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Identifying low risk and profitable crop management practices for irrigated Teff production in northwestern Ethiopia

Fekremariam Asargew Mihretie[a,b,c,*], Kindie Tesfaye[d], Gerrit Hoogenboom[e,f], Atsushi Tsunekawa[c], Adamu Molla[g], Kindiye Ebabu[c], Shinjiro Sato[b], Yuji Masutomi[a]

[a] Center for Climate Change Adaptation, National Institute for Environmental Studies, 16–2, Onogawa, Tsukuba, Ibaraki 305–8506, Japan
[b] Department of Science & Engineering for Sustainable Innovation, Soka University, 1–236 Tangimachi, Hachiojishi, Tokyo 192–8577, Japan
[c] Arid Land Research Center, Tottori University, 1390 Hamasaka, Tottori 680–0001, Japan
[d] International Maize and Wheat Improvement Center (CIMMYT), PO Box 5689, Addis Ababa, Ethiopia
[e] Department of Agricultural and Biological Engineering, University of Florida, Gainesville, Florida 32611–0570, USA
[f] Food Systems Institute, University of Florida, Gainesville, Florida 32611–0570, USA
[g] Amhara Regional Agricultural Research Institute, PO Box 527, Bahir Dar, Ethiopia

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ABSTRACT

Teff (*Eragrostis tef* (Zucc.) Trotter) is one of the most important staple crops in Ethiopia. However, the optimal agronomic practices of the crop under irrigation remain unclear. The objectives of this study were to evaluate the Cropping System Model (CSM)-NWheat-Teff and to determine the optimum planting date, nitrogen (N) application rate, and irrigation threshold in northwestern Ethiopia. The model was calibrated and evaluated using published data from field experiments conducted from 1996 to 1998 in the Adet and Bichena districts and from 2001 to 2003 in the Dangila district. The model was then used to simulate different planting dates (Jan 1, Jan 15, Feb 1, Feb 15, Mar 1), N rates (0, 20, 40, 60, 80 kg ha^{-1}), and irrigations (irrigation when required/automated, 50% and 25% available soil moisture thresholds) levels for Adet, Bichena and Dangila using historical weather data (1983–2020). The model was able to simulate teff phenology and yield adequately as indicated by low root mean square error (RMSE) and a high index of agreement (d) for both the calibration and evaluation datasets. Grain and straw yield increased with increasing N, but the rate of increment was higher under irrigation when required (automated) compared to 50% and 25% thresholds. Late planting (March 1) at Adet and early planting (January 1 and February 15) at Bichena and Dangila resulted in the highest profit with a minimum variability in output. The combined use of 80 kg N ha^{-1} and irrigation when required gave the most profitable option with low risk of irrigated teff production at the three sites studied. This study showed that the new CSM-NWheat-Teff model can be used to optimize agronomic practices for irrigated teff production systems in Ethiopia. Further research is needed to improve model performance in predicting teff yield for contrasting biophysical and socio-economical environments.

1. Introduction

Teff (*Eragrostis teff* (Zucc.) Trotter) originated in Ethiopia (Assefa, 2003; Vavilov, 1951). Teff is a cereal crop and is the staple food crop of the local people in Ethiopia, while teff straw is preferred as feed for livestock (Assefa et al., 2011). Annually, 3 million ha of land is cultivated in teff, producing 5.2 million tons of teff grain (CSA, 2018). Teff flour is used to make the traditional flat bread *injera* as well as pancakes, porridge, and alcoholic beverages. Teff is more tolerant to drought (Ketema, 1997) and less susceptible to waterlogging (Assefa et al., 2015) compared to other cereals such as wheat and barley. The demand for teff grain products is increasing globally owing to its lack of gluten (Zhu, 2018), while it is also rich in nutrients, including lysine, iron, and calcium (Mengesha, 1966).

The grain yield for teff has remained below 1500 kg ha^{-1} despite its importance as a staple crop in Ethiopia (CSA, 2018) and increasing

Abbreviations: DSSAT, Decision Support System for Agrotechnology Transfer; CSA, Central Statstics Authority; DZ, Debre Zeit; N, Nitrogen; P, Phosphorus.

* Corresponding author at: Center for Climate Change Adaptation, National Institute for Environmental Studies, 16–2, Onogawa, Tsukuba, Ibaraki 305–8506, Japan.

E-mail address: Fikruas2005@gmail.com (F.A. Mihretie).

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demand for its product globally. The average yield is 26–28% lower than yield of wheat and barley (Demeke, 1999). As a result, it is difficult to satisfy the increasing market demand for teff grain (Minten et al., 2013). The price of teff grain is more expensive than other cereals in Ethiopia (Lee, 2018), and the export of teff grain has been banned since 2006 to avoid a shortage on the domestic market.

Teff cultivation in Ethiopia depends entirely on rainfall. Thus, the government is planning to expand its production using irrigation (Machado Mendes and Paglietti, 2015), but best management practices for irrigated teff have not yet been established. Optimizing agronomic inputs for teff is a prerequisite for its success, but little effort has been made until now. An appropriate planting window, N management, and irrigation water requirements are key components that need to be carefully defined (Singh and Jain, 2000; Srivastava et al., 2018). In Ethiopia, rainfed crop production is from June to December, while irrigated production is from January to May (Taffesse et al., 2012). Similarly, the crop calendar for irrigated crop production lays between January to May (Tilahun et al., 2011). Generally, the irrigated crop production window (January to May) in Ethiopia is alternatively called as dry season because its dry and hot compared to the main rainy season (June to December). As teff is a C_4 crop that performs relatively well at high temperatures [10–27 °C;(VERHEYE, 1993)], irrigated teff should yield better than rainfed teff owing to better moisture availability and higher temperatures during the dry season (Tilahun et al., 2011).

It is well known that there is an increasing demand for water for crop production in developing countries including Ethiopia where both the number and the capacity of existing irrigation facilities are also very low (Desta et al., 2017). Knowledge of crop water requirements and appropriate irrigation strategies will play an important role in increasing yield by avoiding unnecessary loss of water because of the high cost of irrigation infrastructure and the limited availability of water during the dry season in Ethiopia (Desta et al., 2017). The total water requirement for teff ranges from 260 to 317 mm in the semi-arid environment (Araya et al., 2011), which is relatively less compared to most field crops such as wheat and barley (Araya et al., 2011; Ojeda et al., 2020). Crop water requirement varies with cultivar (Zhang et al., 2005), soil type, and local weather conditions (Allen et al., 1998). Therefore, the irrigation schedule must be matched to a specific growing environment. In irrigated environments, a more profitable yield is achieved with efficient water management and appropriate soil nutrient management practices (Wiedenfeld, 1995). Nitrogen improves crop growth by enhancing the radiation use efficiency and photosynthesis capacity (Harper, 1994; Sinclair and Horie, 1989). Teff production in Ethiopia is highly constrained by a decline in soil fertility (Haileslassie et al., 2006), aggravated by the application of little N-based inorganic fertilizers (Mwangi, 1996), high fertilizer costs, and lack of knowledge of appropriate N rates. The low yield of teff is associated mainly with low N application rates (Vandercasteelen et al., 2014). The economic N application rate recommended for rainfed teff ranges from 40 to 90 N kg ha^{-1} depending on location (Assefa et al., 2006; Habtegebrial et al., 2007; Liben et al., 2004). A farmer's decision to apply N fertilizer to teff is constrained by the high cost and occurrence of lodging (Araya et al., 2010). Yield reduction due to lodging becomes serious at higher N rates (>60 N kg ha^{-1}); yield losses increased by 60% when N increased from 60 to 90 N kg ha^{-1} in northwest Ethiopia (Habtegebrial et al., 2007). Because N management is a key component in irrigated crop production, N application rates for irrigated teff appropriate to soil type, the farmer's economic status, and lodging should be optimized to save time and money.

