



Research article

Establishment and validation of site specific fertilizer recommendation for increased barley (*Hordeum spp.*) yield, northern EthiopiaShimbahri Mesfin^{a,b,*}, Mitiku Haile^a, Girmay Gebresamuel^a, Amanuel Zenebe^{a,b}, Abera Gebre^c^a Land Resource Management and Environmental Protection, Mekelle University, Mekelle, Ethiopia^b Institute of Climate and Society, Mekelle University, Mekelle, Ethiopia^c Soil Resource and Watershed Management, Aksum University, Shire, Ethiopia

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ABSTRACT

Establishing model based balanced nutrient requirements for barley (*Hordeum spp.*) in the northern Ethiopia can solve the fertilizer recommendation problems and enhance crop yield. The Quantitative Evaluation of Fertility of Tropical Soils (QUEFTS) model was used to estimate balanced nitrogen (N), phosphorus (P) and potassium (K) requirements for barley production in Alaje, northern Ethiopia. The objectives were to (i) quantify soil N, P and K supply and recommend fertilizers using QUEFTS model; (ii) investigate response of QUEFTS fertilizer application on yield and nutrient uptake and (iii) validate QUEFTS model performance. The experiment had four treatments: (T1) model based fertilization; (T2) blended fertilization; (T3) farmers' fertilization practices and (T4) control/no fertilizer. Soil information of the experimental plots were analyzed and used as model input to estimate soil nutrient supplies and recommend fertilizer. Yield and agronomic data were recorded and nutrient uptake and use efficiencies were analyzed. Model performance and accuracy were also checked using root mean square error, coefficient of determination, index of agreement and percent bias. The result revealed that the N, P and K soil supply ratio in the field experimental plots were 9:1:6. The higher grain yield of 4747 kg ha⁻¹ was recorded in the QUEFTS based fertilization plots. Validation results indicated that there is a good correlation between the QUEFTS predicted and observed grain yields implying that the QUEFTS model can be a base for development of simple and cost-effective decision support tools for nutrient management and fertilizer recommendations. Thus, the model performance and prediction accuracy is promising and can help farmers to adjust fertilizer application rates based on crop requirements.

1. Introduction

The need for food security, along with the decreasing arable land resources will generate great pressure on crop production in the future (Sattari et al., 2014). This food gap is common in sub-Saharan Africa (SSA) countries. One of the causes for low crop production is inappropriate soil fertility managements (Rahman and Zhang, 2018; Xu et al., 2014). To solve this soil fertility problem, farmers have been using fertilizers; however, the high costs of fertilizers and farmers' limited financial resources resulted in reduced fertilizer application (Wairegi and van Asten, 2010). Moreover, the fertilizer recommendation did not consider existing soil nutrient supply and resulted in low crop yield response in the region (Masvaya et al., 2010). Ethiopia used different strategies and policies to solve the soil fertility management problems and in order to enhance agricultural production (Belete et al., 2018).

However, the population growth, low economy of farmers and inappropriate fertilizer recommendations limit future agriculture production development (Mesfin et al., 2020a, 2020b). Farmers in the study area continuously cultivate crops with very limited nutrient replacement which often results in low crop yields (Agegnehu and Bird, 2014; Mengistu and Abera, 2014). The management of organic materials such as crop residue and manure in the farming systems are also constrained due to removal of crop residues for animal feed and low applications of manure because local farmers use cow dung for fuel (Mesfin et al., 2018a, 2018b, 2019, 2020c; Lema et al., 2016, 2019; Gebremedhin et al., 2017; Lemma et al., 2017; Tadesse et al., 2016).

To meet these challenges, farmers have been using inorganic fertilizers. However, the fertilizer recommendations in the previous two decades was similar for all soil and crop types (Agegnehu and Bird, 2014). To improve this blanket fertilizer recommendation, Ethiopian soil

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information system (EthioSIS) program has been established to study the soil and developed soil fertility map which show the existing soil fertility status (ATA, 2014). Based on this study, Nitrogen Phosphorus, Sulfur, Zinc and Boron (NPSZnB) containing fertilizer in a blended form was introduced into the study site but the blended fertilizer recommendation was not site specific. Moreover, farmers have been applied fertilizers based on their own rate which they consider is sufficient based on their resources. Thus, the previous blanket recommendation (application of diammonium phosphate and urea to all soils and crops) and the current blended fertilizer recommendation did not address existing soil fertility problem and farmers' capacity to afford costs of fertilizer.

Therefore, developing site specific fertilizer recommendations that consider existing soil nutrient supply and recommend fertilizer based on crop nutrient demand to achieve target yield is required. The Quantitative Evaluation of Fertility of Tropical Soils (QUEFTS) model based fertilizer application is very limited in Ethiopia and has the potential to estimate soil N, P and K supply on the basis of soil laboratory data, predict yield and recommend N, P and K containing fertilizers to achieve target yields (Yang et al., 2017; Dai et al., 2015; Setiyono et al., 2010). Soil nutrient differences in farmers' fields due to different managements as a result of farmers' wealth variations and soil parent materials may require different fertilizer rates to achieve target yield. Therefore, it is hypothesized that the model based fertilizer recommendation can fill the fertilizer recommendation gap in northern Ethiopia and will contribute to increased crop yield. In this study, we used soil and field experiment data on barley (*Hordeum spp.*) in northern Ethiopia to adjust QUEFTS model based fertilizer recommendation and achieve target yield. Therefore, the objectives were to (i) quantify soil Nitrogen (N), Phosphorus (P) and Potassium (K) supply and recommend fertilizers using QUEFTS; (ii) investigate response of QUEFTS fertilizer application on yield and nutrient uptake and (iii) validate QUEFTS model performance.

2. Methodology

2.1. Study area description

The study was conducted in Alaje found at 39°25'52" to 39°44'50" E and 12°15'28" to 12°59'21"N in the northern highlands of Ethiopia (Figure 1). Alaje has an elevation of 2824 m a.s.l. and it was selected purposively because it is potential area for barley.

The annual rainfall of the experimental areas during 2017 and 2018 cropping seasons were 417 and 479 mm, respectively with daily minimum and maximum temperature of 8 and 26 °C during 2017 cropping season and 8 and 27 °C during 2018 cropping season, respectively (Mesfin et al., 2020a, Figure 2).

