

Exploring optimal farm resources management strategy for Quncho-teff (*Eragrostis tef* (Zucc.) Trotter) using AquaCrop model



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ABSTRACT

Teff is a major staple food crop in Ethiopia. Moisture and soil fertility are the two major factors limiting teff yield. Studies were conducted across three sites in Ethiopia [Mekelle (MK) in 2012 and 2016, Ilala (IL) in 2012 and Debrezeit (DZ) in 2009 and 2010]. The objectives of these studies were (1) to assess the response of Quncho-teff to different fertilizer and irrigation levels; 2) to quantify irrigation water productivity (IWP), and (3) to collect data to calibrate and validate AquaCrop model for simulating yield and evaluate optimal irrigation and sowing date strategy for Quncho-teff at different locations in Ethiopia. The different fertilizer levels were: 1) 64 kg N and 46 kg P/ha (N2P2); 2) 32 kg N and 23 kg P/ha (N1P1); 3) 0 kg N and 0 kg P/ha (N0P0) and 4) 52 kg N and 46 kg P/ha (N3P3). The four irrigation treatments were: zero (rainfed), two, four and full irrigation applications. Findings showed that full irrigation in combination with high fertilizer (N2P2) could give better yield. However, during abnormal rainfall, spreading the available fertilizer at a rate of 32 kg N and 23 kg P/ha may be preferable to applying 64 kg N and 46 kg P/ha. This study also indicated that the regional fertilizer recommendations for teff need to be revised taking in to account the soil characteristics, climate and irrigation water availability. The AquaCrop model was able to simulate the observed canopy cover, soil water, biomass and yield of teff satisfactorily. Canopy cover was simulated with normalized root mean square error (NRMSE), index of agreement (I) and R² of 7%, 0.5 and 0.8, respectively. Soil moisture during the season was simulated with NRMSE of 11.4–15.7%, I of 0.99 and R² of 0.85–0.9. Simulated final aboveground biomass values were in close agreement with the measured (NRMSE, 7.8%, I, 0.89 and R², 0.66). There was also good agreement between simulated and measured grain yield with NRMSE, I and R² values of 10.9%, 0.93, 0.80, respectively. Scenario analysis indicated that early sowing was the best option to maximize teff yield with the least amount of irrigation. Scenario analysis also showed that one irrigation during flowering stage could substantially improve irrigation water productivity (IWP) of teff and minimize the yield losses which could occur due to shifting of sowing date from early to normal. Two irrigation applications also substantially improved the yield and IWP of late sown teff. However, to get high yield, a late sown teff should receive at least four irrigation applications during the mid-growth stage of the crop. These results suggest that AquaCrop model can be used to identify optimal farm resource management strategies for teff production.

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1. Introduction

Teff (*Eragrostis tef* (Zucc) Trotter), belongs to grass family. It is believed to have originated in Ethiopia where extensive teff genetic

diversity is available (Demissie, 2001). Among other cereals, teff ranks first in its area coverage and second in its total volume of production in the country (CSA, 2012). Contrasting to its large area coverage, teff's volume of production is low, among others, due to its low genetic yield potential (Assefa et al., 2003), low nutrient use efficiency (Habtegebrail and Singh, 2006), lodging (Assefa et al., 2003) and drought stress (Araya et al., 2010c, 2011; Araya and Stroosnijder, 2011; Shiferaw et al., 2012).

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Because of its gluten free nature, the crop has received more attention as source of food (Spaenij-Dekking et al., 2005) as well as animal forage (Rosenberg et al., 2005). Researches carried out to investigate trait diversity in teff germplasm (Assefa et al., 1999; Demissie, 2001; Ayalneh et al., 2012) and to evaluate teff's genetic variability to nitrogen use efficiency (Balcha et al., 2006) indicated that teff has greater potential that might contribute to the efforts in achieving food security in Ethiopia. However, teff production potential could also depend on other factors including agro-ecological suitability (preference), management and other external factors.

Teff National Improvement Programs mainly in Debrezeit Agricultural Research Center in Ethiopia has released several improved teff varieties including the famous and improved high yielding teff variety known as DZ-Cr-387 ('Quncho') (Assefa et al., 2011). Genetically, *Quncho* was a result of breeding processes from two well-known improved teff varieties, DZ-01-974 and DZ-01-196 (Assefa et al., 2011). The variety has an outstanding adoption by farmers not only for its high yield but also for its high market demand mainly due to its whitish seed color (Assefa et al., 2011; Fufa et al., 2011) which makes it preferable for making good 'Enjera' (pancake type of Ethiopian traditional food) quality.

Given the significant teff genetic variability and heritability (Demissie, 2001; Ayalneh et al., 2012), it would be very important to understand the response of teff (dominant teff cultivars) to water and sowing date under various agro-ecologies. Despite its economic importance and its contribution to food security, the dominant teff cultivar's (such as *Quncho*-teff's) response and performance under different climate, water, and sowing date condition have not yet been adequately understood. Such research could be addressed less costly and timely if researchers and extension workers are supported and guided by crop modeling techniques.

Among the crop models, AquaCrop (the FAO model) is well known for its good performance in simulating yield and biomass of many different crops under various management conditions (Steduto et al., 2009; Hsiao et al., 2009; Raes et al., 2009; Todorovic et al., 2009; Heng et al., 2009; Araya et al., 2010a, 2010b, 2016; Paredes et al., 2014). The model was developed by FAO to improve crop water productivity and reduce food insecurity in water scarce areas (Hsiao et al., 2009; Raes et al., 2009; Steduto et al., 2009).

Previous AquaCrop model calibration exercises for exploring irrigation strategies in teff (e.g. Araya et al., 2010a), and the rigorous attempts made to improve and refine teff AquaCrop model calibration and optimizing water productivity by Tsegay et al. (2012) and Yihun, (2015) have presented substantial important information. For example, Tsegay et al. (2012) verified that Normalized Water Productivity (NWP) for improved teff varieties considerably differs from local cultivars. However, Teff is a C4 crop, the Normalized Water Productivity (NWP) documented for teff so far is relatively lower (Araya et al., 2010a; Tsegay et al., 2012; Yihun, 2015) than those suggested for other C4 crops in literatures (Steduto et al., 2009; Raes et al., 2009; Hsiao et al., 2009; Heng et al., 2009). Previous teff cultivars presented in Araya et al. (2010a) seem to be less grown or out of cultivation from the majority of northern Ethiopia at least for the last four years (pers. Com). *Quncho*-teff has, thus, become the most dominant teff variety under the current farming system. This implies that more research might be needed to comprehensively assess the water productivity of teff and improve the performance of the model for *Quncho*-teff to utilize the model as a tool for resources optimization strategy.

The objectives of this study were, therefore (1) to study the response of *Quncho*-teff to different fertilizer and irrigation levels; 2) to quantify irrigation water productivity (IWP), and (3) to collect data to calibrate and validate AquaCrop model for evaluating

optimal irrigation and sowing date strategy for *Quncho*-teff grown at different locations in Ethiopia.

2. Materials and methods

2.1. Experimental studies

Field experiments were conducted in Ethiopia at Mekelle (MK) site in 2012 and 2016 (39°6' E longitude and 13°3' N latitude with altitude of 2212 m.a.s.l.) and at Ilala (IL) site within the Agricultural Research Institute experimental sites, in 2012 (longitude 39°6' E and latitude 13°4' N with altitude of 1890 m.a.s.l.). In addition, separate experimental data was obtained from Debrezeit (DZ) Agriculture Research Center for the 2009 and 2010 growing season (located at 39°01' longitude and 8°42' latitude with an altitude of approximately 1920 m.a.s.l.). The data from DZ site was obtained through an official request in support of MSc student research (Tsedale, 2014).

The short term daily climate data of MK [daily rainfall, daily maximum and minimum temperatures, wind speed, relative humidity and sunshine hours (in 2012) and only daily rainfall, daily maximum and minimum temperatures (in 2016)] and two years (2009 and 2010) daily climate data of DZ site that includes daily rainfall, daily maximum and minimum temperatures, wind speed, relative humidity and sunshine hours were obtained from National Meteorological Agency (NMA). MK and IL sites are close to Mekelle (MK) meteorological stations hence both experimental sites were assumed to be represented by the same climate data. The short term ETo (only for the experimental period) for both MK (in 2012) and DZ sites were calculated based on FAO Penman Monteith equation using ETo calculator (FAO, 2009). The daily rainfall data and the applied irrigation during the crop growing season in 2012 at MK and IL experimental sites is presented in Fig. 1. The short term (2016) daily climate data for MK site and the long-term (1980–2009) daily climate data (daily rainfall, daily maximum and minimum temperatures) for MK and DZ sites (needed for scenario analysis) were also obtained from NMA. Due to data limitation, ETo of the experimental season in 2016 for MK site and the long-term ETo for both MK and DZ sites were estimated based on Hargraves method as presented in Allen et al. (1998).

