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ORIGINAL PAPER

The effect of irrigation strategies and nitrogen fertilizer rates on maize growth and grain yield

María I. Zamora-Re[1] · M. D. Dukes[1] · D. Hensley[2] · D. Rowland[2] · W. Graham[1]

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Abstract
In North Florida, increasing nitrogen loads and water quality declines have become a major concern, in part as result of anthropogenic non-point source activities such as agriculture. The main objective of this study was to investigate the effect of irrigation strategies and nitrogen (N) fertility rates on maize biomass, yield and water productivity in sandy soils. The field experiment was conducted 2015–2017 in Live Oak, Florida using a randomized complete block with a split plot design and four replicates. Treatments evaluated five irrigation strategies: (i) GROW, mimicking grower irrigation practices in the region, (ii) SWB, using a soil water balance to schedule irrigation; (iii) SMS, using soil moisture sensors to schedule irrigation; (iv) RED, applying 60% of the GROW treatment; and (v) NON, non-irrigated, and three N fertility rates: (i) low (157 kg N/ha), (ii) medium (247 kg N/ha), and (iii) high (336 kg N/ha). In comparison to GROW, the SWB, SMS and RED irrigation treatments showed no differences in final biomass, N uptake nor grain yield; however, these treatments achieved on average 41, 47, and 36% irrigation reduction, respectively, without impacts on yield during the three maize seasons evaluated. For most of the variables, statistical differences were found between the low and the high N rates, but no differences compared to the medium N rate. A 26% reduction of N fertilizer was achieved using the medium N rate without negative impact on N uptake, biomass nor yield in comparison to the high N fertilization rate. During this experiment, maize N uptake reached a plateau; thus, potential N losses resulted from applications exceeding recommended rates. Furthermore, the implementation of these more efficient irrigation and N fertilizer management strategies reduced irrigation and N fertilizer applications without negative impacts in yield. Thus, these practices may prevent potential N leaching to waterbodies while improving profits.

Introduction

The United States is the largest producer of maize (*Zea mays* L.*)* worldwide, with average production increasing from about 273 Mg in 2012 to 371 Mg in 2017 (FAOSTAT 2018). Maize (field corn) is the second largest commodity in the United States, and although its economic value has changed during the last decade, it reached the highest value in 2011 accounting for $76.9 billion in the US economy (USDA 2019). In Florida, maize production for grain and silage is important and it is commonly grown in rotation with peanuts resulting in yield benefits for both crops (Wright et al. 2003). According to the 2012 census data, maize harvested area in Florida was 27,132 ha and accounted for $43.7 million (USDA 2012).

Irrigation, fertilization, disease control and harvest should be managed to achieve high maize yields (McWilliams et al. 1999). Potential yield is set by the genetics of the cultivar grown; however, the interaction of the crop management and the environment determines the actual

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✉ M. D. Dukes
mddukes@ufl.edu

María I. Zamora-Re
mzamora@ufl.edu

D. Hensley
dhensley@ufl.edu

D. Rowland
dlrowland@ufl.edu

W. Graham
wgraham@ufl.edu

1 Agricultural and Biological Engineering Department, University of Florida, 1741 Museum Road, Gainesville, FL PO Box 110570, USA

2 Agronomy Department, University of Florida, 1676 McCarty Drive, Gainesville, FL P.O. Box 110500, USA

yield (Fischer et al. 2014). The effect of irrigation and water stress at different developmental stages on maize growth and grain yield has been evaluated across different studies (Cakir 2004; Cakir 2004; Denmead and Shaw 1960; Denmead and Shaw 1960; Shanahan and Nielsen 1987). Final biomass reductions of 28–32% resulted after short-term water deficits occurring in vegetative stages; whereas, up to 40% yield losses occurred when water deficit occurred during sensitive growth stages (i.e., tasseling and ear formation) (Cakir 2004; NeSmith and Ritchie 1992; Robins and Domingo 1953). Water application, either through irrigation or rainfall, can significantly impact maize yield and profitability. In Florida, water required for plant growth in a given season is typically supplied by both rainfall and irrigation; however, due to large spatial and temporal rainfall variability, and typically well drained soils, irrigation is frequently relied upon for successful crop production levels, especially during dry periods (Kisekka et al. 2016). Total freshwater withdrawal in Florida was estimated at 21.7 million m^3/d in 2015; where public water supply and agriculture represented the largest users with withdrawals up to 8.3 and 7.9 million m^3/d, respectively (Marella and Dixon 2018). Nearly half of the estimated harvested cropland (890,308 ha) in Florida is irrigated (USDA 2014). In general, irrigation during a maize season varies between 51 and 61 cm depending on weather, plant density, fertility, days to maturity and soil type (Wright et al. 2003).

Irrigation scheduling (i.e., timing and depth of irrigation) is more efficient when based on ET or soil moisture sensors (SMS) (Irrigation Association 2011) to properly schedule irrigation events aligned with plant water requirements. Evapotranspiration (ET)-based irrigation scheduling uses estimates of soil evaporation (E) and plant transpiration (T) to determine when and how much water needs to be replaced in the rootzone to fulfill plant requirements. The use of real-time soil moisture data (SMS), or a soil water balance algorithm to replenish water depleted by ET, has been studied and successfully improves irrigation scheduling in maize (Derby et al. 2005).

Nitrogen (N) is also essential for achieving optimal maize yields. In Florida, recommended N application rates are based on crop needs as documented in research literature rather than based on soil testing and range from 168 to 235 kg N/ha for non-irrigated and irrigated maize, respectively (Mylavarapu et al. 2015). Thus, addition of N fertilizer is generally required to maximize yields (Hauck 1984). Although most of the plant N uptake occurs before anthesis (Francis et al. 1993; Pearson and Jacobs 1987), any application exceeding the potential N uptake is susceptible to loss, thus leading to a risk of N leaching to the environment (Fageria and Baligar 2005; Gholamhoseini et al. 2013). This risk is especially high in sandy soils where leaching can lead to high nitrate–N (NO_3–N) levels in groundwater (Casey et al. 2002; Derby et al. 2005; Ferguson et al. 1991; Gehl et al. 2005a, b).

Aiming to understand why growers over-apply nutrients, Sheriff (2005) identified a few conditions in which growers may benefit from applying fertilizers at rates greater than the recommended. One condition refers to the perceived relevance of a generic recommendation to an individual grower's field. Thus, if the growers' perception of the recommendation is too conservative (i.e., not appropriate for their individual situations), then they can maximize profit by applying more fertilizer than the recommended amount. Another condition refers to uncertainty; characteristic of agricultural production (e.g., due to weather conditions and prices). Therefore, growers may exceed the recommended application rate if the expected gain in profit due to the increased in yield is greater in a good state of nature than the expected loss in profit due to wasted fertilizer in the bad state of nature (Sheriff 2005).

Around the world, anthropogenic activities have resulted in water quality declines; threatening overall groundwater sustainability (Andraski et al. 2000; Arthur et al. 2007; Casey et al. 2002; Rabalais et al. 1996). Particularly in north Florida, due to karst topography and rapid timescales of groundwater and surface water exchange, high NO_3-N concentrations have been reported in springs within the Suwannee River Basin (SRB) (Katz 2004; Upchurch et al. 2007). Therefore, careful management and coordination of N fertilization and irrigation is recommended due to the mobility of N and the leaching potential in sandy soils (Wright et al. 2003). To achieve this coordination, it is important to consider the amount, timing and placement of fertilizer and the scheduling of irrigation around fertilization events to keep nutrients within the rootzone for optimum plant uptake and lower potential environmental risks.

Aiming to improve irrigation efficiency and reduce N losses from crops fertilization to the environment, studies have evaluated the performance of irrigation scheduling methods combined with N rates (Attia et al. 2015; Klocke et al. 1999; Stanger and Lauer 2008) among other practices. Sigua et al. (2017) evaluated three irrigation scheduling methods: Irrigator Pro (IPRO), normalized difference vegetative index (NDVI) and soil water potentials (SWP), and two N rates (157 and 224 kg N/ha) on nitrate level in shallow groundwater, water use and maize yield. Results showed no differences in yield across the irrigation methods, but the IPRO, which uses a soil water balance calculation approach, resulted in lower nitrate leaching, indicating an alternative to reduce N losses from fertilizers applied in maize fields (Sigua et al. 2017). Spencer et al. (2019) evaluated the effect of different irrigation water management (IWM) practices on the amount of water applied, maize yield and profitability compared with the regional standard practices. The IWM resulted in near 40% reduction in irrigation applied, while significantly increasing yield, irrigation water use efficiency and net returns. Therefore, previous studies have shown that the adoption of management strategies has a great potential for improvement in irrigation application and reduction of N losses from agricultural fields.

The hypotheses of this study were: (i) irrigation strategies (SWB, SMS and RED) achieve water savings without impact on maize grain yield compared to conventional practices (GROW), (ii) a medium N rate (similar to UF/IFAS recommended rate) allows similar N uptake and grain yield than higher rates typically applied in the region, and (iii) maize N uptake reaches a plateau; thus, high fertility rates result in excess N with no benefit. Therefore, to evaluate current maize irrigation and N fertilization practices in Florida, a 3-year experiment was established to: (i) evaluate the use of irrigation scheduling strategies including a calendar-based practice similar to that used by growers in the region (GROW), a daily soil water balance (SWB), a real-time soil moisture sensor (SMS), a reduced conventional practice (RED) and non-irrigated (NON) and quantify their associated impacts to yield; and (ii) determine the response of maize biomass, N uptake and yield to the interaction of these five irrigation treatments (GROW, SWB, SMS, RED and NON) with three N fertility rates (high, medium and low).

