Ginchi (Vertisol)	Ude 1 (Vertisol)	Ude 2 (Vertisol)	Kajima (Andosol)	Seibersdorf ** (Eutrocrept)
Texture	Clay	Clay	Clay loam	Clay	Sandy loam	Clay loam
pH 1:1 (Soil:H_2O)	5.5	6.5	6.4	6.5	6.8	8.2
Total N g kg^{-1}soil	1.5	1.10	1.4	1.2	1.0	2.3
OC g kg^{-1}soil	19.5	13.1	12.5	13.2	19.1	
P mg kg^{-1}soil	7.83	9.8	4.3	3.8	41.8	176
K cmol kg^{-1} soil	1.5	3.9	1.8	1.9	2.0	1.0
Calcium (cmol kg^{-1} soil	2.6	40.3*	23.7	34.0	17.5	
Magnesium (cmol kg-^{1} soil)	7.8	9.0*	10.8	12.5	7.3	
CEC cmol kg^{-1}soil	23.6	53.4	43.1	44. 9	34.3	70.3

(* Asgelil et al. 2001;**Hood et al., 2000).

Table 2. Effect of urea and ammonium sulphate on the dry matter yield, total N uptake, percent nitrogen derived from fertilizer (% Ndff), and percent fertilizer nitrogen use efficiency (% NUE) of four tef varieties grown in a Typic Eutrocrept soil under greenhouse conditions.

Varieties	Dry matter (g pot[1])		% Ndff		Total N, (mg pot $^{-1}$)		% NUE	
	Urea	$(NH_4)_2SO_4$	*Urea*	$(NH_4)_2SO_4$	*Urea*	$(NH_4)_2SO_4$	Urea	$(NH_4)_2SO_4$
DZ-354	33.7	33.8	8.2	6.1	250	210	50.6	33.2
DZ-196	32.4	33.8	7.6	6.0	260	220	49.0	33.0
CR-37	35.4	35.8	7.9	5.9	250	240	48.9	35.7
Dabbi	33.2	34.1	7.6	5.7	240	260	44.8	36.1
mean	33.7	34.4	7.8	5.9	250	233	48.3	34.5
LSD $_{0.05}$								
N source	ns		1.0		ns		3.90	
Variety	2.5		NS		ns		ns	
Interaction	2.0		0.9		ns		5.6	
CV (%)	4.0		8.6		8.8		9.1	

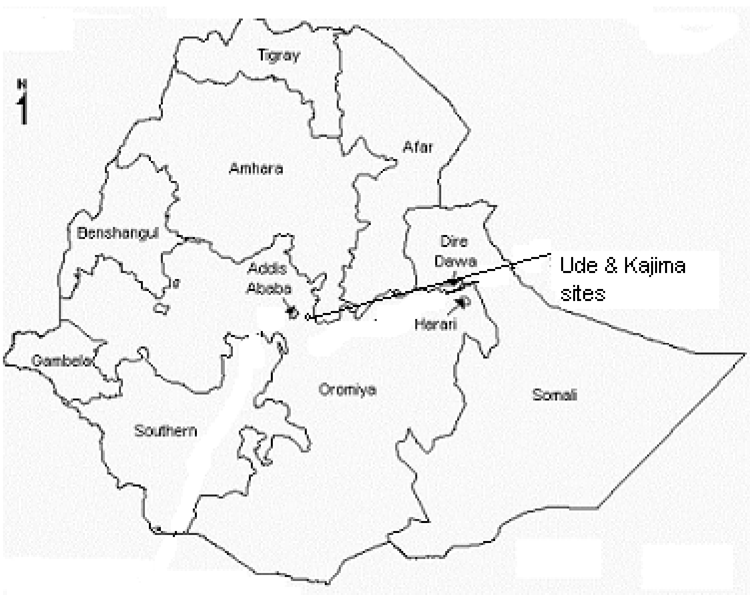
Table 3. Response of tef varieties, grown in Vertisol and Nitosol to ammonium sulphate N under greenhouse condition, Holetta Research Centre, Ethiopia.

Variety	Dry matter (g pot^{1})		% Ndff		Total N (mg pot $^{-1}$)		Fertilizer N yield (mg pot^{-1})		% N utilization efficiency	
	Vertisol	Nitosol	Vertisol	Nitosol	Vertisol	Nitosol	Vertisol	Nitosol	Vertisol	Nitosol
DZ-354	4.3	7.9	28.4	37.5	66	110	19	41	29.9	63.8
DZ-196	4.0	7.2	28.3	34.6	67	99	19	35	29.9	54.6
CR-37	4.1	7.3	29.5	34.4	67	107	20	38	30.8	59.2
Dabbi	3.4	6.7	28.4	35.9	56	121	16	43	24.2	67.7
mean	4.0	7.3	28.6	35.6	64	109	18	39	28.7	61.3
LSD $_{0.05}$										
Soil type	0.7		1.8		13.0		5.3		8.7	
Variety	Ns		2.7		Ns		Ns		Ns	
Interaction	0.1		2.7		17.8		6.0		10.0	
CV	27		13		23		15		15	

Table 4. Effect of urea fertiliser on the yield and fertiliser N use efficiency of tef grown in farmers' fields, Central Highland of Ethiopia.