Crop models are important tools that can assist with analyzing and understanding the effects of different crop management strategies on yield and determining the best options with respect to yield, economic returns, and sustainability (Kihara et al., 2012; Tsuji et al., 1998). Unlike field experiments, they can support decision-making with minimal time and cost and reasonable accuracy (Boote et al., 1996). However, until now there have been limited studies on the use of crop models for teff. Recently, a new crop model Cropping System Model (CSM)-NWheat-Teff (Paff and Asseng, 2019) was developed as part of the Decision Support System for Agricultural Technology Transfer platform (DSSAT; www.DSSAT.net; Hoogenboom et al., 2019a; 2019b). The CSM-Nwheat-Teff until now has not been applied in Ethiopia because of the limited experimental data for model calibration and evaluation following standard procedures before practical application (Hoogenboom et al., 2019b; Jones et al., 2003). This study hypothesizes that the CSM-NWheat-Teff model can reasonably simulate teff yield for conditions in Ethiopia and be applied for identifying the best crop management practices for maximizing crop yield and economic benefits for irrigated teff. Therefore, the objectives of this study were to evaluate the CSM-NWheat-Teff model and to determine optimum management practices for irrigated teff production in northwestern Ethiopia.

2. Materials and methods

2.1. Study areas

This study sites are located in Adet (11°16′N, 37°29′E; 2216 m), Bichena (10°27′N, 38°12′E; 2541 m) and Dangila (11°16′N, 36°50′E; 2137 m a.s.l.) districts in the Upper Blue Nile Basin of northwestern Ethiopia (Fig. 1). The three districts were selected because of their good availability of soil profile and long-term weather data; they are also the major teff growing areas in Ethiopia (Mihretie et al., 2020). The elevation is 2216 m at Adet, 2541 m at Bichena, and 2127 m at Bichena (Ebabu et al., 2020). According to Gebreselassie (2002), the dominant soils are Nitosols at Adet and Vertisols at Bichena, and Acrisols at Dangila according to the Food and Agriculture Organization classification system. Based on long-term (1983–2020) climate observations, the mean annual rainfall is 1909 mm at Adet, 1266 mm at Bichena, and 1383 mm at Dangila (Fig. 2). The three sites receive more than 80% of their annual rainfall from June to September (Fig. 2). The mean daily temperatures are 19.0 °C at Adet, 23.1 °C at Bichena, and 20 °C at Dangila.

2.2. Model calibration and evaluation

The data that were used for the study were obtained from experiments previously conducted in the study areas (Adet, Bichena and Dangila districts). The field experiments were selected for the availability and relevance of the data to the purpose of this study. Two independent datasets from two studies conducted under rainfed condition were used for model calibration and evaluation. Dataset 1 was adapted from an experiment that was conducted by Assefa et al. (2006) during the 2000–2003 cropping seasons (June–December) at the Dangila site. The study evaluated five N rates (0, 20, 40, 60, and 80 kg ha^{-1}) combined with four P rates (0, 17.5, 26, and 35 kg ha^{-1}) in a randomized complete block design. Dataset 2 was adopted from an experiment that was conducted by Liben et al. (2004) during the 1996–1998 cropping seasons (June–December) at Adet and Bichena. The study assessed four N application rates (0, 20, 40, and 60 kg ha^{-1}) and four P application rates (0, 8.7, 17.5, and 26 kg ha^{-1}) in a randomized complete block design. Data for the 60 N kg ha^{-1} treatment, with the highest yield in the Adet were used for model calibration. The highest P rate were used for calibration (26 kg ha^{-1}). N rates from Bichena and Dangila were used for model evaluation **(supplement 1)**. The highest P rates were used for model evaluation. The teff cultivar DZ-01–354 was used for both experiments.

The new CSM-NWheat-Teff module of DSSAT Version 4.8 is developed to simulate the effects of weather, soil characteristics, genotype, and management factors on the growth and development teff (Hoogenboom et al., 2019a). DSSAT requires cultivar coefficients, daily weather, soil profile and crop management data as general input. The soil input data include soil texture, total N, organic carbon, bulk density, and pH at three depths (0–30, 30–90, 90–140 and 140–200 cm) as indicated in Table 1. The weather input data include daily total rainfall,

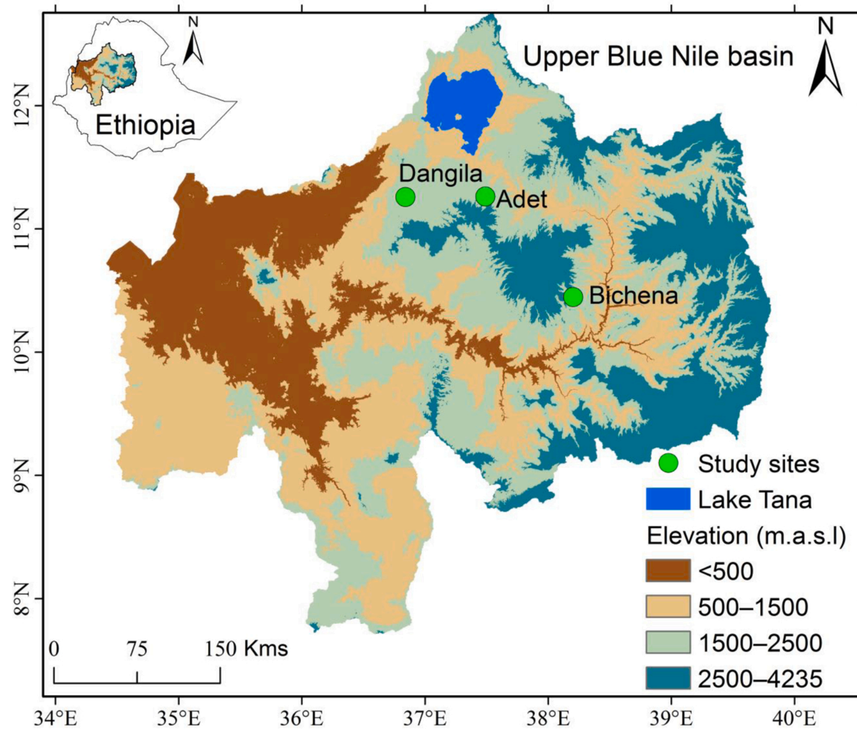

Fig. 1. Location of the study sites in the Upper Blue Nile basin of Ethiopia, representing teff growing areas of the northwestern highlands.

maximum and minimum temperatures, and solar radiation. The initial soil water content was set as 100% since teff is typically planted at the study sites when the soil is saturated (Oicha et al., 2010). Initial soil N was 10 kg ha^{-1} based on the average soil N values estimated by laboratory analysis of samples collected in teff fields at pre-planting in the study areas (Agegnehu et al., 2016). The average teff residue cover was set as 200 kg ha^{-1}, as > 90% of the crop biomass is removed from teff fields for livestock feed (Yami, 2013). Seeds were broadcasted by hand.

CSM-NWheat-Teff model was calibrated using actual soil data, weather data, and crop management practices applied in the field experiment (Adet district). Model calibration followed the procedures of Hoogenboom et al. (2012); Yang et al. (2014). During calibration, the genetic coefficients **(Supplement 2)** for cultivar DZ-01–354 were adjusted until the simulated growth and phenology values were close to the observed values.

Following calibration of the CSM-NWheat-Teff model, the number of days to anthesis (DTA), days to maturity (DTM), grain yield (GY), and straw yield (SY) were simulated for each treatment at each location (averaged over years) for model evaluation. For each treatment, the measured GY, SY, DTA, and DTM were compared with the simulated values. For model evaluation, we used a statistical fitness tests (Eqs.1 to 4) based on the normalized root mean square error (NRMSE), R^2, and an index of agreement (IA):

$$\text{Mean square error(MSE)} = \frac{\sqrt{\sum_{i=1}^{n} [Si - Oi]^2}}{n} \tag{1}$$

where $_{Si}$ = simulated, O_i = observed, and n = number of treatments.

$$\text{RMSE} = \frac{MSE}{X} \tag{2}$$

where x = mean of observed value.

$$\text{IA} = 1 - \frac{\sum_{i=1}^{n} (Si - Oi)^2}{\sum_{i=1}^{n} (abs(Si - x) - abs(Oi - x))^2} \tag{3}$$

where abs indicates absolute value.

$$\text{NRMSE} = \frac{RMSE}{Y} \tag{4}$$

where y = mean of predicted value.

