2950 Niles Road, St. Joseph, MI 49085-9659, USA
269.429.0300 fax 269.429.3852 hq@asabe.org www.asabe.org

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IMPACT OF WATER AND NITROGEN AVAILABILITY ON MAIZE EVAPOTRANSPIRATION AND SOIL WATER TRENDS UNDER HIGH FREQUENCY SPRINKLER IRRIGATION

Bradley A. King David D. Tarkalson David L. Bjorneberg
USDA ARS Northwest Irrigation and Soils Research Laboratory 3363 N. 3700 E. Kimberly, ID 83341

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Abstract. *One potential advantage of variable rate irrigation (VRI) is that less water can be applied to field areas with low productivity, without adversely affecting yield, thereby reducing water use, nutrient leaching, and pumping costs. This inferred potential advantage of VRI has not been fully evaluated experimentally. A three-year field study on maize (Zea mays L.) grain yield was conducted to test the hypothesis that high and low productivity has no effect on crop ET. High and low productivity were established using high and low soil nitrogen (N) supplies. The effect of 0 kg N* ha^{-1} *(low N supply) and 246 kg N* ha^{-1} *(high N supply) application under fully irrigated (FIT) and three limited irrigation rates (75% FIT, 50% FIT, and 25 FIT) on maize grain yield and soil water trends were investigated in 2017, 2018 and 2019 under lateral-move irrigation in south central Idaho. Maize evapotranspiration (*ET_c*), grain yield and soil water contents were significantly different (*$p < 0.05$*) between irrigation treatments and study year. Grain yield decreased nonlinearly as seasonal irrigation amount decreased regardless of N supply. The maize* ET_c *and soil water contents from the two N rates within each irrigation level were the same. During each year of the study and within each irrigation treatment, there were no significant (*$p < 0.05$*) maize ET or soil water content differences between the N treatments. Assuming yields under different N application rates were representative of high and low maize productivity areas of fields, the results show that reducing water application to low productivity areas will reduce grain yield at the same rate as in high productivity areas. Thus, VRI does not provide the opportunity to reduce water use and pumping costs while maintaining yield levels in low production areas*

Keywords. *Maize, Deficit irrigation, Evapotranspiration, Variable rate irrigation, Yield, Water use*

Introduction

Historical irrigation water supplies in the western US are being diverted to growing urban and environmental uses for ecosystem restoration. Groundwater levels in many areas have steadily decreased from historic levels as urban areas and municipalities grow and ground water uses are approaching unsustainable levels. Warmer winter temperatures due to climate change are predicted to reduce mountain snowpack that was the source of early irrigation developments in much of the western US. The growing demand on irrigation water supplies for other societal uses combined with climate change

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necessitates increased water use efficiency in irrigated agriculture.

The dairy industry in southcentral Idaho has undergone rapid expansion in the region over the past 25 years transforming the common irrigated crop mix from sugarbeet, dry bean, and cereal grains to include more forages to support the dairy feed consumption. Consequently, the acreage of alfalfa and maize, both for grain and forage, has increased. For example, the hectares of maize grain corn harvested in Idaho has increased from 12,100 ha in 1990 to 52,600 ha in 2020 (USDA-NASS, 2021). Because maize has historically been a minor crop in the region, limited local information about water use is available. Additionally, advances in maize genetics over the past 30 years have increased productivity that may affect water use. The relatively short maize growing season in the region prevents direct transfer of water use data from more humid longer growing season regions.

The aim of variable rate center pivot irrigation (VRI) is to increase water use efficiency by addressing spatial variation in crop water availability to only apply water where needed, when needed, and in the amount needed. There are several potential applications of VRI (O'Shaughnessy et al., 2019) to increase water use efficiency or reduce the environmental impact of irrigated agriculture. One perceived potential advantage of VRI is that less water can be applied to field areas with low productivity, without adversely affecting yield, thereby reducing water use, nutrient leaching, and pumping costs. This inferred potential advantage of VRI has not been fully evaluated experimentally.

The objectives of this study were to quantify and evaluate maize water use, grain yield, and soil water trends under multi-year nitrogen and irrigation deficits in southcentral Idaho. A secondary objective was to test the hypothesis that maize evapotranspiration (ET_c) is independent of maize productivity in a high evaporative demand environment with frequent irrigation required to achieve maximum yield. Nitrogen deficiency created by multiyear deficit nitrogen application was used obtain reduced crop productivity to test the hypothesis.

METHODS AND MATERIALS

SITE DESCRIPTION

The field study was conducted during 2017, 2018, and 2019 at the USDA-ARS Northwest Irrigation and Soils Laboratory near Kimberly, Idaho. The climate is borderline arid-semiarid where the 20-yr average annual precipitation and alfalfa-reference evapotranspiration (ET_r) are approximately 253 and 1479 mm, respectively. Approximately 45% of annual precipitation and 83% of annual ET_r occurs during April through mid-October. June through September monthly average air temperature, solar radiation, relative humidity, wind speed, vapor pressure deficit between hours of 7:00 to 19:00 MDT, daily rainfall, and ET_r in each study year are given in Table 1. Growing season climatic conditions were similar in all three study years with exception of rainfall which was much lower in 2018. The soil at the study site is a Portneuf silt loam (coarse-silty mixed mesic Durixerollic Calciorthid). The soil profile is classified as very deep and well drained with weak silica cementation ranging from 30 to 45 cm deep that can restrict root growth (USDA, 1998).

Table 1. Monthly average air temperature, solar radiation, relative humidity, wind speed, vapor pressure deficit between hours of 7:00 to 19:00 MDT, daily rainfall and alfalfa reference crop evapotranspiration (ET_r) in each study year.