Materials and methods

Experimental field

This research study was conducted from 2015 to 2017 at the North Florida Research and Education Center–Suwannee Valley (NFREC–SV), near Live Oak, Florida (30.31353–82.90122 W). Three maize seasons grown on a predominantly Chipley-Foxworth-Albany soil (USDA 2013) were evaluated for this study.

Typically in Florida, the maize growing season spans from mid-March or early April to August. Planting is performed after the risk from major freeze events passes since a minimum temperature of 10 ± 2.2 °C in the top 5 cm for at least three consecutive days is required for maize germination and root growth (Sanchez et al. 2014; Wright et al. 2003). During the 3 years of this study, maize growing seasons spanned (planting to harvest) from 4 April to 18 August 2015, from 22 March to 3 August 2016, and from 21 March to 16 August 2017. The maize hybrid Pioneer 1498 YHR/Bt was planted each year. This hybrid has a high drought tolerance, making it very suitable under limited rain or dryland conditions (DuPont 2016). Maize was planted east–west at 76.2 cm row and 16.5 cm plant spacing for a total density of approximately 80,000 plants per hectare. The three growing seasons consisted of maize 2015 following a mix of grasses (predominantly Bahia grass), whereas the 2016 and 2017 maize seasons followed peanuts. To incorporate previous crop residues, the field was plowed and harrowed about ninety and ten days prior planting each year, respectively.

Weather

Weather parameters (i.e., daily rainfall, maximum, minimum and average temperature and ET_o) were collected from the on-site Florida Automated Weather Network (FAWN) weather station located in Live Oak, FL (FAWN 2017). The FAO-Penman Monteith equation (Allen et al. 1998a, b) is used to calculate ET_o by FAWN. To quantify crop development rate based on annual temperature variation, growing degree days (GDD) or units were calculated using the following equation (Angel et al. 2017):

$$GDD = \left[\left(T_{max} + T_{min}\right)/2 - T_{base}\right] \quad (1)$$

T_{max} = daily maximum temperature (°C)
T_{min} = daily minimum temperature (°C)
T_{base} = base temperature for growth to occur in maize (T_{base} = 10 °C)

Maize development was assumed to be limited by 30 and 10 max and min temperatures (°C). Thus, if T_{max} was >30 °C, a value of 30 was used and when T_{min} was <10 °C, a value of 0 was used for GDD.

Experimental design

The research site was divided into two systems according to the timing of rotation. System 1 (southern portion of the site) was a maize-peanut-maize rotation planted during 2015-17, and System 2 (northern portion) was a peanut-maize-peanut rotation grown during the same period. No irrigation was applied during the bare fallow intercropping periods. In this manuscript, the three maize seasons are presented. The experimental design consisted of a randomized complete block arranged in a split plot design with four replicates for each treatment. Irrigation treatments were the main plots and N fertility rates were the sub-plots. Experimental units were 12.2 m long and 6.1 m wide separated by 6.1 m alleys. Between the blocks, 12.2 m alleys were used to allow time for the irrigation system achieve adequate cycling of the variable rate system to switch irrigation rates among treatments (Fig. 1). A summary of the experimental field soil chemical analysis is included in Online Resource 1.

Irrigation treatments

Irrigation treatments were applied using a two span Valley Linear End Feed 8000 (Valmont Industries 2015), Valley, NE) with a Variable Rate Irrigation (VRI) package.

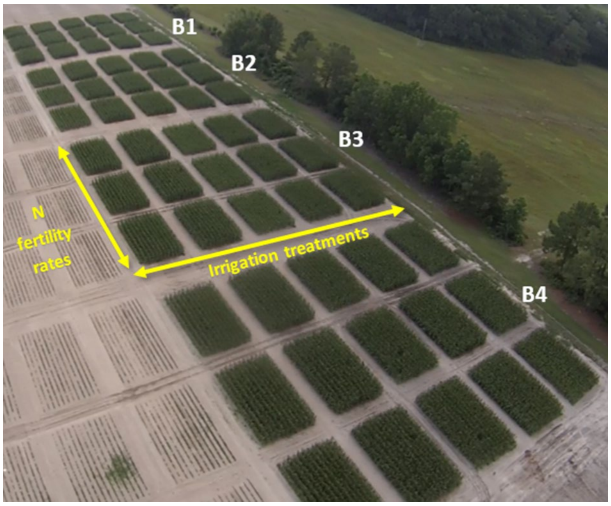

Fig. 1 Aerial view of experimental site located at North Florida Research and Education Center – Suwannee Valley (NFREC-SV), near Live Oak, Florida (30.31353 N, -82.90122 W)

Senninger (Senninger Irrigation Inc. 2015) LDN-UP3 Flat Medium Groove ¾ M NPT nozzles were attached to drops approximately 1.5 m height at a 3 m sprinkler spacing. Valley 69 kPa pressure regulators (PSR-2 10 10(PSI) ¾ F NPT) were installed on each drop to maintain a constant flowrate. The VRI system was used to irrigate different amounts to individual plots based on the corresponding treatments.

The irrigation treatments evaluated consisted of:

GROW: mimics growers' irrigation practices for the region. Information from local growers was collected from extension agents and the Suwannee River Water Management District to develop this irrigation strategy. The target irrigation rates varied based on growth stages. When irrigation was scheduled, individual events were 10 mm. No irrigation was applied for the first 30 days after planting (DAP) (unless severe windy conditions occurred that caused sand blowing to damage plants). At 31 DAP, 25 mm/wk was targeted unless rainfall events were ≥ 10 or > 20 mm, then one or two scheduled irrigation events were skipped, respectively. At 40–59 DAP, the target irrigation was 38 mm/wk. If rainfall events were ≥ 13–19 mm one irrigation event was skipped, and two events were skipped if > 19 mm of rain occurred. Afterwards, the target irrigation total increased up to 51 mm/wk. Irrigation events of 10 mm were applied unless 13–25 mm of rain occurred, then one scheduled event was skipped, or two events were skipped if ≥ 25 mm of rain occurred. Finally, at full dent stage (105 DAP), the weekly target irrigation total was 41 mm/wk. If rainfall events were ≥ 13–19 mm one irrigation event was skipped, and two events were skipped if rainfall > 19 mm occurred. Irrigation was terminated after physiological maturity (i.e., black layer) around 115 DAP.

SWB: soil water balance. Irrigation was determined using a theoretical SWB equation which calculates daily soil water storage in the maize active root zone (0–61 cm) due to changes in effective rainfall (R), effective irrigation (I), run-off (RO), estimated crop evapotranspiration (ET_c), and deep drainage (D). It assumes negligible rates for RO and D unless water exceeds water holding capacity in the rootzone. The simplified (without RO and D) daily SWB equation used to call for irrigation in this treatment is described as following:

$$SWC_i = SWC_{i-1} + R_i + I_i - ET_{ci} \quad (2)$$

For each day, the soil water content ($SWC_{i,}$ where subscript i is the current day) is calculated by adding R_i and I_i and subtracting $ET_{c\,i}$ to the soil water content from the previous day ($SWC_{i\text{-}1}$). The allowable depletion (AD) is referred as the recommended level of stored moisture depletion to minimize water stress to the plants. AD is a function of root depth (RD_i) (i.e., stored soil moisture), maximum allowable depletion (MAD) and the soil water holding capacity (WHC, 0.07 mm/mm).

$$AD = RD{*}\mathrm{MAD}{*}\mathrm{WHC} \quad (3)$$

In the SWB, water exceeding the AD, it is assumed to leave the soil each day (i.e., if $SWC_i < AD$, $SWC_i = SWC_{i\text{-}1} + R_i = I_i + ET_{ci}$; however, if $SWC_i > AD$, $SWC_i = AD$). In 2015, MAD values of 50% were used during the entire growing season. However, to reduce water stress during reproductive stages, MAD values of 50% and 33% were used during vegetative and reproductive stages, respectively in both 2016 and 2017. Minimum (R_{zmin}) and maximum (R_{zmax}) root depths were set as 7.6 and 61 cm, respectively, (USDA 2005). RD_i is assumed to increase as the crop grows and theoretically, reach R_{zmax} at 43 DAP when 80% canopy cover is achieved (Allen et al. 1998a, b). Thus, daily root depth increase (RDI) was calculated dividing the difference between maximum and minimum root depths by 43 days

$$RDI = \left(R_{zmax} - R_{zmin}\right)/43 \text{ days} \quad (4)$$

Thus, 1.24 cm/day corresponds to the daily root depth increase (RDI). Then, RD_i is calculated by adding RDI to the root depth of the previous day ($RD_{i\text{-}1}$)

$$RD_i = RD_{i-1} + RDI \quad (5)$$

Weather data (i.e., rainfall, ET_o, temperature) were obtained from the on-site FAWN weather station located in Live Oak, FL (FAWN 2017). Crop evapotranspiration (ET_c) was calculated using phenologically based crop coefficients (K_c) (K-State Research and Extension Mobile

Table 1 Crop coefficient (K_c) values for maize used to calculate ET_c for treatments under non-water stress conditions and for schedule irrigation in the Soil Water Balance (SWB) treatment

DAP	Root depth (mm)	K_c[a]
2	99	0.25
6	150	0.25
10	201	0.41
14	249	0.57
18	300	0.73
22	351	0.89
26	399	1.05
30	450	1.05
34	500	1.05
38	551	1.05
42	600	1.05

[a]K_c values: $K_{c\text{-ini}} = 0.25$, $K_{c\text{-max}} = 1.05$ and $K_{c\text{-end}} = 0.55$ (K-State Research and Extension Mobile Irrigation Lab, 2014)

Irrigation Lab 2014) (Table 1) and reference evapotranspiration (ET_o) as follows:

$$ET_c = K_c * ET_o \tag{6}$$

The calculated ET_c (Eq. 6) was used in (Eq. 2) to determine SWC_i. The SWB treatment irrigation was initiated when SWC_i fell below the MAD threshold corresponded to each crop growth stage.