NRMSE < 0.1 indicates good performance, 0.1–0.2 moderate, 0.2–0.3 fair, and > 0.3 poor (Yang et al., 2014). IA < 0.70 indicates poor agreement, 0.71–0.80 moderate, 0.81–0.90 good, and > 0.91 excellent (Willmott, 1982).

2.3. *Model application: long-term simulation scenario*

Following calibration and evaluation, the CSM-NWheat-Teff model was used to study the effects of annual climate variability on teff productivity and stability over 37 years (1983–2020) under different planting dates, irrigations, and N rates by using the seasonal analysis module of DSSAT (Thornton and Hoogenboom, 1994) at Adet, Bichena and Dangila districts using one cultivar (DZ-01–354). Daily rainfall, maximum and minimum temperatures, and solar radiation for the irrigation period (January to May) were obtained from the Ethiopian National Meteorology Agency (Fig. 2). A simulation experiment was conducted for a total of 75 scenarios: five planting dates (Jan 1, Jan 15, Feb 1, Feb 15, Mar 1), five N rates (0, 20, 40, 60, 80 kg ha^{-1}), three irrigations of maximum allowable depletion (MAD) of available soil water content (AWC) in the top 30 cm soil depth (automated irrigation-irrigating whenever required; 50% threshold - irrigation application triggered when the volumetric soil moisture content drops below 50% of the AWC; and 25% threshold - irrigation application triggered when the volumetric soil moisture content drops below 25% of AWC). To trigger the auto-irrigation option (automated irrigation) in the model, "Automatic when required" was specified in the model setting which determines the timing and amounts of irrigation water required based on the available AWC in the 0–30 cm soil layer. The automated irrigation in DSSAT is triggered by soil moisture and by evapotranspiration. Moreover, irrigation amounts are determined based on deficit; events are determined based available water within the growth periods and

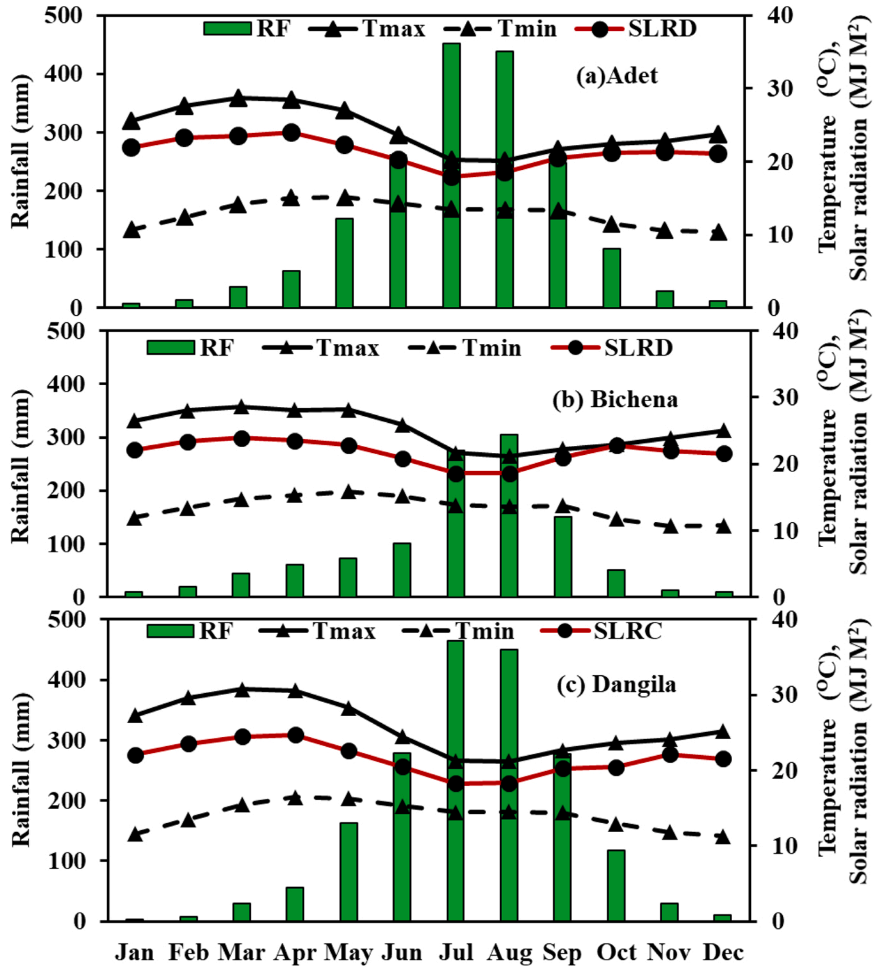

Fig. 2. Long-term (1983–2020) average monthly total rainfall, monthly average maximum and minimum temperatures (Tmax and Tmin), and daily average solar radiation (SLR) in the Adet (a), Bichena (b) and Dangila (c) districts, northwest Ethiopia.

Table 1
Soil parameter inputs for the model at Adet, Bichena and Dangila districts of northwest Ethiopia.

District	Depth (cm)	Clay (%)	Silt (%)	Stones (%)	BD ($g\ cm^{-3}$)	TN (%)	OC (%)	pH	PWP ($m^3\ m^{-3}$)	FC ($m^3\ m^{-3}$)	SAT ($m^3\ m^{-3}$)
Adet	0–30	47.0	25.0	28.0	1.3	0.2	1.4	5.9	0.2	0.4	0.5
	30–90	66.0	24.0	12.0	1.1	0.1	1.3	5.2	0.3	0.5	0.5
	90–140	69.0	15.0	16.0	1.2	0.1	1.0	6.3	0.3	0.4	0.5
	140–200	68.0	18.0	14.0	1.2	0.1	0.8	6.8	0.3	0.4	0.4
Bichena	0–30	71.0	17.0	12.0	1.2	0.1	2.1	6.0	0.4	0.5	0.5
	30–90	71.0	16.0	13.0	1.2	0.2	2.4	5.8	0.4	0.6	0.6
	90–140	73.0	18.0	9.0	1.3	0.2	1.5	5.5	0.4	0.4	0.5
	140–200	70.0	20.0	8.0	1.3	0.2	1.3	5.5	0.3	0.5	0.5
Dangila	0–30	46.0	26.0	28.0	1.2	0.3	2.3	5.4	0.3	0.4	0.4
	30–90	57.0	31.0	12.0	1.0	0.2	1.5	5.6	0.3	0.4	0.5
	90–140	67.0	17.0	16.0	1.0	0.1	1.5	6.2	0.3	0.4	0.5
	140–200	78.0	11.0	11.0	1.1	0.1	1.1	6.6	0.4	0.5	0.6

BD, bulk density; TN, total nitrogen; OC, organic carbon; pH, soil acidity; PWP, permanent wilting point; FC, field capacity; SAT, saturation point.

duration between consecutive irrigation events. In this study, we assumed that the automated irrigation represents the non-water stressed condition representing adequate availability of irrigation water for crop production. Practically, there is a high competition for irrigation water almost in all irrigated areas in Ethiopia where there is an irrigation facility. Likewise, 50% and 25% thresholds represent scenarios when irrigation water availability is reduced by 50% and 75%, respectively.