In the study area trap volcanic rocks are common parent materials, having mainly a basalt lithology, on which Cambisols, Regosols, Leptosols and Vertisols have been developed (CASCAPE, 2015). The study area has a cold sub-moist highland agro-ecology with mixed farming system in which livestock is integrated with cropping system (van Beek et al., 2016). Livestock and crop production are complementary in which livestock are important for nutrient recycling through providing manure which is important for soil fertility and crop yield improvement. Livestock are used for farmland management such as plowing and traction while crop production provides residues for animal feed. The dominant crops in Alaje are barley (*Hordeum spp.*), wheat (*Triticum spp.*), faba bean (*Vicia spp.*) and field pea (*Pisum spp.*). Thus barley was selected for QUEFTS model validation. This field experiment was conducted on 6 farmers' fields for model validation in the rain-fed agriculture for two consecutive cropping seasons (2017 and 2018). The cropping seasons were extended from July to October.

2.2. Model description and experiment set up

The Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) model initially developed by Janssen et al. (1990) is one of the important tools to derive site-specific fertilizer recommendations tailored to the target yield (Wairegi and van Asten, 2010; Tittone et al., 2008). Apart from water supply and temperature, QUEFTS model assumes that crop yield is mainly a function of N, P and K nutrients derived from soil supply and mineral fertilizer. The QUEFTS model predicts on the basis of assumed relationships between grain yield and nutrient supply from the soil and applied fertilizer, and further used to evaluate relationships between grain yield and nutrient uptake. Intensive soil samples were collected by Capacity Building for Scaling up of Evidence Based Best Practices in Ethiopia (CASCAPE) project from the study area to calibrate QUEFT model for soil fertilizer recommendation (CASCAPE, 2015). The sampling sites followed the on-farm demonstration and trial sites being implemented by the CASCAPE project in the area. The main purpose of

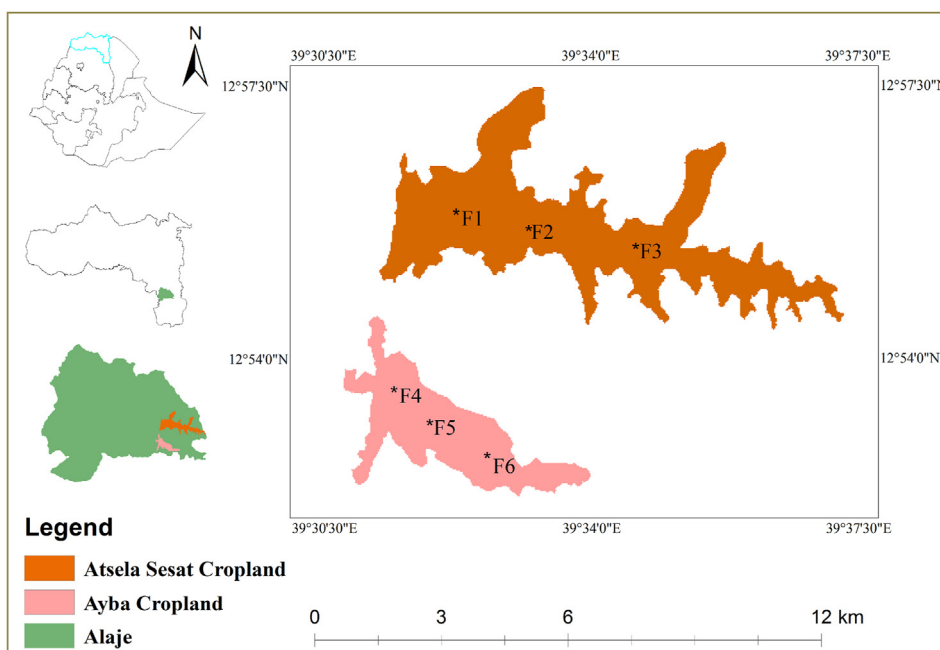


Figure 1. Location maps of the study area with six farms located in the croplands, where F is experimental farmland.

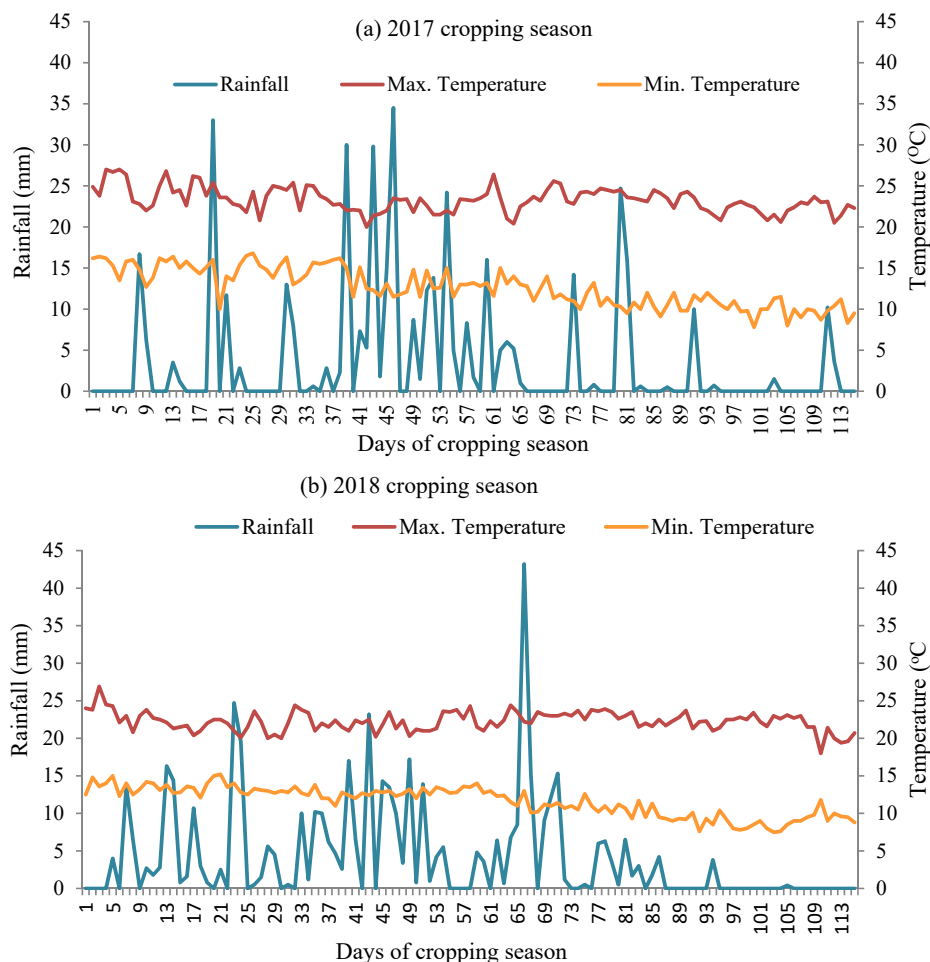


Figure 2. Daily rainfall and temperature at Alaje, during July to mid-October of (a) 2017 cropping season and (b) 2018 cropping season in northern Ethiopia (Mesfin et al., 2020a).

this sampling was to generate data for QUEFT model calibration. Accordingly, the model was calibrated in the study area.