SMS: soil moisture sensor-based. Capacitance probes monitored volumetric water content (VWC, manufacturer's reported values) in three blocks (B2–B4) of the field experiment. The Sentek drill and drop probes consist of nine sensors placed every 10 cm from 5 to 85 cm (Sentek Pty Ltd 2003). These probes were installed in the row in between two plants in three of the four blocks for this treatment. Irrigation was determined using the MAD as 50% of the difference between FC and PWP to refill the active root depth with irrigation according to guidelines proposed by Zotarelli et al. (2013). Root depth was considered in calculating the water storage to be replenished with irrigation; thus, as maize was growing, the total VWC was adjusted based on root development (i.e., sum of VWC from sensors in the most active root zone). During the growing season, three root zones were used: 30 cm (i.e., initial vegetative growth stages ~ V3 to V6), 40 cm (i.e., peak of growth in vegetative stages ~ V7 to VT) and 60 cm (i.e., tasseling, when crop is developed and reproductive stages begin). One irrigation event totaled 10 mm. Soil physical properties [field capacity (FC) = 9.1% (by volume), 50% MAD = 6.3%, available water holding capacity (AWHC) = 5.6% and permanent wilting point (PWP) = 3.5% (NRCSS 2016b)] obtained from SSURGO database were compared with field values (VWC using the probes in 2015 and following Zotarelli et al. (2013) guidelines. SSURGO and field values comparison performed for 0–60 cm soil depth resulted in similar values (e.g., average FC = 9.3% (± 0.2%) in a 30 cm root zone depth vs. 9.1% FC SSURGO value). Therefore, SURGO FC and 50% MAD values were used as thresholds to irrigate this treatment. Based on the adjusted crop root development, the soil water content measured by the different sensors was adjusted through the growing season. Irrigation in this treatment was triggered when VWC in any of the probes showed values below the 50% MAD threshold.

RED: applied 60% of GROW at the same frequency with fixed application rates of 6 mm vs. 10 mm for a single event, representing a lower irrigation treatment scenario.

NON: non-irrigated/rainfed plots. These plots received only precipitation during the growing season, except for periods directly following granular fertilizer. All plots (including NON) received on average 7.6 mm irrigation after granular fertilizer applications to ensure the incorporation of the fertilizer into the soil and to provide adequate moisture conditions for nutrient uptake.

Nitrogen fertility treatments

The three N fertility rates evaluated were 'high' (336 kg N/ha) representing rates commonly applied in maize production in Florida; 'medium' (247 kg N/ha), which is 5% above the UF/IFAS recommended N rate (235 kg N/ha; Mylavarapu et al. (2015); and 'low' (157 kg N/ha). The low and high N rates deviated ± 36% from the medium rate.

The application of N fertilizer was scheduled according to GDD values during the three growing seasons (Online Resource 2). Generally, this consisted of an initial 34 kg N/ha liquid application of N-P-K (16–16-0) applied in the row on all treatments, two granular (at approximately V3 and V6 maize growth stages), and four liquid sidedress applications weekly until tasseling. All N fertility treatments included the same initial application, with differential treatment rates starting at the first granular application.

Following the agronomic crops BMP manual (FDACS 2015), depending upon the stage of crop development, a single N and or K application may be applied if rainfall exceeds 76 mm in 3 days or 102 mm in 7 days. A large amount of rainfall occurred 2 April 2016 (totaling 76 mm), thus, following the BMP manual, an application of 34 kg N/ha (21-0-0-24S, ammonium sulfate) was performed on 19 April 2016. In 2017, a few days after planting a large rain event occurred on April 4 (95 mm), hence a supplemental application of 17 kg N/ha was performed to compensate for possible N leaching. Although extra N was applied, the fertility rates were consistent as high, medium and low (Online Resource 2). In addition, a supplemental application of 24 kg K/ha of

K-Mag (0-0-22) was added to the second granular K applications on 20 April 2017 to address sulfur and magnesium concerns. A pre-plant soil sampling analysis was performed to determine soil initial conditions each year. Maize fertilization for phosphorus, potassium and micronutrients was adjusted based on soil testing results performed prior to each crop season and applied equally across all fertility rates as required. Online Resource 2 summarizes all fertilizer applications during the three maize growing seasons.

Biomass sampling and N analysis

Maize tissue samples were collected during key growth periods (i.e., two sampling events during vegetative stages in the early season, one at 80% tasseling, one at dough stage, and one at mature stage close to harvest). Final tissue samplings were performed on 19 August 2015, 2 August 2016 and 7 August 2017 just prior to harvest. Tissue samples were collected from a 1 m linear section within a row, representative of the plot. The total number of plants were counted and sectioned into stalks, leaves, and ears (when present). Additional parameters measured included the number of leaves per plant and number of ears. All samples were placed in ovens and dried in 60 °C for 72 h, then weighed. Dry maize samples (from plant sections) were chopped with a chipper machine and afterwards, samples were ground in a Wiley mill using 2 mm screen and mixed well before taking a subsample (approximately 100 g) for the lab analysis. Samples were analyzed for Total Kjeldahl Nitrogen (TKN). For N analysis, samples were digested using a modification of the aluminum block digestion procedure of (Gallaher et al. 1975). A sample weight of 0.25 g and a catalyst of 1.5 g of 9:1 K_2SO_4:$CuSO_4$ were used to conduct digestion for at least 4 h at 375 °C using 6 ml of H_2SO_4 and 2 ml H_2O_2. Nitrogen in the digestate was determined by semi-automated colorimetry (Hambleton 1977). Estimated N uptake (kg/ha) of the different plant tissues was calculated using the N concentrations (%) within the biomass obtained from TKN laboratory analysis (i.e., %N * dry weight). Total final aboveground (AG) biomass was calculated as the sum of leaves, stems and ears dry weight for each treatment. To evaluate the effect of irrigation and N rate treatments on final biomass and N uptake, only final tissue samples of aboveground plant sections were considered.

Harvest

Maize harvest took place on 18 August 2015, 3 August 2016 and 16 August 2017. In 2015 and 2016, yield determination was performed on the 6th and the 7th planting rows starting three meters inside each plot to avoid border effects and harvesting a total of six meters. In 2017, representative rows were selected for yield determination since predetermined rows were impacted by low seed density at planting. Before harvesting, all plants within the two rows were counted. Immediately after, ears were hand harvested and placed in bags, counted after removing the husk, and total ear weight was recorded. All ears per plot were shelled using a manual sheller and shelled maize was weighted. Three replicate grain moisture measurements were taken from each sample of shelled grain for final average moisture calculation using a moisture meter (John Deere Grain Moisture Tester SW08120). Final grain yield was calculated to 15.5% moisture content. The weight of 100 kernels was measured as a second yield variable.

Water productivity calculations

Better use of existing water resources must be implemented to achieve higher agricultural production, either by increasing the available amount of water to the plants, or by increasing the efficiency with which the water is used for growth and yield (Wallace and Batchelor 1997).

In the literature, several definitions and indicators have been used to describe the terms efficiency and water productivity (WP) (Howell 2001; Pereira et al. 2012; Perry 2011; Trout and DeJonge 2017; Viets 1962) which often are used interchangeably leading to misunderstanding (Allen et al. 1997; Jensen 1996; Pereira et al. 2012; Rodrigues and Pereira 2009). Therefore, water productivity (WP) in agriculture and landscape irrigation was adopted to express the quantity of product or service produced by a given amount of water used (Pereira et al. 2009, 2012). The denominator may consider the total water use (TWU) which includes irrigation and rainfall, or just the irrigation water use (IWU), resulting in two different indices described as follows (Pereira et al. 2009, 2012):

$$WP = Y_a / TWU \tag{7}$$

WP = water productivity (kg/m^3)
Y_a = actual crop yield achieved (kg/ha).
TWU = total water use (irrigation and rainfall) (mm)

$$WP_{irrig} = Y_a / IWU \tag{8}$$

To calculate water productivity with respect to the amount of the irrigation applied, WP_{irrig} was calculated.
WP_{irrig} = irrigation water productivity (kg/m^3)
Y_a = actual crop yield achieved (kg/ha).
IWU = total irrigation applied (mm).

Then, to calculate water productivity with respect to the amount of crop evapotranspiration ($ET_{c\ adj}$) (Allen et al. 1998a, b), the CWP index was calculated.

$$CWP = Y_a / ET_{cadj} \tag{9}$$

CWP = crop water productivity (kg/m^3)

Y_a = actual crop yield achieved (kg/ha).