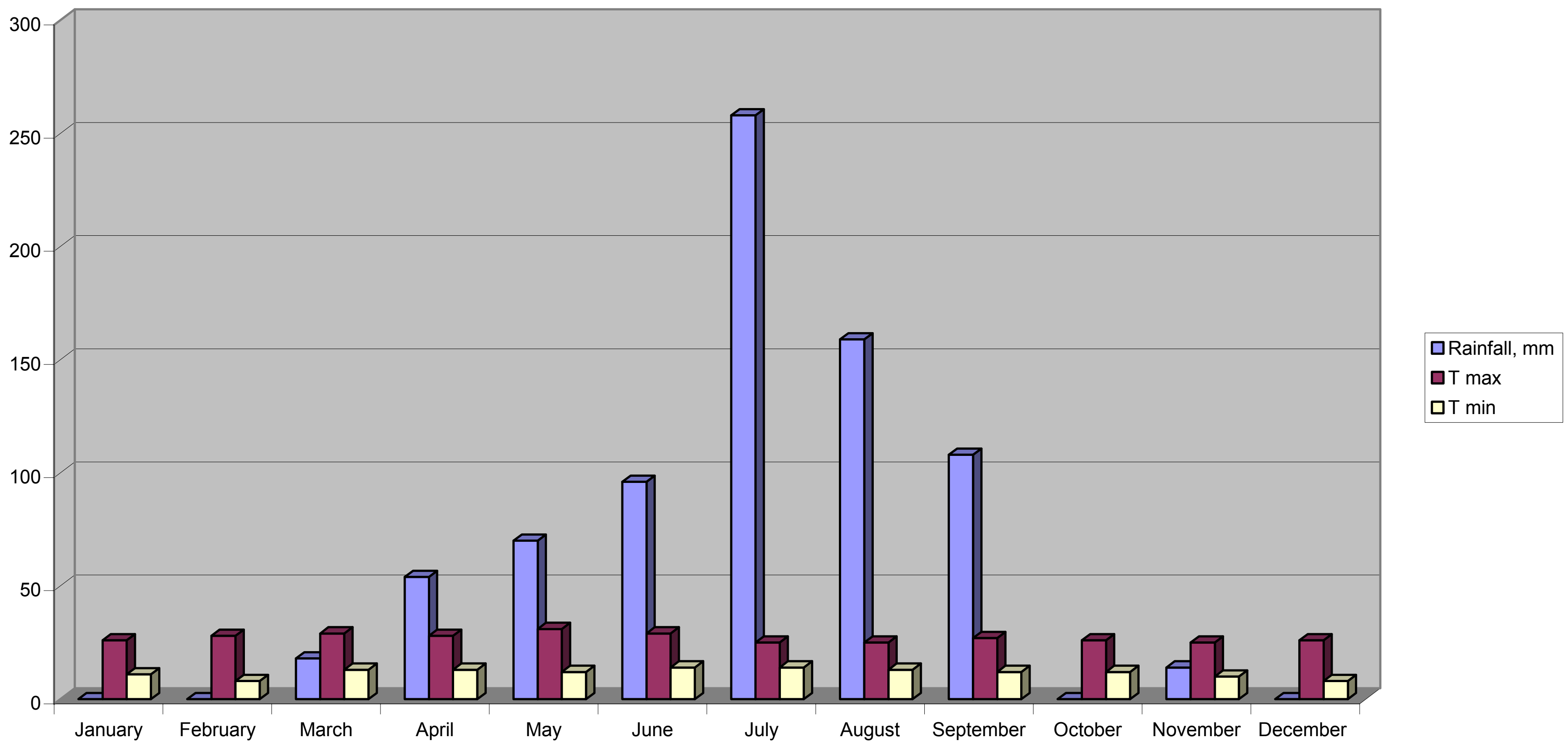
Site	Soil type	Dry matter yield kg ha $^{-1}$	Grain yield kg ha $^{-1}$	Total N yield kg ha^{-1}	%Ndff	% FNUE
Ude 1	Vertisol	6262.5	1560	103.4	15.3	26.6
Ude 2	Vertisol	3234.3	772	57.6	18.0	16.9
Kajima	Andosol	6528.3	1925	126.3	16.0	33.3
mean		5341.7	1419	95.8	16.4	25.6
LSD $_{0.05}$		3106	410	55.9	NS	13.3
CV %		33.6	17	33.7	15.3	30.4

Fig. 1 Map of Ethiopia showing the study site



Map not to scale

Figure 2. Monthly rain fall , monthly maximum and minimum temperatures in the study area in 1997



Paper 5

Agronomic, economic and cultural implications of zero/reduced tillage in Tef (*Eragrostis tef* Zucca) and Wheat (*Triticum aestivum*) production in Gare Arera, West Shawa Zone of Oromiya, Ethiopia

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Short version of the title: Implications of zero/reduced tillage.