Soil samples were collected by auger at the depth of 0–20 cm prior to sowing from 6 experimental plots during both seasons. These soil samples were air dried, crushed, and sieved by a 2-mm sieve and preserved for analysis. Soil properties were analyzed using different soil analysis standards; soil organic carbon (SOC) using Walkley and Black method (Walkley and Black, 1934), total nitrogen (TN) using Kjeldahl method (Bremner and Mulvaney, 1982) and available phosphorous (Av.P) using Olsen method (Olsen et al., 1954), exchangeable potassium (Exc. K) using ammonium acetate method (Jackson, 1958), EC using an EC meter in 1:2.5 soil-water ratio and soil pH using a pH meter in 1:2.5 soil-water ratio (Peech, 1965). Soil organic carbon (C_{org} g kg^{-1} soil), total nitrogen (N total, g N kg^{-1} soil), P-Olsen (P-Olsen, mg P kg^{-1} soil), exch. K (K exch. mmol K kg^{-1} soil), EC and pH-H₂O of the soil were used as QUEFTS model input. These soil data were fed into the QUEFTS tool box to estimate soil N, P and K supplies. Finally, the model estimated soil N, P and K nutrient supplies and predicted yield based on soil nutrient supplies and recommend fertilizer to achieve target yield of 4000 kg ha^{-1} .

In order to analyses and map the important soil nutrient contents (N, P and K), 45 and 16 composite soil samples were collected from Atsela Sesat and Ayba croplands with a support of GPS points at 20 cm soil depth. Total nitrogen (TN) was analyzed using Kjeldahl method (Bremner and Mulvaney, 1982), available phosphorous (Av.P) using Olsen method (Olsen et al., 1954) and exchangeable potassium (Exc. K) using ammonium acetate method (Jackson, 1958). Ordinary kriging, one of the geo-statistical interpolation techniques, was used to analyze spatial

distribution of soil organic carbon using the spatial analyst tools of the ArcGIS 10.2 software (Poshtmasari et al., 2012). The semi-variogram model obtained from the semi-variance analysis was used to estimate observations in the un-sampled locations within the study areal. Finally, soil N, P and K content maps of the cropland soils were developed using Arc GIS software.

2.3. Experimental design and crop management

Model validation experiment was conducted in 6 smallholder farms. These farmlands are in two sites (three of them are in Atsela Sesat and the rest three are in Ayba site). These selected farmlands have similar cropping history such as similar previous cropping practice; no manure is applied to the farmlands, equally ploughed using oxen. Moreover, the soil type of these experimental plots is Cambisol with similar farm managements in respect to plowing, weeding and harvesting during both study seasons. The model validation trials had four treatments: (i) QUEFTS model based N (145 kg N ha^{-1}), P (60 kg P ha^{-1}) and K (50 kg K ha^{-1}) fertilizer application, (ii) blended fertilizer application (100 kg of NPSZnB per hectare or 17.7N, 35.3P2O₅, 7.6S, 2.2Zn, 0.25B), (iii) farmers' fertilizer application practices (75 kg of NPSZnB or 17.7N, 35.3P2O₅, 7.6S, 2.2Zn, 0.25B) and (iv) control (without any fertilizer). The experiment was arranged in a randomized complete block design (RCBD) with four treatments and three replicates. A plot size of 3 m by 3 m was prepared manually with 1 m between blocks and 0.5 m between experimental plots. The N, P and K containing fertilizers were urea, triple super phosphate and potassium chloride, respectively. Triple super

phosphate, potassium chloride and blended fertilizers were broadcast applied during planting at the beginning of July while urea was applied by split (one third of it is applied during sowing and the rest two third after thirty days of sowing date). Barley was planted on the first week of July of both 2017 and 2018 cropping seasons. During the growing period, all plots had received adequate soil moisture through rainfall, no heat stress and weeds were removed manually and harvested using sickles in early October of both 2017 and 2018 cropping seasons.

2.4. Data collection

Five plants from each plot were randomly selected from the middle rows of the plots for recording plant height, effective tiller, spike length and number of seeds per spike at plant maturity. A quadrat (1 m by 1 m) sample from middle part of each treatment was collected to determine grain and biomass yield. Crop was harvested manually using sickle and bundles of biomass yield were dried for 3 days to determine dry biomass while grains were weighted after threshed and winnowed and mass of 1000 were weighed for each plot. Representative grain and straw samples were taken to laboratory to analyze plant N, P and K contents. N was analyzed using a Kjeldahl method while the ground plant tissues were wet digested to determine P and K using flame photometry. Concentrations of N, P and K in both grain and straw were analyzed (Chuan et al., 2013). The N, P and K nutrient uptake of each treatment were calculated by multiplying grain and straw yields (kg ha^{-1}) with their respective nutrient concentrations while total N, P and K uptake were estimated by sum of grain and straw nutrient uptake.

The agronomic nutrient use efficiency (ANUE) was estimated by the ratio of yield difference between fertilized and control to applied nutrient. Physiological use efficiency (PNUE) was also estimated with a ratio of yield differences between fertilized treatments and control to the nutrient uptake difference between fertilized and control. Since all applied fertilizer is not utilized by the crop, analyzing apparent nutrient recovery efficiency (ANR) is important to know the nutrient use efficiency and calculated through the ratio of nutrient uptake differences between fertilized and control to applied nutrient (Fageria et al., 2008) while Physiological Efficiency Index of Nutrients (PEIN) was estimated by the ratio of grain yield to nutrients absorbed by plant (Tittonell et al., 2008). Nutrient harvest index (NHI) is also estimated by the ratio of grain nutrient uptake to total biomass nutrient uptake. The conversion efficiencies for N, P and K were estimated by the ratio of above ground biomass to plant nutrient uptakes.

Data normal distribution and homogeneity tests were checked before variable tests and one-way analysis of variance (ANOVA) was used to detect mean differences due to treatments using the Gen Stat 16th edition. Significant differences among treatments were tested using least significant differences (LSD) test at $p \leq 0.05$. All data were presented as means of the two consecutive cropping seasons because there was no significant difference between seasons.