$ET_{c\ adj}$ = adjusted crop evapotranspiration (mm) (Allen et al. 1998a, b).

$ET_{c\ adj}$ was calculated as

$$ET_{cadj} = ET_o * K_c * K_S \tag{10}$$

using the soil water stress coefficient, K_s, described by Allen et al. (1998a, b) as:

$$K_S = \frac{(TAW - D_r)}{(TAW - RAW)} = \frac{(TAW - D_r)}{(1 - p)TAW} \tag{11}$$

K_S = dimensionless transpiration reduction factor dependent on available soil water [0–1]. $K_S = 1$ for $D_r \leq$ RAW and decreases linearly to 0.0 when D_r = TAW.

D_r = root zone depletion (mm).

TAW = total available water in the root zone (mm). TAW = 1000 ($SWC_{FC} - SCW_{WP}$) RD.

RAW = the readily available soil water in the root zone (mm).

p = fraction of TAW that a crop can extract from the root zone without suffering water stress (assumed to be 0.5 in this model).

The effectiveness of irrigation strategies was evaluated through the WP, WP_{irrig} and CWP indices described above.

Statistical analysis

Data was analyzed using the SAS GLIMMIX proc procedure (SAS Institute Inc. 2013), with irrigation, N fertility rates and year as main (fixed) effects while treating the replication and its interactions with class variables as random effects. Normality assumptions were met; thus, no data transformation was required. Covariance structures were selected for each response variable using the corrected Akaike information criterion (AICC). Covariance-structure (CS) used for response variables was CHS (Heterogeneous CS). Analysis of Variance (ANOVA) and least squared means (LSM) differences with normal p values were used for multiple comparison with significant differences at the 95% confidence level.

Results

Weather conditions

Climatic conditions at the experimental field varied during the three growing seasons (Online Resources 3 and 4). In 2016 and 2017, maize development rate was slower due to early season low temperatures (minimum temperature 1.8 °C and 5.4 °C, respectively), causing a delay in biomass formation. The cumulative growing degree days (GDDs) were 3,934, 3,685 and 3,647 GDDs, in the 2015–2017 seasons, respectively. Early in the 2015 season, minimum temperatures were higher (9.5 °C) than subsequent years, which resulted in a positive effect on maize development rate and in GDD accumulation, and therefore in biomass production compared to 2016 and 2017 seasons (Online Resource 3).

In the study area, annual precipitation is variable in both magnitude and timing. Cumulative rainfall was 531, 370 and 688 mm during the 2015–2017 maize growing seasons, respectively. The 2016 season received 30 and 46% lower rainfall compared to the 2015 and 2017 seasons, respectively. However, rainfall distribution varied, and early June heavy rainfall events occurred (cumulative rainfall 58 and 120 mm, respectively). Afterwards, more frequent rainfall events occurred in the season (Online Resource 4).

An analysis of variance of maize response variables evaluated in response to year (Y), irrigation (I) and N fertilizer rate (N) from 2015 to 2017 at NFREC-SV is shown in (Table 2). No interactions were found between main effects (I, N and Y); except on final grain yield and WP_{irrig} (i.e., I x

Table 2 Analysis of variance of maize total aboveground (AG) biomass, total AG N uptake, 100 kernel weight, final grain yield, water productivity (WP), water productivity of irrigation water (WP_{irrig}) and crop water productivity (CWP) indices in response to year, irrigation and N fertilizer rate from 2015 to 2017 at NFREC-SV

Source of variation	Total AG Biomass	Total AG N uptake	100 Kernel weight	Yield	WP	WP_{irrig}	CWP
Year (Y)	***	NS	***	NS	*	***	NS
Irrigation (I)	***	***	***	***	**	***	**
N fertility rate (N)	NS	**	*	***	***	**	***
Y x I	NS	NS	NS	***	N	***	NS
Y x N	NS	NS	NS	NS	NS	NS	NS
I x N	NS	NS	NS	NS	NS	NS	NS
Y x I x N	NS	NS	NS	NS	NS	NS	NS

NS nonsignificant

*Significant at $P \leq 0.05$

**Significant at $P \leq 0.01$

***Significant at $P \leq 0.001$

Y was significant) (Table 2). Therefore, results and discussion are shown separately by main effects.

Irrigation treatments

Cumulative irrigation applied across the irrigation treatments during the three seasons is shown in Fig. 2. The GROW treatment consistently applied greater amounts of irrigation during the three seasons. In comparison, irrigation strategies proposed (i.e., SWB, SMS and RED) resulted in reduced irrigation of 42, 53 and 34% in 2015; 39, 43 and 37% in 2016; and 42, 45 and 36% in 2017, respectively. Irrigation requirements varied across seasons due to rainfall variability (Fig. 2 and Online Resource 4).

Irrigation had an effect on final aboveground (AG) biomass (i.e., sum of leaves, stems and ears dry weight), final AG N uptake, 100 kernel weight and it also affected WP and CWP. A significant interaction between irrigation

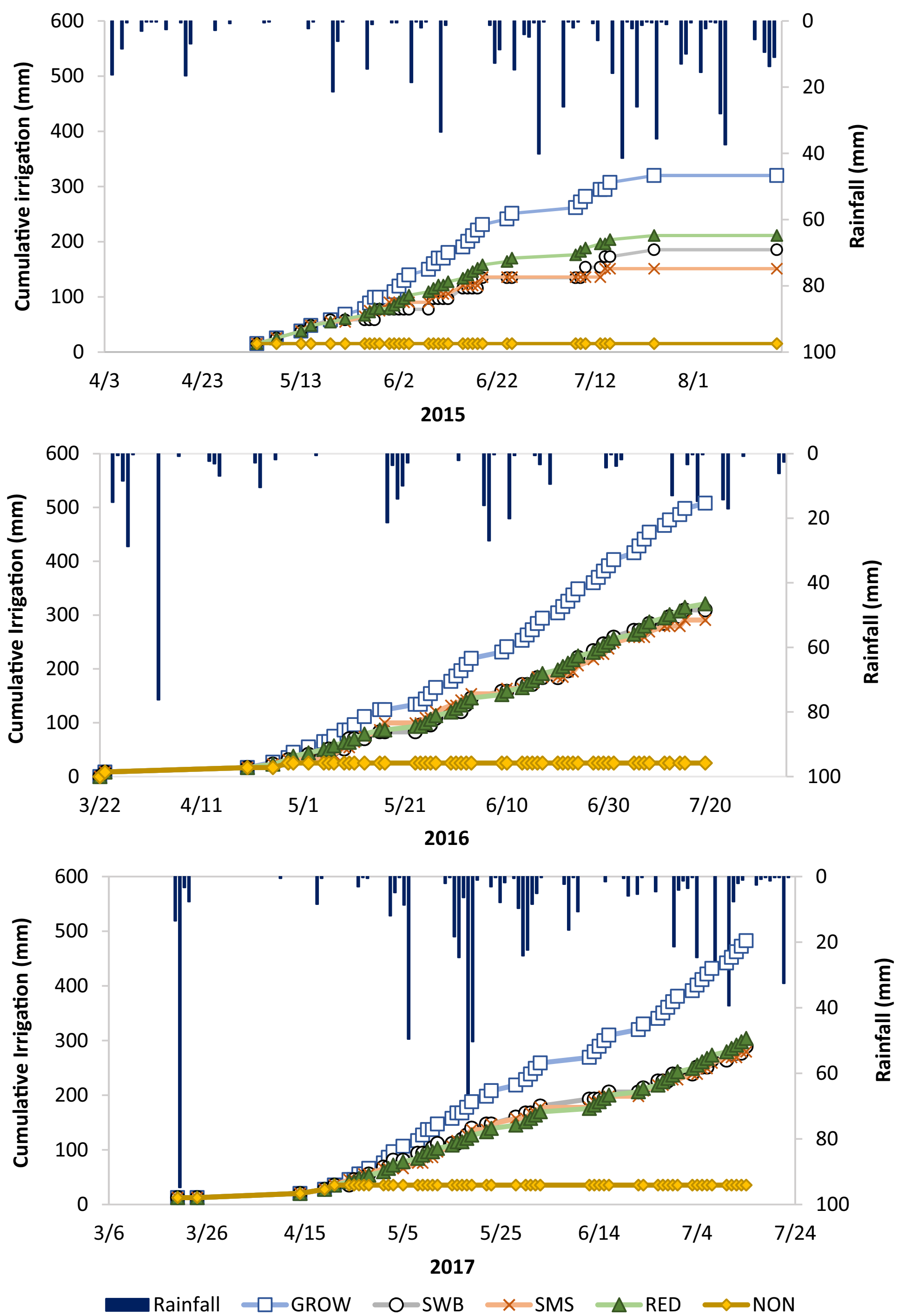

Fig. 2 Cumulative irrigation applied per treatment and daily rainfall in 2015 – 2017

and year was found on final grain yield and on WP_{irrig} (Table 2). Thus, results are discussed based on significant effects.

Final AG biomass. Irrigation and year had a significant effect on AG biomass (Table 2, Fig. 3). Final AG biomass means for the GROW, SWB, SMS, RED and NON irrigation treatments during the three maize seasons were 22,640, 22,897, 23,226, 23,384 and 14,542 kg/ha, respectively (Fig. 3a). Only the NON treatment showed lower final AG biomass compared to the irrigated treatments. Annual final AG biomass mean was higher in 2015 than in 2017; however, final AG biomass in 2016 did not differ from 2015 or 2017 (annual AG biomass means in 2015-17 = 23,356, 21,497 and 19,161 kg/ha, respectively) (Fig. 3B).

