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Comparative analyses of variable and fixed rate irrigation and nitrogen management for maize in different soil types: Part I. Impact on soil-water dynamics and crop evapotranspiration

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Abstract

Understanding the soil-water dynamics and maize evapotranspiration (ETc) under variable rate irrigation (VRI) and variable rate fertigation (VRF) management with respect to soil spatial variability constitutes the basis for developing effective variable rate water and nitrogen management strategies. This long-term research was designed to quantify and compare the soil-water dynamics, including available water (AW), and ETc during vegetative and reproductive growth periods of VRI, fixed rate irrigation (FRI) and no-irrigation (NI) under fixed rate fertigation (FRF), VRF and preplant (PP) nitrogen management in three different soil types [Crete silt loam (S1); Hastings silty clay loam (S2) and Hastings silt loam (S3)] with different topography in the same field under the same environmental and management conditions. The research was conducted in the Irmak Research Laboratory in south central Nebraska, U.S.A., in 2015, 2016 and 2017 maize (*Zea mays* L.) growing seasons under a variable-rate linear move sprinkler irrigation system. No effect of irrigation and nitrogen fertilizer on AW was observed in the vegetative period. Overall, greater AW was observed in S3 as compared with S1 and S2 due to lower elevation. Maize ETc during the vegetative period was significantly ($P < 0.05$) impacted by soil type in all three years and by nitrogen treatment in two of the three years. The vegetative ETc in S1 was 27 and 19 mm greater than S2 and S3, respectively, for the pooled 2015, 2016 and 2017 data. During the reproductive period, both ETc and AW were impacted by nitrogen and irrigation

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treatments, but differently in different soil types and years. Average reproductive ETc for FRI and VRI in 2015, 2016 and 2017 was 175 and 178 mm; 294 and 241 mm; 258 and 206 mm, respectively. Averaged across three years, ETc under FRI was significantly ($P < 0.05$) greater than in VRI; however, in 2015, no significant difference ($P > 0.05$) in ETc between FRI and VRI was observed in any soil type. Similarly, in 2017, no significant difference in reproductive ETc was observed between VRI and FRI in S1. During reproductive period, averaged across years, soil types and irrigation treatments, the PP nitrogen treatment had greater ETc and lower AW than VRF and FRF. The results indicate that vegetative period ETc was primarily affected by soil type, weather conditions (evaporative demand and soil wetting) and nitrogen fertilizer application timing. The findings of this research showed that soil-water dynamics is a strong function of not only management practices (irrigation and nitrogen treatments), but also soil type, topography and soil physical properties, which all need to be taken into account for effective management of VRI and FRI under VRF, FRF or PP nitrogen management in different soil types. This research quantified the impact of these management practices on soil-water dynamics and ETc which can be used as a guidance.

Keywords: Irrigation management, Nitrogen, Soil-water, Variable rate management, Water use, Vegetative period, Reproductive period

1. Introduction

Freshwater is a scarce resource and is essential for maintaining an adequate food supply and living environment for humans, animal and plants. Because of increasing population, demand for freshwater is becoming greater and is projected to increase more rapidly than the renewable supplies by 2025 (Postel et al., 1996). Around 60% of the global population may experience water scarcity by 2025 (Qadir et al., 2007). According to the United Nations estimation, in order to meet the increasing population's food demands, land under cultivation must increase by 40% and the amount of water allocated to irrigation must increase by 14% by 2030. Thus, there is a pressing need for significant changes and implementing effective approaches in agricultural water management to address the issue of water shortages and increase productivity. Efficient irrigation water management strategies for maximum water use efficiency are imperative for the sustainability of water resources and crop production. Two of the most important components in crop production are water and nitrogen and their adequate and timely supply during the growing season. Studies have reported the substantial influence of soil-water availability on crop yield and evapotranspiration (ETc) (Pandey et al., 2000, Payero et al., 2009, Djaman and Irmak, 2012). Deficit soil water can significantly decrease crop yield as compared with adequate available soil water conditions (Zhang et al., 2004). Also, excessive soil water can sometimes decrease crop yields significantly (King et al., 2006, Irmak, 2014). In traditional irrigation management, it is usually assumed that the field under consideration is uniform. It is a common practice to use a single mean value of crop response to water and ETc for deciding water application timing and depth. In this research, this practice is referred to as uniform or fixed rate irrigation (FRI), which is most practiced globally. Depending on numerous factors, crop response to water can vary in space and time (spatio-temporal variability) due to differences in plant emergence, plant density, soil-water availability, spatial soil characteristics, field slope and other factors that affect crop growth and nutrient availability, which thereby impacts crop yield and quality (Evans and King, 2010). Also, uniform application of fertilizers [fixed rate fertigation (FRF)] or pre-plant (PP) nitrogen application can have negative environmental consequences such as pollution of surface and groundwater resources (Basso et al., 2016, Pierce and Nowak, 1999) because of excessive fertilizer application at locations in the field where it is not required coupled with untimely precipitation events and/or poor irrigation management. The realization and understanding of these challenges and advancements in precision agriculture technologies in the last several decades has also increased the interest in the concept of variable rate irrigation (VRI) and variable rate fertigation (VRF) to manage spatial and temporal variabilities within agricultural fields (Evans et al., 2013, Robert, 2002).

VRI is referred to as applying the right amount of water at the right time and at the right location in a given field. It is an irrigation scheduling method based on site-specific soil-water holding capacity that should be measured/determine using real-time site-specific soil moisture measurements. Development in the site-specific water application technologies made it possible to vary both water and agricultural chemicals (fertilizers and pesticides) to meet specific needs of the crops in each unique zone within a field. Different aspects and effectiveness of VRI technology using primarily self-propelled center pivot or linear-move irrigation systems have been studied by several researchers (Fraisse et al., 1995, Evans et al., 1996, Sadler et al., 1996, King et al., 1999, King et al., 2009, King and Kincaid, 2004, Han et al., 2009, Chávez et al., 2010a, Chávez et al., 2010b); however, most of these researches focused on the development and improvement of hardware and software to implement site-specific technology on irrigation systems and to achieve precision in applying water and other chemicals spatially in the field. Limited studies have been conducted to evaluate the potential benefits of VRI in regards to water conservation and impact of VRI on the soil-water-plant relationship (soil-water dynamics) and ETc.

Al-Kufaishi et al. (2006) investigated the feasibility of using VRI on a 7 ha field with sugar beet in Germany using a daily soil-water balance simulation model. Irrigation applications of 20, 30 and 40 mm were simulated, and management zones were created based on available soil-water holding capacity. The loss of water was higher for the uniform application scenarios than that for the VRI scenarios for the applications of 20 and 30 mm. They observed that VRI scenario of 20 mm water application was the best option for water conservation. Hedley and Yule (2009) compared VRI and uniform irrigation scenarios for three years of climate data on a 156 ha pasture and 53 ha maize field in New Zealand. The management zones for VRI were delineated by relating apparent electrical conductivity with available soil-water holding capacity. A soil-water balance model was used on a daily basis for simulations of irrigation needs. The VRI scenarios saved 23–26% of irrigation water as compared with uniform irrigation. The same model was used by Hedley et al. (2009) on 40 ha pasture, 24 ha potato and 22 ha maize sites in New Zealand to evaluate irrigation water use, drainage water use, nitrogen leaching and other parameters between VRI and uniform irrigation scenarios. They reported an annual water use reduction of 9–19% under VRI as compared with uniform irrigation. However, in all these studies, soil moisture was simulated using models rather than measured data for specific fields and for different sites/locations within a field.