Year	Month	Air Temperature (°C)	Solar Radiation ($W\ m^{-2}$)	Relative Humidity (%)	Wind Speed ($m\ sec^{-1}$)	Vapor Pressure Deficit (kPa)	Rainfall (mm)	Alfalfa Reference ET_r (mm)
2017	June	21.1	545	43.5	3.4	1.6	11.9	230
	July	26.9	538	37.6	2.3	2.5	3.0	254
	August	24.8	472	40.0	2.4	2.2	0.8	226
	September	18.1	370	48.2	2.6	1.4	14.7	158
2018	June	20.1	617	46.4	3.0	1.4	15.5	218
	July	26.4	625	33.1	2.6	2.6	0	276
	August	23.4	513	38.2	2.5	2.1	0	224
	September	19.2	452	33.8	2.7	1.7	0	195
2019	June	20.3	644	42.3	3.1	1.5	0	225
	July	24.3	550	45.3	2.6	1.9	2.0	228
	August	24.4	549	42.2	2.4	2.0	7.4	227
	September	18.0	412	54.1	2.7	1.2	20.3	155

Experimental Design

The field study utilized a strip plot randomized complete block design to evaluate two nitrogen treatments and four irrigation treatments with four replications. The two nitrogen treatments were 0 and 246 kg N ha^{-1}. The four irrigation treatments were fully irrigated (FIT), 75% FIT, 50% FIT, and 25% FIT. The FIT represents the conditions where the crop was irrigated two or three times a week with a cumulative depth less than or equal to weekly cumulative estimated maize evapotranspiration (ET_c), and soil water content was monitored to ensure that soil water depletion in the FIT plots remained above 55% of total available water to avoid water stress. Irrigation applications depths to FIT plots were limited to soil water storage availability to prevent deep percolation. Water was applied with a lateral move irrigation system, where each replicated irrigation block was separated by a 12 m wide strip of spring barley bounded by 3 m (4 rows) corn border rows where the irrigation system was stopped, and sprinkler nozzles changed to achieve randomized water treatment amounts using different sized sprinkler nozzles. The irrigation system was equipped with Nelson S3000 red plate sprinklers (Nelson Irrigation Corp., Walla Walla, WA) attached to Nelson 138 kPa pressure regulators. The irrigation treatments were achieved by using sprinkler nozzles with flow rates in proportion to the desired relative irrigation treatment amounts. The FIT treatment used nozzles with a flow rate of 24.71 L min^{-1} (#29) and the 75% FIT, 50% FIT, and 25% FIT treatments used nozzles with flow rates of 28.24 (#25), 12.71 (#21), and 6.58 (#15) L min^{-1}, respectively. Irrigation treatment plots were 18.2 m wide (24 rows) by 41.1 m long, which was the length of the lateral move irrigation system span. The harvest area within each plot was 3.7 m (2 rows) by 22.9 m centered in the plot to avoid the effect of sprinkler overlap from adjacent lateral move spans and non-uniform application caused by the lateral move irrigation system structural elements. All treatments were irrigated at the same time with different irrigation depths corresponding to sprinkler nozzle size for each treatment. Rain gauges designed for minimum evaporation loss (All-Weather Rain Gauge, Forestry Suppliers, Jackson, MS) on adjustable height stands were used in each plot to verify water application amounts to each plot.

The experimental plots and treatments were in the exact same physical location in each year of the study. The purpose was to investigate the cumulative effects of deficit N and irrigation on maize yield and assure successive years of zero N application resulted in low and high maize yields enabling evaluation of the effect on ET_c.

Cultural Practices

In each study year tillage consisted of four tillage passes: two passes with a tandem disk, roller harrow and bedding in the spring prior to planting. Maize was planted on 19 May 2017, 22 May 2018 and 23 May 2019 (Pioneer P9188R Roundup Ready corn 2; Raxial PPST 250 seed treatment) with a row spacing of 0.76 m. All plots were dammer-diked after planting to prevent surface water movement within and among plots. Full emergence was achieved on 27 May 2017, 1 June 2018 and 1 June 2019. Urea nitrogen fertilizer to high N plots was surface applied within 3 weeks of emergence and immediately irrigated with a uniform irrigation amount applied to all plots. Grain yield samples were collected 5 October 2017, 18 October 2018, and 15 October 2019. Herbicide and pesticide practices followed local practices for Roundup Ready maize production. Pesticides, herbicides, insecticides, and fungicides were applied to all plots uniformly when required.

Irrigation Scheduling and Soil Water Measurement

In each study year irrigation scheduling for the FIT was based on balancing estimated cumulative weekly ET_c with the weekly cumulative irrigation and precipitation. Estimated ET_c was based on the ASCE standardized reference evapotranspiration equation (Allen et al., 2005) and daily crop coefficients (Wright, 1982), which were obtained from an AgriMet (U.S Bureau of Reclamation, https://www.usbr.gov/pn/agrimet/) weather station located within 4.5 km from the study site. Irrigation was applied 1 to 3 times a week depending upon weekly ET_c, less frequent at the beginning and end of the growing season. Soil water content was measured in 0.3 m depth increments from 0.3 to 2.1 m using a neutron probe calibrated to the experimental site soil using the methods of Hignett and Evett (2002). Soil water content was measured at 100% emergence, immediately before harvest and at about 2-week intervals between emergence and harvest.

Seasonal Evapotranspiration

Seasonal maize ET_c (mm) was calculated using a soil water balance between emergence and harvest:

$$ET_c = \Delta S + P + I - DP - R \qquad [1]$$

where

ΔS = the change in soil water storage in the soil profile between emergence and harvest (mm).
P = cumulative precipitation between emergence and harvest (mm).
I = cumulative irrigation applied between emergence and harvest (mm).
R = the difference between plot runoff and run-on (mm).
DP = cumulative water percolating below the root depth between emergence and harvest (mm).

Precipitation was recorded in rain gauges in each plot and used to verify amounts measured in the rain gauge at the nearby Agrimet weather station site (US Bureau of Reclamation; https://www.usbr.gov/pn/agrimet/). Deep percolation was assumed to be zero based on soil water content in the lower depths of the 2.1 m soil profile remaining less than field capacity and constant or decreasing from emergence to harvest. Runoff was assumed to be zero as all plots were dammer-diked to prevent surface water movement within and between plots and visually confirmed over the season.

