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\*Corresponding author: Mulugeta Habte Werede, Southern Agricultural Research Institute (SARI), Hawassa, Ethiopia  
E-mail: [mulerhab2006@yahoo.ca](mailto:mulerhab2006@yahoo.ca)

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## SOIL & CROP SCIENCES | RESEARCH ARTICLE

# Integrated soil fertility management for sustainable teff (*Eragrostis tef*) production in Halaba, Southern Ethiopia

Mulugeta Habte Werede<sup>1\*</sup>, Jo U. Smith<sup>2</sup> and Shiferaw Boke Ambaye<sup>1</sup>

**Abstract:** Low applications of inorganic fertilizer and decline in soil organic matter often contribute to loss of production in Sub-Saharan Africa. A trial was conducted on integrated soil fertility management of teff (*Eragrostis tef*) in Southern Ethiopia during the main cropping season of 2015. Treatments were based on recommended rates of inorganic fertilizer, applying organic fertilizer to provide the equivalent amount of N. Randomised treatments were replicated across six farms, including 100% as inorganic fertilizer, and inorganic and organic fertilizers in ratios 50:50, 67:33 and 33:67. All crop characteristics measured, except number of tillers and straw yield, showed statistically significant differences ( $p < 0.05$ ). An inorganic-to-organic fertilizer ratio of 67:33 provided highest grain yield, while lowest total variable costs were obtained with the 33:67 ratio. Highest net benefit (520(±50) US\$/ha) was obtained with the ratio 67:33, but the marginal rate of return over the 33:67 treatment was only 54 (±8)%, and so did not provide sufficient return on the extra investment for inorganic fertilizer. Therefore, 33% inorganic fertilizer to 67% organic fertilizer is more economically viable. These trials demonstrate that, in addition to reducing

### ABOUT THE AUTHOR

Mulugeta Habte is a researcher in South Agricultural Research Institute (SARI) at Hawassa agricultural research center, Ethiopia. He has conducted several research activities related to soil fertility and acid soil management. He has also an experience in collaborating research with national and international projects. He has an interest in conducting research in soil carbon.

### PUBLIC INTEREST STATEMENT

Crop production using organic fertilizer is an ancient practice in the study area, as well as in Ethiopia as a whole. This has helped to maintain soil organic matter and reduce rate of soil degradation. However, large volumes of organic fertilizers are required to meet crop nutrient demand. Furthermore, organic wastes are used for other purposes, such as household fuels, so use of organic fertilizers is declining. Inorganic fertilizers are promoted by the government to boost agricultural production and minimize food insecurity. While this can maintain yields, soil organic matter decline, and this can be damaging to the environment. We look at the potential of integrated soil fertility management to maintain crop yield while balancing the economic benefits to farmers. Integrated soil fertility management (67% organic fertilizer + 33% inorganic fertilizer) was found to be most economically viable option to farmers as well as reducing soil degradation in the long term.

long-term soil degradation, integrated soil fertility management can be an economically viable way of managing crops.

**Subjects:** Agricultural Development; Crop Science; Agriculture and Food; Agronomy

**Keywords:** Integrated soil fertility management; teff; Ethiopian soils; use of organic fertilizer

## 1. Introduction

Decline in soil fertility is the major constraint to agricultural production and food security in Ethiopian farming systems. Farmers have very limited capacity to invest in fertilizers or soil conservation measures. As a result, yields are low and many farmers are forced to put fallow and marginal lands into production to meet their food needs (Tilahun, 2004).

Kumwenda, Waddington, Snapp, Jones, and Blackie (1996) suggested that the low level of inorganic fertilizer use and declining soil organic matter (OM) levels contribute most to loss of soil fertility in Africa. Inorganic fertilizers containing nitrogen (N), phosphorus (P) and potassium (K) provide an important means to improve soil fertility. However, applications of inorganic fertilizers by many subsistence farmers in Africa are well below the rates recommended for their crops because they are too expensive for farmers to afford (Kasozi, 2005).