The soil texture at MK, IL and DZ experimental sites were sandy clay loam, loam and clay, respectively. The soil water and chemical characteristics of the experimental sites are presented in Tables 1,2, respectively. For scenario analysis, three most commonly used soil types for growing teff in the study areas are also shown in Table 3.

2.2. Experimental setup and crop management

In 2012, *Quncho*-teff (DZ-Cr-387) was sown at Mekelle (MK) and Ilala (IL) sites on July 23 and 26, respectively while in 2016 (MK), it was sown during the dry season (on March 5). Before sowing, plowing was done three times using oxen drawn plough. Sowing was conducted by broadcasting at a seeding rate of 20 kg/ha. On the date of sowing, the moisture content of the top soil was at field capacity.

The treatments at MK and IL site in 2012 were three combination sets of nitrogen (N) and phosphorous (P) fertilizer rates: 64 kg N and 46 kg P/ha (N2P2); 32 kg N and 23 kg P/ha (N1P1); and 0 kg N and 0 kg P/ha (N0P0). Unlike in the 2012, teff in 2016 at MK site was treated with fertilizer treatments of 52 kg N and 46 kg P/ha (N3P3).

There was only one fertilizer treatment at DZ sites during the cropping season in 2009 and 2010. The fertilizer application rates at DZ site was as per the optimal recommended practice (approximately 64 kg N and 46 kg P/ha) and there was no irrigation application (rainfed).

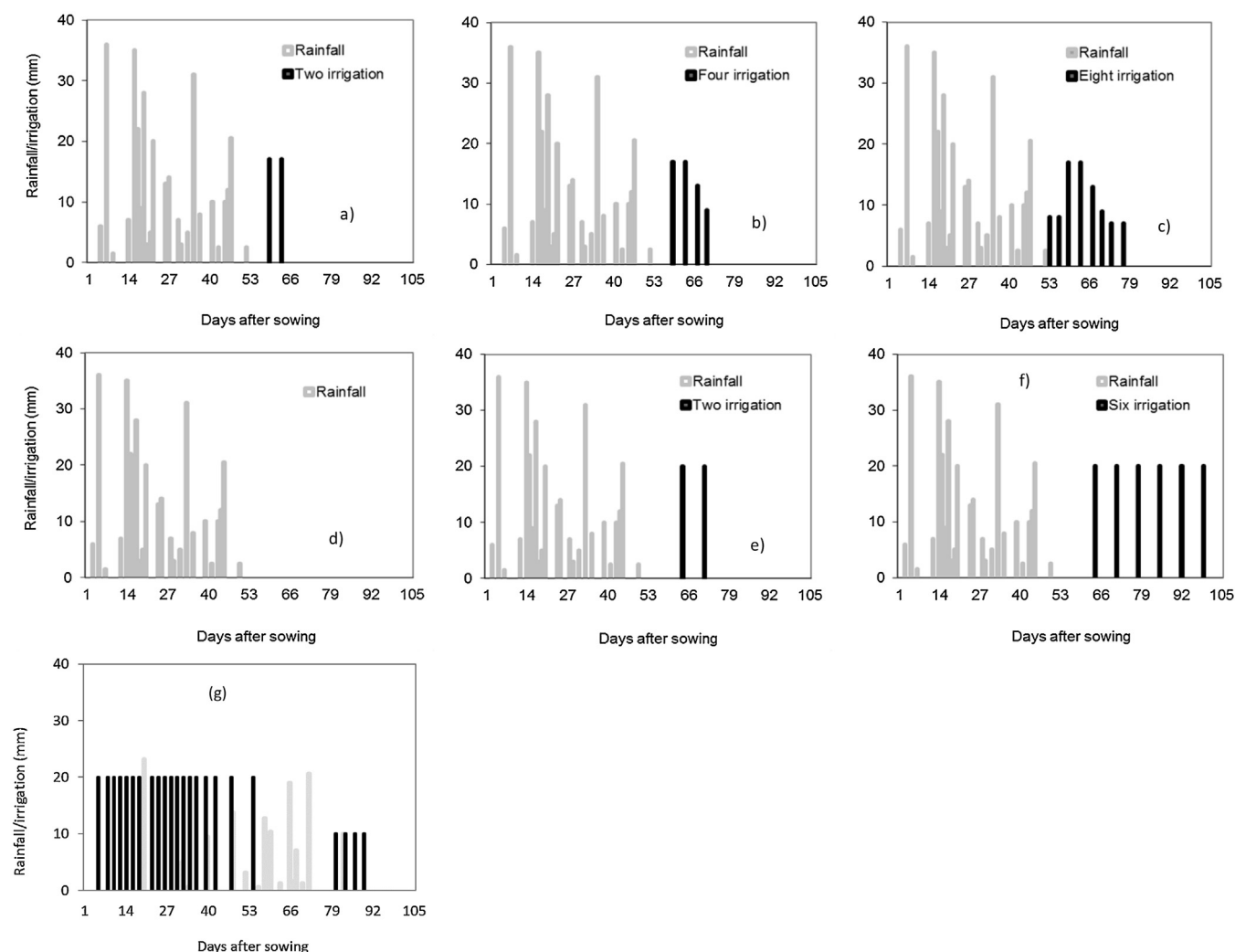


Fig. 1. Rainfall received and irrigation applied at MK during the cropping season in 2012 (a–c) and 2016 (g) and Ilala(d–f) site during the cropping season in 2012.

Table 1
Soil water characteristics for three experimental sites (MK, IL and DZ) in Ethiopia.

Site	Thickness (cm)	PWP (V%)	FC (V%)	SAT (V%)	TAW mm/m	Ksat mm/day
MK	0–15	15.2	26.1	47	109	250
	15–30	17.6	29.0	47	114	250
	30–45	16.5	25.2	50	87	250
IL	0–30	15	30	50	150	150
	30–45	15	28	50	130	150
	45–60	18	27	50	90	150
DZ	0–120	19.3	37.7	54	184	100

PWP, permanent wilting point; FC, field capacity; TAW, total available soil water; SAT, water content at saturation; Ksat, saturated hydraulic conductivity.

Source: [Hailay \(2012\)](#) and [Tsedale \(2014\)](#).

In 2012, there were four levels of irrigation treatments at MK site: I0 = no irrigation; I2 = two irrigations (total 35 mm during the mid-growth stage) and I4 = four irrigations (total 56 mm during the mid-growth stage) and, IF = full irrigations (eight irrigations with a total 86 mm during mid and late growth stage) ([Fig. 1a–c](#)). In 2016, the irrigation water treatment at MK sites was only full irrigation (IF) ([Fig. 1g](#)).

The irrigation water treatments (in 2012) at IL site slightly differed from MK site mainly due to differences in soil characteristics. The irrigation treatments at IL site were: I0 = rainfed (water

Table 2
Some of the chemical properties of the study sites in Ethiopia.

Soil chemical property	Unit	Sites		
		MK	IL	DZ
pH	1:2.5 past	7.2	7.75	7.4
EC	(dS/cm)	0.03	–	–
OM	%	0.36	4.79	–
P-Olsen	mg/kg	3.13	20.06	–
Total N	%	0.01	0.24	0.16
CEC	meq/100 g soil	–	42.4	52

EC, electrical conductivity; OM, organic matter; P, phosphorus; CEC, cation exchange capacity; MK, IL and DZ are Mekelle, Ilala and Debrezeits sites.

Source: [Hailay, 2012](#); [Kiros, 2012](#) and [Tsedale, 2014](#).

Table 3
Soil water characteristics of three selected soils types in Ethiopia (for scenario analysis).

Soil Type	Thickness (m)	PWP (Vol%)	FC (Vol%)	SAT (Vol%)	TAW mm/m	Ksat mm/day
CL	1.5	23	39	50	160	100
L	1.5	15	31	46	160	250
SL	1.5	10	22	41	120	500

CL, clay loam; L, loam; SL, sandy loam; FC, field capacity; TAW, available soil water; SAT, water content at saturation; Ksat, saturated hydraulic conductivity.

stressed, no irrigation), I2 = two irrigations during the mid-growth stage (total 40 mm), and IF = full irrigation (six irrigations during the mid and late growth stages with total amount of 120 mm) (Fig. 1d–f).

At both MK and IL sites, irrigation was applied manually by using a container of a well-known volume and calibrated watering cane. The treatments were arranged in a randomized complete block design. The size of each plot was 4 × 4 m. The distances between plots and between blocks were 1 m and 1.5 m, respectively. The treatments were replicated three times at MK and DZ sites and four times at IL site.

For all sites, fertilizer was applied in form of DAP (diammonium phosphate) and Urea as sources of phosphorus and nitrogen, respectively. Urea was applied in two splits: half of it on date of sowing and the remaining half one month after sowing. Whereas, DAP was applied on date of sowing. The Urea (nitrogen) fertilizer application timing in 2016 was slightly different from the other seasons. About 18 kg N/ha was applied on date of sowing. The remaining 34 kg of N was applied in three splits approximately 11.5 kg N/ha per application event (on 30, 50 and 70 days after sowing).