Statistical Analysis

Data reduction and analysis were conducted using MS Excel. Statistical data analysis was conducted using PROC MIXED in SAS (SAS Institute, Cary, NC) to test for treatment differences of multiple measures. Treatments were designated as fixed effects and replication and year as random effects. Least square means (LSMEANS) was used to differentiate significance of treatment and interaction effects ($p \leq 0.05$). Residual diagnostics were conducted to evaluate the assumptions of ANOVA and determine the need for data transformations. Graphical presentations were generated using Sigmaplot 13 (Systat Software, San Jose, CA).

Results

Soil Water Trends

Soil water content profiles at emergence and prior to harvest are depicted in Figs. 1-3 for study years 2017, 2018, and 2019, respectively. Nominal field capacity and permanent wilting point for the Portneuf silt loam at the study site is 32% and 14% by volume as determined in the laboratory using a pressure plate apparatus (McDole et al., 1974). In this manuscript, field capacity and permanent wilting point were taken as the maximum and minimum soil water contents

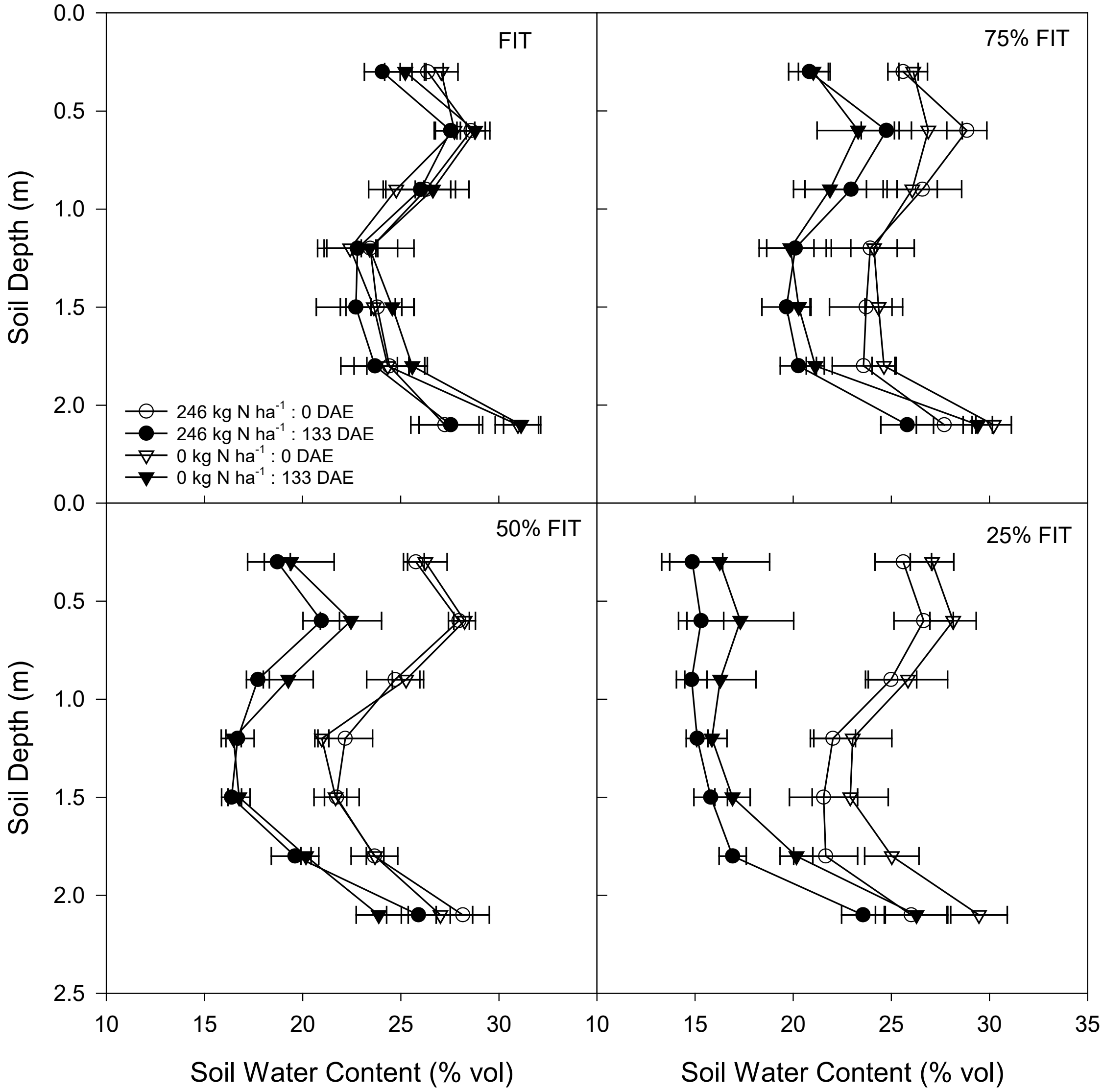

Figure 1. Soil water content profiles for two nitrogen application rates, 0 and 246 kg N ha^{-1}, and four irrigation rates, full irrigation (FIT), 75% FIT, 50% FIT and 25% FIT, at emergence (0 DAE) and harvest (133 DAE) in study year 2017.

measured by neutron probe over the three-year study period, which generally occurred at the beginning and end of the season (Figs. 1-3). In this manner, field capacity and permanent wilting point were 34% and 11%, respectively. The real behavior of crops often reveals that soil water can be extracted below the classical limit of -1.5 MPa (Cabelguenne & Debaeke, 1998). Based on observed field capacity and permanent wilting point, maintaining 40% available soil water (60% allowable depletion) to avoid crop water stress corresponds to 20% soil water content. In all study years, the upper 1 m of the soil profile in FIT treatments remained greater than 20% soil water content at the end of the season (Figs. 1-3) and throughout the season (data not shown), indicating that FIT treatment irrigation amounts adequately replaced seasonal ET$_c$ and avoided plant water stress.