Organic fertilizers provide an option for supplementing inorganic fertilizer application to improve soil condition and nutrient availability. According to Rutunga, Steiner, Karanja, Gachene, and Nzabonihankuye (1998), locally available inputs such as farmyard manure, and tree and shrub biomass, may be a realistic option for improving soil fertility in Sub-Saharan Africa. In addition to providing nutrients, organic fertilizers improve the physio-chemical characteristics of the soil, potentially reducing soil erosion and improving water holding capacity, so also increasing the efficiency of nutrient use. Therefore, new farming systems have been devised based on integrated soil fertility management (ISFM), which make use of organic fertilizers, such as farmyard manure, composts, green manures and leguminous trees, integrated with inorganic fertilizer use (Vanlauwe et al., 2010).

Teff is a cereal grown primarily in Ethiopia. It originated in Ethiopia as a food crop and was distributed to other countries in the nineteenth century; it is now cultivated as a forage grass in Australia, India, Kenya and South Africa (Costanza, DeWet, & Harlan, 1979). Teff flour is mainly used to make *injera*, a spongy fermented flatbread that serves as a staple food for millions of people in Ethiopia. It is an important source of nutrition, containing 339 calories, 11.1 g protein, 2.4 g fat, 73.6 g carbohydrate, 3.0 g fibre, 156 mg calcium, 366 mg P and 18.9 mg iron per 100 g of white teff, and is also an excellent source of amino acids (Ågren & Gibson, 1968). However, its shallow rooting structure makes it highly susceptible to drought.

Previous work on ISFM has suggested that integrated use of inorganic and organic fertilizers can increase crop yields. A five-year study conducted in the central highlands of Ethiopia found consistently higher yields for treatments that combine half dose of inorganic fertilizer and half dose of organic fertilizer compared to full dose of inorganic or organic fertilizer alone (Workineh et al. 2012). By contrast, in a two-year study on wheat and teff in the highland Nitisol area of Ethiopia, Agegnehu., Vanbeek, and Bird (2014) observed that yields were maintained, but not significantly increased, when 50% of the inorganic fertilizer application was replaced by an N equivalent rate of organic fertilizer. Organic matter enhances soil structure and increases capacity to retain water (Zia, Rahmatullah, & Salim, 1998), so using organic fertilizers within an ISFM system has great potential to reduce water stress. The differences in results observed may be due to differences in the soils and environments selected for the trials. The trials presented here were conducted on teff in a moisture-stressed

area of Ethiopia, where water retention is aggravated by sandy soil with a low capacity to retain water. This work provides evidence for the potential impact of ISFM on the yields of this important crop in Ethiopia.

## 2. Materials and methods

### 2.1. The study site

An ISFM trial was conducted with teff in Halaba Special Woreda (district) of the Southern Nations, Nationalities and Peoples Regional State (SNNPRS) in the main cropping season of 2015. The experimental site was located between 07.35566 N latitude and 038.05105 E longitude at an altitude of 1850 m above sea level. Between 1996 and 2015, the area received an average 83 annual rainfall of 946 mm. The mean values for maximum and minimum annual air temperatures were 28.4°C and 14.2°C, respectively (Figure 1). The soils vary from sandy loam to sandy silt loam in texture, the area being dominated by sandy silt loam. The chemical properties of soils in the study area are given in Table 1.

### 2.2. Organic fertilizer

Organic fertilizer was prepared from locally available materials (tree leaves, grasses, maize residues, cow dung—proportions unknown). The organic fertilizer was stored for 4 months in a pit and protected from rain and direct sunlight using a plastic sheet. The organic fertilizer was analysed for total N by the micro-Kjeldahl digestion, distillation and titration method (Jackson, 1958). This allowed the treatment rate to be calculated based on the N content (0.98% by weight) of the organic fertilizer. It was assumed that P was not limiting crop growth, so no account was taken of the P present in the organic fertilizer.