Other agronomic practices such as weeding were done two to four times during the growing seasons. Insect pests, such as shoot flies were controlled by spraying pesticides.

2.3. Measurements at experimental sites

At MK site, soil water, canopy cover and sequential dry above-ground biomass were measured in 2012. Soil water was measured gravimetrically to a soil depth of 45 cm at intervals of 15–20 cm every 10 days. The irrigation demand was predetermined taking into account crop characteristics (k_c for initial, mid and late) (Araya et al., 2011), soil characteristics (amount of water in the soil and water holding capacity), and long-term climate data. The computation of the crop water requirement was carried out using cropwat 8 software program.

The canopy cover was estimated every 10 days from time of sowing to maturity. Canopy cover was taken using a digital camera as presented in Nielsen et al. (2012). The camera was placed in a locally made 2 m height mast with its top having 1.5 m horizontal extension to which the digital camera was attached at right angle. A spirit level was also attached to the mast to make sure that all the photos were taken from the same position. The photos were analyzed using 'SamplePoint' measurement software version 1.55 (Booth et al., 2006). The SamplePoint software was set to select 64 randomly located points in each image. Then, each selected pixel in the picture was categorized manually and their percentage classifications summarized by the SamplePoint software. Data on canopy cover was obtained by taking averages of three photographs from each treatment for each observation period (approximately in 10-days interval).

Sequential aboveground biomass was taken randomly from each plot every 10 days starting from 40 days after sowing until maturity. The aboveground biomass was dried in an oven at 65 °C for 24 h and then weighed using a sensitive balance. The dried aboveground biomass, from the same treatments, was then averaged and converted to per hectare basis.

Final aboveground biomass and grain weight were measured at maturity from 2 × 2 m² area, from the middle part of the plot. The grain was threshed after taking the total weight of the dried total aboveground biomass.

2.4. Teff- water and fertilizer relations

To assess the response of *Quncho*-teff to different fertilizer and irrigation levels, the yield and biomass of teff at MK and IL site collected during the experimental season in 2012 and 2016 were

used. Yield changes and irrigation water productivities were calculated for comparisons among the treatments. The irrigation water productivity was calculated based on Eq. (1).

The irrigation water productivity for teff (IWP_{GY}) was estimated as the difference of teff grain yield (kg/ha) obtained between the irrigated (GY_I) and rainfed (GY_R) treatments (control) divided by the applied irrigation (IN) (m³) (Eq. (1)).

$$IWP_{GY} = \frac{(GY_I - GY_R)}{IN} \quad (1)$$

where, IN is applied irrigation (m³/ha). All grain yields of teff were estimated in kg/ha.

2.5. Model calibration

First, the soil and climate conditions of the experimental sites were entered into the model. The effect of temperature was considered and thus the phenology was estimated based on the growing degree days. The base temperature for teff was assumed to be 7 °C. Crop calibration parameters in previous studies (Araya et al., 2010a; Tsegay et al., 2012; Yihun, 2015) were also reviewed and entered in to the model as starting point and then adjustments were made based on site specific information such as for canopy cover and phenology for treatment with optimal irrigation and fertilizer for experimental season in 2012 at MK site (independent dataset). The conservative parameters were also adjusted in order to simulate the measured results. The maximum transpiration for teff was obtained from Araya et al. (2011).

Crop response to water stress could vary depending on the duration, severity and timing of the occurrence and is expressed in four plant processes: leaf growth, stomata conductance, canopy senescence and harvest index (HI) (Steduto et al., 2009). Except for HI, the relative scale of the water stress effects is expressed as fractional depletion (p) of the total available soil water (Hsiao et al., 2009; Steduto et al., 2009). To calibrate the inhibition of the canopy growth and stomata conductance as well as the acceleration of leaf senescence, calibration values (mentioned above) for local teff cultivars presented in previous studies were adopted and were adjusted and readjusted along with other crop parameters until the measured results were satisfactorily reproduced.

One of the drawbacks of this study was that the daily transpiration was not measured in the field but was rather estimated by the model after canopy cover and other crop parameters, which are necessary for estimating the daily transpiration were calibrated in the model.

Literature suggests that the normalized water productivity (presented in Eq. (2) below) (NWP) for C4 crops are expected to range from 30 to 35 g/m² (Raes et al., 2009). Normalized water productivity is expressed as a slope of the regression of periodically harvested aboveground dry biomass against the normalized cumulative transpiration (Steduto et al., 2007; 2009).

$$NWP = \left[\frac{BM}{\sum \frac{T}{ET_0}} \right]_{[CO2]} \quad (2)$$

Where, BM is aboveground dry biomass; T is transpiration; and ET_0 is reference evapotranspiration. Since the sequential biomass was harvested throughout the growing season every 10-days interval, it was regressed against the sum of the transpiration normalized for ET_0 that correspond from the time of sowing to each of the periodically harvested biomass. Finally, a good estimate of NWP value was obtained which allowed to reproduce the measured results.

2.6. Model validation

Model validation was done for canopy cover, soil water and sequential biomass by using a separate data set (other than the calibration data set) obtained from MK experimental site. The model was also evaluated based on separate sets of yield and biomass obtained from the MK, IL and DZ sites. The performance evaluation of the model was carried out by comparing the observed/measured against the simulated values using some statistical parameters namely, index of agreement, normalized root means square of error, percent of deviation and R^2 .

Index of agreement was estimated based on Willmott (1982). Whereas, the normalized root mean square of error (NRMSE) was calculated based on Eq. (3).

$$NRMSE = \left[\frac{RMSE}{x} \right] \times 100 \quad (3)$$

RMSE is root mean square of error. NRMSE is a statistical indicator of model uncertainty. Values close to zero indicate excellent agreement and hence better performance of the model. and x is the average of the observed/measured values for a given dataset.

R^2 values closer to 1 are also indications of the strong relationship between the measured and simulated values. Percentage of deviation (d) (Eq. (4)) of the model indicates the deviation of the simulated from the observed/measured values. The d values close to zero indicates an excellent agreement between the measured and simulated values.

$$d = \left[\frac{S_i - O_i}{O_i} \right] \times 100 \quad (4)$$

2.7. Scenarios and analysis

2.7.1. Climate and soil data sets

Mekelle (MK) and Debrezeit (DZ) sites were selected for evaluating optimal irrigation and sowing date strategies for teff due to relative availability of long-term climate data and as these two sites are among the potential teff growing areas in Ethiopia. The daily average long-term (1980–2009) rainfall, temperature (max and min) and ET_o data for MK and DZ sites (mentioned in section 2.1 above) was then entered into calibrated and validated crop model. Three soil types (clay loam, loam and sandy loam) (Table 3) that are commonly used by many farmers (for growing teff) in the study sites were used as soil input in the model for scenario evaluation.

2.7.2. Sowing date and irrigation scenarios

Three sowing windows were defined for MK and DZ sites. The sowing windows for MK site were early (6–13 July), normal (14–22

July) and late (23 July–4 August) (e.g. Araya et al., 2012; Tsegay et al., 2015). The sowing windows for DZ site were also defined as early (12–22 July), normal (23 July–4 August) and late (5–15 August) (e.g. Tsegay et al., 2014; Araya et al., 2015). Along with three soil types (clay loam, loam and sandy loam), averages of the three sowing windows were used for assessing optimal sowing date strategy for the period 1980–2009. Simple statistics (mean and standard deviations) were then used to assess the effects of sowing date on grain and biomass yields of *Quncho*-teff.

Teff irrigation scenarios and irrigation scheduling sensitivities were first evaluated with the calibrated and validated crop model. Following sensitivity test, four irrigation scenarios were then defined as zero (control), one, two and four irrigation application. Field measurements showed that the majority of teff roots are found at the top 40 cm of the soil profile and thus an irrigation amount of 20 mm per each irrigation event was considered. The traditional furrow method with an irrigation efficiency of 60% was assumed to represent farmers practice in the sites. The teff irrigation scenarios were then simulated for both MK and DZ sites for three sowing dates (early, normal and late) and three soil types (clay loam, loam and sandy loam) mentioned in above section. Irrigation water productivities (defined in Eq. (1)) were then analyzed.

3. Results

3.1. Teff – water and fertilizer relations and irrigation water productivity (IWP)

At the MK site, the highest IWP_{GY} (2.8 kg/m³) was obtained in a treatment with combinations of deficit irrigation (I2=2 irrigation during mid stage) and high fertilizer application rates (N2P2=64 kg N: 46 kg P/ha) (Table 4). In contrast, at IL site, the highest IWP_{GY} (1.0 kg/m³) was obtained in treatment combinations with full irrigation (IF) and high fertilizer application rates (N2P2) (Table 4).

At MK site, a decrease in fertilizer by half did not substantially decrease grain yields (Table 4) when teff was supplied with adequate water. At MK site, teff grain yield increased only by 10% due to doubling of the fertilizer from N1P1 to N2P2 under full irrigation (IF). Whereas, at IL site, teff grain yield increased by 19% due to doubling of the fertilizer from N1P1 to N2P2 under similar level of irrigation (IF) (Fig. 2).

