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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 Ethiopa [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 R^2 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 R^2 of 0.85–0.9. Simulated final aboveground biomass values were in close agreement with the measured (NRMSE, 7.8%, I, 0.89 and R^2, 0.66). There was also good agreement between simulated and measured grain yield with NRMSE, I and R^2 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 loses 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 (Habtegebrial 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 scare 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 asses 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).