Final AG N uptake. During the 3-year field experiment, total N uptake means were 225, 242, 248, 241 and 167 kg N/ha in GROW, SWB, SMS, RED and NON treatments, respectively. Irrigation significantly affected final AG N uptake (i.e., N uptake from aboveground plant sections). On average, the NON treatment (rainfed) resulted in 30% lower N uptake means compared to the irrigated treatments. No significant differences were found among the years of evaluation (Fig. 4).

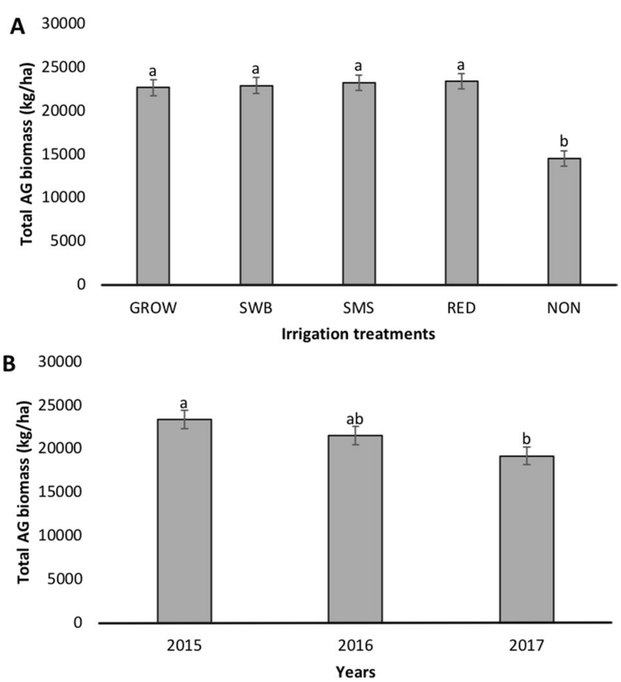

Fig. 3 Total maize aboveground (AG) biomass means as a response to five irrigation treatments (GROW, SWB, SMS, RED and NON) (n= 3yr*3N*4repl. = 36) (**A**) and years of evaluation (2015-17) (n= 5Irr*3N*4repl. = 60) (**B**). Different letters indicate differences at the 95% CI for irrigation means and across the three years of evaluation. Error bars show SE of total aboveground biomass and N uptake across means

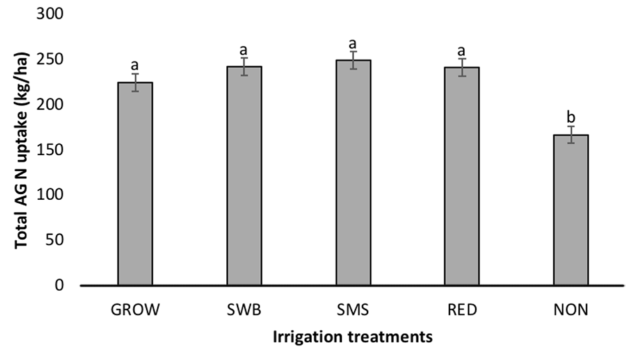

Fig. 4 Total maize aboveground (AG) N uptake means as a response to five irrigation treatments (GROW, SWB, SMS, RED and NON) during 2015-17 maize growing seasons (n= 3yr*3N*4repl. = 36). Different letters indicate differences at the 95% CI for irrigation means and across the three years of evaluation. Error bars show SE of total aboveground biomass and N uptake across means

Grain yield

A significant interaction between irrigation and year was found on final grain yield. During the three growing seasons, irrigation had a positive effect on final grain yield; thus, no difference in grain yields was observed across irrigated treatments, but lower yields resulted in the NON treatment. An exception occurred during the 2015 season, when the NON treatment resulted in similar yields (8,993 kg/ha) compared to the SWB (11,201 kg/ha); however, yields were lower compared to the other irrigated treatments (Fig. 5). The 2015 season mean grain yields were 12,105, 11,201, 12,011, 12,638 and 8,993 kg/ha for the GROW, SWB, SMS, RED and NON treatments, respectively; and the corresponding treatment cumulative irrigation was 320, 185, 151, 211 and 15 mm, respectively. The SWB, SMS, RED and NON treatments cumulative irrigation was 42, 53, 34 and 95% lower than the GROW treatment. In 2016, GROW, SWB, SMS, RED and NON treatment mean grain yields were 12,705, 11,554, 11,818, 11,964 and 7,973 kg/ha, respectively, whereas cumulative irrigation was 508, 310, 291, 321 and 25 mm, respectively. The SWB, SMS, RED and NON treatment total irrigation were 39, 43, 37 and 95% lower than GROW treatment, respectively. In the 2017 season, GROW, SWB, SMS, RED and NON treatment mean yields were 12,566, 12,740, 12,203, 12,190 and 5,779 kg/ha, respectively. The corresponding cumulative irrigation per treatment was 546, 315, 302, 347 and 48 mm. Thus, compared to the GROW treatment, irrigation reductions of 42, 45, 36 and 91% were achieved by SWB, SMS, RED and NON treatments, respectively.

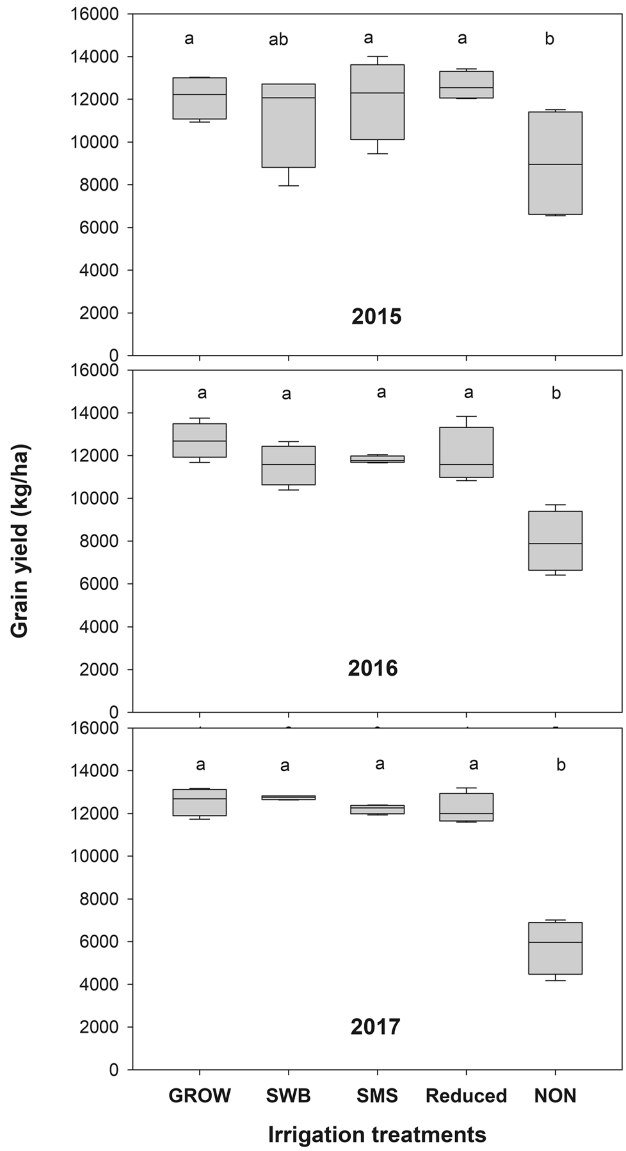

Fig. 5 Maize grain yield across irrigation treatments (GROW, SWB, SMS, RED and NON) during the 2015-17 maize seasons (n= 1yr*3N*4repl. = 12). Yield is expressed at 15.5% moisture content. Boxplots: lower boundary indicates the 25th percentile, the line within the box marks the median, and the upper boundary indicates the 75th percentile. Whiskers (error bars) above and below the box indicate the 90th and 10th percentiles. Different letters indicate differences at the 95% CI for irrigation means per season

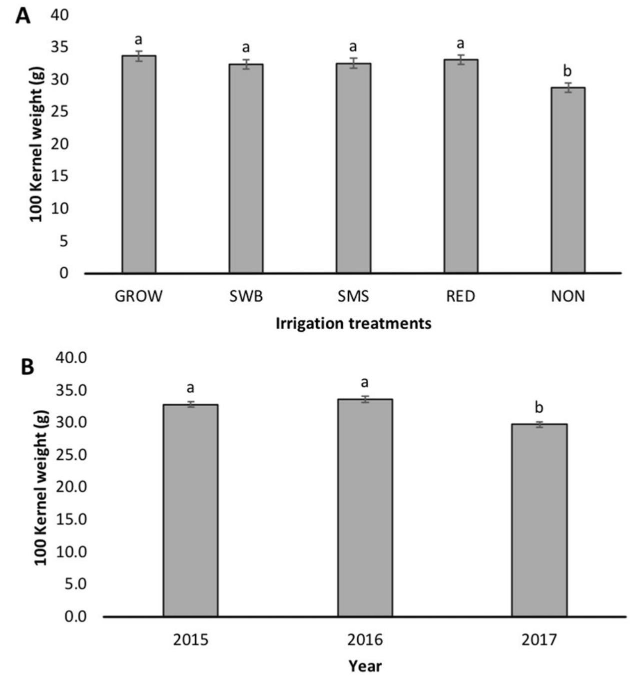

Fig. 6 The 100 kernel weight means as a response of five irrigation treatments (GROW, SWB, SMS, RED and NON) (n= 3yr*3N*4repl. = 36) (**A**), and years of evaluation (2015-17) (n= 5Irr*3N*4repl. = 60) (**B**). Different letters indicate differences at the 95% CI for irrigation means per season. Error bars show SE of kernel weight across means

The 100 kernel weight

Irrigation and year showed a significant effect on a 100 kernel weight. In terms of irrigation, the NON treatment resulted in lower 100 kernel weight mean (28.7 g) compared to the irrigated treatments (33.7, 32.4, 32.6, 33.1 g for GROW, SWB, SMS, RED, respectively) (Fig. 6A). Across the 3 years evaluated, lower 100 kernel weight occurred in 2017 (29.8 g) compared to 2015 and 2016 (32.8 and 33.6 g, respectively) (Fig. 6B).