The impact of irrigation scheduling (amount and timing) based on real- or near-real-time soil moisture measurements on plant water uptake and growth has not been studied sufficiency through field experiments. It is not well known if addressing the assumed spatial variations in the field in terms soil properties (e.g., soil texture, soil-water holding capacity, etc.) will result in water conservation or not. While a limited number of studies suggested that there may be a water conservation advantage to VRI, numerous studies suggested otherwise and the adoption of VRI technology has been extremely limited in large scale production fields. Evans and King (2012) stated that 20+ years of private and public research on site-specific irrigation has resulted in very limited commercial adoption of the technology. They also stated that the primary reason for the very low rate of commercial adoption appears to be the absence of a market for the technology and a low rate of return. Documented and proven water conservation strategies using VRI for crop production are quite limited and its cost-effectiveness has not been demonstrated. Furthermore, they suggested that there is very little scientific information documenting the capability of site-specific sprinkler irrigation systems to conserve water or energy on a field scale for crop production in either arid or humid environments. In addition, the hydrologic conditions of reported studies were usually not widespread enough to be able to denote large-scale water savings. However, the VRI technology has been evolving and effectiveness, robustness and associated benefits have the potential to improve over time through scientific research and development.

In many regions, the lack of plant available soil-water generally has the predominant adverse effect on yield. Understanding the impact of delaying irrigation until a set soil moisture threshold (management allowable depletion) is reached using soil moisture sensors on soil-water dynamics and plant water uptake at different nitrogen levels is critical. Radin et al. (1989) showed an increase in cotton yield when interval between water applications decreased. It has been observed that under longer irrigation cycles, plants get stressed at the end of the irrigation cycle; however, frequent irrigations could alleviate this stress allowing the crop to reach its production potential (Bucks et al., 1988). In addition, site-specific characteristics such as slope and topography interact with nitrogen fertilizer. Ruffo et al. (2006) indicates that terrain attributes as soil water content affect corn yield and its response to nitrogen fertilizer. Zhou et al. (2011) found no significant effect of nitrogen fertilizer rate over 120 kg N ha^{-1} on soil water storage and corn grain yield in a six-year study in Shaanxi province, China. In general, plant water uptake is also strongly correlated to root distribution (Proffitt et al., 1985) which has been found to depend on type of irrigation, nitrogen fertilizer and availability of soil water (Phene et al., 1991).

The first step in understanding the impacts of variable rate application of water and fertilizer on crop response is understanding the variability in soil properties that exist in the field and how these natural variabilities affect the overall dynamics of soil-water. The knowledge about variability that exists in the soil within a field is fundamental to the development of effective site-specific or variable rate management, because different soils have different water holding capacities (Han et al., 1996) that impact plant growth, development and yield vs. water dynamics and ET differently. Soil-water dynamics has not been studied in a system that couples VRI technology with variable rate fertigation in different soil types simultaneously. The objectives of this research were to: (i) to quantify the horizontal and vertical variability in soil properties for three soil types in the same research field so that their influence(s) can be quantified and accounted for in any potential variation in soil-water dynamics, and (ii) evaluate how various nitrogen fertilizer management practices (FRF, VRF and PP) under various irrigation management practices [VRI, FRI and no irrigation (NI)] affect seasonal soil-water trends and cumulative ETc at different growth stages of maize. Quantifying and analyzing such variabilities can provide important information, data and guidance to further enhance the effectiveness of variable water and nitrogen management strategies in fields with spatially variability.

2. Materials and methods

2.1. Site description and soil sampling

This project is part of a larger and ongoing long-term project in the Irmak Research Laboratory that also investigated seasonal ETc, production functions, crop water productivity response and economics of maize, soybean and sorghum production under VRI, FRI and NI with VRF, FRF and pre-plant fertilizer management in three soil types. Thus, some of the materials and methods, including experimental details and cultural practices, soil moisture measurements and irrigation management and nitrogen management practices reported in this work and those reported by Sharma and Irmak (2020) may overlap. The Irmak Research Laboratory is located at the University of Nebraska-Lincoln South Central Agricultural Laboratory (SCAL), near Clay Center, Nebraska. The research was conducted in 2015, 2016 and 2017 growing seasons on a 2.3 ha field located at latitude 40° 34′ N and longitude 98° 8′ W with a west to east elevation gradient in the field ranging from 550.8 m to 552.1 m above mean sea level. The long-term average annual precipitation at the research site is 680 mm. The long-term maximum and minimum air temperatures are 25 °C and −5 °C, respectively (Irmak and Mutiibwa, 2009). Three soil types existed in the research field: (i) Crete silt loam, 0–1% slope [soil 1 (S1)], (ii) Hastings silty clay loam, 3–7% slope [soil 2 (S2)] and (iii) Hastings silt loam, 1–3% slope [soil 3 (S3)] (Figure 1).

As reported by Sharma and Irmak (2020), fixed rate and variable rate water and nitrogen applications were achieved using a two-span 75 m long model 7000SL variable rate linear-move sprinkler irrigation system (TL Irrigation, Co., Hastings, NE). The linear move system has a VRI that manages the watering regime of the system using up to a maximum of 48 irrigation and fertigation channels (12 zones, 4 sprinklers per zone). The controllers manage the watering rates of the sprinkler zones by actuating solenoids ON/OFF to enable the zones to deliver the desired application rates. Sprinkler spacing was 1.2 m and sprinklers were mounted on drop tubes at approximately 2 m above the ground level.

In April of each research year, soil samples were collected from 42 locations within the experimental field (Figure 1). From each sampling location, two soil samples per depth were collected at the soil depths of 0–0.30, 0.30–0.60, 0.60–0.90, 0.90–1.20 and 1.20–1.50 m with a Giddings soil sampling probe (Giddings Machine Co., Fort Collins, Co). Two cores from each plot were mixed per soil depth and all soil analyzes were conducted by the (Ward Laboratory, Kearney, NE). Soil was sampled to determine the existing nitrogen conditions to determine soil fertilizer recommendations and irrigation management. In variable rate management of irrigation and nitrogen fertilizer, a thorough analysis of soil properties is essential for various purposes, including determining VRI requirements for individual soil layers that have different soil properties rather than assuming a uniform soil layer for the entire crop root zone. Soils from all depths were analyzed for nitrate-N for all three years. However, at the beginning of the experiment (i.e., for the first soil sampling in April 2015), soil samples were analyzed for bulk density (BD), electrical conductivity (EC), organic matter content (OMC), field capacity (FC), permanent wilting point (PWP), and soil particle size distribution (sand, silt and clay). The FC and PWP values were determined using pressure plate apparatus at 1/3 bar and 15 bar pressure, respectively. The soil particle size distribution was determined by hydrometer method (Blake and Hartge, 1986). Since these values do not change