The model outputs that were analyzed included grain yield (GY), straw yield (SY), irrigation water productivity (IWP), plant nitrogen uptake (PNUP) and gross return (GR). N application time was set half at planting and half at tillering stage (30 days after planting) as recommend by Gebremeskel et al. (2016). The prior crop was set as teff, with a crop residue of 200 kg ha^{-1} and a residue soil N content of 0.65 mg g^{-1} (Yami, 2013). Details of crop management inputs are indicated in **Supplement 1**.

Seasonal analysis in DSSAT allows box-plot and mean–variance analyses to identify treatments with high GY and SY and minimal seasonal variations. It was also used to assess economic and weather risks using economic and strategic analysis modules (Hoogenboom et al.) For economic analysis, the gross return (GR) of each treatment was determined by subtracting the total income (obtained from selling grain and straw) from the total variable cost of fertilizer, and irrigation (labor, rental and fuel for pumping) in each treatment, based on long-term (2000–2017) market prices for yields (grain and straw) and inputs (N fertilizer, labor and irrigation) collected from district cooperative offices **(Supplement 3)**. The cost of water is not included in our study (negligible). Usually, famers do not have to pay for irrigation water, since they use water resources (rivers, lakes and ponds) in Ethiopia. Even the cost of irrigation water for government-built irrigation facilities (few in number) is also negligible. The average price data for 2020 and long-term variation (2000–2017) were used in the DSSAT price file. Treatments with high GR and less seasonal variability were considered as economically feasible and stable. Mean-variance plot was produced in DSSAT seasonal analysis module to visualize mean GR of treatments and variability across seasons (1983–2020). The results of the mean-variance analysis indicates the efficiency of the treatments (Sarkar and Kar, 2006).

3. Results

3.1. Model calibration and evaluation

Using the calibration dataset at Adet, the observed and simulated average days to anthesis (DTA) were 68 and 71 days, respectively, whereas the observed and simulated days to maturity (DTM) were 110 and 129 days. The RMSEs for DTA and DTM were 1.5 and 9.5 days, respectively. The model simulated GY with $R^2 = 0.9$, RMSE = 72.1 kg ha^{-1}, and IA = 0.9 (Fig. 3a). The model simulated SY with R^2 = 0.9, RMSE = 421.8 kg ha^{-1}, and IA = 0.9 (Fig. 3b).

For model evaluation (using Bichena and Dangila datasets), the observed and simulated average DTA were 77 and 88 days at Bichena and 81 and 85 days at Dangila, respectively. The observed and simulated DTM were 117 and 130 at Bichena and 125 and 136 days at Dangila, respectively. The RMSE values were 5 days for DTA, and 13 days for DTM. The model simulated DTA with NRMSE = 10% and IA = 0.9; DTM with NRMSE = 12% and IA = 0.9. The RMSE values were 51.0 kg ha^{-1} with R^2 = 0.9, RMSE = 51.0 kg ha^{-1}, NRMSE = 5%, and IA = 0.9 for GY (Fig. 3c). The RMSE values for SY was 242.9 kg ha^{-1} with R^2 = 0.9, RMSE = 242.9 kg ha^{-1}, NRMSE = 20%, and IA = 0.9 (Fig. 3d).

3.2. Management scenario analysis

3.2.1. Planting dates

Overall, GY and SY at Adet were greater than at Bichena and Dangila. GY and SY were higher at late planting dates than earlier, and this was more pronounced at Adet compared to Bichena and Dangila (Figs. 4 and 5). The amounts of seasonal GY and SY were in order of Jan 1 < Jan15 < Feb 01 < Feb 15 < Mar 01 at Adet, Feb 01 < Jan15 < Feb 15 < Jan 01 < Mar 01 at Bichena, and Jan 15 < Feb 01 < Jan 01 < Feb 15 < Mar 01 at Dangila. Late planting also resulted in higher plant nitrogen uptake (PNUP) but with greater seasonal variability (Table 2).

3.2.2. Effect of N rate and irrigation application

When automated irrigation was applied, GY increased with increasing N but more slowly for rates above 40 N kg ha^{-1} at the three

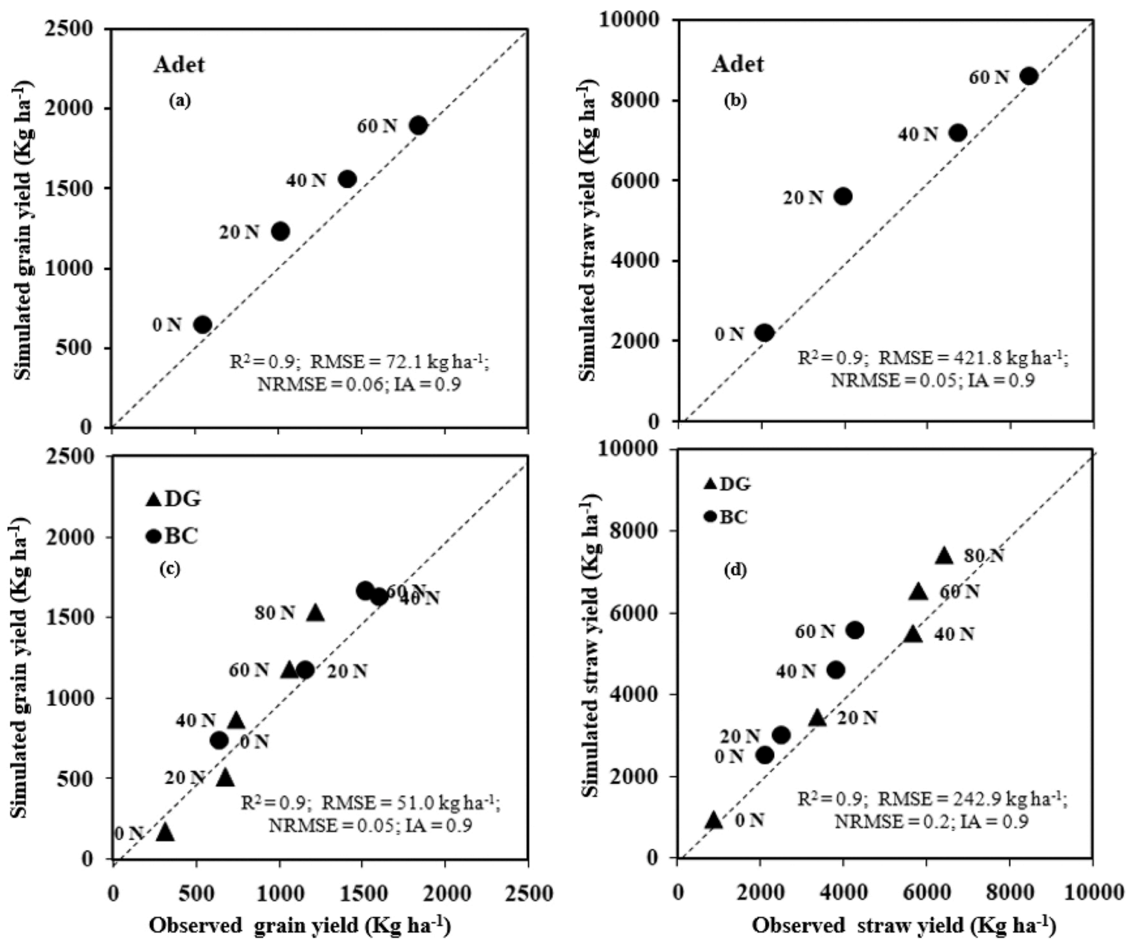

Fig. 3. Relationships between observed and simulated teff grain and straw yields used for model calibration in the Adet district for the period 1996–1998 (a, b), and model evaluation in the Bichena district (BC) for the period 1996–1998 and in the Dangila district (DG) for the period 2002–2003 (c, d). R^2, correlation coefficient; RMSE, root mean square error; NRMSE, normalized RMSE; IA, index of agreement.