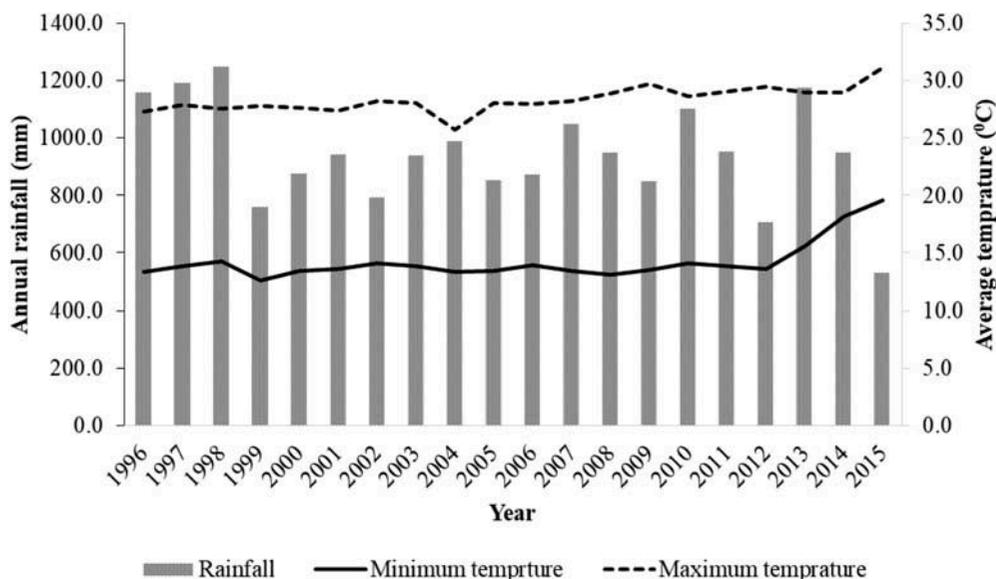
### 2.3. Treatments

The experiment consists of four treatments as shown in Table 2.

### 2.4. Experimental layout

The experiment was laid out using three replicates of each treatment in a randomized complete block design using 4 m by 4 m plot size and replicated across six farms (2 locations × 3 adjacent farms). To avoid cross-contamination of treatments, the plots were separated by 1 m and there was a 1.5 m space between blocks. To protect from cross-contamination by surface erosion, ridges were constructed along each block. Seven days before planting, organic fertilizer was uniformly

Figure 1. Total annual rainfall of Halaba from 1996 to 2015.



**Table 1. Chemical properties of soils of the study area (standard errors are given in brackets)**

Parameter	Average
NO <sub>3</sub> <sup>-</sup> (ppm)	11 (1.2)
Al (ppm)	11 (0.8)
Cation exchange capacity (meq. per 100 g)	15 (0.7)
pH	6.6 (0.1)
Organic matter (% by weight)	2.4 (0.2)
Na (ppm)	50 (6)
K (ppm)	600 (51)
P (ppm)	11 (1.1)
S (ppm)	1.4 (0.3)
Zn (ppm)	6 (0.6)
Fe (ppm)	150 (9)
Mo (ppm)	8.9 (0.2)
Cu (ppm)	1.5 (0.09)
B (ppm)	0.76 (0.05)
Mn (ppm)	200 (21)
Mg (ppm)	180 (8)
Ca (ppm)	2000 (150)
Total C (%)	1.4 (0.1)

**Table 2. Treatments used in the trial**

Treatment	Description
1. 100% recommended N and P in inorganic fertilizer	69 kg/ha N + 30 kg/ha P as inorganic fertilizer
2. 50% recommended N and P in inorganic fertilizer plus 50% recommended N in organic fertilizer	34.5 kg/ha N + 15 kg/ha P as inorganic fertilizer + 50% organic fertilizer based on N equivalence (3.52 t ha <sup>-1</sup> )
3. 67% recommended N and P in inorganic fertilizer plus 33% recommended N in organic fertilizer	46 kg/ha N + 20 kg/ha P as inorganic fertilizer + 33% organic fertilizer based on N equivalence (2.32 t/ha)
4. 33% recommended N and P in inorganic fertilizer plus 67% recommended N in organic fertilizer	23 kg/ha N + 10 kg/ha P as inorganic fertilizer + 67% organic fertilizer based on N equivalence (4.72 t/ha)

spread on each plot and incorporated into the soil manually using a hand hoe. Diammonium phosphate (DAP) was applied at planting time and urea was top-dressed 45 days after planting. The test crop was planted in rows, 0.2 m apart with a seed rate of 15 kg/ha; other crop management practices (ploughing, weeding) were used as recommended for the crop. Note that the rainfall in 2015 was lower than average; only 528 mm.