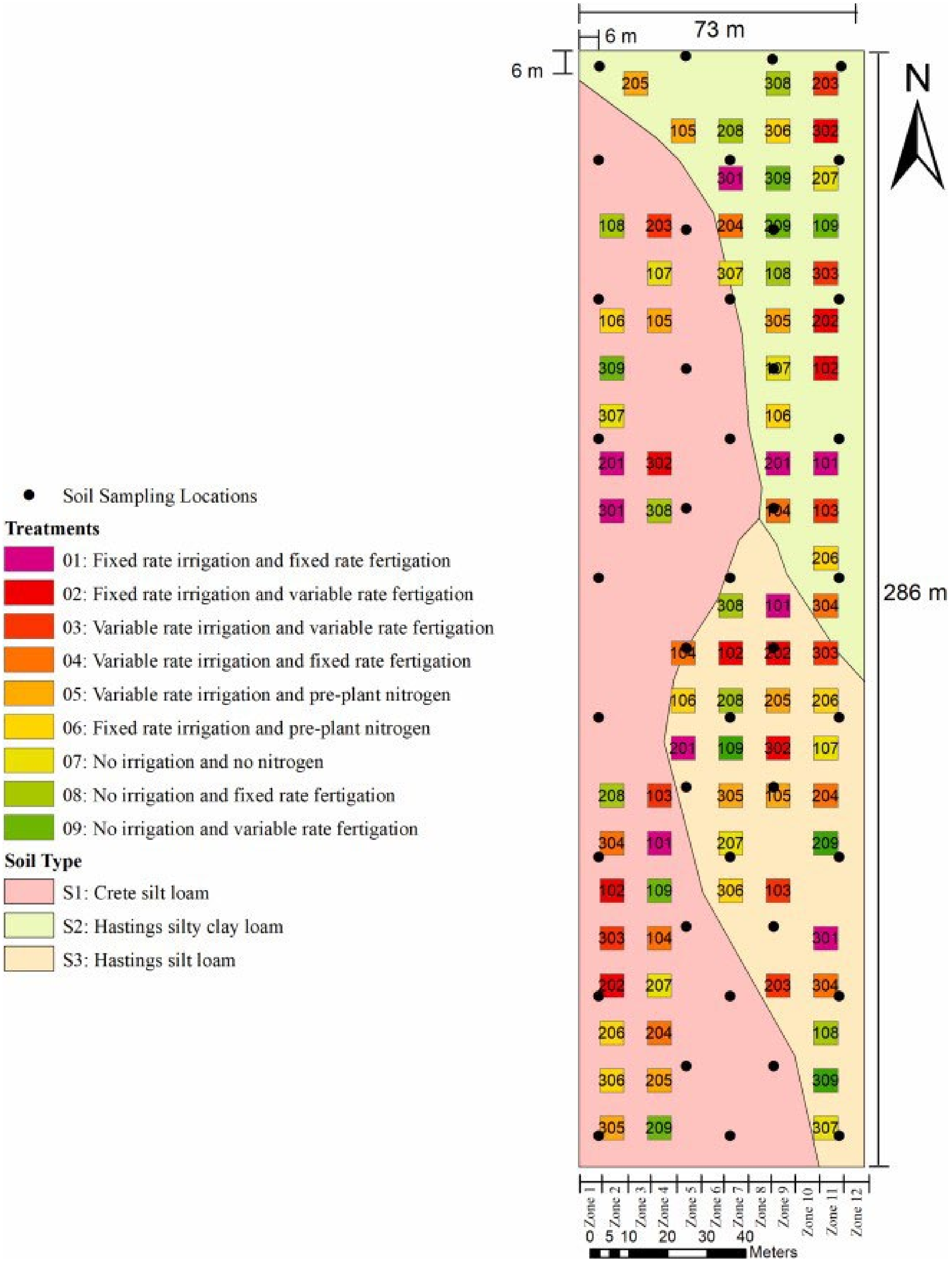

Figure 1. Field experimental plot layout and soil sampling locations for three soil types (S1 is Soil 1; S2 is Soil 2; S3 is Soil 3) used in 2015, 2016, and 2017 growing seasons. The thick lines show soil types, small boxes are the treatment plots which are replicated three times in each soil type and black dots are the soil sampling locations in the Irmak Research Laboratory variable rate and fixed rate irrigation and fertilizer management research facility.

in a short period (i.e., three years of research duration), same values for these soil properties were used in estimating site-specific nitrogen and irrigation requirements for all three years. In ArcGIS software (ver. 10.1, ESRI, Redlands, California), the inverse distance weighted interpolation method was used to model the spatial distribution of all soil physical properties in the research field.

2.2. Experimental details and cultural practices

In each research year, each soil type was divided into 27 plots (experimental units) where VRI and FRI and fertigation treatments were randomly assigned to plots in each soil (Figure 1). Each treatment is a combination of three levels of irrigation (VRI, FRI and NI) and three levels of nitrogen fertilizer [fixed rate fertilizer management (FRF), variable rate fertilizer management (VRF) and pre-plant N (PP)], which makes a total 9 treatment combinations (Figure 1). Treatments were randomly assigned to the plots in each growing season. The treatment combination of NI and PP nitrogen management was not studied in this research; instead, NI and no nitrogen combination treatment was evaluated.

Each plot was 6 m × 6 m in size with a 6 m × 6 m buffer plot on all four sides of each plot (Figure 1). The buffer plots were established to prevent/eliminate sprinkler overlap between the plots (sprinkler wetted diameter was 6 m). Cultural management practices/operations for the three years and common practices, including planting, emergence, and fertilizer applications, tasseling and harvest dates are shown in Table 1. The research field was managed as disk-till. Maize seeds were planted in rows at a depth of 6.3 cm. Row spacing was 0.76 m and the planting population density was 84,500 plants/ha in all years. The growing season in this research refers to the time between plating and harvest. To determine the value of soil properties for each plot for VRI and VRF management, extract by mask tool in ArcGIS was used to extract values from interpolated maps. By this method, FC, PWP, OMC, soil texture and soil nitrate-N for each plot was determined. Based on plot average values of soil properties, irrigation and nitrogen amounts were quantified and the details are discussed in the latter sections.

Table 1. Summary of agronomic management practices in 2015, 2016 and 2017 growing seasons.

Operation	*Growing Season*		
Material Applied	*2015*	*2016*	*2017*
Planting			
P1151AMX maize	27 May		
G07F23-3111		6 May	
Channel 209-53STXRIB			5 May
Emergence	7 June	19 May	16 May
Pre-plant N in treatment 05 and 06			
UAN[a] 32-0-0	27 May	13 April	19 April
In season FRF[a]			
UAN[a] 32-0-0	13 July	30 May	5 June
	16 July	28 June	23 June
In season VRF[a]			
UAN[a] 32-0-0	19 July	31 May	6 June
		27 June	22 June
Tasseling	25 July	19 July	17 July
Physiological maturity	15 Sep.	20 Sep.	13 Sep.
Harvest	19 Oct.	13 Oct.	25 Oct.

a. FRF = Fixed rate fertigation; VRF = Variable rate fertigation; UAN = Urea ammonium nitrate.