Water productivity indices

Daily rainfall amounts and distribution varied across all three seasons (Fig. 2 and Online Resource 4); however, overall most of the rainfall occurred during mid or late season (June–August) (Online Resource 4). Cumulative rainfall amounts during the 2015–2017 growing seasons were 556, 370 and 673 mm, respectively.

All main effects (i.e., irrigation, fertility rates and year) influenced WP (Table 3); however, no significant interactions among them were found. In terms of irrigation, the GROW treatment resulted in a lower WP index (1.29 kg/m^3) compared to the other irrigated treatments (SWB, SMS and RED average WP = 1.53 kg/m^3). Differences in WP among the years of evaluation were found, where a lower WP was found in 2017 compared to the WP in 2015 and 2016 (Table 3). Among the N fertility rate treatments, no differences in WP were found between the medium and high N rates treatments (WP = 1.48 and 1.54 kg/m^3, respectively), however, the low N rate treatment resulted in lower WP (1.40 kg/m^3).

Table 3 Total water productivity (WP) and crop water productivity (CWP) as a response of four irrigated treatments (GROW, SWB, SMS and RED), three N fertility rate treatments (low, medium and high = 157, 246 and 336 kg N/ha) and years of evaluation (2015–2017)

Irrigation treatment	WP[b] (kg/m^3)	WP_{irrig}[c] (kg/m^3)	CWP[d] (kg/m^3)
GROW	1.29 b		2.96 b
SWB	1.50 a	*	3.28 a
SMS	1.58 a		3.32 a
RED	1.52 a		3.33 a
N fertility rate treatment[a]	WP (kg/m^3)	WP_{irrig} (kg/m^3)	CWP (kg/m^3)
Low	1.40 b	4.06 b	3.06 b
Medium	1.48 a	4.34 ab	3.24 a
High	1.54 a	4.52 a	3.36 a
Year[a]	WP (kg/m^3)	WP_{irrig} (kg/m^3)	CWP (kg/m^3)
2015	1.56 a	5.95 a	3.24 a
2016	1.67 a	3.50 b	3.13 a
2017	1.19 b	3.47 b	3.29 a

Different letters indicate differences at the 95% CI for irrigation, N fertility and year means, respectively

[a]Supplemental N application (34 and 17 kg N/ha) due to leaching rain events modified all N fertility rates in 2016 and 2017 growing seasons, respectively

[b]WP = calculated as the ratio of the achieved yield to the sum of rainfall and irrigation applied, expressed in kg/m^3

[c]WP_{irrig} calculated as the ratio of the achieved yield to the irrigation applied, expressed in kg/m^3

[d]CWP = calculated as the ratio of the achieved yield to the ET_c adj using the soil water stress coefficient (K_S)

*Significant interaction (Irrigation x Year) found in WP_{irrig}. Results are described in Table 4

Table 4 Grain yield (kg/ha), irrigation applied, cumulative rainfall and water productivity of irrigation water index (WP_{irrig}) across irrigation treatments during 2015–2017 maize growing seasons

Year	Grain yield[a] (kg/ha)	Irrigation (mm)	Rainfall (mm)	WP_{irrig}[b] (kg/m^3)	Irrigation reduction[c] (%)
2015			556		
GROW	12,105 a	320		3.78 c	
SWB	11,201 ab	185		6.05 b	42
SMS	12,011 a	151		7.95 a	53
RED	12,638 a	211		5.99 b	34
NON	8993 b	15		–	95
2016			370		
GROW	12,705 a	508		2.50 b	
SWB	11,554 a	310		3.73 a	39
SMS	11,819 a	291		4.06 a	43
RED	11,964 a	321		3.73 a	37
NON	7974 b	25		–	95
2017			673		
GROW	12,567 a	546		2.30 c	
SWB	12,740 a	315		4.04 a	42
SMS	12,203 a	302		4.04 a	45
RED	12,191 a	347		3.51 b	36
NON	5779 b	48		–	91

[a]Grain yield standardized for 15.5% market moisture content

[b]WP_{irrig} calculated as the ratio of irrigated yield by total irrigation applied, expressed in kg/m^3

[c]Irrigation reduction compared to the irrigation applied by the GROW treatment

Different letters indicate differences at the 95% CI for irrigation means for each year of evaluation due to interaction between main effects (I x Y) for grain yield and WP_{irrig}

A significant interaction between irrigation and year was found on WP_{irrig} index (Table 4). During the 2015 growing season, the highest WP_{irrig} index was achieved by the SMS (7.95 kg/m^3) followed by the SWB and RED treatments (WP_{irrig} = 6.05 and 5.99 kg/m^3, respectively). In contrast, the GROW treatment resulted in significantly lower WP_{irrig} compared to all irrigated treatments (WP_{irrig} = 3.78 kg/m^3). Similarly, during 2016, no differences in WP_{irrig} were found between the SWB, SMS and RED treatments (mean WP_{irrig} = 3.84 kg/m^3); however, the GROW treatment resulted in a lower WP_{irrig} index (2.50 kg/m^3) than the irrigation strategies evaluated. During the 2017 season, the SWB and SMS treatments resulted in significantly higher WP_{irrig} values (4.04 for both), followed by the RED treatment (3.51 kg/m^3) and the lowest WP_{irrig} value was in the GROW treatment (2.30 kg/m^3). Statistical differences were found among all treatments except SWB and SMS. This index reflects the irrigation contribution to final grain yield. The SWB, SMS and RED treatments resulted in no significant differences in yield; however, achieved 42%, 45% and 36% irrigation reduction in comparison to the GROW treatment (Table 4).

Irrigation also had a significant effect on CWP (Table 2), where higher values were obtained by the irrigation strategies proposed in this study (SWB, SMS and RED average CWP = 3.31 kg/m^3) compared to the GROW treatment (CWP = 2.96 kg/m^3).

Nitrogen fertility treatments

Final AG biomass and N uptake

During each of the growing seasons, N fertility rates did not have an effect on final biomass dry weights (Table 2). Therefore, final biomass means (i.e., across the three N fertility rates) were 23,353 kg/ha in 2015; 21,496 kg/ha in 2016 and 19,160 kg/ha in 2017. Although no differences among the N rates evaluated within each season were found, differences on final AG biomass were found between years of evaluation (Table 2). The N rates applied in 2015 resulted in higher mean AG biomass than corresponding rates in 2017 (Fig. 3B). In contrast, the N rates had an effect on final AG N uptake (i.e., N uptake from aboveground plant sections). Differences on total AG N uptake were found between the low and the high N rates (N uptake means = 212 and 236 kg/ha, respectively), whereas the medium N rate (225 kg/ha) did not differ from any of the other two rates (Table 2, Fig. 7).

Grain yield and 100 kernel weight

Fertility had an effect on grain yield and on 100 kernel weight. In terms of final yield means, differences were not found between the medium and high N rates (12,196 and 12,685 kg/ha, respectively), only versus the low rate that resulted in lower yields (11,543 kg/ha) across all years of evaluation (Fig. 8). Similarly, in terms of 100 kernel weight, differences were found only between the low (31.2 g) and the high N rates (32.9 g). The medium N rate (32.2 g) was not different from the other rates evaluated (Fig. 9).