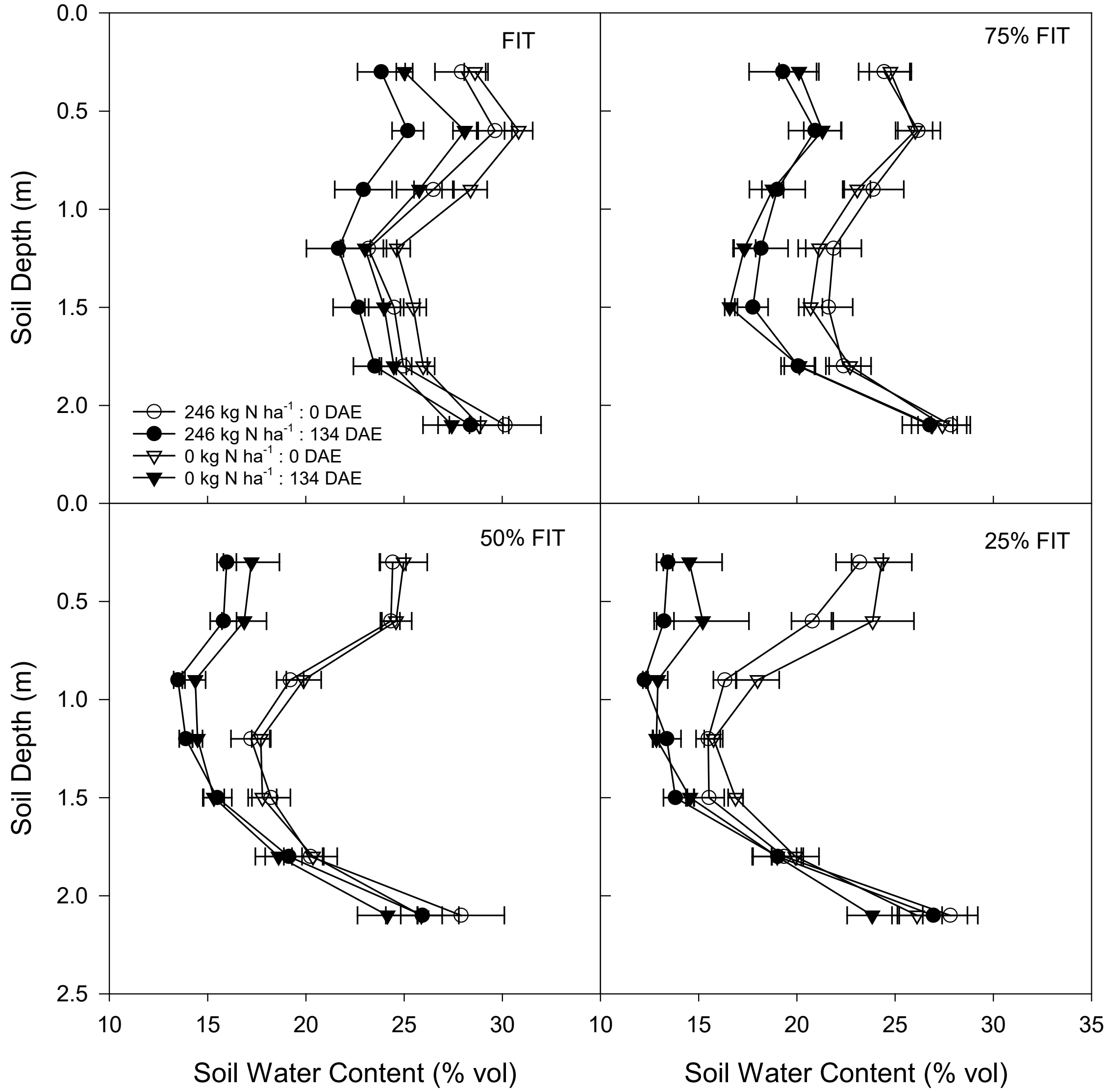

Figure 2. Soil water content profiles for two nitrogen application rates, 0 and 246 kg N ha^{-1}, and four irrigation rates, full irrigation (FIT), 75% FIT, 50% FIT and 25% FIT, at emergence (0 DAE) and harvest (134 DAE) in study year 2018.

Soil water content profiles in the four irrigation treatments in 2017 (Fig. 1) were very similar at emergence. Soil water stored in the 2.1 m soil profile was not significantly different ($p < 0.05$) between irrigation or nitrogen treatments at emergence. The soil water profiles prior to harvest in 2017 differed substantially between the four irrigation treatments with seasonal soil water extraction greatest for the 25% FIT treatment. Stored soil water in the 2.1 m soil profile prior to harvest was significantly different between irrigation treatments ($p \leq 0.001$) but not significantly different ($p < 0.05$) between nitrogen treatments.

Soil water profiles in the four irrigation treatments at emergence in 2018 (Fig. 2) were substantially different between irrigation treatments due to carryover effects from the irrigation treatments in 2017. Wright (1993) reported 1985 through 1991 nongrowing season evapotranspiration at Kimberly ID averaged 180 mm. Non-growing season precipitation October 2017 through May 2018 was 290 mm, thus only about 110 mm of precipitation was available for nongrowing season soil water recharge. Stored soil water in the 2.1 m soil profile at emergence was significantly different between irrigation treatments ($p < 0.05$) but not significantly different ($p \leq 0.001$) between nitrogen treatments, paralleling differences present at 2017 harvest. The soil water profiles prior to 2018 harvest differed substantially between the four irrigation treatments, however, soil water profiles for the 50% FIT and 25% FIT were similar, likely due to soil water contents approaching permanent wilting point in much of the crop root zone. Stored soil water in the 2.1 m soil profile prior to 2018 was significantly different between irrigation treatments ($p \leq 0.001$) but not significantly different ($p < 0.05$) between nitrogen treatments.