2.5. Validation of QUEFTS model performance

The accuracy of QUEFTS model was evaluated using statistical tools such as Root mean square error (RMSE), Coefficient of determination (R^2), Index of agreement and Percent bias (PBIAS). The RMSE is an error index with its lower value shows better model accuracy (Moriassi et al., 2007, Eq 1). The coefficient of determination (R^2) calculates the combined dispersion against each dispersion of the actual and simulated series (Eq 2). The coefficient of determination varies from 0 to 1, where a value of 0 shows no correlation between observed and predicted and value of 1 shows the dispersion of predicted values are equal to that of observation values. The index of agreement (d) indicates the ratio of mean square error to the potential error. The d is described like R^2 and it has the capability to overcome low sensitivity of R^2 to the differences between observed and predicted values (Eq 3). The optimal value of PBIAS is 0.00, with its low values indicate better model simulation

performance. Its positive and negative values indicate model underestimation bias and overestimation bias, respectively (Gupta et al., 1999, Eq 4).

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^n (Y_i^{obs} - Y_i^{pre})^2}{n}} \quad (\text{Eq 1})$$

$$R^2 = \left(\frac{\sum_{i=1}^n \frac{\sum_{i=1}^n (Y_i^{obs} - \bar{Y}^{obs})(Y_i^{pre} - \bar{Y}^{pre})}{\sqrt{\sum_{i=1}^n (Y_i^{obs} - \bar{Y}^{obs})^2} \sqrt{\sum_{i=1}^n (Y_i^{pre} - \bar{Y}^{pre})^2}}}{\sum_{i=1}^n \frac{\sum_{i=1}^n (Y_i^{obs} - \bar{Y}^{obs})(Y_i^{pre} - \bar{Y}^{pre})}{\sqrt{\sum_{i=1}^n (Y_i^{obs} - \bar{Y}^{obs})^2} \sqrt{\sum_{i=1}^n (Y_i^{pre} - \bar{Y}^{pre})^2}}} \right)^2 \quad (\text{Eq 2})$$

$$d = \frac{\sum_{i=1}^n \frac{\sum_{i=1}^n (Y_i^{obs} - Y_i^{pre})^2}{\sum_{i=1}^n (|Y_i^{pre} - \bar{Y}^{obs}| + |Y_i^{obs} - \bar{Y}^{obs}|)^2}}{\sum_{i=1}^n \frac{\sum_{i=1}^n (Y_i^{obs} - Y_i^{pre})^2}{\sum_{i=1}^n (|Y_i^{pre} - \bar{Y}^{obs}| + |Y_i^{obs} - \bar{Y}^{obs}|)^2}} \quad (\text{Eq 3})$$

$$\text{PBIAS} = \frac{\sum_{i=1}^n \frac{\sum_{i=1}^n (Y_i^{obs} - Y_i^{pre}) * (100)}{\sum_{i=1}^n Y_i^{obs}}}{\sum_{i=1}^n \frac{\sum_{i=1}^n (Y_i^{obs} - Y_i^{pre}) * (100)}{\sum_{i=1}^n Y_i^{obs}}} \quad (\text{Eq 4})$$

where Y_i^{obs} = i^{th} grain yield observed, Y_{obs} = mean of the observed grain yield, Y_i^{pre} = i^{th} grain yield predicted by the QUEFTS model, Y_{pre} = mean of the predicted grain yield and n = number of observations.

2.6. Partial economic analysis

Economic benefits of the treatments were estimated using procedures described by CIMMYT (1988). Labor costs involved for application of fertilizers of each treatment were recorded and used for analysis. The current average price of grain and straw yield of each crops during study time were valued at an average open market price of 25.00 ETB kg^{-1} of grain and 4.5 ETB kg^{-1} of straw. Adjusted grain and straw yield (AGY and ASY) (kg ha^{-1}) which were downward by 10% to reflect the difference between the experimental yield and yield of farmers were used for gross field benefit (GFB) (ETB ha^{-1}) estimation by multiplying adjusted grain and straw yields with their respective current price. Total variable cost (TVC) (ETB ha^{-1}) was estimated by summing up costs that vary among treatments. Where similar costs for all treatments such as labor cost for land preparation, planting, weeding, harvesting, threshing and seed cost were not included in the analysis. Net benefit (NB) (ETB ha^{-1}) was calculated by subtracting TVC from gross benefits (GB) for each treatment. The marginal rate of return (MRR) was calculated by dividing change in net benefit by change in TVC.

3. Results and discussion

3.1. Pre sowing soil chemical properties and soil nutrient supplies

Pre sowing soil analysis result indicated pH of the soil was neutral soil reaction. This indicated that the pH of soil is suitable for barley production. The electrical conductivity (EC) is also low with free of salt accumulation in the soil (Table 1).

According to Gimenez et al. (2012) the organic carbon content of the soil was low. According to Tekalign (1991) total nitrogen (TN) and available P (av.P) of the study experimental plots were also low and medium, respectively while the experimental plots had high exchangeable potassium (exch.K) (Table 1). These results indicated that applications of higher N containing fertilizer followed by higher P containing fertilizers than K containing fertilizers were required for the experimental plots.

Soil fertility map of the study croplands were generated in GIS environment on the basis of TN, Av.P and exch.K of the soils (Figure 3). The soil fertility map of the croplands generated in the GIS environment showed homogeneous zones of 5 different classes consisting of the TN, Av.P and exch.K content. Most croplands have low TN, medium av.P but in case of exch.K most croplands have medium to high exch.K. The map

Table 1. Model input chemical soil properties of the experimental plots in Alaje, north Ethiopia.

Model input soil properties	Values	Rating	Reference
pH (H ₂ O)	6.3 (6.2–6.4)	Neutral	Tekalign (1991)
EC (ms/cm) (1:2.5)	0.2 (0.1–0.3)	Low	Landon (1991)
SOC (g kg ⁻¹)	14.8 (14.7–14.9)	Low	Gimenez et al. (2012)
TN (g kg ⁻¹)	1.1 (91.0–1.3)	Low	Tekalign (1991)
P-Olsen (mg kg ⁻¹)	13.5 (11.9–14.5)	Medium	Tekalign (1991)
Exch. K (mmol kg ⁻¹)	2.4 (1.6–2.9)	High	FAO (2006)

clearly shows that the croplands have very low organic carbon and TN due to intensive cultivation and losses.