### 2.5. Agronomic analysis

Agronomic data for teff, including tiller number, plant height, straw yield, total biomass and grain yield, were collected. To estimate the biological yield and the grain yield, the whole plot (16 m<sup>2</sup>) was harvested and threshed manually. Analysis of variance for all data was done using Statistix10 analytical software. The least significant difference at 5% probability level was used to establish the significance of differences between the means.

### 2.6. Economic analysis

An economic analysis was used to investigate the economic feasibility of the ISFM technology for teff production. The partial budget, dominance and marginal rate of return were calculated.

The partial budget was calculated using an average yield that was adjusted downwards by 10%, because we assumed that farmers would get ~10% less yield than is achieved on an experimental site. The average open market price for teff (18 Ethiopian Birr (ETB) per kg or 0.81 US\$/kg) and the official prices for N (urea) and P (DAP) were used for the analysis (urea-N: 0.54/0.47 = 1.15 US\$/kg, DAP-P: 0.67/0.24 = 2.79 US\$/kg). The total variable costs were calculated from the cost of urea-N and DAP-N applied. The cost of organic fertilizer was not included because organic fertilizer is usually produced from waste materials on the farm, and there is a limited market to sell organic fertilizer. A dominance analysis was used to indicate the most economically viable options. This was done by arranging the treatments according to increasing total variable costs. The net benefit for each treatment was calculated by subtracting the total variable costs from the revenue provided by the crop. If the net benefit of a treatment was less than that of a treatment with lower total variable costs, then the treatment was considered to be dominated, and the treatment with the higher total variable costs and lower net benefit was rejected. For a treatment to be considered a worthwhile option for farmers, the minimum acceptable marginal rate of return (i.e. the gain achieved by a treatment using higher investment over one with a lower investment, expressed as a percentage of the difference in the investment cost) should be over 50% (CIMMYT, 1988). However, working in Ethiopia, Gorfu, Taa, Tanner, and Mwangi (1991) suggested a minimum acceptable rate of return should be 100%. Therefore, the minimum acceptable marginal rate of return is assumed to be 100% in this study.

### 3. Result and discussion

#### 3.1. Yield and yield components

The average yield of teff in the experimental year was lower than in a typical year due to moisture stress. The Halaba area received significantly lower than average annual rainfall in 2015 (Figure 1) and most annual crops were affected.

A statistically significant difference was observed between treatments for all yield components except for tiller number and straw yield (Table 3). Application of 67% recommended N and P as inorganic fertilizer plus 33% recommended N in organic fertilizer (treatment 3) provided the highest grain yield, while the lowest yield was recorded from plots treated with 50% recommended N and P as inorganic fertilizer plus 50% recommended N in organic fertilizer (treatment

**Table 3. Yield and yield components of teff in integrated soil fertility management trials at Halaba**

Treatments	Plant height (cm)	No of tiller	Straw yield (t/ha)	Biomass (t/ha)	Grain yield (kg/ha)
1 100% recommended N and P in inorganic fertilizer	67(1.3) <sup>ab</sup>	4.7(0.2)	3.0(0.2)	3.8(0.3) <sup>a</sup>	800(73) <sup>a</sup>
2.50% recommended N and P in inorganic fertilizer plus 50% recommended N in organic fertilizer	61(3.4) <sup>b</sup>	4.9(0.4)	2.3(0.3)	3.2(0.4) <sup>b</sup>	700(110) <sup>b</sup>
3. 67% recommended N and P in inorganic fertilizer plus 33% recommended N in organic fertilizer	68(2.4) <sup>a</sup>	5.0(0.4)	2.9(0.1)	3.8(0.1) <sup>a</sup>	900(70) <sup>a</sup>
4. 33% recommended N and P in inorganic fertilizer plus 67% recommended N in organic fertilizer	68(3.5) <sup>a</sup>	5.0(0.3)	2.8(0.1)	3.6(0.2) <sup>ab</sup>	800(60) <sup>ab</sup>
Least significant difference coefficient of variation	6.2	NS	NS	0.56	170
	7.6	9.6	17.6	13.0	18

Note: Values followed by the same letter are not significantly different at  $p < 0.05$ . Standard errors are given in brackets.