2.3. Soil moisture measurements, irrigation management and nitrogen management

Irrigation timing and amounts for VRI plots were determined by soil-matric potential (SMP) values that were measured using Watermark Granular Matrix Sensors (WGMS, Irrometer, Co., Riverside, CA) installed at four soil depths (0.30, 0.60, 0.90 and 1.20 m) in 20 plots (first two replications of each treatment) in each soil type. WGMS were installed in the middle of each plot in the maize row. The soil moisture sensors and data logging systems were installed immediately following the crop emergence each year and were removed from the field at the end of each growing season for harvesting. WGMS were used to monitor SMP (kPa) on an hourly basis, which was then converted to volumetric soil-water content using soil-water retention curves for each soil type for the research site developed and presented in Irmak, 2019, Irmak et al., 2012, Irmak et al., 2016 for different soil types at Clay Center, NE, and in other locations. Since there were differences in the soil textural properties depthwise (in a vertical domain in addition to the horizontal domain), for 2016 and 2017 growing seasons, soil-water retention curves based on soil texture at each soil depth were used. In total, there were six types of soils existed in the research field. These soil types were silt loam, silty clay loam, clay loam, loam, sandy clay loam and sandy loam. To the best of our knowledge, this approach of using different soil characteristic curves to determine VWC for different depths at the same location has not been considered previously for VRI and VRF management. The volumetric soil-water content (VWC) at each soil depth was then multiplied by the representative depth intervals to determine the total soil-water stored (SWS) in each depth and then summed up to obtain total soil-water for the 0–1.20 m soil profile for each plot. Whenever the SMP values at any soil depth was below 33 kPa (which means soil was at or near field capacity), it was adjusted to 33 kPa to prevent very high or erroneous VWC values. The total available water (TAW) was calculated by subtracting soil-water at PWP from soil-water at FC for each plot. Management allowable depletion (MAD) for all plots was set to 40% of TAW.

Irrigation was triggered whenever total soil-water stored in the effective rooting depth as represented by SMP values was approaching to or below MAD. Crops do not extract water uniformly from the entire root zone throughout the growing season. Effective rooting depth is the portion of the root zone from where the crop can extract water. Based on the rooting depth and growth stage of the crop, the effective root zone depth for irrigation amount and timing was decided accordingly for each growing season. The timing of irrigation for both VRI and FRI was decided in this manner. However, for FRI plots, the amount of irrigation was fixed to be 25.4 mm per irrigation application. Each time any of the FRI plots needed irrigation, all FRI plots were irrigated with 25.4 mm depth of water considering no variability in the field and assuming that crop responds in the same manner at all locations in the field, which is the most commonly used irrigation practice in Nebraska and greater Midwestern region. A total of 1, 7 and 10 irrigations were applied to FRI plots in 2015, 2016 and 2017 growing seasons, respectively. For VRI plots, irrigation amounts varied substantially and were applied to bring the soil-water to approximately 85% of FC or to maintain 85% of TAW to reserve some soil-water deficit for any potential precipitation. Only those plots where soil moisture depletion was greater than MAD were irrigated in any irrigation event for VRI plots. Thus, the number and amount of irrigation events for each VRI plot was different. The irrigation dates and amounts for each treatment are presented in Table 2.

Table 2. Irrigation dates and amounts (mm) for all treatments in three soil types.

Date	*FRI*	*Date*	*S1 VRI*			*S2 VRI*			*S3 VRI*		
			VRF	*FRF*	*PP*	*VRF*	*FRF*	*PP*	*VRF*	*FRF*	*PP*
9/1/2015	25.4	9/1/2015	0	14	18	32	0	0	25	22	19
		9/7/2015	0	14	0	17	10	15	12	13	0
Total	25.4	Total	0	28	18	49	10	15	37	35	19
7/12/2016	25.4	7/12/2016	8	0	27	0	0	13	0	0	0
7/21/2016	25.4	7/21/2016	15	0	22	0	0	0	0	0	0
7/25/2016	25.4	7/25/2016	14	0	53	0	21	6	18	27	0
8/3/2016	25.4	7/28/2016	15	19	52	25	14	14	17	0	0
8/9/2016	31.7	8/3/2016	0	0	15	0	22	41	22	0	0
8/15/2016	31.7	8/9/2016	23	0	66	9	28	43	29	0	24
8/23/2016	25.4	8/15/2016	28	13	25	34	45	31	41	36	58
		8/23/2016	0	0	28	36	57	36	29	0	24
Total	190.4	Total	103	32	288	105	187	184	155	62	107
6/26/2017	25.4	7/5/2017	0	22	0	11	0	13	0	0	0
7/5/2017	25.4	7/10/2017	23	17	15	13	0	13	0	0	0
7/10/2017	25.4	7/19/2017	25	22	19	15	0	0	0	0	0
7/19/2017	25.4	7/22/2017	0	20	0	39	0	22	0	0	42
7/22/2017	25.4	7/25/2017	0	25	0	0	0	0	0	0	13
7/25/2017	25.4	7/28/2017	0	0	0	0	0	0	0	0	0
7/28/2017	25.4	7/31/2017	18	0	20	0	0	0	0	0	32
8/2/2017	25.4	8/2/2017	25	18	20	20	0	0	0	0	0
9/6/2017	25.4	8/10/2017	0	42	0	17	0	0	0	0	13
9/13/2017	25.4	8/14/2017	19	0	18	0	0	18	0	0	0
		9/6/2017	0	53	36	0	19	22	0	0	23
		9/13/2017	0	25	0	116	19	86	0	0	0
Total	254	Total	110	244	128	231	38	173	0	0	122

Abbreviations: S1 is soil 1; S2 is soil 2; S3 is soil 3; FRI is fixed Rate Irrigation; VRI is Variable Rate Irrigation; FRF is Fixed Rate Fertigation; VRF is Variable Rate Fertigation; PP is Pre-Plant Nitrogen.

For this research, irrigation amounts and timing in each experimental plot was needed prior to irrigation to calculate the irrigation requirements for FRI and VRI plots. To accomplish this, the soil moisture sensor data were downloaded from each plot every other day and were uploaded to an irrigation scheduling worksheet that was developed in the Irmak Research Laboratory for each plot based on the plot-specific soil properties. Computed irrigation values were then used to develop water control/prescription maps for delivering precise irrigation amount to each experimental unit. The final map was then uploaded to the linear-move control panel and irrigation was applied when needed.

Nitrogen was applied in the form of urea ammonium nitrate (UAN 32-0-0) using fixed rate fertigation (FRF), variable rate fertigation (VRF) and pre-plant nitrogen (PP) application methods. For the PP treatment, 246 kg ha^{-1} of nitrogen was applied in 2015, 2016 and 2017 (Table 1). In VRF and FRF treatments, in-season fertilizer was applied (fertigation) using linear-move sprinkler system. The nitrogen fertilizer rate for VRF plots was calculated using the nitrogen recommendation equation proposed by the University of Nebraska-Lincoln fertilizer guidelines (Shapiro et al., 2008). This fertilizer requirement equation for maize was based on the expected yield, soil organic matter and soil nitrate-nitrogen content. The nitrogen requirements for VRF plots for each year based on this procedure are presented in Table 3. Each VRF plot received different N amount based on the soil analysis. The decline in the N rate from 2015 to 2017 could be attributed to the residual nitrate-N left from the previous year. A constant rate of 246 kg ha^{-1} of nitrogen fertilizer was applied to all FRF plots in all three years. Since multiple applications of nitrogen are generally more efficient than single large doses due to nitrogen loss potential, the N fertilizer application was divided in two applications in 2016 and 2017 growing seasons. Half of the required nitrogen was applied at the V2 stage of maize plant growth and the remaining amount was applied at V8 stage for both VRF and FRF plots in 2016 and 2017 growing seasons. In the 2015 growing season, two applications which were several days apart were applied to the FRF plots whereas only one application was done for VRF plots (Table 1).