Abstract
The soil in Ethiopia is traditionally repeatedly ploughed with an oxen drawn plough before sowing. The oxen ploughing system exposes the soil to erosion and is expensive for farmers without oxen. This study was undertaken to quantify agronomic and economic benefits and perceptions of farmers towards zero/reduced tillage. Field experiments were carried out on Vertisol and Nitosol for two years to study the effect of zero tillage, minimum tillage, conventional tillage and broad bed furrow (BBF) on the yield of tef (*Eragrostis tef* Zucca) and wheat (*Triticum aestivum*). No significant differences in tef biomass and grain yields were observed between the treatments on both soils in the first year. In the second year, zero tillage significantly reduced plant height, biomass and grain yield. No difference between single plough, conventional and BBF was observed. Grass weed population was highest on zero tillage and lowest on BBF on both soils. Total cost varied significantly between zero tillage and the other tillage systems. Pre-planting land preparation and weeding costs of tef were highest for zero tillage. Highest and lowest gross margins were obtained on BBF and zero tillage, respectively. No difference was observed in gross margin between minimum tillage and conventional tillage. In wheat, highest yields in both years were obtained on BBF treatments followed by zero tillage in 2001 and single plough in 2002. The willingness of farmers to adopt the zero tillage was low and varied with age and sex. Minimum tillage is an interesting option, particularly for female headed households as it reduces the tillage cost. It may also improve overall productivity of the farming system because it allows partial replacement of oxen with cows and reduces the soil erosion.
Keywords: cereals, Ethiopian highland, farmers' perception, minimum tillage, Nitosol, oxen plough, Vertisol.

Introduction

Soil tillage is a practice to make a fine seed bed, control weeds, loosen the soil and improve infiltration. However, ploughing also causes soil erosion by making the soil more exposed to water and wind erosion (FAO, 1998).

In the Ethiopian highlands, agriculture based on cultivation of cereal grains is thought to have occurred 7,000 or more years ago (Ehret, 1979). The traditional ard called '*maresha',* pulled by a pair of oxen, is used by smallholder peasant farmers throughout the country (Goe, 1990). Three to seven passes, each cultivation pass perpendicular to the previous one with the maresha, is required to make a plot ready for planting, depending on its prior use and the type of crop to be planted (Goe, 1990).

Intensive seedbed preparation with five to eight passes is required for tef (*Eragrostis tef* Zucca) (Fufa *et al.,* 2001). Tef is a major staple food and cash crop for the smallholder peasant farmers and is annually cultivated on about two million hectares of land: it covers 30 % of the total area of cereals and about 26% of the area cultivated to annual field crops (Hailu & Seyfu, 2001).

Tillage induced erosion due to multiple passes with the maresha, without considering difference in topography, soil type and agro climatic zone, has been regarded as the main factor of land degradation and loss of productivity in the Ethiopian highlands (Constable, 1984; Hurni & Perich, 1992). Nearly half of the total erosion amounting to 1354 million Mg per year originates from croplands. This cropland constitutes only 13% of the country's total area (Hurni 1993). According to an Ethiopian highland reclamation study, one third of the Ethiopian highlands have slopes exceeding 30% gradient, making them unsuitable for intensive cultivation (FAO, 1986). The soil erosion in the highlands is so severe that Dejene (1990) and Admasse (1995) argue that there is nowhere in the world where erosion is more destructive to the environment than in the Ethiopian highlands.

Besides runoff and erosion, the extensive utilisation of animal drawn implements has created a situation where oxen ownership is a fundamental resource for crop production. The primary reason for keeping cattle in crop producing areas of Ethiopia is for animal traction (Shiferaw, 1999). About six million oxen are used to plough close to 10 million ha of land annually (Zinash, 2000). The estimated cultivated land area per draught oxen is low, only 1.7 ha, compared to 12.9 ha for Sub Saharan Africa (Nyagumbo, 2004). Oxen tillage was probably a more feasible practice in the past when landholdings were larger and pastures more abundant (Aune *et al.,* 2001).

Tillage systems that reduce soil surface disturbance and leave residue cover on the soil surface, termed as conservation tillage, can be a solution to the problems associated with tillage-induced erosion (Fowler & Rockstorm, 2001). Therefore, a shift to conservation tillage, characterised by zero tillage and minimum tillage, might be the best approaches for reducing tillage frequency and soil erosion.

Studies in Ethiopia, Zimbabwe and elsewhere have shown that conservation tillage techniques can reduce soil loss to a large extent (Astatke *et al.,* 2003; Fowler & Rockstorm, 2001). In addition, on farm and on station experiments in different parts of Ethiopia have revealed promising results of zero and minimum tillages in wheat, maize and sorghum production (Asefa *et al.,* 2004; Sasakawa Global (SG), 2001; Astatke *et al.,* 2000). Nevertheless, information on the potential of using zero or reduced tillage in tef production is lacking, as the traditional land preparation has been a standard both on research and farmers' fields.

The objectives of this study were to assess the effects of different tillage systems on the yield and yield components of tef and wheat on Vertisol and Nitosol, its effect on farm income and the cultural implications of suggesting alternatives to the traditional land preparation method. The study is part of the research project "Combating nutrient depletion in the Ethiopian highlands".

Material and methods

The study site

The study was undertaken in Gare Arera (Dendi district ($09^0$03' N, $38^0$30' E) West Shawa Zone of Oromiya Regional State, Ethiopia. The site is located 95 km south west of Addis Ababa, on Nekemt road (Figure 1). The topography is undulating land at mid altitude (2200 m. a. s. l.).

The area has a bimodal rainfall pattern, with the main rainy season from June to September and the short rainy season *'Belg'* (vernacular name) from February to April. The annual rainfall in 2001 and 2002 was 1,011 and 1,046 mm, respectively (Weather data from Ginchi Research Centre). During the long summer monsoon the area received 68% of the rain.