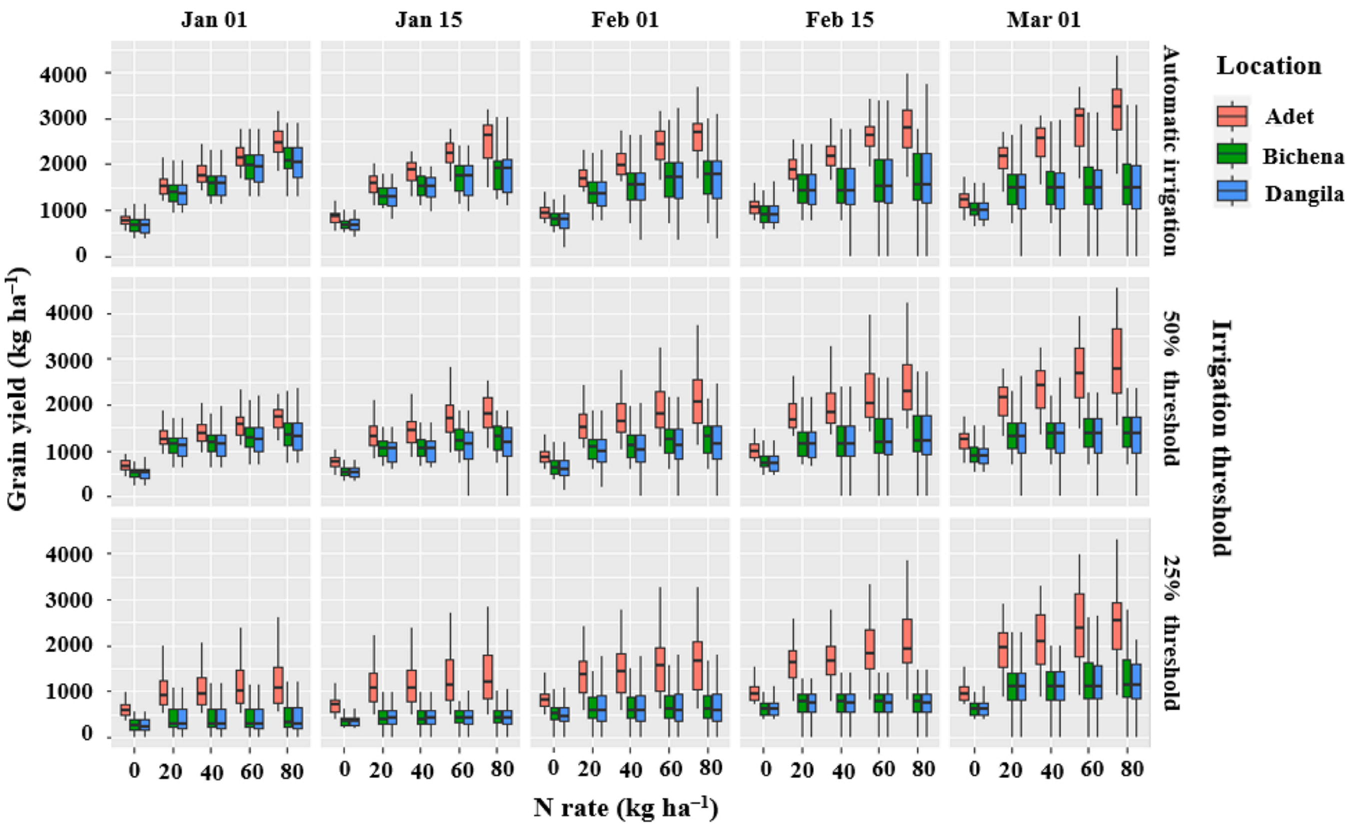

Fig. 4. Effects of planting dates and N rates on grain yield (GY) of irrigated teff at the three irrigations during 1983–2020 in Adet, Bichena, and Dangila districts, northwest Ethiopia. The top and bottom of each box represent the upper and lower quartiles, respectively; the horizontal line within each box represent the median, vertical lines represent variability outside the upper and lower quartiles.

study sites. However, GY declined or remained constant above a rate of 20 N kg ha^{-1} when planted on Feb 15 and Mar 01 at Bichena and Dangila (Fig. 4). When irrigation was applied using the 50% threshold, GY increased with an increase in the amount of N applied, but more slowly above 20 N kg ha^{-1} at the three study sites when planted between Jan 01 and Feb 01. However, it remained constant above a rate of 20 N kg ha^{-1} when planted on Feb 15 and March 01 at Bichena and Dangila. Similarly, when irrigation was applied using the 25% threshold, GY increased with an increase in N applied but the rate of increase was slow or became flat above 20 N kg ha^{-1} for all sites.

When automated irrigation was applied, SY increased with increasing N but declined after 60 N kg ha^{-1} when planted between Jan 01 and Feb 10, declined or became flat after 40 N kg ha^{-1} when planted on Feb 15 and Mar 01 at all the study sites (Fig. 5). For the 50% irrigation threshold, SY increased with increasing N but more slowly above 20 N kg ha^{-1} when planted before March 01. However, it declined or remained constant above a rate of 20 N kg ha^{-1} for all the three study sites. For the 25% irrigation threshold, SY increased with increasing N up to 20 N kg ha^{-1} and remained constant above a rate of 20 N kg ha^{-1} for all the threes study sites. However, the SY did not show a response to N rate when planted in Jan 01 and Jan15 at Bichena and Dangila sites.

Generally, the rate of GY and SY increment with N rate were in the order of Adet > Bichena < Dangila (Figs. 4 and 5). The response of GY and SY to N rates was more pronounced for automated irrigation treatment than for 50% and 25% irritation thresholds. Moreover, GY and SY reduced with reduced irrigations (automated > 50% threshold >25% threshold). The rate of GY and SY reduction with less application of irrigation was relatively lower for Adet than Bichena and Dangila. Moreover, the responses of GY and SY to N rate and irrigation levels were more pronounced when planting was late.

Using historical weather data representing 37 growing seasons, the variability of GY and SY increased with an increase in N rates. Both GY and SY were more stable for automated irrigation than in 50% and 25% irrigation thresholds (Figs. 4 and 5). Across N and irrigation application treatments, a delay in planting date resulted in higher GY and SY but with high annual variability. In general, a greater seasonal variability of GY and SY was observed for the Adet location compared to Bichena and Dangila irrespective of irrigations (irrigation when required, 50% and 25% irrigation thresholds).

PNUP (plant nitrogen uptake) increased with increased N and irrigation application at the three study sites (Table 2). Similarly, the seasonal variability in PNUP increased with N rate and across sites (Table 2).

3.2.3. Irrigation water productivity

At Adet, irrigation water productivity (IWP), which is the amount of yield produced per volume of water applied, was in the order of 50% threshold > 25% threshold > irrigation when required, however at Bichena and Dangila, IWP was in order of 25% threshold > irrigation when required > 50% threshold (Fig. 6). IWP increased with N rate, but the response was most pronounced for automated irrigation when required (Fig. 6). Similarly, IWP was more variable at higher N rates for all irrigation thresholds (Fig. 6). Across the three study sites, the rate of IWP increase became slow or flat after the 20 N kg ha^{-1} (Fig. 6). The IWP at Adet was relatively higher compared to Bichena and Dangila (Fig. 6). Seasonal variability of IWP was in order of 50% threshold > 25% threshold > irrigation hen required regardless of the N application rates. Relatively, the seasonal IWP variability was greater at Adet than Bichena and Dangila.