The soil water profiles at emergence in 2019 (Fig. 3) paralleled those prior to harvest in 2018 reflecting the cumulative effects of the irrigation treatments in 2017 and 2018 and only 90 mm of nongrowing season precipitation for soil water recharge. Nongrowing season precipitation increased soil water contents for the 50% FIT and 25% FIT plots to a depth of 1.5 m. The soil water profiles prior to harvest in 2019 were substantially different between irrigation treatments. Soil water stored in the 2.1 m soil profile prior to harvest in 2019 was significantly different ($p \leq 0.001$) between irrigation treatments but not significantly different ($p < 0.05$) between nitrogen treatments. In each study year soil water contents prior to harvest for the FIT were numerically greater for the zero N treatment compared to the 246 kg N ha^{-1} treatment and the magnitude of the difference tended to increase with each study year. However, the magnitude of the difference in soil water contents between the N treatments was not sufficient to result in a significant difference in stored soil water over the three study years.

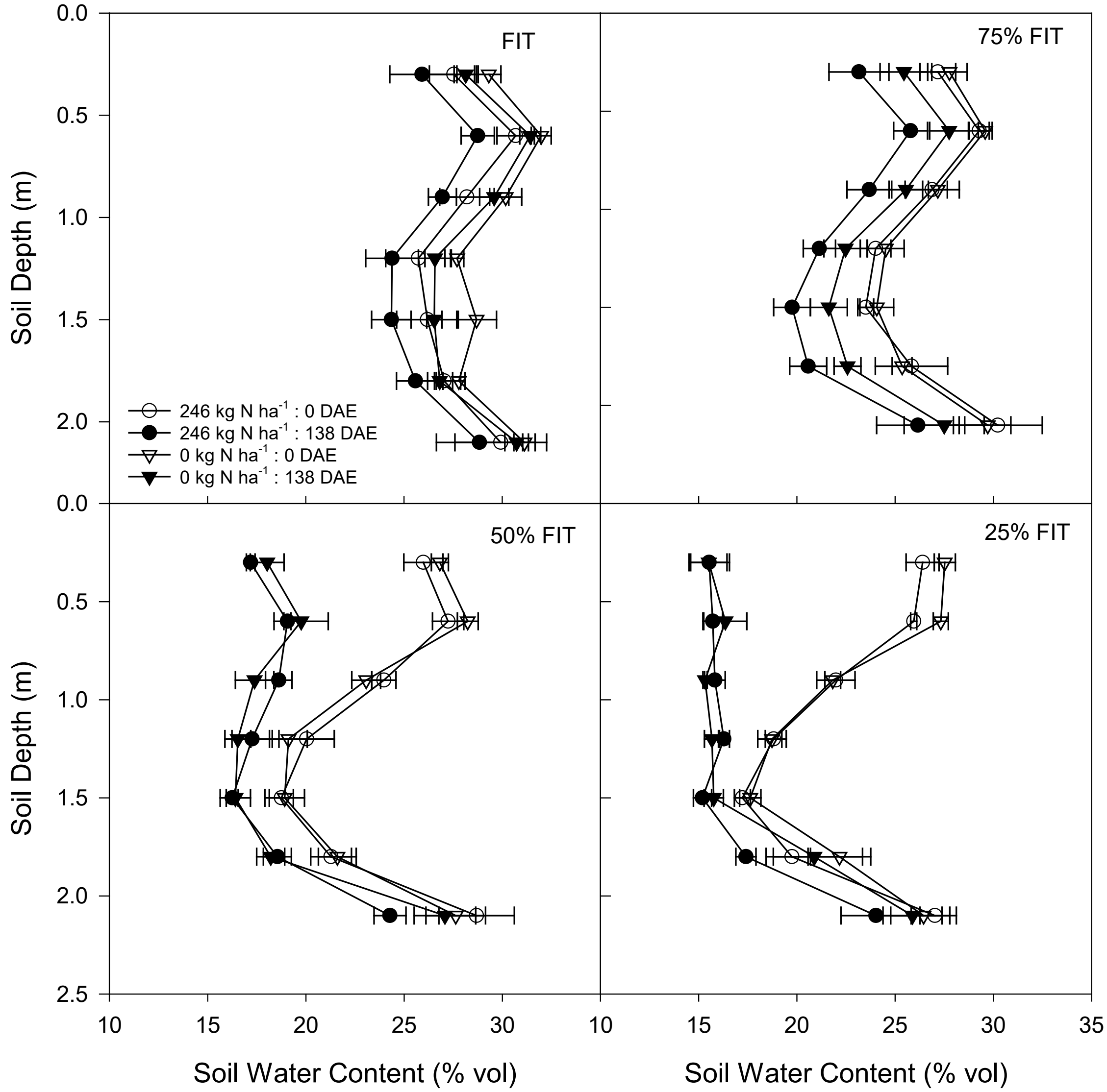

Figure 3. Soil water content profiles for two nitrogen application rates, 0 and 246 kg N ha^{-1}, and four irrigation rates, full irrigation (FIT), 75% FIT, 50% FIT and 25% FIT, at emergence (0 DAE) and harvest (138 DAE) in study year 2019.

The ANOVA results for soil water depletion between emergence and harvest are displayed in Table 2. There was a significant ($p < 0.05$) interaction between irrigation treatment and study year. This interaction was expected since nongrowing season precipitation minus nongrowing season evapotranspiration was less than seasonal soil water deficit for the 50% FIT and 25% FIT treatments and soil water deficit accumulated across study years. The interaction between nitrogen treatment and study year was not significant ($p \leq 0.05$). The irrigation main effect was significant ($p < 0.05$) but nitrogen main effect was not significant ($p < 0.05$) (Table 2), consistent with the observed trends in soil water stored in the soil profile at emergence and harvest. Study year was not significant ($p < 0.05$) as the relative magnitude of soil water depletion between treatments was largely consistent across study years, Table 3. In 2017 and 2019 soil water depletion was significantly less ($p < 0.05$) for the FIT treatment compared to the other irrigation treatments and significantly less than the 50% Fit and 25% FIT treatments in 2018. In 2017 soil water depletion for the 25% FIT treatment was significantly ($p < 0.05$) larger than for other irrigation treatments. In 2018 and 2019 there was no significant difference ($p < 0.05$) in soil water depletion between the 50% FIT and 25% FIT treatments due to limited soil water recharge between study years.