The QUEFTS model used the soil contents to estimate soil N, P and K supplies. Accordingly, the QUEFTS model estimated soil N, P and K supplies of the experimental fields were 80, 9 and 53 kg ha⁻¹. This is equivalent to N, P and K soil supply ratios of 9:1:6. These soil indigenous nutrient supplies reflect the soil nutrient condition or soil fertility and can be developed as guideline for fertilizer recommendation. This soil nutrient supply data was used as a base for developing fertilizer recommendation to achieve 4000 kg ha⁻¹ barley target yields. The amount of nutrients supplied from soil and fertilizer after fertilization were 147, 15 and 90 kg ha⁻¹. The findings indicated that the soil nutrient supply of the study area was low because the soil in the study area has low level of organic matter which release lower N and P nutrients. Moreover, N is found to be the most limiting nutrient, because the N demand (145 kg N ha⁻¹) of the crop was more than twice that of P (60 kg P ha⁻¹) and three times that of K (50 kg K ha⁻¹) to achieve target yields. This is because soil N content of the soil was low while P and K were medium and high, respectively. Thus soil nutrient supply results indicated that higher N containing fertilizers was demanded by the crop. This agrees with research conducted by Abegaz (2008) who reported that the soils in the northern Ethiopia required higher N containing fertilizers than P and K containing fertilizers. This soil nutrient supply is also important to evaluate existing soil nutrient potential and to investigate yield limiting nutrients. Moreover, this soil nutrient investigation is helpful to recommend fertilizers which achieve barley target yield (Xu et al., 2017). Though each experimental field requires different amount of N, P and K containing fertilizers, in this study the model recommends average fertilizers for the six farmers' field in order to achieve average target yield (4000 kg ha⁻¹) of malt barley variety.

3.2. Agronomic performance

Plant height, effective tiller and spike length, and biomass yields were significantly ($p < 0.05$) higher in the QUEFTS model based fertilization plots than the other treatments (Table 2). This is because the model recommends balanced N, P and K nutrients while blended and farmers' fertilization practices provide similar nutrients for all the soils. The study revealed that increased biomass of the crop was attributed to model based balanced N, P and K nutrient application. This agrees with the results of Mengistu and Abera (2014) and Wang et al. (2017) who reported a significant increase in crop growth and biomass in the treatments with higher and balanced N, P and K fertilization.

This indicated that balanced N, P and K application is important to improve soil nutrient management, crop production and contribute to food security (Ataulkarim et al., 2017). However, lower plant growth parameters were observed on the control due to poor existing soil nutrient content (Nyombi et al., 2010). Wakene et al. (2014) also suggested that crop growth parameters and biomass yield of barley was increased with increasing rates of N, P and K. The poor agronomic response to farmers' fertilization practice was due to application of low and similar fertilizer rate for all soils and low soil nutrient supply capacity of the soil which all together affected photosynthesis and nutrient uptake.

3.3. Yield

Highest barley grain yield was observed in QUEFTS based fertilized plots. Highest barley mean grain yield recorded in the two production seasons from plots treated with QUEFTS based fertilizer application was 4747 kg ha⁻¹ (Table 2). This indicated that QUEFTS based fertilizer application has a yield advantage of 702, 1110 and 2020 kg ha⁻¹ over the blended fertilization, farmers' fertilization practices and control plots, respectively. Like the grain yield, higher biomass yield was observed in QUEFTS based fertilized plots. The mean biomass yield found in the plots treated with QUEFTS based fertilizer application was 13117 kg ha⁻¹. This showed that biomass yield advantage of 2726, 3588 and 5974 kg ha⁻¹ over the blended fertilization, farmers' fertilization practices and control plots, respectively.

The result revealed that mean grain yield of barley in plots treated with QUEFTS model based fertilizer application was significantly ($p < 0.05$) higher than plots with farmers' fertilizer application rate and control (Table 2). Moreover, significant differences in mean grain yield were observed among plots with blended fertilizer application, farmers' fertilizer application rate and the control as well as between farmers' fertilizer application rate and control. Whereas, differences in mean grain yield was not significant between blended fertilizer application and farmers' fertilizer application practices and between model based fertilization and blended fertilization (Table 2). The mean biomass yield was significantly ($p < 0.05$) higher in the model based fertilizer application than all treatments (Table 3).

The highest biomass and grain yields recorded in QUEFTS based fertilizer application is attributed to the recommendation of balanced N, P and K nutrients. Moreover, this QUEFTS model based fertilizer recommendation is on the basis of soil supply obtained from soil laboratory analysis and N, P and K fertilizer applications. This is because application of balanced N, P and K fertilizer based on soil test significantly improved N, P and K availability in the soil solution which resulted in higher grain yield and nutrient uptake. The main reason for this increased crop yields in the model based fertilization is that when the proportion of N, P and K nutrients are balanced based on crop nutrient requirement, the N, P and K uptake is also significantly increased which resulted in an increased crop yield. However, if one of the N, P and K nutrients in the soil solution is below crop requirement for achieving a target yield, the N, P and K uptake and crop yield are also proportionally lower. This agrees with Alam and Haider (2006) who suggested increased and balanced N, P and K level enhanced yield. Other studies in Ethiopia have also confirmed that grain yield and nutrient uptake have increased when adequate N, P and K nutrients were supplied (Agegehu and Bird (2014). Nyombi et al. (2010) has also suggested that improved crop yields and growth parameters were observed due to good and balanced soil fertility management.

The observed grain yield in most experimental fields was above the target yields (Figure 4). This implied that model fertilizer recommendation was adequate to achieve target yields. The higher yield response to model based N, P and K nutrient applications indicated that the soil has nutrient deficiency (Chuan et al., 2013).

However, the lower yield obtained in the plots with farmers' fertilizer application practice than yield of model based and blended fertilization