3.3. Economic analysis

At Adet, the gross return (GR) increased with an increase in the N and irrigation application rates, while the response was relatively lower at

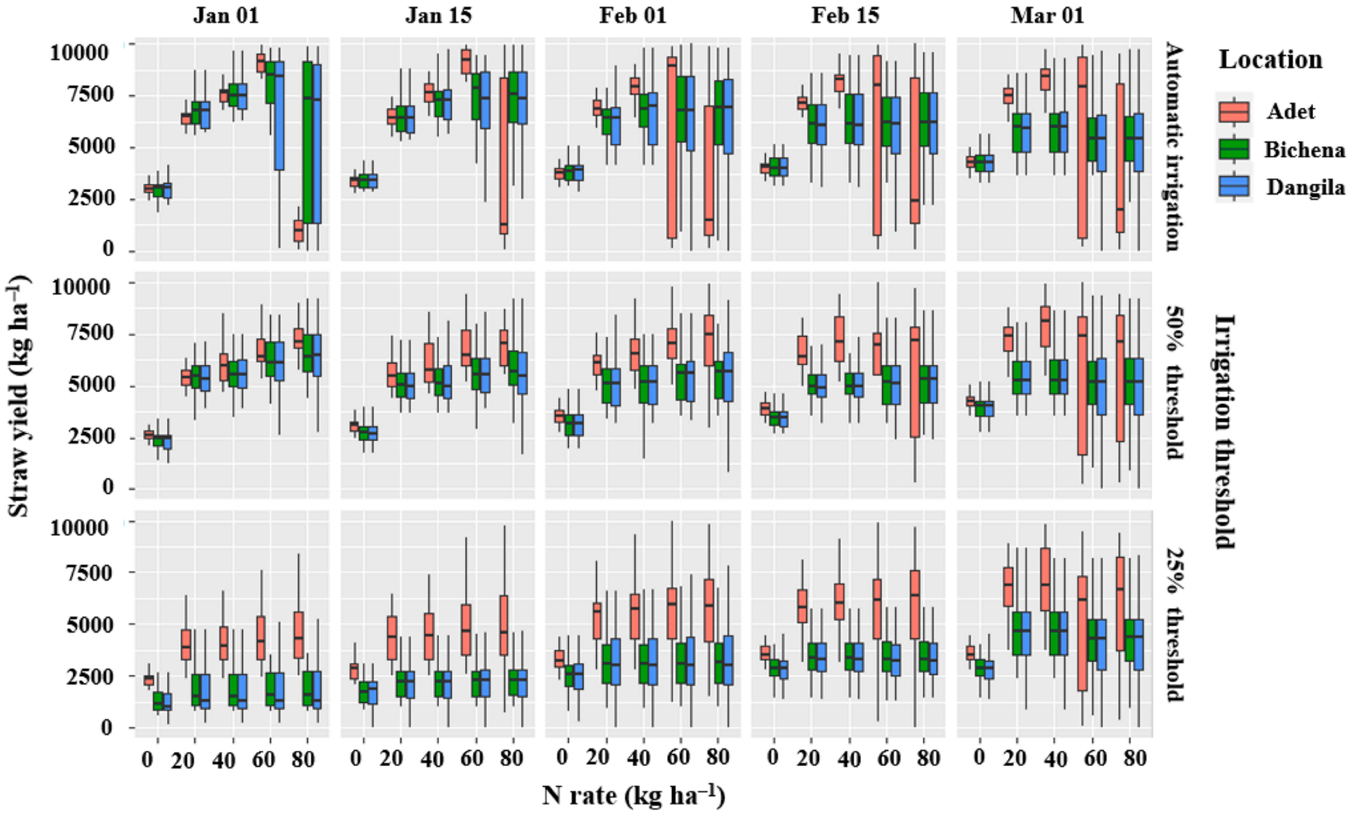

Fig. 5. Effects of planting dates and N rates on straw yield (SY) of irrigated teff at the three irrigations during 1983–2020 in Adet, Bichena and Dangila districts, northwest Ethiopia. The top and bottom of each box represent the upper and lower quartiles, respectively; the horizontal line within each box represent the median, vertical lines represent variability outside the upper and lower quartiles.

Table 2
Individual effects of planting date, N rate, and irrigations on nitrogen uptake efficiency of irrigated teff during 1983–2020 in Adet, Bichena and Dangila districts, northwestern Ethiopia.

	Rate of nitrogen uptake (kg ha^{-1})					
	Adet		Bichena		Dangila	
	Mean	Variance	Mean	Variance	Mean	Variance
Planting date						
Jan 1	58.4	560	48.1	1016	46.3	1035
Jan 15	61.6	510	50.0	856	47.5	917
Feb 1	69.0	487	57.3	803	53.8	990
Feb 15	74.9	450	61.5	779	58.0	1009
Mar 1	83.6	537	68.6	807	64.5	1087
N rates (kg ha^{-1})						
0	44	95	37	334	35	402
20	65	246	56	653	53	795
40	71	345	59	783	56	939
60	80	507	65	1012	61	1201
80	87	666	68	1178	65	1388
Irrigations						
Automated irrigation	82	510	78	609	74	893
50% threshold	68	472	59	583	56	757
25% threshold	58	504	35	608	33	671

Bichena and Dangila (Fig. 7). Despite some inconsistency across locations, a higher GR and lower seasonal uncertainty was generally observed when teff was planted early (Fig. 7). In the Adet district, a late planting (Feb 15 and March 01), application of 80 N kg ha^{-1} and irrigation when required were the most economical and stable combinations with a gross return of 1885 USD ha^{-1} (Feb 15) and 2266 USD ha^{-1} (March 01). However, for the Bichena and Dangila districts, early planting (Jan 01), application of 60 or 80 N kg ha^{-1} and irrigation when required were the most economical and stable combinations with a gross return of 1337 USD ha^{-1} (60 N kg ha^{-1}) and 1484 USD ha^{-1} (60 N kg ha^{-1}) (Fig. 7).

4. Discussion

4.1. Model calibration and evaluation

Until now, CSM-NWheat-Teff has had no examples of practical application under field conditions. This study, based on NRMSE and IA showed that the model predicted GY with low error and SY with moderately low error; and the simulated outputs agreed well with observed values (Fig. 3c and d). The NRMSE and IA for teff phenology were within the acceptable range. Similarly, the NRMSE for GY and SY ranged from good to moderate were reported by Soler et al. (2007). The IA values of 0.9 for GY and SY is in a good agreement with Yang et al. (2014). However, the model slightly overestimated both GY and SY (particularly at higher N rates), probably because the model currently does not include a lodging response function (Mirutse et al., 2009). Paff and Asseng (2019) also reported that CSM-NWheat-Teff accurately simulated teff growth and phenology, but with some overestimation of GY and SY. In general, teff modeling has been challenged by a lack of adequate field data and adequate input data reflecting the crop response to N, water management, CO_2, and radiation use efficiency (Paff and Asseng, 2018). Lodging and seed shattering are major constraints on teff production (Assefa et al., 2011) that need to be considered in modeling (Paff and Asseng, 2019). More field agronomic studies are required to further improve CSM-NWheat-Teff model by generating data for teff yield response to future climate (elevated CO_2 and temperature), quantifying the impact of N application and excess rainfall on teff yield attributes such as radiation use efficiency, leaf photosynthesis, teff lodging and shattering. Overall, the results of this study verified that the