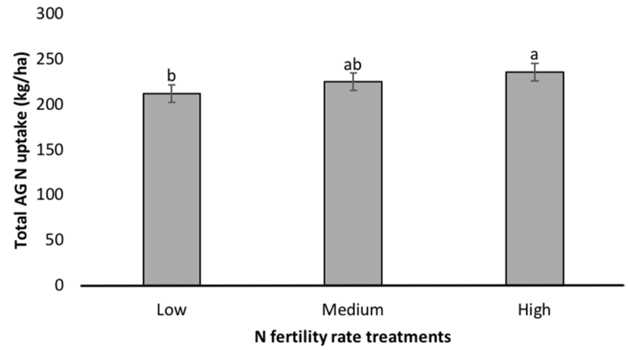

Fig. 7 Total aboveground (AG) N uptake means as a response of three N fertility rates (low, medium and high = 157, 247 and 336 kg N/ha, respectively) (n= 3yr*5Irr*4repl. = 60) during the three maize growing seasons (2015-17). Note: N rates were modified in 2016 and 2017 due to leaching rain; thus, additional 34 and 17 kg N/ha were applied to all rates, respectively. Different letters indicate differences at the 95% CI for fertility means across the three years of evaluation. Error bars show SE of total aboveground biomass and N uptake across means

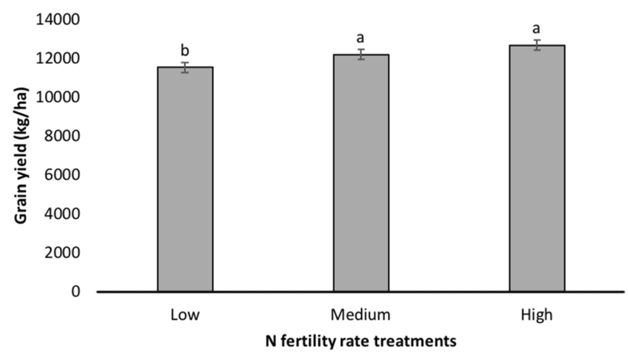

Fig. 8 Maize grain yield (kg/ha) as a response of three N fertility rates (low, medium and high = 157, 247 and 336 kg N/ha, respectively) (n= 1yr*5Irr*4repl. = 20) during three maize growing seasons (2015-17). Yield is expressed at 15.5% moisture content. Note: N rates were modified in 2016 and 2017 due to leaching rain; thus, additional 34 and 17 kg N/ha were applied to all rates, respectively. Different letters indicate differences at the 95% CI for fertility means per season

Water productivity indices

Fertility rates had a significant effect on all the indices evaluated (WP, WP_{irrig} and CWP). The high and medium N rates resulted in higher WP (average WP = 1.51 kg/m^3) compared

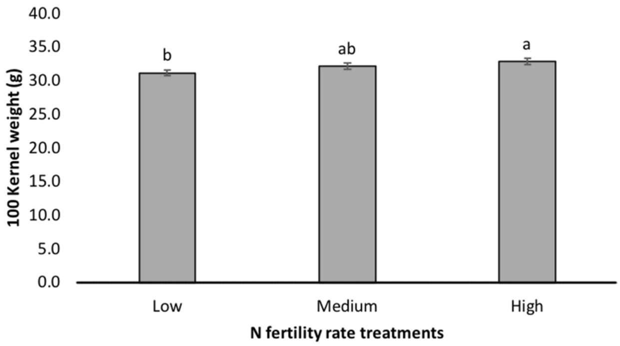

Fig. 9 The 100 kernel weight means as a response of three N fertility rates (low, medium and high = 157, 247 and 336 kg N/ha, respectively) (n= 3yr*5Irr*4repl. = 60). Different letters indicate differences at the 95% CI for fertility rate means per season. Error bars show SE of the 100 kernel weight across means

to the low N rate (1.40 kg/m^3). Similarly, higher CWP indices were obtained on the medium and high N rates (average CWP = 3.30 kg/m^3) compared to the low rate (3.06 kg/m^3). In terms of WP_{irrig}, only the high N rate resulted in a statistically higher WP_{irrig} compared to the low rate. The medium rate did not differ statistically from the high or the low rates (WP_{irrig} low, medium and high = 4.06, 4.34 and 4.52 kg/m^3, respectively) (Table 3).

Discussion

Irrigation treatments

Final AG biomass, N uptake, Yield and 100 kernel weight

Results showed lower final AG biomass, AG N uptake and yield in the NON treatment, whereas no differences among the irrigated treatments evaluated. Except on yield, a significant interaction between irrigation and year was found.

Water in the plant could be considered as a continuous hydraulic system that connects the water in the soil with the water vapor in the atmosphere (Taiz et al. 2015). Transpiration is regulated mainly by guard cells, which control the stomatal pore size to meet photosynthetic demand for carbon dioxide (CO_2). The ability of plants to uptake and transport water is represented by the whole plant hydraulic conductance, which consist of leaf, stem and root hydraulic conductance and is the limiting factor for water uptake under deficiency conditions (Qiao et al. 2020; Vandeleur et al. 2009). As water content of the plant decreases, its cells shrink and the cell walls relax resulting in lower turgor pressure and the subsequent concentration of solutes in the cell. Then, turgor dependent activities such as leaf expansion and root elongation are the most sensitive to water deficit (Taiz et al. 2015). Water deficiency in plants can cause stomatal closure or destruction in photosynthetic reaction centers, thus, a reduction of photosynthetic rate and consequently impact the accumulation of dry matter (Cornic et al. 1983; Flexas et al. 2004; Gleason et al. 2017).

Similar to the NON treatment results, previous studies found that water stress occurring at a vegetative growth stage decreases plant height and LAI (due to smaller leaf size), whereas water stress during ear formation and milk stages reduces dry biomass and grain yield (Cakir 2004; Denmead and Shaw 1960; NeSmith and Ritchie 1992). Water deficiency stress caused by insufficient water supplied, causes stomata closure which decreases transpiration and photosynthesis (i.e., reduction of CO_2 assimilation and thus growth). NeSmith and Ritchie (1992) tested long-term responses of maize to pre-anthesis soil water deficit and found that limiting water for 21 or 18 days after the 8th or 9th leaf emerged, resulted in reduced leaf size and internodes, delays of tassel, silk emergence, the onset of grain filling and yield losses of 15–25% (NeSmith and Ritchie 1992). On the other hand, in comparison to the irrigated treatments evaluated, similar results were obtained by Klocke et al. (1999) where dry matter accumulation per plant did not differ across irrigation treatments that evaluated target application depths of 100, 80, 70, 50, 40, and 25% of full irrigation.

In terms of yield, a significant interaction between irrigation and year was found. During all the years of evaluation, the NON treatment resulted in lower yields compared to the irrigated treatments; however, rainfall occurring during critical stages during the 2015 growing season (cumulative rainfall = 556 mm), ameliorated the negative impacts in the NON irrigated treatment, resulting in similar mean yields as the SWB treatment but lower than the other irrigated treatments yields. In 2015, the SWB treatment used a 50% MAD during the entire growing season, which resulted in water stress events during reproductive stages and thus, similar yields than the rainfed treatment. In the following years, a 50% MAD was used during vegetative stages; however, a 33% MAD was used during reproductive stages to avoid water stress that could potentially reduce yields. Mainly due to the lower amounts and non-uniform rainfall distribution in 2016 (cum. rainfall = 371 mm), more irrigation was required; thus, the GROW cumulative irrigation was 63% greater than the amount applied in 2015. Nevertheless, irrigation reduction of 39, 43 and 37% were achieved using the SWB, SMS and RED irrigation strategies compared to the GROW treatment (Fig. 2). In contrast, cumulative rainfall through the 2017 season totaled 680 mm; however, it was sporadically distributed mostly in large magnitude events (i.e., rainfall amounts greater than soil water holding capacity) resulting in drainage and potential N leaching. Therefore, there was a high demand for irrigation during the growing season (Fig. 2). Nevertheless, the irrigation strategies (SWB, SMS and RED) applied 42, 45 and 36% less irrigation than the GROW treatment during the 2017 season.

Furthermore, irrigation had a positive effect on 100 kernel weight, where only the NON-treatment resulted in lower weights than the irrigated treatments. Zinselmeier et al. (1999) evaluated the effect of low water potentials on reproduction development in maize. It was found that when water stress occurred during pollination, embryos formed but abortion occurred causing a decrease in kernel number. Embryo abortion occurred due to an interruption on the sugar stream causing starch depletion during early ovary development, resulting in mature seed and fruit losses (Zinselmeier et al. 1999). Another study evaluated the effects of water deficits timing and intensity on kernel setting, by assessing how these factors could limit leaf productivity (source), the translocation of assimilated sugars (flow) and yield formation (sink) (Li et al. 2018). In maize, long distance sucrose transportation depends on the vascular bundle system that connects leaf vein, stem and ear peduncle (Baker et al. 2016); thus, the vascular bundle in the ear peduncle is the end of sucrose transportation for ear growth. From the perspective of source-flow-sink, water deficits occurring during $V_{9–12}$ and $V_{13\text{-}T}$ resulted in 12% and 11% kernel weight reductions, respectively, as a result of a reduced leaf area (source) and a reduced vascular bundle number in the ear peduncles (limited assimilate flow) (Li et al. 2018). These studies support the lower yields and lower kernel weight obtained in the NON treatment during the 3 years of evaluation.

Water productivity indices

Water Productivity (WP) is defined as the ratio between the achieved final grain yield and the total water use (i.e., sum of irrigation and rainfall) during the growing season. Rainfall amounts and distribution varied across all three seasons playing an important factor and influencing the WP index and potential yields (Pereira et al. 2012; Pereira et al. 2012; Turner 2004). Cumulative rainfall amounts during the 2015–2017 growing seasons were 556, 370 and 673 mm, respectively. However, overall most of the rainfall occurred during mid or late season (June–August) (Online Resource 4). Maize usually reaches physiological maturity (i.e., crop growth stage at which maximum kernel weight is achieved (Daynard and Duncan 1969)) by the end of July/early August, therefore rainfall amounts occurring after this growth stage can be considered inefficient, since most of the water uptake required for final grain yield occurs prior to physiological maturity. During 2015, the amounts and distribution of rainfall were optimum for growth and development, reducing water stress and achieving high yields. In comparison, cumulative rainfall during the 2016 growing season was 33% and 45% less than 2015 and 2017 rainfall. Therefore, the irrigation requirement was almost double than in those years to achieve similar yields. Nevertheless, during 2016 no differences in WP were found compared to WP obtained in 2015. Although cumulative rainfall during the 2017 growing season was the highest (673 mm) among the years of evaluation, uneven temporal and spatial rainfall distribution caused an increase in irrigation requirement across all treatments resulting in lower WP indices. Furthermore, several rainfall events exceeded the water holding capacity of sandy soils, hence increasing drainage while reducing WP for that year.