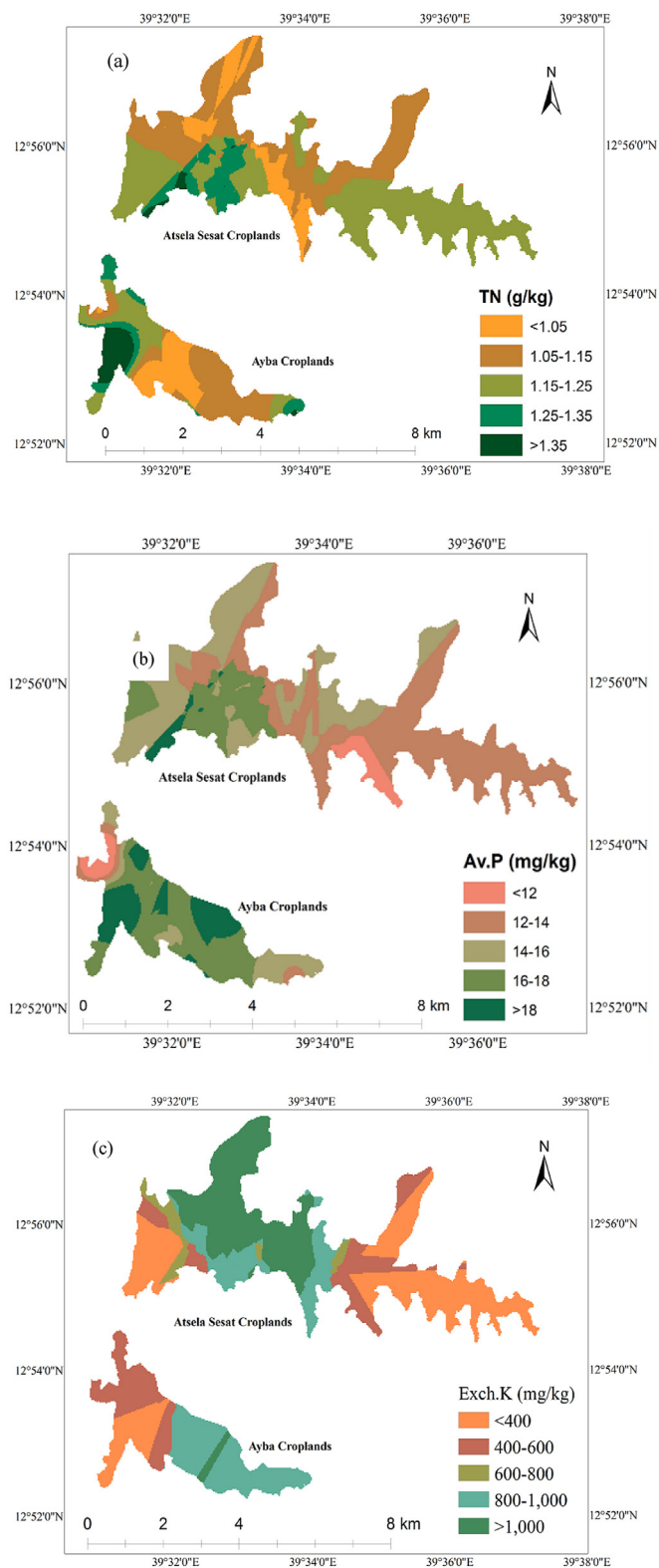


Figure 3. Soil (a) nitrogen, (b) phosphorus and (c) potassium content maps of the study sites.

treatments is due to inadequate nutrient application rate. Many studies also suggested that yield difference between soil test based fertilization and farmers' fertilizer application practice is mainly due to inefficient fertilizer application of the farmers (Ataulkarim et al., 2017). Thus, QUEFTS model provided significant benefits to site specific nutrient management through estimating the soil nutrient supply, fertilizer

recommending needed fertilizer and predicted yields. This model provides fertilizer recommendation and nutrient management enabling farmers to dynamically adjust fertilizer application rates based on crop requirements and their economy. This model also enables demand based soil nutrient management and in turn promotes nutrient uptake by better tailoring nutrient supply to crop and target yield demands.

3.4. Nutrient uptake

The average mean nutrient content and nutrient uptake results of the crop in the two seasons revealed that grain, residue and total N uptake was significantly ($p < 0.05$) different among treatments (Table 3). Higher mean N, P and K content and uptake was recorded in plots fertilized with QUEFTS model (Table 3). QUEFTS based fertilization significantly ($p < 0.05$) increased N, P and K nutrient uptake than the other treatments.

In relationships between grain yield and nutrient uptake of crops in the four treatments, increased uptake of N, P, and K was related to increased grain yield (Fig 5a-c). At a given grain yield, higher N, P and K nutrients uptake were found in the plots treated with model based fertilizer application (Fig 5a-c). The higher N, P and K uptake obtained in the model was due to the application of balanced N, P and K fertilizers which significantly improved N, P and K availability in the soil solution. This in turn resulted in higher grain yields of the crop.

This confirmed that the plant nutrient content and nutrient uptake can be increased when adequate N, P and K nutrients that fulfill the nutrient gaps. This indicated that integrated and balanced N, P and K nutrient applications improved nutrient uptake. This showed that there is good relationship between grain yield and N, P and K nutrient uptake in the QUEFTS based fertilization (Figure 5). This agrees with Sheoran et al. (2017) who reported that total N, P and K uptake was higher in a soil fertilized due to balanced N, P and K containing fertilizers which caused to a lower nutrient uptake when one of the N, P and K nutrients is lower in the soil (Setiyono et al., 2010). When these N, P and K nutrients are balanced according to the crop demand, the N, P and K uptake are also increased which resulted in increased crop yield.

3.5. Nutrient use efficiency

Nutrient use efficiency indices such as PEIN and CE (N) were found significantly ($p < 0.05$) different among all treatments. Conversion efficiencies such as CE (P) and CE (K) were significantly ($p < 0.05$) higher in plots treated with QUEFTS based fertilizer application than farmers practices and control plots. Significant ($p < 0.05$) differences in nutrient harvest index of N, P and K were observed among some of the treatments (Table 4). The greatest ANR and ANUE were recorded in a treatment with blended fertilizer application. Highest PEIN, CE (N), CE (P) and CE (K) were observed in the control followed by farmers practice. The greatest ANR and ANUE were observed in the blended fertilizer application plot.

Though application of model based fertilizers brought a significant change in grain yield and NPK nutrient uptakes, lower ANR, ANUE, PNUE, PEIN and nutrient converting efficiencies were observed in plots with QUEFTS based fertilizer application (Table 4). Lower nutrient use efficiency implies that there is high nutrient loss to the environment. This higher nutrient loss in the study area limits use efficiency of the model based fertilizer application. This is similar with Tittonell et al. (2008) who suggested that promotion of inorganic fertilizer use has to go hand-in-hand with the implementation of nutrient use efficiency measures such as application of manure and soil conservation practices. The highest ANR and ANUE observed in plots with blended fertilizer application are due to high crop responses to applied fertilizers. Similar to this study, Sheoran et al. (2017) suggested that an increase fertilizer dose decreased use efficiency. Haile et al. (2012) also found a decreased in nutrient utilization efficiency with an increase in fertilizer application rates.

The highest ANR efficiency means plant transforms the nutrients acquired from fertilizer into grain yield (Belete et al., 2018). As the model

Table 2. Average yield and yield components of the two cropping seasons (2017 and 2018), northern Ethiopia.