**Table 4. Economic (partial budget and dominance) analysis of integrated soil fertility management trials on teff at Halaba**

Treatment	Organic fertilizer N equivalent (kg/ha)	N (kg/ha)	P (kg/ha)	Ave. grain yield (kg/ha)	Adj. grain yield (kg/ha)	TVC (US \$/ha)	Revenue (US\$/ha)	NB (US \$/ha)	
T4	46	23	10	800(60)	700(54)	55	570(40)	510(40)	
T2	34.5	34.5	15	700(110)	600(99)	83	500(80)	400(80)	R
T3	23	46	20	900(70)	800(63)	111	650(50)	540(50)	
T1	0	69	30	800(60)	700(54)	165	570(40)	400(40)	R

Yield adjustment = 10%, field price of teff = 0.81 US\$/kg (1 US\$ = 22.22 Ethiopian Birr), official price for urea-N = 1.15 US\$/kg, and P as diammonium phosphate = 2.79 US\$/kg, TVC = total variable costs (calculated from applied fertilizer only), NB = net benefit, R indicates dominated treatments that are rejected, standard errors are given in brackets (error in rate of fertilizer application is unknown, so no error term given for total variable costs). Revenue is calculated from grain yield only as there is no significant difference in the yield of straw between treatments.

2). The yield advantage was 29% in treatment 3 compared to treatment 2. Similar differences were observed in the total biomass, which is the other economically valuable component of teff, teff straw being widely used for animal feed and house construction in rural as well as urban areas.

These findings are consistent with yield improvements observed in ISFM studies on other crops. When inorganic and organic fertilizers were applied in combination to maize by Singinga and Woome (2009), a strong positive yield response was observed, equivalent to twice that achieved using inorganic fertilizers alone. Similarly, over a five-year study on Humic Andosols in the central highlands of Ethiopia, Workineh et al. (2012) observed consistently higher yields for treatments that combined a half dose of fertilizer and a half dose of organic fertilizer compared to the full dose of inorganic or organic fertilizer alone. The response of the crop to replacing N inputs with organic sources is dependent on the factors limiting crop growth. Because a portion of the N in the organic fertilizer is held in organic compounds that are inaccessible to the crop without release by mineralization, for an N limited crop, some yield decline might be expected when inorganic N fertilizer is replaced by an organic source. However, other factors, such as water and other macro- and micro-nutrients can also limit crop growth, and the limitation due to these factors may be reduced by the application of an organic fertilizer, which provides a range of nutrients and can significantly increase the water holding capacity of the soil (e.g. Tilahun, Nigussie, Wondimu, & Setegn, 2013).

The current experiment was conducted in a year with significantly reduced rainfall compared to normal years, so crop yields are likely to be limited by water availability. Treatment 5 (application of 67% recommended N and P as inorganic fertilizer plus 33% recommended N in organic fertilizer) provided reduction in the growth limiting factors other than N (water and possibly other nutrients), whereas reducing recommended N applied as inorganic fertilizer to 50% in treatment 2 resulted in the yield being limited by the available N. The factors limiting crop growth are highly site- and crop-specific, which explains the differences in crop responses observed by other authors. In future work, it will be important to develop simple methods to accurately determine which factors are limiting crop growth at a particular site, so allowing the proportions of inorganic and organic fertilizers to be tailored to different conditions and crops.

### 3.2. Economic analysis

As shown in Table 4, treatment 4 (33% recommended N and P in inorganic fertilizer plus 67% recommended N in organic fertilizer) had the lowest total variable costs and higher net benefits than the treatment with the next lowest total variable costs, treatment 2 (50% recommended N and P in inorganic fertilizer plus 50% recommended N in organic fertilizer). Therefore, treatment 4 was the preferred option compared to treatment 2. Treatment 3 (67% recommended N and P in inorganic

fertilizer plus 33% recommended N in organic fertilizer) had higher total variable costs than treatment 4, but also had higher net benefits. Therefore, treatment 3 was also a potential option. Treatment 1 (100% recommended N and P in inorganic fertilizer) had higher total variable costs than treatment 3, as well as lower net benefits. Therefore, treatment 3 was the preferred option compared to treatment 1 (100% recommended N and P in inorganic fertilizer). Therefore, treatments 1 and 2 were eliminated from further economic analysis and only the dominant treatments, 4 and 3, were considered further in the partial budget analysis (Table 5). The dominance analysis indicates that, in addition to improving yield and soil condition, ISFM is more affordable than using inorganic fertilizers alone (Table 4).

