



Assessing spring maize responses to irrigation and nitrogen regimes in north-west India using CERES-Maize model

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ABSTRACT

Inadequate availability of fresh water and rising cost of fertilizers warrant their judicious use in agriculture. In intensively-cropped Punjab state of north-west India, alarming decline in groundwater resources pose a challenge to spring maize that otherwise has high profitability. This study is an assessment of water use and productivity responses of spring maize to irrigation and nitrogen regimes in a subtropical environment using CERES-Maize model. Database was generated from a field study on maize planted in second half of February with combinations of two irrigation regimes viz., irrigation water to pan evaporation ratio of 1.0 ($I_{1.0}$) and 0.5 ($I_{0.5}$), and four N rates viz., 0, 50, 100 and 150 kg ha⁻¹ on a sandy loam soil. Irrigation and N had significant effects on grain yield, water use and N uptake. Performance of the model was reasonable with normalized root mean square of deviations between simulated and measured values less than 20% for harvest-time biomass, grain yield and water use; and slightly greater variance (30%) for grain N uptake. Scenario analysis showed that ET-based water productivity (WP_{ET}) was greater in January 31 than February 14 planted maize crop. The WP_{ET} was greater with $I_{0.5}$ than with $I_{1.0}$ suggesting that increase in yield was less than proportional increase in ET. The WP_{ET} responses to N with increase in irrigation were greater at lower than at higher initial soil water.

1. Introduction

Inadequacy of fresh water supply for irrigation has become a big challenge in agriculture. In Punjab state of India, intensive rice-wheat cropping since 1970's has caused an alarming decline of groundwater levels (Singh, 2011a, 2011b) due to fast depletion of aquifers. Maize is one option to diversify from rice-wheat system. However, productivity of maize during rainy season (as replacement to rice) is low (about 5.0 Mg ha⁻¹) and is uneconomical. Spring maize (as replacement to wheat) has better prospect owing to high yield (around 8.0 Mg ha⁻¹) due to less probability of pest incidence thereby gaining the attention of growers. However, the crop has high evapo-transpiration (ET) and irrigation needs due to hot and dry weather conditions during a large part of the growing season. In this scenario, the trade-off is to enhance water productivity (crop yield per unit of water). In a review, Molden et al. (2010) remarked that under water limitations, non-water factors (soil fertility, tillage and residues) have a significant role to enhance crop water productivity. Water and nitrogen (N) have strong synergistic effects on crop yield (Prihar et al., 2000). Under water limitations, over-use of N reduces crop growth and yield due to imbalance between these two factors. This necessitates optimizing N use in relation to water availability.

A large volume of research is available on interaction effects of water and N on growth and yield of maize (Eck, 1984; Pandey et al., 2000; Hammad et al., 2011) that help to enhance water productivity and N use efficiency. However, results of such empirical studies should not be extrapolated beyond experimental datasets. Crop simulation techniques are used to supplement field research in decision making. A number of crop-specific model packages (CERES, CropSyst and In-Crop) that simulate the dynamics of growth and development, soil water and N balance are available in literature. The CERES-Maize model in framework of Decision Support System for Agro-technology Transfer (DSSAT) (Jones et al., 2003) has been evaluated in different regions of the world (Basso et al., 2016). This model has also been used to optimize irrigation (Nouna et al., 2000; Panda et al., 2004; Jiang et al., 2016) and N management (Jagtap et al., 1999; Chisanga et al., 2015). However, there is little information on modeling combined effects of water and N limitations on water productivity in maize. This study is an assessment of water balance and productivity responses of maize to irrigation and N regimes using CERES-Maize model with overall objective to optimize water productivity in sub-tropical north-west India.

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2. Materials and methods

2.1. CERES-maize model

The CSM-CERES-Maize model (v4.6) is a deterministic model capable to simulate effects of cultivar, plant time, weather, and soil water and nitrogen (N) on maize growth and yield (Jones and Kiniry, 1986). It accounts for crop development in relation to genotype, air temperature and photoperiod; leaf area growth, biomass accumulation and partitioning, soil water balance and crop water use, and N uptake among different plant organs. The CERES-Maize model describes conversion processes of soil carbon, water and nitrogen balances on daily basis and predicts temporal changes in crop growth, N uptake, water use, and yield. Inclusion of water and nitrogen balance helps to assess water and N effects on crop performance. Dataset to calibrate the model for genetic coefficients of the cultivar included dates of emergence, anthesis and physiological maturity (PM), and above-ground biomass, and grain yield for a stress-free environment. These genetic coefficients are thermal time from seedling emergence to end of juvenile stage (P_1), photoperiod-sensitivity coefficient (P_2), thermal time from silking to physiological maturity above base temperature of 8 °C (P_5), potential kernel number per plant (G_2), potential grain filling rate (G_3) and interval in degree-days between successive leaf tip appearance (PHINT).

2.2. Experimental datasets

In order to evaluate the model, database was generated from a field study on spring maize under variable irrigation and N regimes. The experiment was conducted on a deep alluvial sandy loam soil (coarse loamy, mixed, hyper-thermic, Typic Ustochrept) in 2015 and 2016 cropping seasons at research farm of the Department of Soil Science, Punjab Agricultural University, Ludhiana (30°54' N, 75°48' E, and 247 m above mean sea level). Combinations of two irrigation regimes viz., irrigation water (IW) to pan evaporation (E_p) ratios of 1.0 ($I_{1.0}$ representing full irrigation) and 0.5 ($I_{0.5}$ representing partial irrigation); and four N rates viz. 0, 50, 100 and 150 kg ha⁻¹ were evaluated in split-plot design with irrigation in the main plot, and nitrogen in subplot with three replications. Each subplot measured 3.6 m × 3.0 m. The main plot treatments had 0.5 m wide buffer strip to minimize lateral flow of irrigation water.