Table 2. Analysis of variance results for the effects of irrigation and nitrogen treatments on soil water depletion (0-2.1 m) between emergence and harvest, seasonal maize evapotranspiration (ET_c) and maize grain yield.

Source	Season Soil Water Depletion	ET_c	Grain Yield
Nitrogen	0.088	0.088	0.047*
Irrigation	<0.001***	<0.001***	<0.001***
Nitrogen x Irrigation	0.396	0.396	<0.001***
Year	0.128	<0.001***	<0.001***
Nitrogen x Year	0.535	0.535	0.198
Irrigation x Year	<0.001***	<0.001***	0.002**
Nitrogen x Irrigation x Year	0.819	0.819	0.287

$^{*}p<0.05$, $^{**}p<0.01$, $^{***}p<0.001$

Table 3. Seasonal water balance components and grain yield (15.5 % moisture) for each of four irrigation treatments (FIT, 75% FIT, 50% FIT and 25% FIT) and two maize productivity levels (high and low) in each study year. Mean values of soil water depletion, crop evapotranspiration (ET_a) or grain yield for a given year with the same superscript letter are not significantly different ($p < 0.05$).

Year	Nitrogen Treatment (kg N ha^{-1})	Irrigation Treatment	Rainfall (mm)	Irrigation (mm)	Soil Water Depletion (mm)	ET_a (mm)	Grain Yield (Mg ha^{-1})
2017	0	FIT	38.9	526.3	-13.6^{a}	551.6^{a}	15.10^{a}
		75% FIT	38.9	362.7	77.8^{b}	479.4^{b}	14.55^{ab}
		50% FIT	38.9	242.6	105.9^{c}	387.4^{c}	12.13^{c}
		25% FIT	38.9	130.8	159.9^{d}	329.6^{d}	6.73^{d}
	246	FIT	38.9	526.3	17.7^{a}	582.9^{a}	15.71^{a}
		75% FIT	38.9	362.7	78.1^{b}	479.7^{b}	14.17^{abc}
		50% FIT	38.9	242.6	116.5^{c}	398.0^{c}	12.66^{bc}
		25% FIT	38.9	130.8	159.0^{d}	328.7^{d}	5.59^{d}
2018	0	FIT	47.2	455.3	45.5^{a}	548.0^{a}	10.84^{b}
		75% FIT	47.2	314.6	75.4^{ab}	437.2^{b}	11.54^{ab}
		50% FIT	47.2	208.6	92.0^{b}	347.8^{c}	7.38^{c}
		25% FIT	47.2	113.6	97.4^{b}	258.2^{d}	1.92^{d}
	246	FIT	47.2	455.3	56.9^{a}	559.4^{a}	13.19^{a}
		75% FIT	47.2	314.6	79.9^{ab}	441.7^{b}	11.52^{ab}
		50% FIT	47.2	208.6	97.0^{b}	352.8^{c}	8.38^{c}
		25% FIT	47.2	113.6	80.5^{b}	241.3^{d}	0.97^{d}
2019	0	FIT	27.2	427.0	21.3^{a}	475.5^{a}	6.06^{b}
		75% FIT	27.2	303.0	46.6^{b}	376.8^{b}	7.34^{b}
		50% FIT	27.2	206.7	97.5^{c}	331.4^{c}	6.06^{b}
		25% FIT	27.2	110.6	110.5^{c}	248.3^{d}	1.63^{c}
	246	FIT	27.2	427.0	32.1^{a}	486.3^{a}	10.17^{a}
		75% FIT	27.2	303.0	81.3^{b}	411.5^{b}	8.05^{ab}
		50% FIT	27.2	206.7	105.9^{c}	339.8^{c}	5.73^{b}
		25% FIT	27.2	110.6	113.3^{c}	251.1^{d}	1.15^{c}

Fraction of available soil water (FASW) in the 2.1 m soil profile at selected dates during each study year are displayed in Table 4. In each study year FASW in the FIT treatment was well above the threshold of 65% available soil water for well-watered maize. There was no significant difference ($p < 0.05$) in FASW between irrigation treatments in 2017 until 56 days after emergence (DAE) demonstrating that soil water at the beginning of the 3-yr study area was relatively uniform. Beyond 56 DAE significant differences ($p < 0.05$) in FASW between the irrigation treatments developed over the season with the 50% FIT and 25% FIT treatments ending the season with the lowest FASW. There were significant differences ($p < 0.05$) in FASW between irrigation treatments at 0 DAE in 2018 as nongrowing season precipitation minus nongrowing season ET was far less that available water storage in any irrigation treatment. Significant differences ($p < 0.05$) in FASW persisted throughout the 2018 season with FASW of the 50% FIT and 25% FIT being statistically equivalent throughout the season with about 25% available soil water in the 2.1 m soil profile at harvest. The 2019 trends in FASW were nearly equivalent to those in 2018 as there were significant differences ($p < 0.05$) in FASW of the irrigation treatments at 0 DAE that remained throughout the season and FASW of the 50% FIT and 25% FIT treatments were statistically equivalent throughout the season. The main difference in FASW between 2018 and 2019 was that FASW was greater at 0 DAE in 2019 apparently from greater non-growing season precipitation available for soil water storage.

Table 4. Effects of four irrigation treatments (FIT, 75% FIT, 50% FIT and 25% FIT) on fraction of available soil water in the root zone on selected dates (indicated as day of year, DOY) during the 2017, 2018 and 2019 growing seasons. Mean values of fraction of available soil water on a given DOY with the same superscript letter are not significantly different ($p < 0.05$).