At both MK and IL sites, teff grain yield increased by 78 and 31%, respectively, when N2P2 was applied as compared to fertilizer treatment with N0P0 both under full irrigation (Table 4). Relative to the control at MK site, there was an increase of teff grain yield by 119, 110 and 41% when teff was treated with full irriga-

Table 4
Percent of yield change and irrigation water productivity of *Quncho*-teff under various fertilizer and irrigation water application at MK and IL sites during the cropping season in 2012.

Trt.	MK				IL			
	Y (t/ha)	d(%)	Irrig. (mm)	IWP (kg/m ³)	Y (t/ha)	d(%)	Irrig. (mm)	IWP (kg/m ³)
N2P2-IF	2.2	119	86	1.4	2.8	75	120	1
N2P2-I4	2.1	110	56	2	–	–	–	–
N2P2-I2	2	96	34	2.8	1.7	6	40	0.3
N2P2-I0	1.9	91	0	–	0.9	–44	0	–
N1P1-IF	2.1	110	86	1.3	2.5	56	120	0.8
N1P1-I4	1.9	86	56	1.5	–	–	–	–
N1P1-I2	1.6	60	34	1.8	1.8	13	40	0.5
N1P1-I0	1.4	42	0	–	1.6	0	0	–
N0P0-IF	1.4	41	86	0.5	2.3	44	120	0.6
N0P0-I4	1.3	31	56	0.6	–	–	–	–
N0P0-I2	1.2	19	34	0.6	1.7	6	40	0.3
N0P0-I0	1	0	0	–	1.6	0	0	–

N2P2, N1P1 and N0P0 are the N: P fertilizer treatments 64: 46; 32: 23; and 0: 0, kg/ha, respectively. IF, I4, I2, and I0 are: 6–8 (full), 4, 2 and 0 irrigation (rainfed) after cessation of rainfall, respectively. IWP, irrigation water productivity. Y, yield; d, percent of deviation (change).

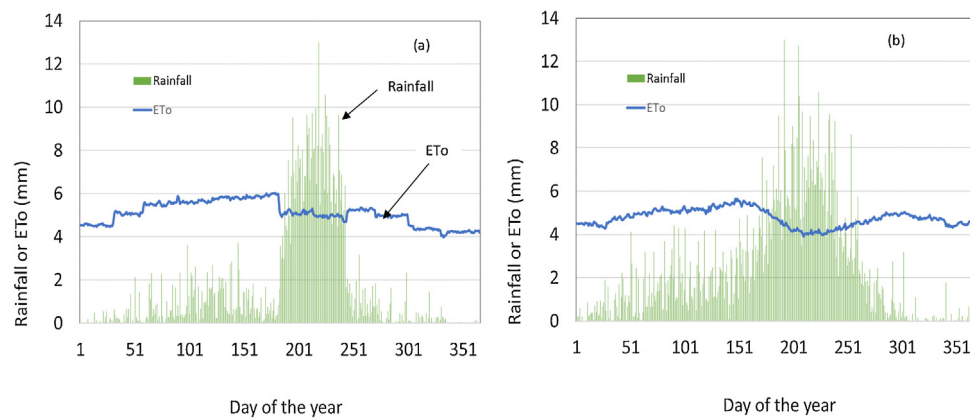


Fig. 2. Long-term (1980–2009) mean daily rainfall versus mean daily reference evapotranspiration (ETo) for Mekelle (a) and Debrezeit sites, Ethiopia.

tion (IF) in combination with N2P2, N1P1 and NOP0, respectively. Whereas, at IL site (under full irrigation), there was an increase of grain yield by 75, 56 and 44%, relative to the control, when teff was treated with N2P2-IF, N1P1-IF and NOP0-IF, respectively (Table 4). The yield increase relative to the control due to an increase in fertilizer from NOP0 to N2P2 for water stressed (I2) treatments at IL site was only 6% which is much lower than the values observed at MK site (Table 4).

Fig. 3a–c presents the periodically cumulative biomass growth of *Quncho*-teff obtained during the growing season in 2012 based on high (N2P2) (a), moderate (N1P1) (b) and zero (NOP0) (c) fertilizer inputs. *Quncho* – teff treated with high (N2P2) fertilizer application showed higher early growth performance when compared to teff with no (NOP0) fertilizer. On average, there was an increase of biomass growth at least by 83% regardless of the irrigation treatment during the early stage of teff when supplied with high (N2P2)

fertilizer compared to teff with no (NOP0) fertilizer application (Fig. 3a&c).

Teff biomass in treatment with NOP0 increased during the mid to late-growth stage (72–92 days after sowing) during which period the difference (in biomass growth) between teff treated with high and zero fertilizer application substantially reduced. Similarly, there was a substantial difference in biomass growth between the treatments with zero (NOP0) and moderate (N1P1) fertilizer applications (Fig. 3b&c).

When compared to treatments with no fertilizer, there was relatively faster early growth in treatments with moderate fertilizer applications. On average, the early growth of teff was improved at least by 38% in treatments with moderate fertilizer application (N1P1) as compared to no fertilizer application. Teff with zero (NOP0) fertilizer supply showed substantial increase in biomass growth when it reached 72 days after sowing. After cessation of

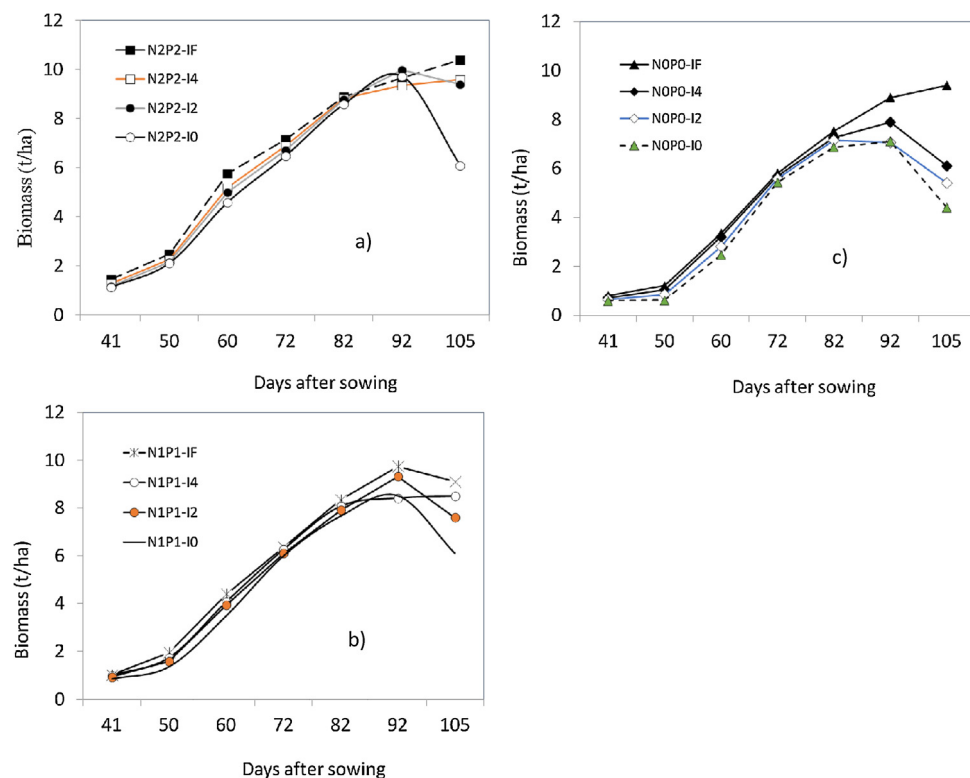


Fig. 3. Cumulative biomass growth of *Quncho*-teff based on high (N2P2) (a), moderate (N1P1) (b) and zero (NOP0) (c) fertilizer input for *Quncho*-teff in combination with four levels of irrigations: IF = full irrigation; I4 = four irrigations; I2 = two irrigations; and I0 = zero irrigation (rainfed) after the cessation of rainfall at MK site during the cropping season in 2012.

rains, the increase in teff biomass, however, stopped and subsequently led to a quick drying of its biomass.

Similarly, the periodical cumulative biomass growth of teff in treatments with moderate (N1P1) fertilizer application was substantially lower than those with high (N2P2) fertilizer application. However, regardless of the irrigation water, the difference in periodical cumulative biomass growth between N1P1 and N2P2 narrowed to less than 20% at harvest maturity.

Biomass growth seems to be more affected by presence or absence of fertilizer than availability of water. This could be attributed to the presence of adequate water supply (rainwater) from sowing up to heading stage of the crop.

3.2. Model calibration and validation

Some of the most important model calibration datasets including the initial and maximum canopy cover, canopy growth and decline coefficients, duration to flowering, senescence and maturity as well as the water stress response values for acceleration of leaf senescence, inhibition of leaf growth and stomata conductance and normalized water productivity are presented in Table 5.