The WP_{irrig} index considers the efficiency of irrigation, as the total irrigation applied over the final grain yield obtained at each irrigation treatment. During the 3 years of evaluation, on average the SWB, SMS and RED irrigation strategies resulted in a 41%, 47% and 36% irrigation reductions compared to the GROW treatment, respectively, without statistical reductions in yield. Therefore, greater amount of irrigation water applied in the GROW treatment did not result in greater yields, whereas the opposite resulted in the other irrigation strategies. The evaluation of WP_{irrig} resulted in a significant interaction of irrigation and year; where the highest index was achieved by the SMS treatment followed by the SWB and RED in 2015. During the following years, all irrigation strategies resulted in higher WP_{irrig} indices compared to the GROW treatment, demonstrating that higher irrigation applications did not result on higher productivity.

Payero et al. (2008) investigated the effect of subsurface drip irrigation on maize yield through the evaluation of eight treatments receiving irrigation ranging from near dryland to overirrigation. The authors calculated irrigation water use efficiency (WUEi) same as WP_{irrig}; thus, results are described as WP_{irrig} for comparison. Across the irrigated treatments, WP_{irrig} indices ranged from 3.46 to 24.94 kg/m^3 and sharply decreased with irrigation. This decreasing tendency is common in areas where dryland yield is positive; however, in areas where no dryland yield is produced, WP_{irrig} is expected to increase with irrigation (Payero et al. 2008). Although the near dryland treatments had the highest WP_{irrig}; the corresponding yields were lower than the irrigated ones. The irrigated treatments resulting in highest yields had a mean WP_{irrig} index of 5.8 kg/m^3 during the 2-year experiment; like the indices found in this study. The major differences between these WP_{irrig} are attributed to the higher water holding capacities of soils in Nebraska, compared to Florida; where yield was affected by other sources of water available besides irrigation (Payero et al. 2008).

Similar results were obtained when evaluating the CWP index, which resulted in lower values for the GROW treatment compared to the SWB, SMS and RED treatments during all years of evaluation. In comparison to the GROW, the irrigation strategies produced similar yields but with lower total ET_c, increasing their efficiency per unit of ET_c. In general, less irrigation was applied during vegetative stages of the crop, which are less susceptible to water stress and did not result in negative impacts on yield. These results are supported by a global study in which CWP values were evaluated based on a review of 16 experimental studies for irrigated maize (Zwart and Bastiaanssen 2004). Results showed that CWP rapidly increased when little irrigation was applied, while optimum levels were reached at 280 mm of irrigation applied in addition to rainfall. Thus, CWP can be increased while simultaneously saving water by reduced irrigations; however, CWP can also be negatively affected by water stress occurred during sensitive reproductive growth stages (Zwart and Bastiaanssen 2004).

The results of these productivity indices support the initial hypothesis in which irrigation strategies (SWB, SMS and RED) achieve water savings without impact in maize grain yield compared to conventional practices (GROW). Irrigation strategies should maximize beneficial water uses (i.e., uses fully oriented to achieve the desired yield), increase water productivity and minimize water losses and wastes.

The major differences among the three irrigation strategies proposed are mostly related to cost and time for data processing. The SWB corresponds to a check-book (inputs/outputs) method that could be implemented in a spreadsheet using data available from nearest weather station. In comparison, the SMS requires a sensor and the cloud software to monitor real time VWC data during the growing season for decision-making. This strategy could require more technical support and time for data analysis. Then, the RED can be implemented using a calendar-based method; however, reducing the depth of application to 60%. Also weather data from a nearest weather station can be obtained to keep records of rainfall events and manage irrigation accordingly.

Nitrogen fertility treatments

Final AG biomass and N uptake

The three N fertilizer rates evaluated did not have an effect on final AG biomass; however, rates did have on final AG N uptake. Similar results have been reported in other studies. Shapiro and Wortmann (2006) observed no increase in biomass when increasing N fertilizer from 168–252 kg N/ha in silty clay loam soils. Similarly, Derby et al. (2005) showed an increase in stover yield with N rates up to 135 kg N/ha, but no for higher N rates (180 and 225 kg N/ha) in loamy fine sands.

Grain yield and 100 kernel weight

Fertility had a positive effect on final yields and on 100 kernel weight. No differences in yield were found between the medium and the high N rates, but the low N rate resulted in lower yields. Similar results were obtained in 100 kernel weight; however, for both parameters, the medium N rate was sufficient to achieve the same results as the high N rate. Studies under different conditions have found similar results (Gehl, Schmidt, Maddux et al. 2005a, b; Gehl, Schmidt, Maddux et al. 2005a, b; Hammad et al. 2018). Hammad et al. (2018) evaluated N rates and timing of N applications for maize optimum development and yield. They found that 250 kg N /ha applied at 1/3 N at V2, 1/3 N at V16 and 1/3 N at R1 stages, was the best BMP for semiarid conditions (Hammad et al. 2018). Similarly, Gehl et al. (2005a, b) evaluated different fertilizer rates and timing for irrigated maize in Kansas sandy soils. Results showed that maximum grain yield was achieved using a split application of 185 kg N/ha; yet, a 125 kg N/ha was satisfactory to reach maximum yield in most cases. They emphasized the implementation of an efficient use and timing of N fertilizer along with optimum irrigation management in sandy soils and susceptible regions to NO_3-N leaching (Gehl, Schmidt et al. 2005a, b).

Water productivity indices

Fertility influenced WP_{irrig} and CWP, where overall, higher productivity values were found on the medium and high N rates, whereas the low N rate resulted in lower indices. These results showed how agronomic mechanisms can enhance WP; maximizing yields through enhanced fertility and water management.

In terms of CWP, both the high and the medium N fertility rates resulted in higher CWP indices (mean = 3.30 kg/m^3) compared to the low rate (3.06 kg/m^3), reflecting a lower productivity as a function of the lower yields obtained by the low N rate. These results also confirm that a medium N rate proved sufficient to reach maximum CWP values because it did not differ from the high rate, and furthermore, a positive effect of combining adequate soil water on N availability simultaneously with plant N uptake for a more effective use when both are at satisfactory levels (Di Paolo and Rinaldi 2008). Previous studies have shown the increase in yield and crop evapotranspiration with applications of N under irrigated conditions (Di Paolo and Rinaldi 2008; Eck 1984; Eck 1984; Hernández et al. 2015; Hernández et al. 2015; Ogola et al. 2002; Ogola et al. 2002). In terms of N fertilization, interventions to increase water productivity may focus more on improving yield (i.e., higher N rate) while using any of the irrigation strategies (SWB, SMS and RED) that resulted in similar results than conventional practices but decreased irrigation water use and plant water consumption.

Conclusions

Irrigation is key in maize production in Florida to achieve high yields. Reducing the irrigation amounts between 36 and 47%, on average for maize production did not have a negative impact on maize growth and yield compared to typical irrigation practices of the region. No differences were found among irrigated treatments; except versus the non-irrigated treatment, which resulted in significantly lower N uptake, growth and yield. Each of the proposed irrigation scheduling strategies provided the adequate irrigation water to produce similar maize yields compared to conventional practices despite rainfall variability during the three seasons. These results support the first hypothesis, where irrigation strategies (SWB, SMS and RED) did achieve water savings without impact in maize grain yield compared to conventional irrigation practices (GROW).

Similarly, N rates had an effect on all variables evaluated except on final AG biomass, in which no differences were found among the three N rates evaluated. Overall, differences were found only between the low and the high N rates. The findings of this experiment demonstrate that following an N rate similar to the UF/IFAS maize N fertilization recommendation (medium = 247 kg N/ha) resulted in no differences in biomass, N uptake, 100 kernel weight nor yield compared to high N applications (high = 336 kg N/ha) during the three growing seasons. Thus, similar yield can be achieved following the medium rate while reducing N fertilizer by 26%. The results of this experiment supported the second and third hypotheses, where a medium N rate allowed similar N uptake and grain yield compared to higher rates typically applied in the region, and that maize N uptake reached a plateau; thus, high fertility rates may result in N losses.

Due to the spatial and temporal rainfall variability in Florida, irrigation scheduling is a difficult task for growers. Nevertheless, the irrigation strategies demonstrated in this work can serve as tools to reduce irrigation and increase water productivity compared to traditional practices. Nitrogen application rates greater than the crop N uptake, will most likely result in N losses; thus, applications of N fertilizer should be timed with the crop N demand. Furthermore, a 26% N fertilization reduction could be implemented without impacting maize yield and potentially reducing N losses to the environment. If potential losses are avoided, these will be converted into economic savings, resulting in larger profits. Growers could potentially save water and fertilizer while achieving similar yields as conventional practices, when implementing the irrigation strategies demonstrated in this work and adhering more closely to the UF/IFAS recommended fertilization rates.

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Compliance with ethical standards

Conflicts of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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