The soils are Vertisols and Nitosols (Ethiopian Agricultural Research Organization (EARO), Gare Arera watershed data (unpublished). The Vertisols are relatively fertile soils and are used for growing a wide variety of crops.

Agriculture is rain-fed and can be characterised as mixed crop livestock subsistence farming. The cropping system is cereal based and tef was the most widely grown crop. Currently, the most dominant cropping rotation is characterised by three years of cereal crops followed by one year of a leguminous or oil crop.

The livestock population is comprised of cattle, sheep, goats, equines and poultry. Oxen are mainly used for ploughing and threshing, equines are used for transport and small ruminants and poultry are used for income generation (Yosef & Aster, 2002)

Field experiments

Conservation tillage (zero/reduced tillage) has not been practised previously in the area. The farmers were unwilling to participate in the experiments as partners, even though repeated negotiations were held to develop an interest. Hence, participation of the farmers was limited to provision of the experimental fields and observation of the practices.

In 2001, the experiment was carried out at two sites on two soil types (Vertisol and Nitosol), with 4 replications for each soil type on each site. The plot size was 12 m^2 for tef as well as for wheat. The experimental treatments were the same throughout except that the treatment of broad bed furrow (BBF) was included on the Nitosol in the second year. After harvesting the first year experiments, the fields were fenced to maintain the crop residue. However, the field on Nitosol was abandoned as the fence was damaged by freely roaming livestock and the crop residue was grazed. The tef and wheat fields of 2001 on Vertisol were maintained intact.

During 2002, six additional fields with plot sizes of 100 m^2 were selected for tef; three on Vertisol (black soil) and three on Nitosol (red soil). The same treatments as in the small plot experiment were included. One field was considered as a replicate.

The experiment on wheat on Vertisol was repeated on the first year field, on which the crop was residue maintained.

Table 1. Treatments and description

Tillage type	Description
Zero (No)	No oxen ploughing of the plots. During planting, the weeds and the crop residues on the soil surface were removed by uprooting with a local weeding knife.
Minimum	The plots were oxen ploughed once in mid June. During planting, crop residue on the soil surface was cleared manually.
Conventional	Four oxen ploughings were carried out corresponding to the farmers' practice.
BBF	Three oxen ploughings were done. During planting, 0.8 m wide raised seedbeds separated by 0.4 m furrow were made manually. The furrows drain excess water.

Composite soil samples from each replicate were collected from 0-20 and 20-40 cm depth before planting and at harvest.

Planting of tef

Animal trampling prior to sowing tef is the traditional method to make a fine seedbed. As foot trampling was equally common in the study area, the plots were compacted by trampling of humans and then the seed and the fertiliser were broadcasted by hand. Recommended NP fertiliser rate of 60 kg N and 26 kg P and 40 kg N and 26 kg P for Vertisols and Nitosols was applied, respectively. Planting with tef variety DZ-01-354 with a seed rate of 35 kg ha^{-1} was carried out on July 24, 2001 and from July 25-27, 2002.

Planting of wheat

The experiment was planted with wheat variety HAR- 1685 with a seed rate of 150 kg ha^{-1}. The recommended NP fertiliser (90 kg N and 40 kg P ha^{-1} on Vertisol) was hand broadcasted followed by seeding and then covered by soil. The planting dates were July 4 and 8 in 2001 and 2002, respectively.

Surface drainage ditches were dug around all the fields to control runoff water.

Weed assessment technique

Weed count data (number m^{-2}) were collected 4 and 7 weeks after sowing dates and prior to hand weeding. Four counts of 0.25 m^2 each using a quadrate were taken from each plot resulting in a total sample area of 1 m^2. Prior to uprooting the weeds, the number of grass and broad leaf weeds in the quadrate were counted and major weed species were identified.

Harvest

At crop maturity, ten plants per plot were randomly selected to record the plant height using a ruler. Plant samples were taken for moisture determination. For the determination of yield on the plots of 100 m^2, ten random harvests of 1 m^2 were made using a metal quadrant and sickle. The whole plot was harvested for the 12 m^2 plot.

The samples for biomass moisture determination were dried in an oven at 70^0 C for 24 hrs.

Threshing was done manually. The grain yield was adjusted to 12 % moisture content. After the measurement, grain and biomass were returned to the farmers.

Calculating gross margins

The profitability of the different tillage systems was assessed based on a calculation of the gross margin. The gross margin was calculated as the difference between the gross income and the variable costs incurred (Makeham & Malcolm, 1986).

The gross margin was calculated for tef based on the 100 m^2 plots during 2002.

The cost of a pair of oxen per day (including labour) in the study area was estimated at 25 Birr based on informal surveys. The mean estimate of area cultivable land by a pair of oxen per day (0.2 ha) was calculated from data collected from 135 farmers. Labour cost for other agricultural activities was estimated at 5 Birr per person per day $^{-1}$.

Labour requirements for weeding each treatment were calculated from the total time spent to uproot the weed by hand on the 100 m^2. Costs of seed, harvesting and threshing were estimated to be the same for all tillage systems. The market price of tef grain was obtained from local grain traders. The annual price in 2002 was 1.8 Birr kg^{-1}. Tef straw yield was calculated as the difference between the biomass yield and grain yield. According to the survey result, only 75 % of the total tef straw was estimated to have market value. The rest was lost during harvesting, transportation from the field to home, threshing and storage. Tef straw is sold as fodder and construction material. The price of straw was estimated at 0.43 Birr kg^{-1}. The estimation was based on informal surveys.