Among the parameters used in the model, canopy cover was a key element in the calibration process (Fig. 4). The result indicated that the simulated canopy cover fitted very well with the measured data (Fig. 4). Statistical evaluation for canopy cover is also presented in Table 6. The NRMSE, index of agreement and R^2 values for canopy cover were 7%, 0.5 and 0.8, respectively. Over the growing season, deviations across the corresponding observed and simulated canopy cover ranged from 5 to 13%. This shows that the simulated canopy cover was in agreement with the observed data. The NWP, derived based on Eq. (2) was estimated to be 31 g/m².

Table 5
Some of the selected *Quncho*-teff crop parameters used for calibrating AquaCrop model.

Crop parameters	Unit	Value	Remark
Normalized crop water productivity	g/m ²	31	Estimated
Maximum canopy cover	%	81	Measured
Initial canopy cover	%	0.5	estimated
Canopy growth coefficient per GDD	%	1.168	Calibrated
Canopy decline coefficient per GDD	%	1.477	Calibrated
Senescence stress coefficient	–	3	calibrated
curve shape			
Upper threshold for early canopy senescence	–	0.71	Calibrated
Upper threshold for canopy expansion	–	0.24	Calibrated
Lower threshold for canopy expansion	–	0.6	Calibrated
Upper threshold for stomata closure	–	0.6	calibrated
Stomata stress coefficient	–	3	calibrated
curve shape			
Crop coefficient for transpiration at max CC	–	1.0	Literature: (Araya et al., 2011)
Maximum rooting depth	m	0.42	Measured
Length of buildup of HI	GDD	387	Estimated
Reference Harvest Index	%	23	Measured
Duration of flowering	GDD	147	Field observation
Duration from sowing to flowering	GDD	565	Field observation
Duration from sowing to emergence	GDD	48	Field observation
Duration from sowing to start of senescence	GDD	864	Field observation
Duration from sowing to maximum canopy cover	GDD	700	Field observation
Duration to maturity	GDD	1032	Field observation

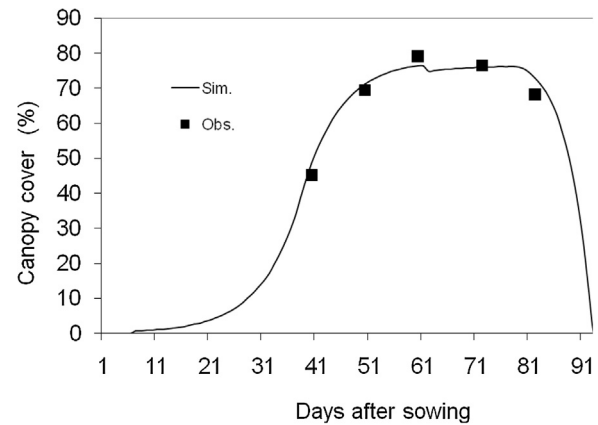


Fig. 4. The simulated and measured canopy cover for fully irrigated teff during the cropping season in 2012.

Table 6

Result of the statistical evaluation between the measured and simulated biomass, yield, soil water, canopy cover and sequential biomass for *Quncho*-teff, Ethiopia.

Statistics	BM	Y	SW	CC	Sq. BM
NRMSE (%)	7.80	10.90	11.4–15.7	7.0	22–30
I	0.89	0.93	0.98–0.99	0.5	0.93–0.95
R ²	0.66	0.80	0.85–0.90	0.8	0.92–0.93

BM, biomass; Y, yield; SW, soil water; CC, canopy cover; Sq. BM, sequential biomass; I, index of agreement; NRMSE, normalized root mean square of error.

Almost all of the measured soil moisture content, during the experimental season in 2012 at MK was well simulated by the model. This was also proved by the overall statistical agreement between the simulated and observed soil moisture during the season (NRMSE, 11.4–15.7%; I, 0.99; R^2 , 0.85–0.90; d, 24.9–27.5%) (Table 6).

The simulated final aboveground biomass was also in good agreement with the measured biomass (Tables 6–8). The model's good simulation result was reflected by the low NRMSE values (7.8%), high index of agreement (0.89), strong R^2 value (0.66) and moderate d values (–9.6 to 14.6%) (Tables 6–8). Similarly, the simulated sequential aboveground biomass was also in satisfactory agreement with the measured data (Fig. 5a–c). Moreover, there was a good agreement between the simulated and measured grain yield (Tables 6–8). The good agreement (between the simulated and measured grain yield) is reflected by NRMSE, index of agreement (I), R^2 and deviation (d) values of 10.9%, 0.93, 0.80 and –13.8 to 8.9%, respectively (Tables 6–8).

Table 7

Simulated versus measured soil water at the top 45 cm for *Quncho*-teff with two and four irrigations during the cropping season in 2012 at MK site, northern Ethiopia.

DAP	With 2 irrigation			With 4 irrigation		
	Obs. SW (mm)	Sim. SW (mm)	d (%)	Obs. SW (mm)	Sim. SW (mm)	d (%)
19	160	160	0	152	160	5.9
29	142	124	–13	144	124	–13.9
38	106	129	21	123	129	4.3
48	122	136	11	107	136	27.5
58	98	91	–7	104	91	–12.2
70	88	87	–2	89	98	10.6
80	77	78	2	104	78	–24.9
90	66	76	16	64	77	20.8

DAP, days after planting; Sim, simulated; Obs., measured; d , is deviation; SW, soil water; d , percent of change.

Table 8

The percent of deviation between measured and simulated yield and biomass for *Quncho*-teff at MK in 2012, IL in 2012 and DZ in 2009 and 2010.

Year	Site	Obs.BM (t/ha)	Sim.BM (t/ha)	d (%)	Obs. Y (t/ha)	Sim. Y (t/ha)	d (%)
*2012	MK	10.4	11.7	12.3	2.2	2.0	−10.3
2012	MK	9.6	10.2	6.3	2.1	1.8	−13.8
2012	MK	9.8	8.9	−9.6	2.0	1.7	−13.8
2016	MK	13.1	12.1	−8.0	3.3	2.8	−14.0
2012	IL	10.8	10.7	−0.9	2.8	2.8	0.0
2012	IL	9.2	9.2	−0.2	1.7	1.8	7.6
2009	DZ	11.2	12.9	14.6	2.7	2.9	8.9
2010	DZ	11.8	12.0	1.7	2.9	2.7	−6.9

BM, biomass; Y, yield; Obs, measured; Sim, simulated; MK, IL and DZ, are Mekelle, Ilala and Debrezeit Experimental sites, respectively. *Calibration dataset.

3.3. Sowing date scenarios

Figs. 6 and 7. show the impact of sowing date on biomass and yield of teff for MK and DZ site as simulated using AquaCrop model. In both sites, the highest biomass and yield were obtained for early when compared to normal and late sowing. Yield and biomass of *Quncho*-teff were lower in sandy loam than clay loam and loam soils.

3.4. Irrigation scenarios

The interaction effect of soil types, sowing date and irrigation levels on *Quncho*-teff yield and irrigation water productivity for both MK and DZ sites are presented in Tables 9–10, respectively. Regardless of the soil types, teff irrigation water productivity was generally improved when one irrigation was applied for the teff sown during normal sowing window and when two irrigations were applied for the teff sown during the late season (sown during late sowing window). The IWP for teff, sown at normal sowing window (with one irrigation) ranged from 1.9 to 4 and 0 to 4 kg/m³ for DZ and MK sites, respectively. In both sites, the highest and lowest

IWP values (as indicated in the ranges) were for teff grown in sandy loam and clay loam soils, respectively. For late sown teff, applying two irrigations was found to be optimal. The IWP for late sown teff with two irrigations were found to be 3.4 and 3.1 kg/m³ for DZ and MK sites, respectively. In both sites, yield did not respond much to irrigation when teff was sown early except for teff sown on sandy loam soils.