	Fraction of available soil water in the root zone			
		2017 season		
DAE	FIT	75% FIT	50% FIT	25% FIT
0	0.64^{a}	0.65^{a}	0.60^{a}	0.61^{a}
41	0.57^{a}	0.55^{a}	0.50^{a}	0.48^{a}
56	0.63^{a}	0.56^{a}	0.50^{ab}	0.44^{b}
66	0.61^{a}	0.53^{a}	0.46^{ab}	0.38^{b}
81	0.67^{a}	0.53^{b}	0.43^{bc}	0.34^{c}
90	0.67^{a}	0.51^{b}	0.41^{bc}	0.31^{c}
112	0.65^{a}	0.48^{b}	0.38^{bc}	0.27^{c}
139	0.66^{a}	0.49^{b}	0.37^{c}	0.28^{c}
		2018 season		
0	0.70^{a}	0.56^{b}	0.46^{bc}	0.40^{c}
40	0.69^{a}	0.56^{b}	0.45^{bc}	0.38^{c}
55	0.67^{a}	0.52^{b}	0.43^{bc}	0.35^{c}
68	0.73^{a}	0.53^{b}	0.40^{c}	0.30^{c}
82	0.75^{a}	0.54^{b}	0.39^{c}	0.28^{c}
104	0.73^{a}	0.51^{b}	0.35^{c}	0.29^{c}
141	0.60^{a}	0.40^{b}	0.27^{c}	0.23^{c}
		2019 season		
0	0.77^{a}	0.69^{a}	0.55^{b}	0.51^{b}
39	0.71^{a}	0.61^{a}	0.50^{ab}	0.46^{b}
49	0.77^{a}	0.64^{b}	0.50^{bc}	0.44^{c}
60	0.75^{a}	0.63^{b}	0.46^{c}	0.39^{c}
74	0.77^{a}	0.61^{b}	0.45^{c}	0.35^{c}
84	0.76^{a}	0.59^{b}	0.38^{c}	0.38^{c}
101	0.79^{a}	0.59^{b}	0.36^{c}	0.30^{c}
140	0.71^{a}	0.56^{b}	0.34^{c}	0.28^{c}

Maize Evapotranspiration

The ANOVA results for maize evapotranspiration (ET$_{c}$) are displayed in Table 2. There was a significant ($p \leq 0.001$) interaction between irrigation treatment and study year, however, the interaction between nitrogen treatment and study year was not significant ($p \leq 0.05$). The irrigation main effect was significant ($p \leq 0.001$) but nitrogen main effect was not significant ($p < 0.05$) (Table 2), consistent with the observed trends in soil water stored in the soil profile at emergence and harvest. Study year was significant ($p < 0.05$) due to ET$_{c}$ being 85 mm less (Table 3) in 2019 compared to 2017 and 2018.

In all three study years, ET$_{c}$ was significantly different between ($p < 0.05$) each of the four irrigation treatments (Table 3). In 2017 and 2018, ET$_{c}$ for FIT were similar but was about 85 mm less in 2019. In 2018 and 2019, ET$_{c}$ for 25% FIT were numerically similar but about 80 mm less than for 2017 due to lower initial soil water contents at zero DAE. In all three study years, ET$_{c}$ for the two nitrogen treatments were numerically similar, which lead to no statistically significant difference between nitrogen treatments.

Maize Yield

The ANOVA results for grain yield are displayed in Table 2. There was a significant ($p \leq 0.002$) interaction between irrigation treatment and study year and a significant ($p < 0.05$) the interaction between nitrogen treatment and study year. The irrigation main effect was significant ($p \leq 0.001$) and the nitrogen main effect was also significant ($p \leq 0.05$). Study year was significant ($p \leq 0.001$) due to decreasing yield over the three-year study (Table 3).

In 2017 there were significant ($p < 0.05$) differences in grain yield between irrigation treatments but there was no significant difference ($p < 0.05$) between nitrogen treatments for a given irrigation treatment. There were no significant differences ($p < 0.05$) in grain yield between the FIT and 75% FIT for either nitrogen treatment despite significant differences in ET_c between the two irrigation treatments. However, there was a trend for decreased grain yield with decreased ET_c. Grain yield for the 25% FIT was significantly different ($p < 0.05$) from the other irrigation treatments but there was no significant difference ($p < 0.05$) between nitrogen treatments. In 2018 grain yield for the 246 kg N ha^{-1} treatment was significantly greater ($p < 0.05$) than zero N treatments for the FIT treatments. Grain yields for the 75% FIT were not significantly different between the nitrogen treatments or the zero N FIT treatment combination. Grain yield for the 50% FT and 25% FIT irrigation treatments were significantly different ($p < 0.05$) not significantly different ($p < 0.05$) between nitrogen treatments and both irrigation treatments were significantly different from the 75% FIT and FIT treatments. In 2019 grain yield for the FIT treatment was significantly different ($p < 0.05$) between N treatments but was not significantly different ($p < 0.05$) from the 246 kg N ha^{-1} N 75% FIT treatment combination. Grain yield of the 50% FIT and 75% FIT were not significantly different ($p < 0.05$) for either N treatments. Grain yield for the 25% FIT treatment was not significantly different ($p < 0.05$) different between N treatments but were significantly different ($p < 0.05$) from the other irrigation treatments.

Discussion

This study differs from most other maize water use studies because plot and treatment locations were stationary over time to investigate the cumulative effect of sequential deficit irrigation and nitrogen on soil water trends and grain yield. Soil water extracted by the crop in deficit irrigated treatments was not fully replaced by nongrowing season precipitation at the study site resulting in lower FASW at emergence in study year two. In the third year of the study, FASW at emergence was greater than for year two due to greater effective nongrowing season precipitation. In general, FASW was not significantly different between the 50% FIT and 25% FIT irrigation treatments as the crop rapidly depleted available soil water due to ET_c demand greatly exceeding irrigation applied and soil water near permanent wilting point in both irrigation treatments. One surprising outcome of the study was that deficit nitrogen did not have a statistically significant effect ($p < 0.05$) on soil water trends. Additionally, deficit nitrogen did not have a significant effect ($p < 0.05$) on soil water balance maize ET_c in any year of the study, which is reflective of the lack of significant difference in FASW between nitrogen treatments. This outcome is counter intuitive as conventional thought suggests that less vegetative growth and yield resulting from deficit nitrogen results in reduced ET_c. This assumption of reduced productivity equating to reduced ET_c is one of the cited potential advantages for precision center pivot irrigation (O'Shaughnessy et al., 2019). In this study, ET_c was statistically equivalent regardless of crop productivity. This may be due to high frequency (~ 3 times weekly) with little rainfall allowing for more plant and soil surface evaporation. Evapotranspiration is the sum of transpiration and evaporation and reduced canopy vegetative cover associated with reduced productivity allows for more soil exposed to direct sunlight leading to more soil evaporation such that ET_c is essentially the same regardless of crop yield. The results of this study may not be applicable to regions with higher relative humidity and greater growing season rainfall, The results of a study on the impact of nitrogen fertilizer rate on maize evapotranspiration in Nebraska (Rudnick & Irmak, 2013) are similar to results of this study as reported ET_c was numerically similar across five nitrogen treatments for each of three deficit irrigation treatments. Unfortunately, they did not conduct statistical analysis of ET_c in the study. Ogola et al. (2002) reported a significant difference ($p < 0.05$) in soil evaporation and transpiration of maize in the UK due to nitrogen treatment. Soil evaporation was 6% less and transpiration was 35% greater with increased nitrogen resulting in an 9% increase in ET_c for conditions where soil evaporation was 70% of transpiration. The results of this study indicate that ET_c of well-watered maize is independent of nitrogen level in a high evaporative demand environment under high frequency irrigation.