The value of the grain together with the value of straw constituted the gross income. Gross income = $(a \times b) + (c \times d)$, where a =tef grain yield in kg per ha, b= price per kg tef grain,

c= tef straw yield kg per ha and d= straw price per kg

Variable cost was calculated by adding fertiliser, seed, land preparation, hand weeding, harvesting and threshing costs. Gross margin was calculated by subtracting variable cost from gross income.

Statistical analysis

The data were analysed for variance using the MSTAT C computer package (Russell, D. Freed, Michigan State University, USA). Where the "F" statistics indicated significance, the means were separated using Fisher's protected Least Significance Difference test (LSD) at P = 0.05.

Soil analysis.

The soil samples were analysed at Soil and Plant Analysis laboratory, Holetta Research Centre, Ethiopia. The soil pH (1:1 H_2O) was measured by a pH meter; soil texture was measured by the pipette method (Day, 1965); organic carbon (Allison, 1960); total N (Bremmer 1965); cation exchange capacity was measured by methods described in (Chapman, 1965); and phosphorus was measured by the Bray 2 method (Bray & Kurz, 1945)

Results.

I. Soil and agronomic data

Major soil characteristics

The soil pH was more acidic in Nitosol in all of the three depths than in the Vertisol. N and OC contents were higher in Nitosol and in both soils the content decreased with the increase in soil depth (Table 2). The content of P and other exchangeable cations was higher in the Vertisol in all of the depths compared to the Nitosol.

Agronomic data

Yield

The yield differed between the treatments according to soil type and year.

On Nitosol, there was no significant effect on grain and biomass yield of tef in 2001, while in 2002 the yield of zero tillage was significantly lower than for the other treatments (Table 3). The mean harvest index (HI) in tef on Nitosol varied from 0.25- 0.32 and 0.25-0.27 in 2001 and 2002, respectively. In 2001, highest index was obtained on zero tillage.

On Vertisol, there was no biomass and grain yield difference in 2001; however, minimum tillage out yielded the other treatments. In 2002, on the large plots of $100m^2$, there were significant biomass and grain yield differences between the treatments. Highest yield was obtained on BBF, but there was no difference between minimum and conventional tillage. The yield on zero tillage treatment was significantly lower than in the other treatments.

On the field on which the previous year crop residue was maintained, the weed infestation at the time of land preparation for the 2002 experiments was high. However, the residue on the conventional and BBF treatment plots was less because of repeated ploughing beginning in May. At the early growth stages, the tef plant of the zero tillage treatment had an inferior crop stand and light green leaf colour. However, the difference diminished gradually and there was no significant yield difference between the treatments at harvest (Table 4).

The effect of soil type on the biomass and grain yields of tef was significant (Table 5) and yields were higher on Vertisol, with the exception of dry matter yield during 2002 when the yield difference was not significant.

In wheat, the highest grain and biomass yields in both years were observed in the BBF treatment (Table 6). Zero and single plough treatments gave the second highest yield in 2001 and 2002, respectively. There was significant yield difference between the two years. For all of the tillage systems the biomass and grain yields obtained in 2002 were higher than the yields of 2001, except for the biomass yield on the zero tillage.

Weed

The effect of tillage on weed infestation was most clearly observed on grass weeds as compared to broad leaf weeds. On the Nitosol, the weed count carried out in tef plots at the first hand weeding showed a significant population difference in the grass weeds (Table 7). The grass weed population on the zero tillage was highest, followed by minimum tillage. Lowest weed population was on BBF. Tillage did not significantly affect broad leaf weed population on Nitosol.

On the 100 m^2 Vertisol plots, significantly more grass and broad leaf weeds were observed on the zero tillage treatment as compared to the other treatments (Table 8). Four weeks after planting, the weed population on minimum tillage, conventional tillage and BBF treatment were 45, 69 and 61 % less than the weed population on the zero tillage treatment, respectively. No difference in weed population was observed at the time of the second weeding.

On the 12 m^2 plots, on which the crop residue was maintained, the grass weed population on the zero tillage treatment was highest during both weeding periods. There was no difference in broad leaf weed population on this field.

The weed population and composition of bread wheat were not affected by tillage.

Economic analysis (based on the 100 m^2 plots)

Clear differences were observed in gross margin of the different treatments. The gross margin decreased in the following order for the tef on Nitosols: BBF > conventional tillage > minimum tillage > zero tillage (Table 9). Zero treatment resulted in negative gross margin, indicating no economic benefit of the practice with the current components. However, the difference between BBF and conventional tillage was not significant. A similar trend of gross margin of the treatments was observed on Vertisol (Table 10), but minimum tillage gave a slightly higher return than conventional tillage. Zero tillage resulted in the lowest gross margin. This was due to the higher cost of the zero tillage treatments, particularly for pre-planting land preparation and hand weeding, compared to the other treatments. In addition, the gross income was lower due to lower yields. BBF gave highest economic return on Vertisol as the gross income was higher than the other treatments and costs were equal to the cost in the conventional tillage.

II. Stakeholders' perception of zero tillage

The first year of the study, the participation of the farmers was limited to lending their fields and to making observations, as the farmers did not have confidence in zero/reduced tillage. The comment given by elderly farmers during the group discussion in June 2001 was:

> 'If there is a technology that can alleviate our problem we would be happy. But we have never heard of planting tef on untilled soil; unless you apply something that will help the plant to grow and produce grain we don't expect it to work'.