Treat	Ph.(cm)	Et	Sp (cm)	Ns	Gy (kg ha ⁻¹)	By (kg ha ⁻¹)	HI	Tsw (g)
T1	93a	5.6a	7.6a	49a	4747a	13117a	0.36a	50.3a
T2	86b	4.5b	6.2b	43b	4045ab	10391b	0.39a	48.2ab
T3	84b	3.7c	5.9c	30c	3637b	9639b	0.38a	49.3a
T4	70c	2.9d	4.8d	26d	2727c	7143c	0.38a	46.5b
lsd	6.3	0.7	0.2	3.9	751.5	1616.6	0.1	2.2
CV	19.1	13.4	14.7	17.2	19.8	14.1	18.9	16.4
P-value	<0.01	<0.01	<0.001	<0.001	<0.001	<0.001	0.08	<0.05

T1: model based fertilization, T2: blended fertilization, T3 farmers' fertilization practices and T4: control/no fertilizer. Ph: plant height, Et: effective tillers, Sp: spike length, Ns: number of seeds per spike, Gy: grain yield, By: biomass yield, HI: harvest index and Tsw: thousand seed weight. Different letters in the same column represent significant differences of mean values at $p < 0.05$.

Table 3. Average N, P and K nutrient content and uptake (mean \pm SD) of the two cropping seasons (2017 and 2018), northern Ethiopia.

Nutrient content in (% for N and ppm for P and K)		Treatments			
		T1	T2	T3	T4
Grain	N	2.3a	1.9b	1.6c	0.9d
	P	2821a	2395b	2125c	1973d
	K	4757a	4577ab	4449b	4437b
Straw	N	1.0a	0.8b	0.7c	0.5d
	P	1814a	1559b	1445c	1269d
	K	7242a	6007b	5345bc	4240c
Total	N	3.3a	2.7b	2.3c	1.4d
	P	4635a	3954b	3570c	3242c
	K	11999a	10584a	9794ab	8677b
Nutrient uptake (kg ha ⁻¹)					
Grain	N	110.9 \pm 29a	77.6 \pm 19b	58 \pm 17c	24.5 \pm 9d
	P	15.7 \pm 4.7a	11.2 \pm 4.2b	8.3 \pm 2.8c	6.9 \pm 3.0c
	K	21.1 \pm 5.7a	17.9 \pm 4.4ab	17.3 \pm 5.7b	12.5 \pm 5.1c
Straw	N	78.9 \pm 16a	47.8 \pm 10b	37.5 \pm 11c	19.1 \pm 8d
	P	15.2 \pm 2.8a	9.3 \pm 1.8b	9.1 \pm 2.5b	5.6 \pm 2.0c
	K	49.8 \pm 24a	46.5 \pm 14a	32.0 \pm 10b	17.8 \pm 7c
Total	N	189.8 \pm 39a	125.4 \pm 26b	95.5 \pm 26c	43.6 \pm 14d
	P	30.8 \pm 6.7a	20.3 \pm 5.5b	17.6 \pm 4.9b	12.5 \pm 4.6c
	K	70.9 \pm 25a	64.4 \pm 16a	49.3 \pm 14b	30.3 \pm 10c

(T1) model based fertilization; (T2) blended fertilization; (T3) farmers' fertilization practices and (T4) control/no fertilizer. N: nitrogen, P: phosphorus and K: potassium. Different letters in the same row represent significant differences of mean values at $p < 0.05$.

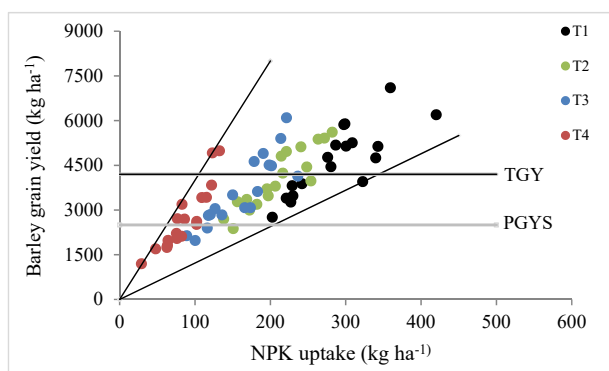


Figure 4. Barley grain yield versus nutrient uptake of the treatments. Where; TGY = target grain yield, PGYS = predicted grain yield based on soil supply.

based fertilizer recommendation, has lower ANR, model based fertilizer application requires fertilizer use efficiency improvement. Highest PNUE obtained in the farmers' fertilizer application practice is because plants physiologically increase their ability to transform more nutrients into

grain yield when the fertilizer rate is inadequate (Gauer et al., 1992). Rutkowska et al. (2014) also suggested that physiological nutrient requirements are controlled by the efficiency with which plant nutrient is converted in to biomass and grain yield. However, the low PNUE observed in the model based fertilizer application is due to application of higher amount of NPK nutrients. This is similar with Belete et al. (2018) who suggested that PNUE decreases with an increase in nutrient application. Gauer et al. (1992) also suggested that maximum and minimum PNUE were recorded in the lowest and highest fertilizer rates, respectively. This implies that poor nutrient utilization could be related to unfavorable soils condition which can limit nutrient availability from the fertilizer which might have led to higher nutrient losses (Janssen and de Willigen (2006). Hence, through improving nutrient use efficiency, model based fertilizer recommendation is the good fertilizer recommendation to increase yield, nutrient uptakes and develop sustainable agriculture (Xu et al., 2014).

3.6. Model accuracy and performance

The contrast between observed and QUEFTS model predicted barley grain yields for both fertilized and unfertilized plots were presented in Figure 6. There was an acceptable agreement between QUEFTS model

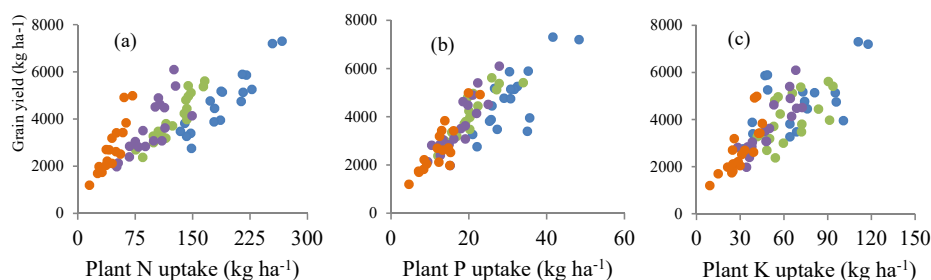


Figure 5. Relationship between grain yields and plant nutrient uptake of barley of different fertilizer recommendation.

Table 4. Nutrient use efficiencies indices for three testing crops as influenced by the interaction effect, northern Ethiopia.