Table 3. Nitrogen fertilizer amounts in variable rate fertigation (VRF) treatment at fixed rate irrigation (FRI), variable rate irrigation (VRI) and no irrigation (NI) in Soil 1 (S1), Soil 2 (S2) and Soil 3 (S#) in 2015, 2016 and 2017 growing seasons.

Soil	*Irrigation Treatment*	*2015*	*2016*	*2017*
		N, kg ha^{-1}		
S1	FRI	228.0	241.0	194.1
	VRI	228.0	229.8	195.4
	NI	227.7	211.9	193.0
S2	FRI	229.6	196.9	162.0
	VRI	227.7	190.5	148.7
	NI	226.9	198.7	152.9
S3	FRI	197.2	186.9	155.5
	VRI	218.8	191.2	161.2
	NI	216.6	185.5	159.3

2.4. Evapotranspiration calculations and statistical analysis

Crop evapotranspiration (ETc, mm) was calculated from a soil-water balance equation (Eq. (1)) for the vegetative growth period (emergence to tasseling) and reproductive growth period (silking to maturity)

$$ET_c = P + I + U - Runoff \pm \Delta SWS - DP \quad (1)$$

where, P is precipitation (mm); I is irrigation (mm); U is upward water flux (mm); Runoff is surface runoff from individual treatments (mm), ΔSWS is change in soil water storage (mm) in the soil profile between the beginning and end of the growth period and DP is the deep percolation from the crop root zone (mm). Since the water table is approximately 30 m below the surface, upward water flux was assumed to be negligible (Irmak, 2015a, Irmak, 2015b). The surface runoff was estimated using the USDA Natural Resources Conservation Service (NRCS, formerly called as the Soil Conservation Service, SCS) curve number procedure (USDA-NRCS, 1985). The runoff was determined for each day over the growing seasons and then summed up for individual treatment for the vegetative period and reproductive period. Deep percolation was estimated using the daily soil water balance computer program (Payero et al., 2009, Bryant et al., 1992, Djaman and Irmak, 2012, Irmak, 2015a, Irmak, 2015b). The dates corresponding to observed vegetative period and reproductive period in three growing seasons are shown in Table 4.

The AW and ETc data were statistically analyzed using Proc Glimmix procedure in SAS (SAS Institute Inc., Cary, NC, USA) to compare the effects of irrigation treatment, nitrogen treatment and soil type on AW and ETc. The means were separated using Least Significant Difference (LSD) test at the 95% level of significance to identify any potential significant differences in AW and ETc between treatments. When no significant interactions occurred between the treatments, main effects were

Table 4. Observed vegetative and reproductive growth stage dates in 2015, 2016 and 2017 growing seasons.

Season	*Vegetative period*	*Reproductive period*
2015	7 June–31 July	1 August–2 Oct
2016	19 May–19 July	20 July–20 Sep
2017	16 May–17 July	18 July–12 Sep

evaluated. Since the NI and PP combination was not studied in this research, the NI level was excluded from the statistical model to complete the factorial design.

3. Results and discussion

3.1. Weather conditions

A summary of weather data for three growing seasons (2015, 2016 and 2017) along with long-term average values is presented in Table 5. The weather data were obtained from the High Plains Regional Climatic Center- Automated Weather Data Network (HPRCC-AWDN) near Clay Center, NE. The weather station was located only 800 m from the research field. The growing season precipitation in 2015, 2016 and 2017 was 353, 375 and 467 mm, respectively. Although the total growing season precipitation in 2015 was lower than 2016 and 2017, the 2015 season experienced very heavy rainfall in June (226 mm) which was 131 mm greater than long-term average (Table 5) which also explain the low irrigation amount required in 2015. A total of 1, 7 and 10 irrigations were applied to FRI plots in 2015, 2016 and 2017 growing seasons, respectively. On average, the 2015 growing season was warmer than 2016 and 2017 with the mean air temperature in 2015 of 20.3 °C and 19.8 °C and 19.1 °C in 2016 and 2017, respectively. The highest monthly average temperature in all three years occurred in July (Table 5). Warmer temperatures in 2015 progressed the crop development hence the physiological maturity. There were large differences in the cumulative growing degree days (CGDD) from planting to harvest between 2015, and 2016 and 2017. Maize was harvested at 145 days after planting (DAP) at CGDD of 1640 in 2015 whereas in 2016 and 2017 it was harvested at 160 DAP (CGDD of 1781) and 173 DAP (CGDD of 1783), respectively.

Temporal patterns of daily average wind speed, relative humidity (RH), vapor pressure deficit (VPD), incoming shortwave radiation and maximum and minimum air temperatures for 2015, 2016 and 2017 growing seasons are shown in Figure 2. Evaporation losses from the surface and water used by plant (transpiration) are heavily influenced

Table 5. Monthly average weather conditions during 2015, 2016 and 2017 maize growing seasons and long-term (1983–2017) averages at the research site in south central Nebraska.

Year	*Month*	*Tmax[a] (°C)*	*Tmin[a] (°C)*	*RHmean[a] (%)*	*Wind speed (m s⁻¹)*	*Precipitation (mm)*	*Incoming shortwave radiation (W m⁻²)*	*VPD[a] (kPa)*
1983–2017	May	22.7	9.3	67.7	4.2	110.7	229.1	0.7
	June	28.5	15.0	68.5	3.7	94.6	263.0	0.9
	July	30.5	17.4	72.1	3.0	84.0	260.2	0.9
	August	29.2	16.3	75.2	2.8	81.9	227.7	0.8
	September	25.5	10.8	68.7	3.2	54.0	182.9	0.8
	October	18.5	3.6	66.3	3.5	52.3	130.7	0.5
2015	May	20.9	9.0	76.2	4.3	144.5	198.4	0.5
	June	27.9	15.7	74.7	3.2	225.8	237.0	0.7
	July	29.7	17.2	77.3	2.5	54.9	246.9	0.7
	August	28.2	15.1	78.0	2.7	32.5	215.6	0.6
	September	27.8	14.5	72.6	3.2	38.4	173.1	0.8
	October	20.9	5.5	61.3	3.1	37.1	129.6	0.7
2016	May	22.0	8.7	70.4	3.9	172.5	225.0	0.6
	June	31.3	17.0	60.4	3.7	5.1	303.7	1.3
	July	30.1	18.0	76.7	3.0	63.5	248.8	0.8
	August	28.3	16.6	78.9	2.8	63.0	224.0	0.6
	September	25.4	13.0	77.0	3.2	66.8	171.6	0.6
	October	21.5	5.6	71.8	3.4	5.6	134.2	0.5
2017	May	22.5	8.7	64.6	4.0	153.9	251.2	0.8
	June	30.1	15.4	61.0	3.0	22.6	290.1	1.2
	July	31.2	18.5	72.5	2.0	50.8	262.5	0.9
	August	27.2	14.3	77.8	1.8	89.6	228.8	0.6
	September	26.8	12.3	69.0	2.3	52.7	173.1	0.8
	October	18.4	4.2	66.4	3.6	102.2	119.3	0.5

a. Tmax: Maximum air temperature; Tmin: Minimum air temperature; RHmean: Mean relative humidity; VPD: Vapor pressure deficit.