The farmers who agreed to participate and rent out their plots for the experiment told us afterwards that they were visiting the fields every morning to see the germination. When they saw normal seed sprout on all of the plots, including the zero tillage treatment, they invited neighbours and friends to show them the germination. However, they said their friends couldn't believe them as they told them that something had been applied to the soil by the researchers. In the second year, even though the study involved more farmers, the comment at the time of planting was almost similar to the previous year. Many farmers said 'middann dagalati bitinachanni demanni', literally translated as 'scattering seed on crop residue and amid weed plant'. At a later stage, the comment from some farmers who visited the fields was:

> ''It grew and yielded well because it is the government's property; had it been ours it wouldn't even have germinated.''

Among the farmers who observed the experiments closely, some have decided to plant tef with reduced tillage in 2002. On the field day organized by the Holetta Agricultural Research Centre (HARC), the farmers who practised reduced tillage were answering several questions asked by the visiting farmers. Some farmers, particularly the young and educated ones, were convinced of the need for reduced tillage to reduce the soil erosion. What they were worried about was the weed problem. According to the farmers, weed control was the main advantage of repeated ploughing next to increased fertility.

Garitu, a woman farmer who commented on the tillage experiment in 2002, said she rented out her plot because she often found timely land preparation and planting very difficult. She said that most of the time she rented out the plot for share cropping late in the season, after exhausting all the possibilities to prepare the land and plant by herself. According to Garitu, when a farmer rented out plots for share cropping late in the crop season, the benefit was not greater than leaving the plot fallow. However, she said it gave her a better feeling than when she watched the plot being grazed by animals the whole year as she has no animals herself. According to Garitu, the plots rented out for sharecropping by women farmers were the most neglected, hence the yields were very low. The share taker can also have reasons for not keeping to the agreement. He can agree to plant tef or wheat but end up planting grass pea if he runs out of time while planting his own plots. Garitu said the possibility of planting tef with one time ploughing is an opportunity for farmers like her who do not have oxen. Ploughing is the only agricultural activity in which females do not take part in the study area.

Biyamale is another female farmer who commented on the zero or reduced tillage. She is a single parent of four children. Biyamale said ploughing was similar to any common agricultural activity, but she cannot plough due to the cultural prejudice. She has been doing all other types of agricultural activities in the house and in the forest, such as felling a tree, cutting it to the preferred size for fuel wood or construction, and carrying the wood from the upland forest to her home or directly to Ginchi town for sale. According to Biyamale, ploughing was not more difficult than any other work that women usually carry out daily. When Garitu and Biyamale were asked if they had known or heard about women farmers carrying out ploughing, they asked a question,'hindandaaama?' meaning 'is it possible?' in a sense of 'does the culture have room for allowing women to do ploughing?'

Garu is an elderly farmer and is well respected by the people in the village. When he was asked if he knew why women do not carry out oxen ploughing his response was that oxen ploughing was for males only. According to him, oxen ploughing needs energy and skill that females do not have, even if they were trained. Boys are born with that potential, as girls were born with the potential of carrying out household jobs and taking care of children. That is why only boys were trained from an early age.

Boys start learning the skill of oxen ploughing very early. In the study area, this training starts between the age of seven and nine. Gradual training is given each year until the boy is strong enough to handle the ploughing independently. This prepares the child physically, emotionally and culturally to accept the male duty of oxen ploughing. Boys can carry out oxen ploughing on their own at 12 years of age.

There are some women farmers who have questioned why women cannot carry out ploughing when small boys can and have started ploughing their plots. However, the challenge from the community is not easy.
However, other than a cultural taboo, there is no reason why women farmers cannot carry out ox ploughing when they are allowed to use hoes to do the same work.

The development workers and researchers were pessimistic at the beginning of the study. Moreover, when the first year result was highlighted in the paper presented at a conference (Aune et al., 2002), the Ethiopian scientists expressed their reservations. However, many researchers, extension personnel and non-governmental organization representatives who visited the second year experiment might have changed their outlook as several comments and suggestions were given for further study.

Discussion

The results of this study show highest yield and gross margin on BBF treatment, however the practice involves ploughing three times before making the BBFs. Use of reduced tillage with BBF can be an alternative but needs further work to validate if it is to be included in the extension practice.

Reduced tillage that involved one time plough pass with the maresha appeared to be the most promising practice in tef production as it gave comparable biomass and grain yield compared to the conventional tillage. Previous studies that compared the effect of tillage frequencies on tef yield had clearly shown the possibility of reduced tillage in tef, though grain yield increased with increasing number of ploughings (Fufa *et al.,* 2001). Tillage may increase yield because it increases mineralisation of nutrient from the soil organic matter (So *et al.,* 2001). Information from Sasakawa Global (SG) (2002) also showed the possibility of conservation tillage in tef production. The yield benefit from zero tillage/reduced tillage may be higher under real farming conditions because farmers that are not able to plough often plant late.

Reduced tillage implies less need for oxen services than conventional tillage. Reduced tillage will also allow farmers without oxen to plant their fields on time and thereby increase the yields. Rich farmers will be motivated to change the composition of livestock and decrease the number of oxen as compared to the number of cows. This will increase milk production.