	Treat. Wealth	ANR	ANUE	PNUE	PEIN	CE (N)	CE (P)	CE (K)
Barley	T1	0.80b	7.91 b	45.4c	16.19d	69.6 d	429.1 c	206.9 b
	T2	0.97a	14.78 a	49.5b	19.17c	83.4 c	522.4 b	164.1 c
	T3	0.91a	13.60a	60.0a	22.36b	103.4b	551.0ab	198.2 b
	T4	-	-	-	31.67 a	165.7a	577.7a	243.5 a

Treatments with the same letter a long a column are not statistically different and there is no interaction effect between treatment and wealth for barley.

predicted and observed yield from the field experiment with comparatively small RMSE and d values and relatively high R^2 (Figure 6a,b). However, the model indicated a small underestimation bias (PBIAS = 8.6% and 17.7% for the fertilized and unfertilized plots, respectively).]

The close agreement between the QUEFTS predicted and observed yields indicated that the QUEFTS model can be used to estimate balanced nutrient requirements and site specific fertilizer recommendations to improve barley yield in the northern Ethiopia. Moreover, the result indicated that there was no significant difference between model predicted and observed barley grain yields. The data used for model validation were experimental data from actual farm field trials where fertilizer rates were recommended by the QUEFTS model. The QUEFTS model, however, assumes that other biophysical factors such as soil moisture, soil temperature, pests, diseases and management are non-limiting. Though the workability of QUEFTS modeling on crop yield at farm level is complex, the QUEFTS model supports to predict yield based on existing soil nutrient supply potential and fertilizer recommendation.

These results showed that the QUEFTS model is used to predict yield and recommend fertilizers that achieve target yields of barley. This verifies that the model is important to predict grain yield with a reasonable degree of accuracy. This is also comparable with other findings by Chuan et al. (2013) who validated QUEFTS model and determined RMSE values of 22.4 kg ha^{-1} . This confirmed that QUEFTS model is used to improve fertilizer recommendations to achieve barley target yield.

3.7. Partial economic analysis

The results of the partial budget analyses revealed that the highest net benefit was obtained in the treatments with model based fertilizer application with a marginal return rate (MRR) of 36.1%, (Table 5). Thus, model based fertilizer application is economically beneficial as compared to the other treatments.

All fertilized treatments have greater net benefit values than control. This shows that all are not dominated because treatment with maximum cost has higher net benefit. According to economic analysis of CIMMYT (1988), treatment with MRR greater than 100% is profitable. Also suggested that MRR with greater than 100% has higher benefits and technologies requiring substantial changes to a farming system. Accordingly, in this study, the highest marginal rate of return was considered as a guarantee for the farmers to accept site specific fertilizer

recommendation. The model based fertilizer application has highest net benefit and MRR. This means MRR in this experiment indicates that investing one ETB in the farmers' fertilizer application practice for barley has 36.1 ETB return (Table 5).

4. Conclusions

The QUEFTS model based fertilizer recommendation significantly increased yield components, yield, nutrient uptake and economic benefits. However, the lower imbalanced fertilizer application of blended and farmers' practices resulted in lower grain yield and nutrient uptake compared to QUEFTS model based fertilizer application. QUEFTS was adapted to estimate barley yields and responses to mineral N, P and K fertilizers in the smallholder farmers in northern Ethiopia; however its nutrient use efficiency has to be improved. The QUEFTS model predicted yield agrees with observed yield suggesting that QUEFTS is an accurate tool to predict yield and recommend fertilizers to achieve barley target yield.

The present QUEFTS model validation study indicated a good correlation between predicted and observed grain yield in northern Ethiopia. This implied that the QUEFTS model can be a base for development of cost-effective decision support tool during nutrient management and fertilizer recommendations in northern Ethiopia and similar regions. Thus, the policy implication of this study is: soil fertility management policies have to consider existing soil nutrient management to achieve target yield. Overall policy message is to design means by which smallholder farmers will improve their crop yield using QUEFTS model based fertilizer recommendation.

Declarations

Author contribution statement

Shimbahri Mesfin: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Mitiku Haile; Girmay Gebresamuel: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Amanuel Zenebe: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

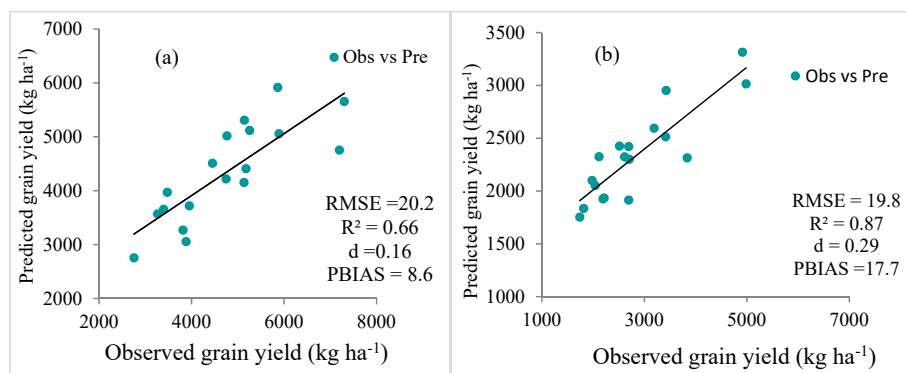


Figure 6. Relation between the observed and QUEFTS predicted barley grain yield for (a) fertilized plots and (b) unfertilized plots. RMSE: root mean square error (kg ha^{-1}); R^2 : coefficient of determination; d = index of agreement; PBIAS: percent bias (%).

Table 5. Partial budget analysis of the experimental plots.

Treat	AGY (kg ha^{-1})	ASY (kg ha^{-1})	GYR (ETB ha^{-1})	SYR (ETB ha^{-1})	TR (ETB ha^{-1})	MTVC (ETB ha^{-1})	NB (ETB ha^{-1})	MRR (%)
T4	2727	4416	68175	19872	88047	0.0	88047.0	0.0
T3	3637	6002	90925	27009	117934	3299.8	114634.2	34.7
T2	4045	6346	101125	28557	129682	3524.3	126157.7	35.8
T1	4747	8370	118675	37665	156340	4209.0	152131.0	36.1

Where; TVC: Total variable cost, Gy: Grain yield, Sy: Straw yield, Aj.Gy: Adjusted grain yield, Adj. Sy: Adjusted straw yield, TR: Total revenue, MTVC: Marginal total variable cost, MRR: Marginal rate of return.

Abera Gebre: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

No data was used for the research described in the article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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