4. Discussion

4.1. Teff – water and fertilizer relations and irrigation water productivity

This study showed a substantial decrease in yield when high (N2P2) fertilizer was applied under water stress (no irrigation) when compared to zero (N0P0) or moderate (N1P1) fertilizer application at IL site. This might be attributed to uptake of nutrients such as nitrogen by the crop during the pre-flowering period when the soil water was adequate which then resulted in high biomass growth and later on enhanced quick senescence and reduced grain formation and grain filling due to shortage of water after the cessation of rain (e.g. Giunta et al., 1993; Acevedo et al., 2002; Rusan et al., 2005). The currently recommended fertilizer rate by the ministry of agriculture for the study sites corresponds to N2P2 (Pers. com). Applying this amount seems not advisable when adequate water is not available during a growing season. For example, teff treated with high fertilizer at IL site was severely affected by water stress compared to those with moderate or no fertilizer application which might be due to quick senescence and reduced translocation of syntheses and eventually reduce yield. On the other hand, a substantial increase in teff yield was observed when N1P1 was applied as compared to that of N0P0. The yield increase due to application of N2P2 compared to N1P1 was minor considering the doubling of the quantity of fertilizer. This implies that farmers are advised to spread the half dose of the recommended rate (N1P1) over larger area when farmers are not in a position to get access to enough

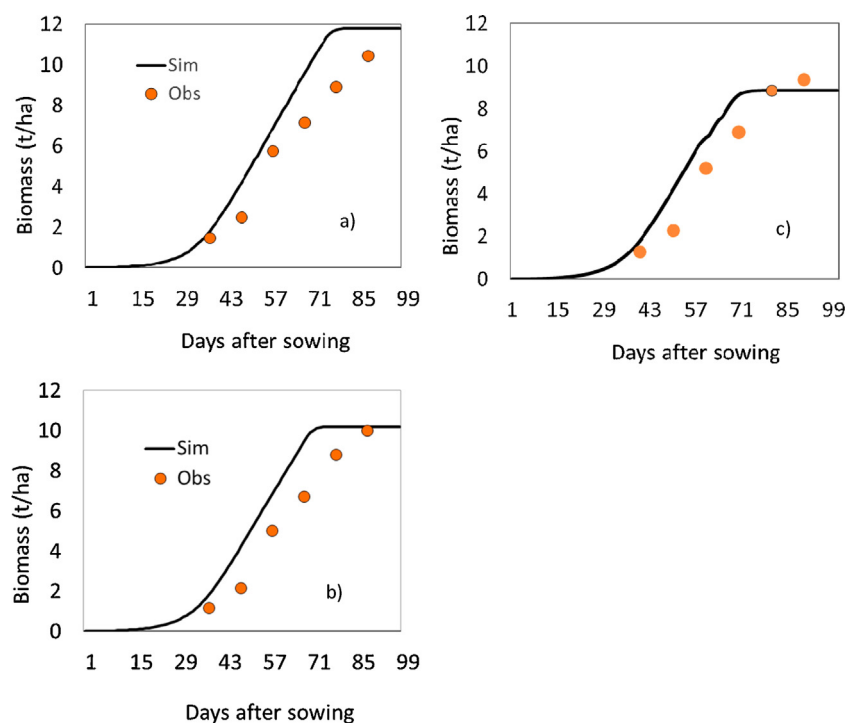


Fig. 5. Simulated versus measured sequential biomass growth during the growing season in 2012 under full (a) four irrigation (b) and two irrigation (c) conditions at MK site, northern Ethiopia.

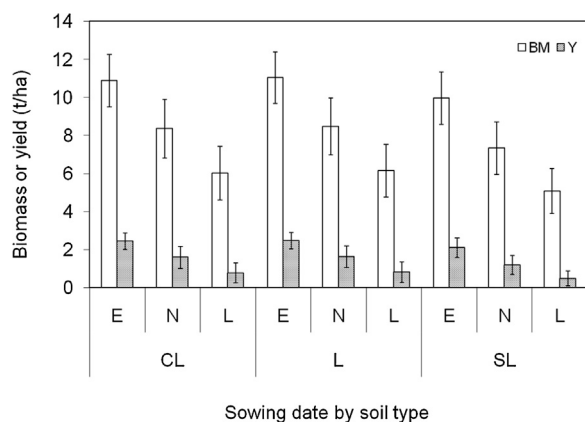


Fig. 6. Simulated average *Quncho-teff* yield and biomass for Mekelle area for the baseline period (1980–2009) based on early (E), normal (N) and late (L) sowing in three soil types (CL, clay loam; L, loam; SL, sandy loam). BM, biomass; Y, yield.

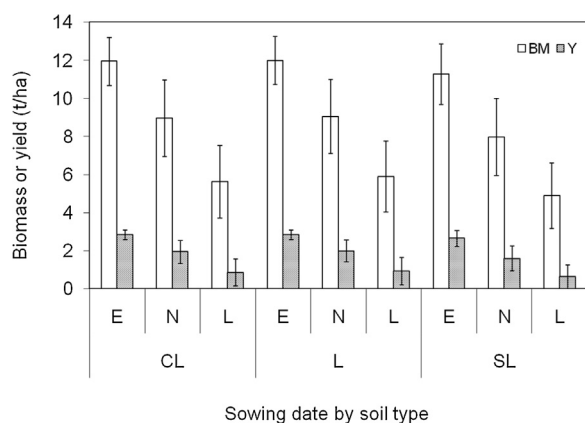


Fig. 7. Simulated average *Quncho-teff* yield and biomass for DZ area for the baseline period (1980–2009) based on early (E), normal (N) and late (L) sowing in three soil types (CL, clay loam; L, loam; SL, sandy loam). BM, biomass; Y, yield.

fertilizer for any reasons. This also suggests that farmers may apply N1P1 when seasonal rainfall forecast is below normal or when rainfall is expected to cease earlier than normal. Tsegay et al. (2015) also verified that farmers with 50% of the recommended fertilizer rate could be able to produce significantly higher yield compared to those with no fertilizer application.

The highest irrigation water productivity at both MK and IL sites were obtained from deficit and fully irrigated treatments, respectively. The inconsistency in IWP at the two experimental sites might be caused by factors such as differences in soil water and initial nutrient conditions as well as spatial rainfall variability. For example, the soil textural class at MK and IL sites were dominantly sandy clay loam with a maximum depth of 0.6 m and loam to clay loam with a depth of 1.2 m, respectively. This may create difference in soil water characteristics which might in turn contribute to variation in teff water use even if similar level of water and fertilizer are applied. Some reports also showed that differences in Sulphur content of the soils may also limit the nitrogen uptake and utilization (Habtegebrail and Singh, 2006; Habtegebrail et al., 2013) which may again affect yield and contribute to inconsistency in water productivity.

4.2. Model calibration and validation

The water stress effects for reduction of stomatal conductance and canopy growth and for acceleration of leaf senescence of *Quncho-teff* were close but slightly deviated from those obtained

Table 9

The interaction effect of soil type, sowing date and irrigation levels on *Quncho-teff* yield and irrigation water productivity for Mekelle (MK) site.

Soil type	plt.d	Parameter	1 irr. (20 mm)	2 irr. (40 mm)	4 irr. (80 mm)	0 irr. (control)
Clay loam	Early	Y (t/ha)	3.0	3.0	2.8	2.9
		IWP (kg/m ³)	0.7	0.3	0.0	
	Normal	Y (t/ha)	2.5	2.5	2.5	2.5
		IWP (kg/m ³)	0.0	0.0	0.0	
	Late	Y (t/ha)	1.0	1.9	2.4	0.6
		IWP (kg/m ³)	1.9	3.1	2.3	
Loam	Early	Y (t/ha)	3.0	3.0	2.9	2.8
		IWP (kg/m ³)	0.8	0.4	0.0	
	Normal	Y (t/ha)	2.5	2.8	3.18	1.8
		IWP (kg/m ³)	3.5	2.5	1.7	
	Late	Y (t/ha)	0.6	1.9	2.5	0.6
		IWP (kg/m ³)	0.0	3.1	2.3	
Sandy loam	Early	Y (t/ha)	2.9	2.9	2.9	2.6
		IWP (kg/m ³)	1.4	0.7	0.4	
	Normal	Y (t/ha)	2.1	2.6	3.0	1.3
		IWP (kg/m ³)	4.0	3.2	2.1	
	Late	Y (t/ha)	0.4	1.5	2.2	0.4
		IWP (kg/m ³)	0.0	2.6	2.2	

plt.d, planting date; irr., irrigation level; IWP, irrigation water productivity; Y, yield.

Table 10

The interaction effect of soil type, sowing date and irrigation levels on *Quncho-teff* yield and irrigation water productivity for Debrezeit (DZ) site.

Soil type	plt.d	Parameter	1 irr. (20 mm)	2 irr. (40 mm)	4 irr. (80 mm)	0 irr. (control)
Clay loam	Early	Y (t/ha)	2.9	2.9	2.9	2.9
		IWP (kg/m ³)	0.0	0.0	0.0	
	Normal	Y (t/ha)	2.9	3.1	3	2.5
		IWP (kg/m ³)	1.9	1.6	0.6	
	Late	Y (t/ha)	1.1	2.1	2.8	0.71
		IWP (kg/m ³)	2.0	3.4	2.6	
Loam	Early	Y (t/ha)	2.9	2.9	2.9	3.0
		IWP (kg/m ³)	−0.3	−0.2	−0.1	
	Normal	Y (t/ha)	2.9	3.1	3.0	2.4
		IWP (kg/m ³)	2.4	1.9	0.8	
	Late	Y (t/ha)	1.3	2.1	2.8	0.7
		IWP (kg/m ³)	3.1	3.4	2.6	
Sandy loam	Early	Y (t/ha)	2.9	2.9	2.9	3.12
		IWP (kg/m ³)	−1.1	−0.6	−0.2	
	Normal	Y (t/ha)	2.6	2.9	3.0	1.8
		IWP (kg/m ³)	4.0	2.9	1.5	
	Late	Y (t/ha)	0.9	1.7	2.8	0.4
		IWP (kg/m ³)	2.6	3.4	3.0	

plt d, planting date; irr., irrigation level; IWP, irrigation water productivity; Y, yield (t/ha).

in previous studies. The disparity could be attributed to the differences in response of the teff cultivars to water stress. Compared to teff varieties grown in previous studies, the variety, *Quncho* – teff, seems yield better when grown under similar agro-ecology. For this reason, farmers in the drought prone areas (such as in the northern Ethiopia) are almost shifting from growing the local teff cultivars to this new variety. Recent reports indicated that *Quncho*-teff (at seedling rate of 5 kg/ha) could even yield far more than (Giday, 2012) the yield level obtained in our study sites.