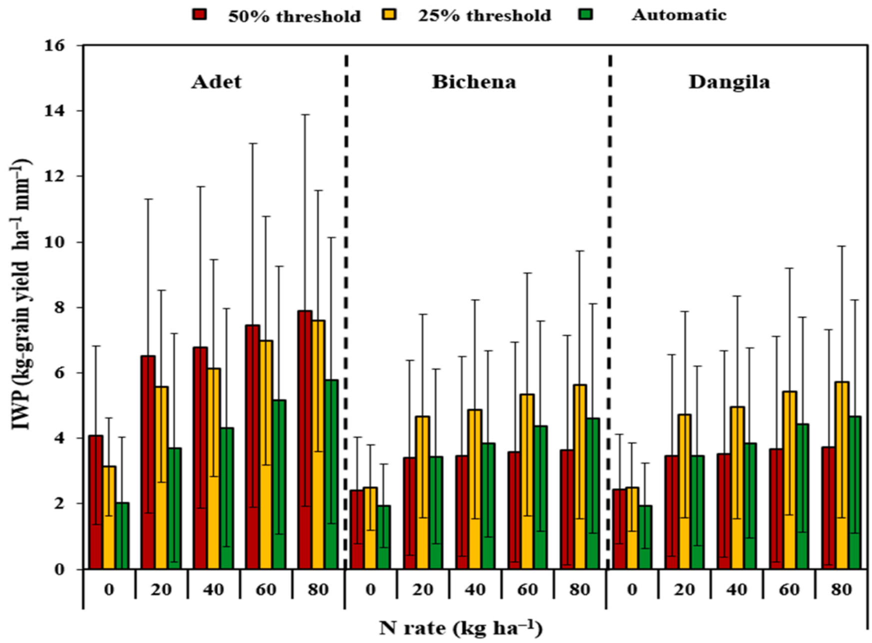

Fig. 6. Effects of N rates at irrigations (automated irrigation applied, 50% and 25% irrigation thresholds) on irrigation water productivity (IWP) of irrigated teff during 1983–2020 in Adet, Bichena and Dangila districts, northwest Ethiopia. Error bars indicate standard deviation.

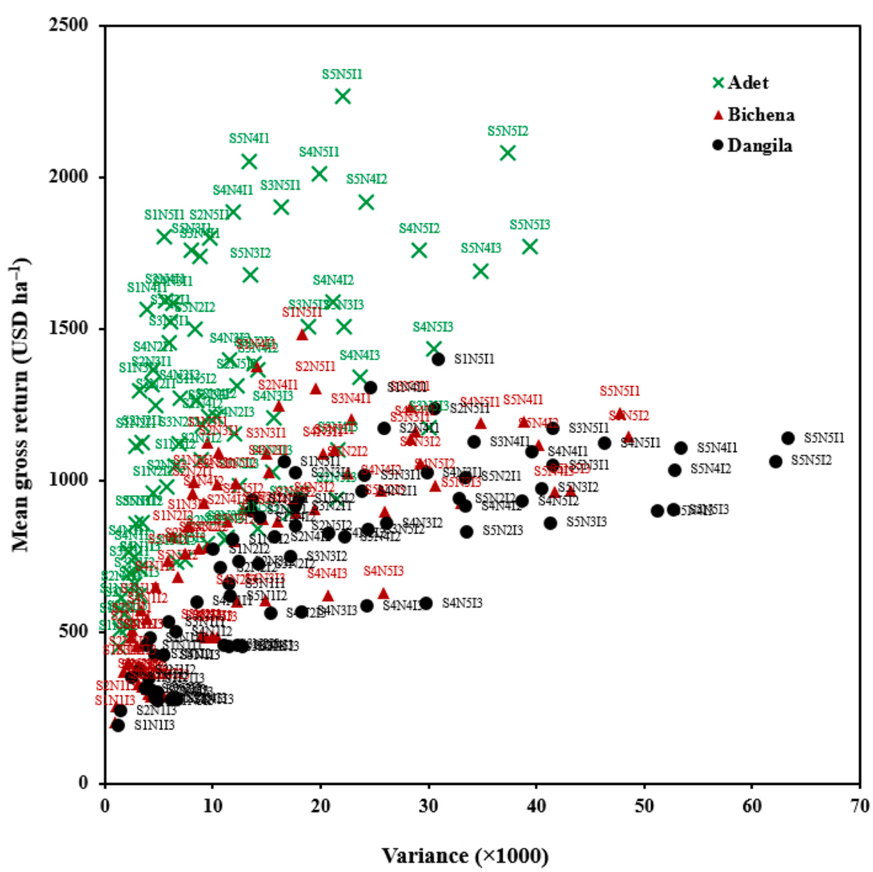

Fig. 7. Simulated gross return and seasonal uncertainties (1983–2020) for different N rates and irrigations for irrigated teff in the Adet, Bichena and Dangila districts, northwest Ethiopia.

model can reasonably simulate phenology, GY, and SY of teff, with an acceptable statistical fitness for cultivar the DZ-01–354.

4.2. Management scenario analysis

4.2.1. Planting dates

For all the study sites, a late planting resulted in greater GY and SY mainly attributed to the increase in temperature from January to March 01 that leads to better crop establishment, and growth, as long as soil moisture is not a limiting factor (Caliskan et al., 2008). Thus, the higher GY and SY at Adet compared to Bichena and Dangila might be attributed to higher temperature and solar radiation from January to march (Fig. 2) coupled with better soil fertility (Table 1). Better growth and yield is expected as teff is a C4 cereal that performs well under high temperature (Assefa et al., 2011). Despite late sowing resulted in higher GY and SY, it was associated with longer days to maturity compared to early sowings. Relatively shorter days to maturity for early planting is because of the greater number days to accumulate amount of heat units (degree days) required for maturity compared to late sowing (Gilmore and Rogers, 1958). Thus, late sowing of irrigated teff might overlap with the growing season under rain fed condition (June–December) particularly when late mature cultivars are used (Tsegay et al., 2015). However, attacks by shoot fly (*Atherigona hyalinipennis*) are becoming a major problem in teff production during dry spells. Therefore, early planting is one strategy to escape the impact of this pest during the main rainy season (June to December). Planting teff on March 01 under irrigated conditions might be feasible for relatively early maturing type cultivars without overlapping with the preparation for the following main rainy season crop without considering the risks associated with climate variabilities. For rainfed cultivation, planting date for most crops including teff is mainly determined based on the rainfall pattern and soil moisture in contrast to irrigated cropping that moisture is not a limiting factor (Yang et al., 2021). Although irrigated teff cultivation is not yet a common practice in Ethiopia, there is an increasing need to expand it so as to satisfy the increasing demand for teff grain (Machado Mendes and Paglietti, 2015). Despite governed by several agronomic factors; on average, improved teff cultivars can provide up to 3500 kg ha^{-1} under irrigated conditions (Yihun et al., 2013) compared to the national rainfed teff yield average of 1700 kg ha^{-1} (Mihretie et al., 2022). Therefore, this study fills an important gap in irrigated teff management by determining the optimum planting date, which was identified as March 01, for irrigated teff production without yield penalty in the northwestern Ethiopia. However, the uncertainty (seasonal variability) in GY increased when planting was late (Fig. 4) due to seasonal changes in radiation, temperature and rainfall. The risk of lodging and shattering due to rain is also higher when planted late as the maturity date might overlap with the beginning of the main rain season (Bayable et al., 2020). Because irrigated teff is a new to the cropping system in the northwestern Ethiopia, future studies should also explore impacts of planting dates on yields and phenology of teff based on field observation of potential pest, weed and disease occurrences and in consideration of different types of cultivars to be used.