In addition to yield, single ploughing will reduce soil erosion as it involves less soil disturbance compared to the other tillage systems, with the exception of zero tillage. Studies elsewhere in Africa have shown that conservation tillage techniques can reduce soil loss to sustainable levels (Kaumbutho *et al.,* 2001). Kemper & Derpsch, (1980), remarked that zero tillage has an impressive record of being the most effective means of controlling erosion degradation and improving soil quality in most soils, including tropical soils.

Wheat is sensitive to water logging and this is probably the reason why BBF treatment performed the best. In a multi location study that evaluated tolerance of different crops to water logging, wheat was found to be the least tolerant and its response to drainage has been well documented (Ephrem, 2000; Astatke *et al.,* 2003). Therefore, the crop is traditionally planted near the end of the rainy season, often resulting in water stress and frost towards maturity. Hence, the farmers in the study area have almost discontinued wheat production. During the study period wheat occupied 3% of the cropland, with a mean yield of 900 kg ha^{-1}. Use of BBF will enable the farmers to plant wheat early in the rainy season and solve the problems associated with late planting. Moreover, early planting of wheat will reduce soil erosion from the fields due to better soil cover. This has been confirmed by studies on Vertisols in Ethiopia (Astatke *et al,* 2003).

Zero and reduced tillage are promising, as early wheat harvest in BBF will give an opportunity to grow legume crops on residual moisture to increase biomass production for feed, land cover and N fixation. The study on wheat did not consider the economic benefit; however, the results from other locations confirm the viability of the system (Astatke *et al,* 2003).

In general, studies conducted in Ethiopia and elsewhere in Africa show promising results of conservation tillage on wheat (Aulakh & Gill, 1988; Asefa *et al.,* 2004; Kamwaga, 1990; Sasakawa, 2001). Results from two sites in East Shawa zone of Oromiya show no significant yield differences on Vertisols between conservation and conventional tillage (Sasakawa, 2002). In northern Zambia, the highest grain yield was obtained with zero tillage when glyphosphate was used for weed control (Aulakh & Gill, 1988).

Zero and reduced tillages are elements of conservation agriculture, but in order to develop full pledge conservation agriculture the principle of continuous soil cover must be respected (FAO, 2004). It is therefore necessary to develop cover crops that can ensure permanent cover throughout the season if conservation agriculture is to be successfully introduced in Ethiopia. Several options also exist to increase biomass production in highlands in general, and in particular in the study area. Intercropping and mixed cropping of cereals with legumes have been found very promising. Data from previous experiments in the study area reported by Kassahun and Likeylesh (2001) show that mixed cropping of wheat with clover increased residue from 2,500 to 4,550 kg ha^{-1}, having no significant effect on wheat grain yield. This system can greatly increase the quality of crop residue that could be used by farmers for the combination of forage and soil conservation applications.

In this study, farmers were unwilling to participate, as they did not believe in the practice. The farmers were still reluctant after seeing the results of the study. This was mainly due to the fact that repeated ploughing was not acknowledged as a factor for soil fertility decline that resulted in low yield, and they are unwilling to take the risk of changing tillage system. According to Nyagumbo (2004), farmer's lack of trust in conservation tillage systems was one of the constraints for its adoption in Southern and Eastern Africa.

The reason why female farmers are more interested than men in reduced tillage is probably because of the cultural taboo against women ploughing the land. Women farmers suffer more to fulfil the requirement of repeated ploughing than male farmers. Renting out their farms at a low price was preferred to cultivating, as the production costs were high.

One of the main advantages of zero tillage/reduced tillage is that it reduces the need to keep oxen for traction purpose. This opens up the possibility to replace oxen with cows and such a livestock system is likely to regenerate more income. This is perhaps the most important benefit of zero tillage/reduced tillage.

Conclusion

Minimum tillage of tef on Vertisol and Nitosol is a feasible alternative to conventional tillage because there are no differences in yield or production cost between the two treatments.

Minimum tillage with BBF can be an option for wheat on Vertisols because this technology reduces the problem with water logging.

There exists considerable cynicism about reduced tillage and BBF in the farming community. Introduction of reduced tillage and BBF is still in the introductory phase and will require a long-term commitment and a participatory approach in order to be adopted by the farmers on a large scale.

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Table 2. Major characteristics of the experimental soils in Gare Arera

Soil type	depth	pH 1:1	% N	%OC	P ppm	K mol kg $^{-1}$	Ca cmol kg $^{-1}$	Mg mol kg $^{-1}$	Clay %	Silt %	Sand %
Vertisol	0-20	5.76	0.19	2.59	3.80	0.50	22.54	8.77	55.83	25.42	18.75
	20-40	5.80	0.14	2.05	3.53	0.41	21.01	13.97	56.67	22.08	21.25
	40-60	5.71	0.15	2.09	5.40	0.41	20.39	11.80	57.92	22.50	19.58
Nitosol	0-20	4.90	0.21	3.77	1.56	0.21	10.09	4.07	48.44	37.81	13.75
	20-40	4.81	0.15	2.88	0.63	0.19	9.74	4.12	53.44	32.19	13.13
	40-60	5.29	0.14	2.20	1.59	0.18	10.00	3.97	50.31	32.19	17.50