In this study both irrigation and nitrogen treatments had a significant effect ($p < 0.05$) on maize yield, consistent with other studies of maize water and nitrogen yield response. Like the results of this study Rudnick and Irmak (2013) found greatest yields for the highest nitrogen and irrigation treatments. In this study, yield was not significantly different ($p < 0.05$) between nitrogen treatments for the 25% FIT, 50% FIT and 75% FIT irrigation treatments each year, however, there was a significant difference for the FIT irrigation treatment in 2018 and 2019. Rudnick and Irmak (2013) found significant differences ($p < 0.05$) in yield between nitrogen treatments for a given irrigation treatment representing a much greater overall yield response to nitrogen deficiency. In this study there was a decisive nonlinear decrease in yield with decreasing irrigation amount for a given nitrogen treatment. Rudnick and Irmak (2013) found a much smaller nonlinear decrease in yield with irrigation amount. This difference in yield response to irrigation is likely due to the greater reduction in ET_c by the irrigation treatments in this study. The 25% FIT treatment in this study resulted in a 52% reduction in ET_c relative to FIT while the rainfed treatment of Rudnick and Irmak (2013) resulted in a 22% reduction in ET_c relative to FIT. The ET_c of the 75% FIT treatment in this study was approximately equal to ET_c of the rainfed treatment in the study of Rudnick and Irmak (2013). In this study irrigation provides irrigation provides 88% of FIT ET_c while irrigation provides 24% of ET_c in the study of (Rudnick & Irmak, 2013).

Maize yield of the FIT irrigation treatment in the first year of this study was representative of yields reported in other studies in the US high plains (Trout & DeJonge, 2017). Yields in this study significantly decreased ($p < 0.001$) with study year. This outcome is attributed to the continuous maize rotation used in this study, which is commonly referred to as the continuous corn yield penalty (CCYP) (Gentry et al., 2013; Seifert et al., 2017). The cause of the CCYP is not fully understood but is likely due to increased disease pressure, allelopathy between corn residue and crop and a decrease in nitrogen availability (Seifert et al., 2017). Under rainfed conditions the CCYP has been reported in the range of 9 to 25% (Seifert et al., 2017). The yield difference for the high nitrogen FIT treatment combination between 2017 and 2019 in this study was 32%, higher than that expected for rainfed conditions it is plausible for a single experimental study not designed to evaluate the CCYP.

Assuming the range in maize yields measured in this study due to nitrogen deficiency and CCYP are representative of maize productivity differences caused by factors other than excess or deficit soil water across a center pivot irrigated landscape, the results of this study indicates that a reduction of water application to low productivity areas will further reduce yield. This inference is based on the decrease in maize yield when irrigation amount is decreased, regardless of FIT yield (full yield potential), and the lack of significant difference in ET_c between nitrogen treatments. The results of this study do not support the precision irrigation hypothesis that reduced yield potential equates to reduced ET_c. The results of this study show that reducing water application to low productivity areas will reduce grain yield at the same rate as in high productivity areas. Thus, VRI does not provide the opportunity to reduce water use and pumping costs while maintaining yield levels in low production areas. The hypothesis that maize evapotranspiration (ET_c) is independent of maize productivity in a high evaporative demand environment with frequent irrigation required to achieve maximum yield cannot be rejected.

Summary and Conclusions

Maize water use and yield were quantified and evaluated for two nitrogen (N) application rates (0 and 246 kg N ha^{-1}) under fully irrigated (FIT) and three deficit irrigation rates of 75% FIT, 50% FIT and 25% FIT in a three year field study at the Northwest Irrigation and Soils Research Laboratory near Kimberly, Idaho in 2017, 2018 and 2019.

Maize ET_c, grain yield and soil water contents were significantly different ($p < 0.05$) between irrigation treatments and study year. During each year of the study and within each irrigation treatment, there were no significant difference ($p < 0.05$) in maize ET_c or soil water content between the N treatments. Grain yield decreased nonlinearly as seasonal irrigation amount decreased regardless of N supply. Grain yield significantly ($p < 0.001$) over the three-year study. This decrease was attributed to use of continuous corn cropping in the three-year study and is commonly referred to as the continuous corn yield penalty (CCYP). The yield difference for the high nitrogen FIT treatment combination between 2017 and 2019 was 32%.

Assuming the range in maize yields measured in this study due to nitrogen deficiency and CCYP are representative of maize productivity differences caused by factors other than excess or deficit soil water across a center pivot irrigated landscape, the results of this study indicates that a reduction of water application to low productivity areas will further reduce yield.. Thus, VRI does not provide the opportunity to reduce water use and pumping costs while maintaining yield levels in low production areas. The hypothesis that maize evapotranspiration (ET_c) is independent of maize productivity in a high evaporative demand environment with frequent irrigation required to achieve maximum yield cannot be rejected.

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