4.2.2. *Effect of N rate and irrigation frequency*

The higher yields at higher N rates and irrigation when required were obviously due to better crop growth and development as a result of no limitation of nitrogen and irrigation water. These results are in agreement with Ul-Allah et al. (2018) who showed that N is one of the major nutrients that controls crop growth, phenology and productivity (Ul-Allah et al., 2018). Rioba et al. (2015) who reported that availability of water determines plant function and metabolic processes. Habtegebrial et al. (2007) also reported that growth and dry matter production in teff increased with increasing N. Tsegay et al. (2015) reported improved GY and SY in most cereals due to greater N application when water is not a limiting factor. Our results further indicate that GY and SY increased with N, but more slowly at 25% irrigation threshold regardless of the study sites. It is well known that the impact of applying more N is more pronounced when combined with availability of soil moisture (Gooding et al., 2003). Despite less has been studied about N requirement for irrigated teff in Ethiopia, Negassa and Abera (2011) reported that under rainfed conditions, reported that the amount of N required for teff production ranges from 16 to 90 kg N ha^{-1}, whereas Assefa et al. (2006) reported that in northwestern Ethiopia, the amount of N required ranges from 60 to 100 N ha^{-1} depends on the soil types. However, application of N above 80 N kg ha^{-1} might aggravate lodging and might not be economical for teff production (Roseberg et al., 2005). Other studies showed that the yield response of rainfed teff to N generally declined after 60 kg N ha^{-1}, mainly on account of lodging (Habtegebrial et al., 2007; Mirutse et al., 2009; Teklu and Tefera, 2005). It is worth noting that the CSM-NWheat-Teff does not consider a lodging function, although teff yield is highly sensitive to lodging, particularly at higher doses of N, which can in turn cause a reduction of yields by 11–20% (Seyfu, 1997). According to Habtegebrial et al. (2007) lodging increased by 60% when N was raised from 60 to 90 kg N ha^{-1}. We, therefore, did not consider N rates above 80 kg N ha^{-1} in our study was due to occurrence of lodging. One of the key constraints of teff production in Ethiopia is a low N input (< 80 kg N ha^{-1}) application to avoid yield loss due to lodging as teff is more sensitive to high N dose driven lodging compared to other cereals such as wheat and rice (Bayable et al., 2020). Furthermore, our results show the potential yield that can be achieved with adequate N supply when lodging is not a limiting factor. The rates at which GY and SY responded to N and irrigation application were different for the three study sites mainly due to differences in teff growth and yield making process driven by variabilities in climatic and soil properties (Shah and Wu, 2019). GY and SY responded better to N and irrigation application when planted late at all three study sites. This can be explained by the enhanced use of resources (water and nutrients) and crop growth due to increase in temperature from January to March (Fig. 2).

The higher variability in GY and SY at higher N rates across seasons (Figs. 4 and 5) is attributable to heterogeneity in seasonal climatic conditions (solar radiation, temperature, and relative humidity) that potentially influenced growth and development of teff. The greater yields but higher uncertainties at higher N rates might be associated with seasonal variability in plant nitrogen uptake and N dynamics in the soil that will expose farmers to unexpected yield losses (Yuan et al., 2007). Besides the economic benefits that could be obtained in the short-term, a judicious decision on N rates for irrigated crop production should consider long-term implications on both the economics and the environment. Regardless of the N rates, the lower variation in GY and SY at irrigation when required than at 50% and 25% thresholds in our study was due to the less seasonal fluctuation in crop growth performance with sufficient availability of soil moisture (Yang et al., 2021). Seasonal variation in crop growth and yield in the tropics where solar radiation is not a problem is majorly caused by seasonal differences in soil moisture availability and temperature (Midmore et al., 1984). Crop yield is highly affected by seasonal variability in precipitation, radiation interception, and temperature that control carbon fixation, nutrient availability, and pests (Ceglar et al., 2016; Kelbore, 2012). The greater PNUP with higher N rates was because of a better availability of N to be uptake by plant roots (Kunrath et al., 2020). PNUP is mainly governed by amount of N in the soil, root development, soil type and climatic factors (Masclaux--Daubresse et al., 2010). In addition, the teff PNUP values in our study were within the ranges (20–45 kg[N] ha^{-1}) reported by Getu (2012). Therefore, our results suggest that application of 80 kg N ha^{-1} and use of automated irrigation (application of irrigation water whenever required) are most appropriate combination for irrigated teff cultivation in all the three study sites assuming inputs (water and nitrogen fertilizer) are not limited.

4.2.3. *Irrigation water productivity*

The water productivity of irrigation levels in our study was different across the study sites mainly because of variability in climatic factors (Fig. 2). Spatial variability in agricultural water productivity is a function of transpiration which is highly dependent on crop performance, soil moisture, temperature, and humidity (Kang et al., 2009). The soil moisture dynamics and water productivity in Ethiopia is highly influenced by the soil and water conservation practices and the agroecological set up (Sultan et al., 2018). Nitrogen is a key nutrient that greatly influences crop productivity and thereby water use efficiency (Liu et al., 2018). However, excess N (> 80 N kg ha^{-1}) application might cause seed burning, delayed maturity, and lodging, all of which can result in a negative impact on crop growth, yield, and water use efficiency (Zhong and Shangguan, 2014). Despite higher yields for automated irrigation applied (when irrigation is applied as required), 50% and 25% irrigation thresholds gave reasonable yields with better IWP (less water consumption), but it might not be sufficient to support maximum growth and yield at higher N application rates if maximum productivity is targeted (if irrigation water is not a limiting factor). It was also reported that as greater IWP was associated with high N application rates in wheat (Liu et al., 2018) and rice (Rezaei et al., 2009) with sufficient irrigation water supply while less has been studied in teff. The simulated IWPs in our study were within the ranges (0.48–0.89 kg m^{-3}) reported by (Araya et al., 2011); Yihun et al. (2013).

4.3. Economic and risk analysis

The optimal planting dates, N application rate and irrigation thresholds are a function of the economic return and minimization of risks posed by weather variability, as farmers are typically risk averse. CSM-NWheat-Teff offers the opportunity to determine both with high economic benefit and low risk. Higher gross return and lower variance are indicators of economic feasibility and low uncertainty. Despite the high cost of irrigation (costs of labor and pumping) and N fertilizer, the use of increased irrigations and higher N rate remains economical with less seasonal variability (low risk) in all the study sites, mainly owing to the high GY and SY with less uncertainty. Although decisions on planting dates did not have any direct implication on input costs, the higher gross income obtained from late planting at Adet and from early planting at Bichena and Dangila were found feasible by our study. Our results are consistent with findings that higher N rates are not practically feasible as yield reduction due to lodging increases with additional N application above 80 kg ha^{-1} (Habtegebrial et al., 2007). Previous studies pointed out that a farmer's decision to apply N fertilizer is highly dependent on affordability (Abebe and Debebe, 2019) and cost of N fertilizers (Tolessa and Friesen, 2004), most farmers apply N below the recommend rate in Ethiopia when they do not afford for high cost. If a higher yield with a minimum risk can be achieved for irrigated teff, farmers in the study areas and elsewhere with similar agro-ecology could afford to apply recommended N rate. Similarly, a farmer's choice of irrigation frequency is highly affected by access to irrigation water and availability of family labor (Yohannes et al., 2019). Because of the negligible cost of water, the low risk of lodging, and low seasonal variability, application of 80 N kg ha^{-1} and irrigation application when required was found to be the most economical and sustainable combination for irrigated teff production in northwestern highlands of Ethiopia and in areas with similar environmental settings.

5. Conclusion

This study demonstrated that the new CSM-NWheat-Teff model can adequately simulate phenology, yield, and biomass of teff in northwest part of Ethiopia. Late planting at Adet (March 01) and early planting (January 01) at Bichena and Dangila sites could improve irrigated teff productivity with minimum seasonal variability. Application of 60–80 N kg ha^{-1} with adequate irrigation water supply could increase GY and SY with relatively lower annual variability for irrigated teff production. The optimum planting date, N rate and irrigation frequency varied across sites indicating the need for developing agro-ecology based agronomic recommendations for irrigated teff production in the northwest part of Ethiopia and other similar regions. Overall, the study indicated the possibility of profitable teff production by optimizing planting date, N fertilizer rate, and irrigation level combinations.

CRediT authorship contribution statement

FM is the major contributor in running the modeling experiment, analyzing and interpretating the data and writing the manuscript. KT assisted in analyzing and interpreting data and writing the manuscript. GH participated in the crop modeling, analyzing the data and writing the manuscript. AS supervised the study, analyzed and interpreted the data. AM assisted in writing the manuscript. KE assisted in analyzing and interpreting data and writing the manuscript. SS assisted in analyzing and interpreting data and writing the manuscript. YM assisted in analyzing, and interpreting data and writing the manuscript. All authors have read and approved the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2022.126572.

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