The length of days to start of senescence and maturity for *Quncho*-teff was also observed to vary with varying nitrogen applications and water availability. For example, nitrogen and water application towards the mid and end of the 2016 cropping season slightly delayed the days to senescence [917° day (dd)] and maturity (1106 dd) when compared to teff in 2012 (senescence 853 dd and maturity 1032 dd). These differences, however, have not appreciably reduced the validity of the model in simulating the measured yield and biomass. Similarly, harvest index (HI) widely varied ranging from 0.16 to 0.31 across the observation years. However, the most common HI value during the calibration year (2012) in our experiment site (MK) was 0.23. The source of this variability was unclear but it could be due to variations, among others, in plant density, extent of lodging, and variations in essential nutrients and water availability during teff growing seasons.

The NWP for C4 crops range between 30–35 g/m² (Steduto et al., 2007, 2009; Raes et al., 2010a, 2010b). The NWP value in this study (31 g/m²) corresponded well to the NWP of C4 crops. This NWP value permitted the simulation of the measured results. One of the possible reasons for the correspondence of *Quncho* – teff's NWP to C4 in this study might be attributed to minimal biomass loss (due to lodging) during the experimental season. Lodging is one of the major problems which could significantly affect the NWP. Other possible reason could be attributed to the increased access to more data set over time. Studies indicated that use of more experimental data from divers location could substantially improve the calibration of the model for a given crop (Hsiao et al., 2009). Furthermore, the cultivar, *Quncho* – teff, seems to slightly differ in its response to water (as mentioned before) compared to other local cultivars. More work may be needed to refine this calibration by adding more datasets from many locations and seasons.

The model satisfactorily simulated the measured sequential aboveground biomass of teff. Similar to the sequential aboveground biomass, the final aboveground biomass and yield were also adequately simulated by the model. In implication, the model can be used as a tool for exploring optimum utilization and management of farm resources.

5. Optimal sowing and irrigation strategies

Optimal sowing strategy could contribute to minimize total crop failure in dryland areas (Araya et al., 2012). Optimal sowing has been considered to be a less costly climate smart farm resources strategy for enhancing yield and biomass through maximizing rainwater utilization. Our study indicated that early sowing could improve yield and biomass regardless of the soil type. Teff can be grown without irrigation if sown at the right time. This confirms previous works for other cultivars by Tsegay et al. (2015). One of the major reasons for better yield performance of teff with early sowing might be mainly attributed to its contribution in minimizing risks of drought stress due to matching of the rainy period with the crop growing season (Araya et al., 2012). Early sowing also contributes to match crop growing cycle with the favorable moist and cool temperatures conditions of the summer rainy period. However, growers should carefully evaluate the optimal sowing date at

local level as teff needs wet seedbed at time of sowing and establishment.

Farmers should try to maximize the benefits from rainwater (by using early sowing strategy) and avoid yield losses due to late season drought stress. In some of the cases, the rainfall in northern Ethiopia was reported to start late or cease early (Araya et al., 2012). In practice, some farmers also sow teff during the late sowing time (due to shortage of labour, oxen or sometimes due to late start of rains) which may lead to unacceptably high loss of yield.

Farmers with access to irrigation should irrigate once approximately during flowering period to get moderate yield from teff sown during the normal sowing window. For late sown teff, two irrigations (approximately at time of heading and flowering) was also found to improve the IWP and yield at both MK and DZ sites. Late sowing could result in total loss of yield if not supplemented with irrigation especially on sandy loam soils. The rainfed yield on sandy loam soils ranged from 0.4 to 0.7 t/ha which is too low considering all the involved costs of production.

On the other hand, application of four irrigations for teff seems not acceptable as teff IWP with four irrigations was lower than teff with two irrigations. Despite the high IWP for late sown teff (with two irrigations), the yield level was substantially lower than that of teff with four irrigations. It is therefore concluded that if irrigation water but not land is a constraint, farmers may maximize teff production with two irrigations from relatively larger area (of late sown teff) than applying four irrigations on a limited area. When the constraint is land but not irrigation water, farmers may apply four irrigations (during the mid- growth stage of the crop) to maximize production from limited area.

6. Conclusions

This research showed that AquaCrop was able to simulate the canopy cover, soil water in the root zone, the final aboveground and grain yield for *Quncho*-teff with satisfactory accuracy.

The normalized water productivity (NWP) for *Quncho*-teff was estimated as 31 g/m². However, it should be noted that this NWP value may not hold the same for other teff cultivars since previous studies for other cultivars reported lower than this value. More work may be needed to refine the calibration for *Quncho*-teff by adding more dataset from many locations and seasons. Once comprehensively calibrated, the conservative calibration data sets may be extrapolated across wide ranges of locations and agro-ecologies.

The highest grain (>2.8 t/ha) and biomass yield (>10 t/ha) were obtained from treatment combinations with full irrigation and high fertilizer (52–64 kg N and 46 kg P/ha). There was some level of inconsistencies in terms of IWP that resulted from initial soil fertility and soil water status and rainfall variability. However, this finding is consistent with previous studies in that (full) irrigation in combination with high fertilizer could give better yield. Also, moderate fertilizer (32 kg N and 23 kg P/ha) application seems to give modest yield for *Quncho*-teff. Thus, when access to nitrogen fertilizer or when economic conditions limit nitrogen application or during abnormal rainfall (when rainy period is expected to be too short due to late start or early cessation), spreading the available fertilizer with a rate of 32 kg N and 23 kg P/ha may be preferable to applying 64 kg N and 46 kg P/ha. We also suggest that the regional fertilizer recommendation for teff need to be revised by considering the soil fertility, long-term climate and water availability.

Early sowing was found to be the optimal strategy for growing *Quncho*-teff in the study sites. Teff growers may be able to obtain good yield without irrigation if early sowing is practiced. If normal sowing is practiced, farmers should apply at least one irrigation (at time of flowering) to get a modest yield. A minimum of two irrigations (at 50 and 60 days after sowing) may be needed if sowing

was carried out late during the season. However, for high teff yield, water and nutrient demand should be met throughout the season.

The approaches used in evaluating agronomic farm resources optimization strategy were meant for guiding different groups of farmers growing *Quncho*-teff and optimize their farm resources for sustainable teff productivity. Such researches supported with crop models could be useful to devise better resources optimization strategy in teff growing areas.