by these climatic variables. On average, wind speeds were greater in 2016 than in 2015 and 2017. Also, greater wind speeds were observed in the early growing season in all three years (May to June), which is common for the area. The 2017 growing season experienced below-normal wind speeds in the late growing season (August and September). Because of minimal precipitation amounts in June in the 2016 and 2017 growing seasons as compared with 2015, large differences in RH were observed. The monthly average RH in June was 75%, 60% and 61% for 2015, 2016 and 2017, respectively, as compared with the long-term average of 68.5%. The incoming solar radiation was, on average, greater in 2017 than in 2015 and 2016. One of the driving forces of plant water

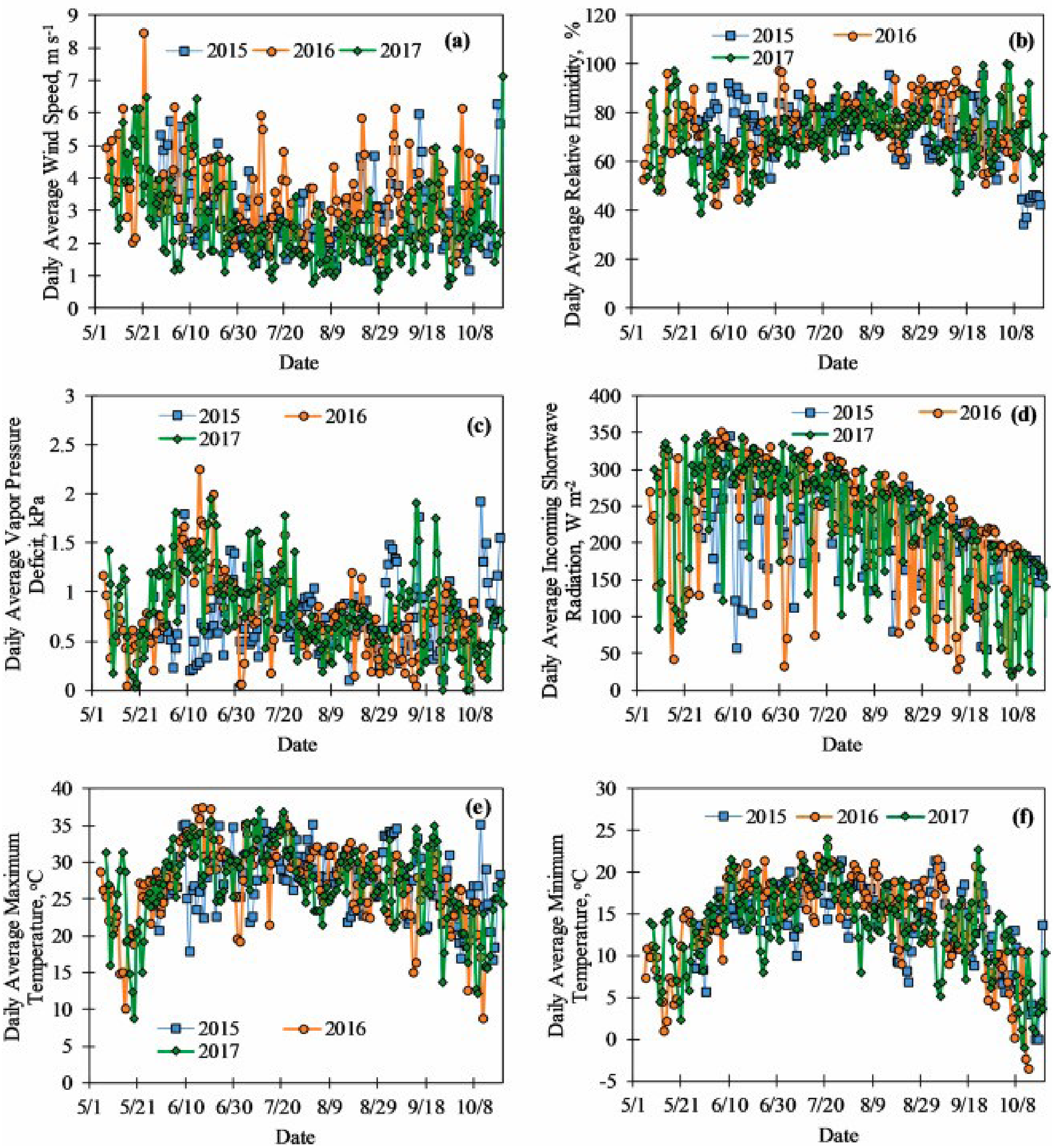

Figure 2. Measured daily average (a) wind speed (u2), (b) relative humidity (RH), (c) vapor pressure deficit (VPD), (d) incoming shortwave radiation (Rs), (e) maximum air temperature (Tmax) and, (f) minimum air temperature (Tmin) for the 2015, 2016 and 2017 growing seasons.

use is the difference in vapor pressure between crop surface and surrounding atmosphere, which is called VPD. The temporal patterns of VPD for three growing seasons are presented in Figure 2c. On average, VPD in 2017 growing season was greater than in 2015 and 2016 growing seasons.

3.2. Spatial distribution of soil properties

The spatial distribution of sand, silt and clay content in 0–0.30, 0.30–0.60, 0.60–0.90, 0.90–1.20 and 1.20–1.50 m soil depths for each soil type are shown in Figure 3a–c, respectively. The measured and interpolated sand fraction in the research field ranged from 15% to 57%; silt fraction ranged from 20% to 74%; and clay fraction ranged from 7% to 39%. The measured silt fraction was highly and negatively correlated with measured sand fraction with correlation coefficient of 0.85, 0.84, 0.76, 0.89 and 0.95 for 0–0.30, 0.30–0.60, 0.60–0.90, 0.90–1.20 and 1.20–1.50 m soil depths, respectively.

The spatial distribution of other soil physical properties, including OMC, BD, EC, FC and PWP, are shown in Figs. 4a–c and 5a and b, respectively. The interpolated OMC ranged from 0.8% to 3.5% with the highest OMC being in the top two soil layers (0–0.30 and 0.30–0.60 m). OMC in soil layers from 0.90 to 1.5 m ranged from 0.8% to 6% with very small variation among soil types (Figure 4a). The BD values ranged from 1.02 to 1.32 g cm^{-3} with highest values in 1.50 m soil layer (Figure 4b). There is large variation in EC values at the research site, varying from 38 to 168 mS m^{-1}. The highest EC values were observed in the 1.50 m soil layer (Figure 4c). For accurate site-specific irrigation management, two of the most important factors to have data and information about is the site-specific FC and PWP values. Large variation was observed in FC and PWP at the research site between the soil types as well as between the soil depths in a given soil type. The range in FC and PWP was 26–43% and 11.5–30%, respectively (Figure 5 and b). The soil-water holding capacity (SWHC) for each soil layer was computed as the difference between soil-water at FC and PWP, which ranged from 20 to 93 mm/0.30 m soil depth for different layers (Figure 5c). The soil physical properties at each soil depth and in each soil type are presented in Table 6. In all three soil types, the minimum silt content and maximum clay content was found at 0.30–0.60 m soil depth.