According to the partial budget analysis (Table 5), the treatment with the higher net benefit (the difference between revenue and the total variable cost) was treatment 3 (540(± 50) US\$/ha (12,000 (±1000) ETB/ha) compared to treatment 4, which gave a net benefit of only 510(±40) US\$/ha (11,000 (±1000) ETB/ha). However, the marginal rate of return for treatment 3 over treatment 4 was only 54 (±8)%. This means that for each 1 ETB investment in teff production, the producer can get only 0.54 (± 0.08) ETB better return using treatment 3 than using treatment 4. Since the minimum acceptable rate of return assumed in this experiment was 100%, treatment 3, requiring application of 67% of the recommended rate of inorganic fertilizer, does not give an acceptable marginal rate of return for the extra investment, compared to treatment 4, which uses only 33% or the recommended rate of inorganic fertilizer. Therefore, treatment 4 (33% recommended N and P in inorganic fertilizer plus 67% recommended N in organic fertilizer) was accepted as the preferred option.

#### 4. Conclusions

Integrated soil fertility management is a potential option for improving the physiochemical and biological characteristics of the soil and improving the sustainability of farming. This study showed that increased teff yield with reduced total cost of production could be obtained using ISFM compared to using inorganic fertilizers alone. The highest net benefit was obtained applying 67% of the recommended rates of N and P as inorganic fertilizer and 33% as organic fertilizer based on N equivalence. However, the marginal rate of return was too low to justify the additional investment needed for the inorganic fertilizer, so the treatment using 33% inorganic fertilizer and 67% organic fertilizer (23 kg/ha urea-N, 10 kg/ha DAP-P plus 46 kg/ha organic fertilizer N equivalent) is instead recommended as the best option for

**Table 5. Economic (partial budget and marginal rate of return) analysis of integrated soil fertility management trials on teff at Halaba**

Treatment	Average grain yield (kg/ha)	Adjusted grain yield (kg/ha)	TVC (US \$/ha)	Revenue (US\$/ha)	NB (US \$/ha)	MRR (%)
4. 33% recommended N and P in inorganic fertilizer plus 67% recommended N in organic fertilizer	800(60)	700(54)	55	570(40)	510(40)	
3. 67% recommended N and P in inorganic fertilizer plus 33% recommended N in organic fertilizer	900(70)	800(63)	111	650(50)	540(50)	54(8)

Yield adjustment = 10%, field price of teff = 0.81 US\$/kg (1 US\$ = 22.22 Ethiopian Birr), official price for urea-N = 1.15 US\$/kg, and P as diammonium phosphate = 2.79 US\$/kg, TVC = total variable costs (calculated from applied fertilizer only), NB = net benefit, standard errors are given in brackets (error in rate of fertilizer application is unknown so no error term given for total variable costs), revenue is calculated from grain yield only as there is no significant difference in the yield of straw between treatments, MRR = marginal rate of return of treatment 3 compared to treatment 4.

teff producers around Halaba. Importantly, these trials demonstrate that, in addition to increasing the inputs of OM to the soil, and so reducing long-term soil degradation, ISFM can be an economically viable way of managing crops that also provide better economic gain to the farmer in the short term.

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#### Author details

Mulugeta Habte Werede<sup>1</sup>  
E-mail: [mulerhab2006@yahoo.co](mailto:mulerhab2006@yahoo.co)  
Jo U. Smith<sup>2</sup>  
E-mail: [jo.smith@abdn.ac.uk](mailto:jo.smith@abdn.ac.uk)  
Shiferaw Boke Ambaye<sup>1</sup>  
E-mail: [abboshiferaw@gmail.com](mailto:abboshiferaw@gmail.com)

<sup>1</sup> Natural Resource Research Directorate, Southern Agricultural Research Institute (SARI), Hawassa, Ethiopia.

<sup>2</sup> School of Biological Science, University of Aberdeen, 23 St Machar Drive, Aberdeen AB24 3UU, UK.

#### Competing interests

The authors declare no competing interests.

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