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References

- Acevedo, E., Silva, P., Silva, H., 2002. Wheat growth and physiology. In: Curtis, B.C., Rajaram, S., Gómez Macpherson, H. (Eds.), *Bread Wheat Improvement and Production*. FAO, Rome, Italy.
- Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration Guidelines for computing crop water requirements. Irrigation and Drainage Paper, 56. FAO, Rome.
- Araya, A., Stroosnijder, L., 2011. Assessing drought risk and irrigation need in northern Ethiopia. *Agric. Forest Meteorol.* 151, 425–436.
- Araya, A., Keesstra, S.D., Stroosnijder, L., 2010a. Simulating yield response to water of teff (*Eragrostis tef*) with FAO's AquaCrop Model. *Field Crops Res.* 116, 196–204.
- Araya, A., Solomon, H., Kiros, M.H., Afewerik, K., Taddese, D., 2010b. Test of AquaCrop model in simulating biomass and yield of water deficient and irrigated barley (*Hordeum vulgare*). *Agric. Water Manage.* 97, 1838–1846.
- Araya, A., Keesstra, S.D., Stroosnijder, L., 2010c. A new agro-climatic classification for crop suitability zoning in northern semi-arid Ethiopia. *Agric. Forest Meteorol.* 150, 1047–1064.
- Araya, A., Stroosnijder, L., Girmay, G., Keesstra, S.D., 2011. Crop coefficient, yield response to water stress and water productivity of teff (*Eragrostis tef* (Zucc.). *Agric. Water Manage.* 98, 775–783.
- Araya, A., Stroosnijder, L., Habtu, Solomon, Keesstra, Saskia D., Berhe, Mache, Meles Hadgu, Kiros, 2012. Risk assessment by sowing date for barley (*Hordeum vulgare*) in northern Ethiopia. *Agric. Forest Meteorol.* 154–155, 30–37.
- Araya, A., Hoogenboom, G., Luedeling, E., Kiros, M.Hadgu, Kisekka, I., Martorano, L.G., Martorano, 2015. Assessment of maize growth and yield using crop models under present and future climate in southwestern Ethiopia. *Agric. Forest Meteorol.* 214–215, 252–265.
- Araya, A., Kisekka, I., Holman, J., 2016. Evaluating yield and water productivity of grain sorghum under deficit irrigation, variable climate, soils, and planting dates using AquaCrop. Model. *Irrig. Sci.*, <http://dx.doi.org/10.1007/s00271-016-0515-7>.
- Assefa, K., Ketema, S., Tefera, H., Nguyen, H.T., Blum, A., Ayele, M., Bai, G., Simane, B., Kefyalew, T., 1999. Diversity among germplasm lines of the Ethiopian cereal teff (*Eragrostis tef* (Zucc.) Trotter). *Euphytica* 106, 87–97.
- Assefa, K., Merker, A., Tefera, H., 2003. Inter simple sequence repeat (ISSR) analysis of genetic diversity in teff [*Eragrostis tef* (Zucc.) Trotter]. *Hereditas* 139, 174–183.
- Assefa, K., Aliye, S., Belay, G., Metaferia, G., Tefera, H., Sorrells, M.E., 2011. *Quncho*: the first popular teff variety in Ethiopia. *Int. J. Agric. Sustain.* 9 (1), 25–34.
- Ayalneh, T., Habtamu, K.Z., Amsalu, A., 2012. Genetic variability, heritability and genetic advance in teff (*Eragrostis tef* (Zucc.) Trotter) lines at sinana and adaba. *Int. J. Plant Breed. Genet.* 6, 40–46, <http://dx.doi.org/10.3923/ijpb.2012.40.46>.
- Balcha, A., Gretzmacher, R., Vollmann, J., 2006. Genetic variation in nitrogen – use efficiency of teff. *J. Plant Nutr. Soil Sci.* 169, 704–710.
- Booth, D.T., Cox, S.E., Berryman, R.D., 2006. Point sampling digital imagery with 'SamplePoint'. *J. Environ. Environ. Monit. Assess* 123, 97–108.
- CSA, 2012. Agricultural sample survey 2011/2012. Report on Area and Production of Major Crops (private Peasant Holding). Vol. I. Addis Ababa, Ethiopia.
- Demissie, A., 2001. Teff genetic resources in Ethiopia. In: Tefera, H., Belay, G., Sorrells, M. (Eds.), *Narrowing the Rift: Teff Research and Development*. Proc. Int. Workshop on Teff Genetics and Improvement, DebreZeit, Ethiopia, pp. 27–31.
- FAO, 2009. ETo calculator version 3.1. In: *Evapotranspiration from Reference Surface*. FAO, Land and Water Division, Rome, Italy.
- Fufa, B., Behute, B., Simons, R., Berhe, T., 2011. Strengthening the Teff Value Chain in Ethiopia Agricultural Transformation Agency, Ethiopia.
- Giday, O., 2012. Soil fertility characterization and response of wheat (*triticumaestivum*) and teff (*eragrostistef*) to different rates of slow release and conventional urea fertilizers in vertisols of Ofra district, southern Tigray, Ethiopia. In: *Athesis thesis submitted to the college of agriculture and environmental sciences. School of graduate studies Haramaya university, Ethiopia*.
- Giunta, F., Motz, R., Deilda, M., 1993. Effect of drought on yield and yield component of durum wheat and triticale in Mediterranean environment. *Field Crops Res.* 33, 399–409.
- Habtegebrail, K., Singh, B.R., 2006. Effects of timing of nitrogen and sulphur fertilizers on yield, nitrogen, and sulphur contents of Tef (*Eragrostis tef* (Zucc.) Trotter). *Nutr. Cycl. Agroecosyst.* 75, 213–222.
- Habtegebrail, K., Mersha, S., Habtu, S., 2013. Nitrogen and sulphur fertilizers effects on yield, nitrogen uptake and nitrogen use efficiency of upland rice variety on irrigated Fulvisols of the Afar region Ethiopia. *J. Soil Sci. Environ. Manage.* 4 (3), 62–70, <http://dx.doi.org/10.5897/JSSSEM13.0389>.
- Hailay, H., 2012. Simulating development, biomass and yield of Quncho-teff using FAO's AquaCrop model. A case study in Mekelle area. In: MSc Thesis. Department of Land Resources Management and Environmental Protection. College of Dryland Agriculture and Natural Resources. Mekelle University.
- Heng, L.K., Hsiao, T., Evett, S., Howel, T., Steduto, P., 2009. Validating the FAO AquaCrop model for irrigated and water deficient field maize. *J. Agron.* 101, 488–498.
- Hsiao, T.C., Heng, L., Steduto, P., Roja-Lara, B., Raes, D., Fereres, E., 2009. AquaCrop-The FAO model to simulate yield response to water: parameterization and Testing for Maize. *J. Agron.* 101, 448–459.
- Kiros, G., 2012. Evaluating performance of teff [*EragrostisTef* (Zucc.)Trotter] under different water levels and N-P fertilizer rates in tigray region, northern Ethiopia. In: MSc Thesis. Department of Crop and Horticultural Sciences. College of Dryland Agriculture and Natural Resources, Mekelle University.
- Nielsen, D., Miceli-Garcia, J.J., Lyon, D.J., 2012. Canopy cover and leaf area index relationships for wheat, triticale, and corn. *J. Agron.* 104, 1569–1573.
- Paredes, P., de Melo-Abreu, J.P., Alves, I., Pereira, L.S., 2014. Assessing the performance of the FAO AquaCrop model to estimate maize yields and water use under full and deficit irrigation with focus on model parameterization. *Agric. Water Manage.* 144, 81–97.
- Raes, D., Steduto, P., Hsiao, T.C., Fereres, E., 2009. AquaCrop-The FAO crop model to simulate yield response to water: II. Main Algorithms and software description. *J. Agron.* 101, 438–447.
- Raes, D., Steduto, P., Hsiao, T.C., Fereres, E., 2010a. Chapter 2 User Guide Refence Manual AquaCrop, Version 3.1. Land and Water Division, Rome, Italy.
- Raes, D., Steduto, P., Hsiao, T.C., Fereres, E., 2010b. Chapter 3 Calculation Procedure Manual AquaCrop, Version 3.1. Land and Water Division, Rome, Italy.
- Rosenberg, R.J., Norberg, S., Smith, J., Charlton, B., Rykbost, K., Shock, C., 2005. Yield and quality of teff forage as a function of varying rate of applied nitrogen and irrigation. In: *Annual Report. Research in the Klamath Basin*.
- Rusan, M.M., Battikhi, A., Zuraiki, S., 2005. Enhancement of nitrogen and water use efficiency by optimizing the combination of soil, crop and nitrogen management. In: *Management of Nutrients and Water in Rainfed Arid and Semi-Arid Areas for Increasing Crop Production*. IAEA-TECDOC- 1468, pp. 155–177.
- Shiferaw, W., Balcha, A., Mohammed, H., 2012. Genetic variation for grain yield and yield related traits in Tef [*Eragrostistef*(Zucc.) Trotter] under moisture stress and non-stress environments. *Am. J. Plant Sci.* 3, 1041–1046.
- Spaenij-Dekking, L., Kooy-Winkelaar, Y., Koning, F., 2005. The Ethiopian cereal teff in celiac disease. *N. Eng. J. Med.* 353, 1748–1749.
- Steduto, P., Hsiao, T.C., Fereres, E., 2007. On the conservative behavior of biomass water productivity. *Irrig. Sci.* 25, 189–207.
- Steduto, P., Hsiao, T.C., Raes, D., Fereres, E., 2009. AquaCrop–The FAO crop model to siMklate yield response to water: i. concepts. *J. Agron* 101, 426–437.
- Todorovic, M., Albrizio, R., Ljubomir, Z., Abi-Saab, M.-T., Stockle, C., Steduto, P., 2009. Assessment of AquaCrop, CropSyst, and WOFOST Models in the simulation of sunflower growth under different water regimens. *Agron J.* 101, 509–552.
- Tsedale, D., 2014. Analysis of future climate change impacts on teff production, a case of Debrezeit district, Oromia region-Ethiopia. In: MSc Thesis. Mekelle University, Institute of Climate and Society, Mekelle, Ethiopia.
- Tsegay, A., Raes, D., Geerts, S., Vanuytrect, E., Abraha, B., Deckers, D., Bauer, H., Gebrehiwot, K., 2012. Unravelling crop water productivity of teff (*Eragrostistef*(Zucc.) Trotter) through AquaCrop in Northern Ethiopia. *Exp. Agric.* 48 (2), 222–237.
- Tsegay, A., Vanuytrect, E., Abrha, B., Deckers, J., Gebrehiwot, K., Raes, D., 2015. Sowing and irrigation strategies for improving rainfedteff (*Eragrostistef* (Zucc.) Trotter) production in the water scarce Tigray region. Ethiopia Agric. Water Manage. 150, 81–91.
- Willmott, C.J., 1982. Some comments on the evaluation of model performance. *Bull. Am. Meteorol. Soc.* 63, 1309–1313.
- Yihun, Y.M., 2015. Agricultural water productivity optimization in a water scarce semi- arid region of Ethiopia. In: PhD Thesis. Delft, The Netherlands.