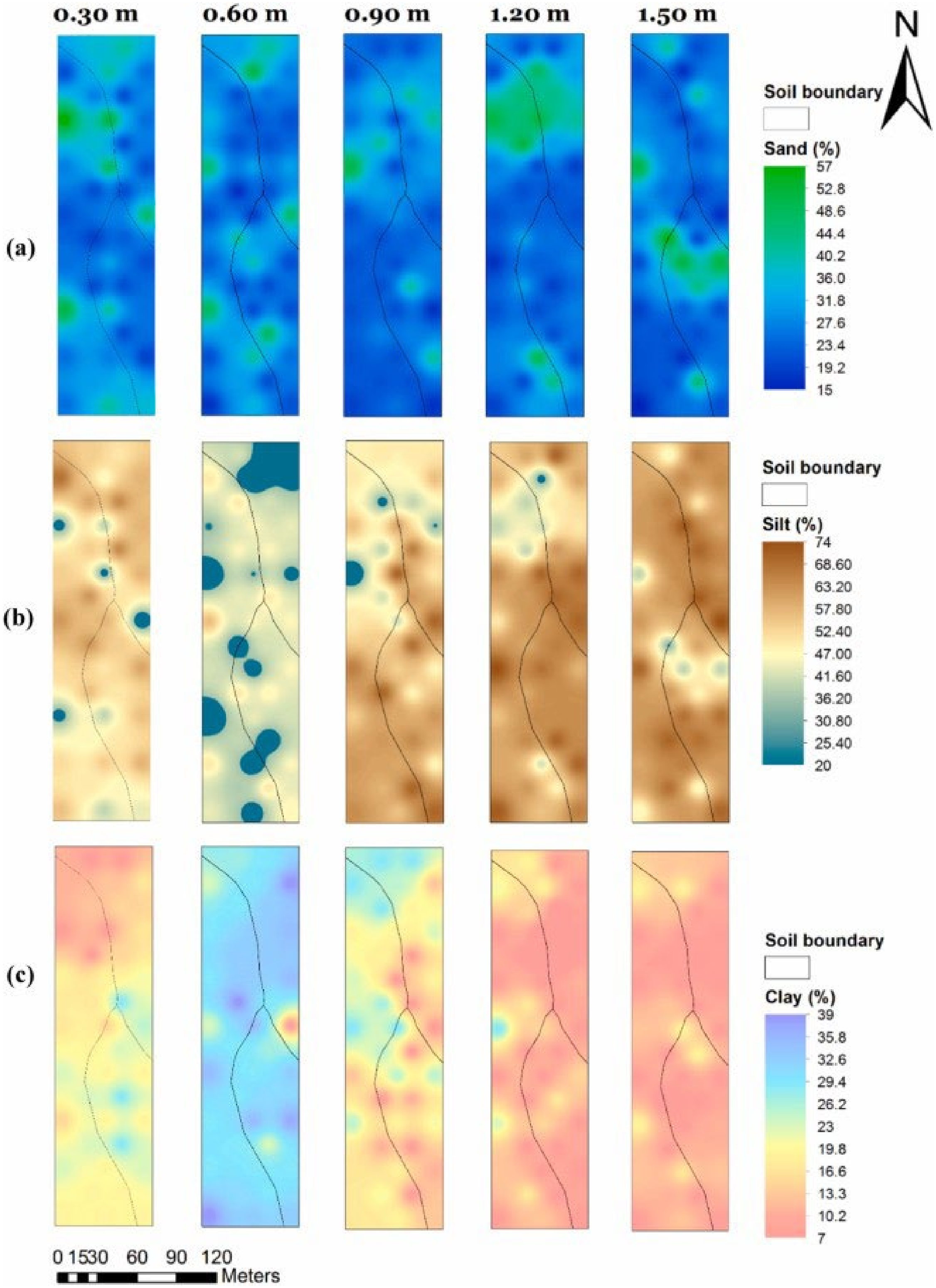

Figure 3. Spatial distribution of soil particle size distribution: (a) sand, (b) silt, and (c) clay fraction percentage across the research field at 0.30, 0.60, 0.90, 1.20 and 1.50 m soil depths.