After harvest of preceding potato crop, the field was pre-irrigated and a seed-bed was prepared by one run of a disc harrow and two runs of a tractor-drawn cultivator. Maize (cv. PMH-1) was planted @ 20 kg ha⁻¹ at row spacing of 0.6 m and plant spacing of 0.2 m (8.3 plants m⁻²) on February 28 in 2015 and February 17 in 2016. The whole amounts of phosphorus (26 kg P ha⁻¹ as single super phosphate), potash (24 kg K ha⁻¹ as muriate of potash), and zinc (5 kg Zn ha⁻¹ as ZnSO₄ ha⁻¹) were applied at sowing; while N (urea) as per treatments was applied in three equal splits at sowing, knee-high (V-8 to V-10) and pre-tasseling stages. Sixty mm irrigation water through surface flooding measured with a Parshal flume was timed when cumulative pan evaporation minus rainfall since previous wetting accumulated to 60 mm ($I_{1.0}$) and 120 mm ($I_{0.5}$) after two common irrigations to ensure crop establishment. The local recommendations were followed for weed, disease and pest control, and the crop were harvested in the first half of June.

The genotypic coefficients of the cultivar were derived using iterations till a close match between simulated and measured phenology, biomass and grain yield was obtained under stress-free environment ($I_{1.0}N_{150}$) in the two cropping seasons. These two points constituted calibration data for model parameterization, and remaining 14 data points were used for validation. The values of these coefficients were 300 for P_1 , 0 for P_2 , 900 for P_3 , 800 for G_2 , 20 for G_3 and 50 for PHINT. Information on physical and chemical characteristics of the soil for the model is given in Table 1. Soil water was monitored gravimetrically in 0.30 m intervals down to 1.50 m depth at sowing and at harvest. Initial soil mineral N (NO_3^- and NH_4^+) in different layers was estimated

using steam distillation method (Keeney and Nelson, 1982). Harvest-time biomass and grain yield was monitored using a net area of 7.2 m². Grain N was estimated using steam distillation method after digesting plant material. Water use (evapo-transpiration + Drainage) was determined by water balance technique utilizing soil water content measurements. The water productivity was estimated as the ratio of grain yield to crop ET. Weather data on maximum and minimum air temperature, sunshine hours, pan evaporation and rainfall was obtained from meteorological station located 2 km south-east of the experimental site (Table 2). The significance of treatment effects on grain yield, water use and N uptake for the field study were analyzed using ANOVA for a split-plot design. Statistical indices to evaluate model performance were root mean square of deviations (RMSD), normalized RMSD (RMSD_n), and goodness of fitness regression and correlation between simulated and measured data (Dar et al., 2017).

2.3. Scenario analysis

Validated CERES-Maize model was employed to assess climatic potential yield and interactive effects of irrigation and N regimes on water use and yield of maize for Ludhiana using 16 years (2001–2016) weather data. Potential yields were simulated for 4 planting dates at two week intervals viz; January 17, January 31, February 14 and February 28. Combinations of two irrigation regimes ($I_{1.0}$ and $I_{0.5}$) with two N rates (0 and 150 kg ha⁻¹) were analysed for test soil representing a typical medium textured soil for January 31 and February 14 planted crop. These options were also examined under two initial soil water conditions (75 and 25% of available water capacity) anticipating water limitations; and two initial soil mineral-N status (50 and 100 kg ha⁻¹) reflecting residual effects of N in proceeding crop. Mean and standard deviation were the statistical indices in the scenario analyses.

3. Results and discussion

3.1. Field study

Maize yield response to irrigation and N during the two cropping seasons is given in Table 3. Mean grain yield was greater in 2015 (5.3 Mg ha⁻¹) than in 2016 (4.7 Mg ha⁻¹) that can partly be attributed to weather conditions in terms of lower maximum air temperature (3–4 °C) during vegetative phase (March and April) in 2015 than in 2016 season (Table 2). Irrigation and N had significant effects on grain yield. Mean yield gain with $I_{1.0}$ over $I_{0.5}$ was 1.7 Mg ha⁻¹ in 2015 and 0.6 Mg ha⁻¹ in 2016; while mean N response was restricted to 100 kg N ha⁻¹ in the two seasons. There was a synergism between irrigation and N for effects on grain yield. Under full irrigation ($I_{1.0}$) regime, N had significant effects with increase in N up to 150 kg ha⁻¹; while under limited irrigation ($I_{0.5}$) regime, N response was restricted to 50 kg ha⁻¹ with little or no gain thereafter. These results on N response of maize in relation to irrigation endorse an earlier report from Pakistan (Hammad et al., 2011) that increase in N from 150 to 250 kg ha⁻¹ increased maize yield from 5.8 to 8.5 Mg ha⁻¹ in no water stress conditions; while water stress in vegetative phase caused a gain in maize yield from 4.7 to 5.4 Mg ha⁻¹. Irrigation and N also had significant effects on water use and N uptake. Increase in irrigation from $I_{0.5}$ to $I_{1.0}$ increased water use by 220–230 mm, while the magnitude of N effects on water use was less. Similar effects of irrigation and N on water use in maize were observed in an arid- (Pandey et al., 2000) and semi-arid environment (Lenka et al., 2013). Greater effect of N on yield than on water use in a given irrigation regime was due to partitioning a greater fraction of water use to transpiration (T) component as shown in the modeling analysis (Table 5). Grain N uptake was affected by irrigation and N regimes similar to their effects on grain yield. Significant effects of $I_{1.0}$ over $I_{0.5}$ regime on N uptake was realized, while N effects were restricted to 100 kg ha⁻¹.

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