Table 3. Effect of tillage on the biomass and grain yield of tef (kg ha^{-1}) during the 2001 and 2002 crop season on Nitosol and Vertisol at Gare Arera, central Ethiopian highlands. (The plot size during 2001 and 2002 were 12 and $100m^2$, respectively)

	Biomass				Grain			
	Nitosol		Vertisol		Nitosol		Vertisol	
Tillage type	2001	2002	2001	2002	2001	2002	2001	2002
Zero	1865[a]	3321[b]	3760[a]	2664[b]	561[a]	890[b]	1486[a]	1368[b]
Minimum	1979[a]	3221[b]	4365[a]	3038[ab]	506[a]	1151[a]	1647[a]	1520[ab]
Conventional	1885[a]	4603[a]	3990[a]	3253[ab]	470[a]	1272[a]	1424[a]	1560[ab]
BBF		4444[a]	4094[a]	3593[a]	-	1309[a]	1520[a]	1768[a]

Means with the same letter in the same column are not significantly different at 5%.

Table 4. Effect of tillage and crop residue on the yield of tef (kg ha^{-1}) during the 2002 crop season on Vertisol at Gare Arera, central Ethiopian highlands

Tillage type	Biomass	Grain
Zero	5990[a]	1855[a]
Minimum	7496[a]	2313[a]
Conventional	7630[a]	2292[a]
BBF	7758[a]	2263[a]

Means with the same letter in the same column are not significantly different at 5%.

Table 5. Mean dry matter and grain yield (kg ha^{-1}) of tef as affected by soil type.

	2001		2002	
Soil type	Dry matter	Grain	Dry matter	Grain
Nitosol	1910b	512b	3898a	1175b
Vertisol	4038a	1518a	3137a	1625a

Means with the same letter in column are not significantly different at 5%.

Table 6. Effect of tillage on the yield of bread wheat (kg ha $^{-1}$) on Vertisol, Gare Arera, central Ethiopian highlands

	Biomass		Grain	
Tillage type	2001	2002	2001	2002
Zero	2012^{b}	2810^{c}	846^{b}	1080^{c}
Minimum	1442^{c}	4143^{b}	576^{c}	1613^{b}
Conventional	1607^{b}	3429^{bc}	654^{ab}	1314^{bc}
BBF	3505^{a}	6357^{a}	1450^{a}	2571^{a}

Means with the same letter in the same column are not significantly different at 5%.

Table 7. Effect of tillage on the weed density (number sq. m^{-1}) and composition (grass and broad leaf) in tef in 2002 crop season on $100m^2$ plots on Nitosol in Gare Arera, central Ethiopian highlands

Tillage type	Grass weed		Broad leaf	
	4 wap	7 wap	4 wap	7 wap
Zero	58^{a}	40^{a}	38^{a}	17^{a}
Minimum	43^{ab}	42^{a}	36^{a}	13^{a}
Conventional	38^{ab}	33^{a}	27^{a}	18^{a}
BBF	28^{b}	27^{a}	17^{a}	14^{a}

wap = weeks after planting. Means with the same letter in the same column are not significantly different at 5%

Table 8. Effect of tillage on the weed density (number sq. m^{-1}) and composition (grass and broad leaf) in tef in 2002 crop season on Vertisol in Gare Arera, central Ethiopian highlands

	Field with 100 m^2 plot				Field with 12 m^2 plot on which 2001 crop residue retained			
	Grass weed		Broad leaf		Grass weed		Broad leaf	
Tillage type	4 wap	7 wap	4 wap	7 wap	4 wap	7 wap	4 wap	7 wap
Zero	48^a	18^a	24^a	26^a	67^a	59^a	18^a	22^a
Minimum	25^b	24^a	12^b	12^a	37^b	31^b	28^a	26^a
Conventional	24^b	10^a	13^b	15^a	21^b	31^b	24^a	26^a
BBF	17^b	34^a	13^b	26^a	26^b	24^b	21^a	17^a

Wap = weeks after planting. Means with the same letter in the same column are not significantly different at 5%

Table 9. Cost distribution, gross income and gross margin for different tillages on tef on Nitosol.

Tillage type	Oxen plowing	Fixed costs	Planting	Weeding	Total cost	Gross income	Gross margin
Zero	0	845	677[a]	972[a]	2494[a]	2386[b]	−108[c]
Minimum	125[c]	845	220[b]	614[ab]	1804[b]	2739[ab]	935[b]
Conventional	500[b]	845	137[b]	509[b]	1991[b]	3364[a]	1374[a]
BBF	375[b]	845	168[b]	475[b]	1863[b]	3367[a]	1504[a]

Birr = official Ethiopian currency; 8.64 Birr =1 US$

Table 10. Distribution of costs, gross income and gross margin for different tillage on tef on Vertisol.

Tillage type	Oxen plowing	Fixed costs	Planting	Weeding	Total cost	Gross income	Gross margin
Zero	0	944	589^{a}	825^{a}	2358^{a}	2879^{b}	520^{c}
Minimum	125^{c}	944	176^{b}	582^{ab}	1827^{b}	3225^{b}	1398^{b}
Conventional	500^{b}	944	117^{b}	471^{b}	2032^{b}	3352^{ab}	1319^{b}
BBF	375^{a}	944	125^{b}	401^{b}	1845^{b}	3770^{a}	1924^{a}

Birr= official Ethiopian currency; 8.64 Birr =1 US$

Map of Ethiopia showing the study site.