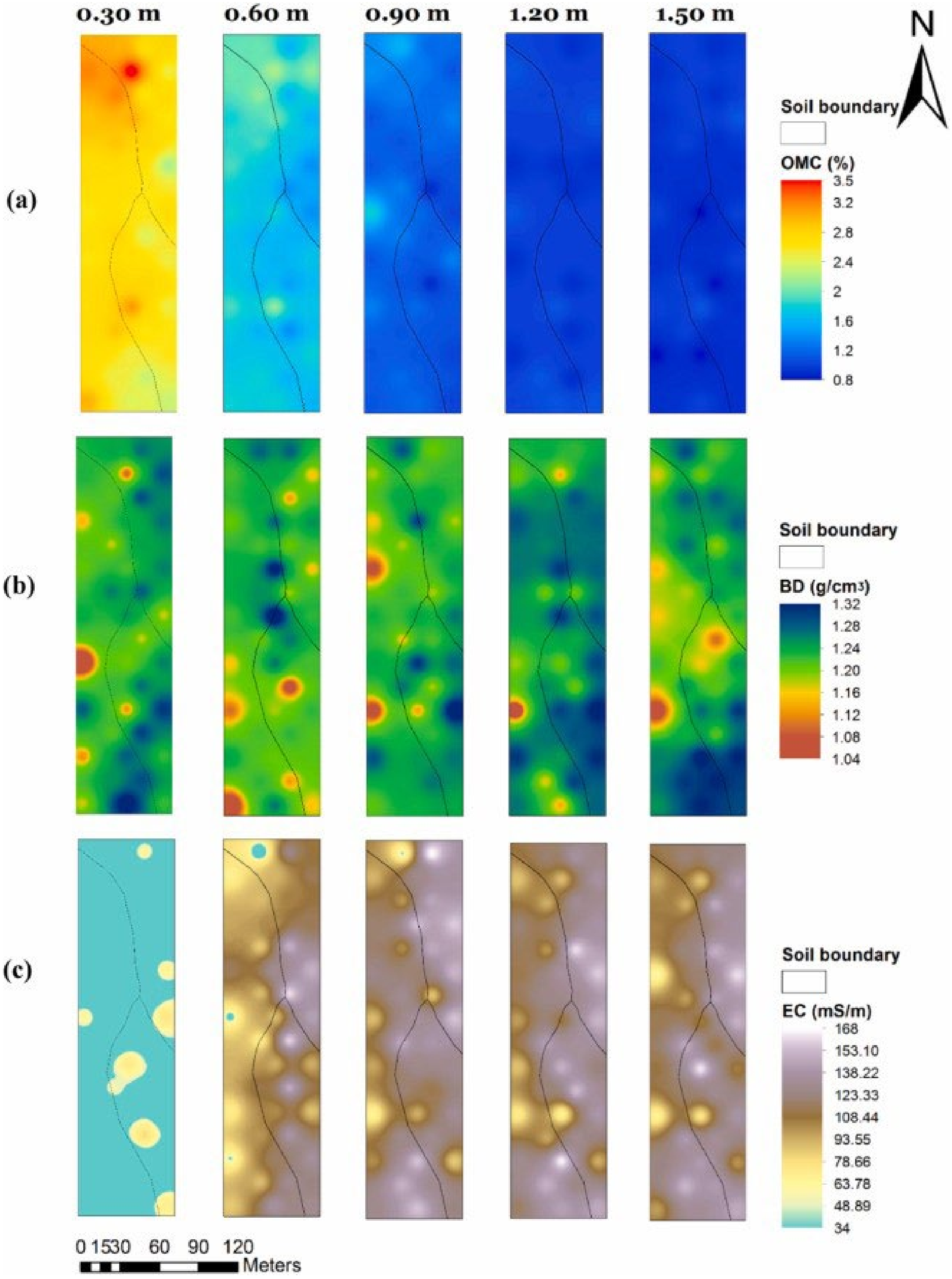

Figure 4. Spatial distribution of (a) organic matter content (OMC), (b) bulk density (BD), and (c) electrical conductivity (EC) across the research field at 0.30, 0.60, 0.90, 1.20 and 1.50 m soil depths.

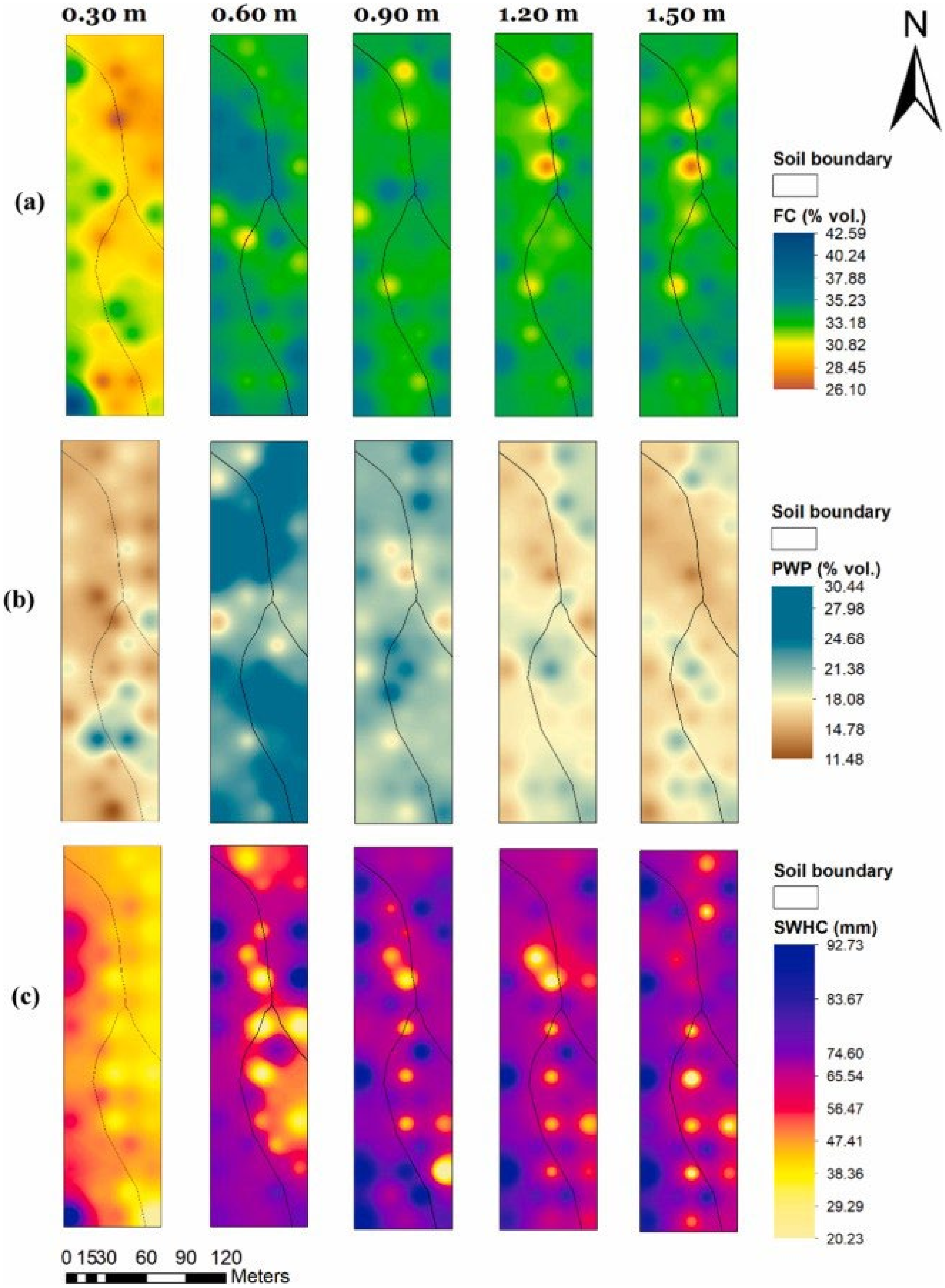

Figure 5. Spatial distribution of (a) field capacity (FC), (b) permanent wilting point (PWP), and (c) soil-water holding capacity (SWHC) across the research field at 0.30, 0.60, 0.90, 1.20 and 1.50 m soil depths.

Table 6. Soil physical properties with standard error in parenthesis for each soil type and depth at the research site.

Soil	*Depth (m)*	*[a] BD (g cm^{-3}) [b]*	*FC (m^3 m^{-3})*	*PWP (m^3 m^{-3})*	*SWHC (mm)*	*OMC (%)*	*EC (mS/m)*	*Sand (%)*	*Silt (%)*	*Clay (%)*
1	0–0.30	a 1.13 (0.01) D	a 0.33 (0.01) D	a 0.16 (0.01) H	a 52.75 (2.27) BAC	a 2.75 (0.06) A	a 48.67 (2.35) F	a 33.33 (2.34) A	a 49.89 (2.32) D	a 16.78 (1.2) CD
1	0.30–0.60	a 1.13 (0.01) D	a 0.37 (0.00) A	a 0.23 (0.01) BA	a 44.45 (2.05) EDF	a 1.81 (0.05) B	a 95.44 (6.48) D	a 28.11 (2.34) BAC	a 41.11 (2.32) E	a 30.78 (1.28) A
1	0.60–0.90	a 1.16 (0.01) DC	a 0.37 (0.00) BA	a 0.21 (0.00) DC	a 48.12 (1.94) EDC	a 1.21 (0.04) C	a 119.33 (6.18) BAC	a 25.89 (2.34) BC	a 54.44 (2.32) DC	a 19.67 (1.71) CB
1	0.90–1.20	a 1.21 (0.01) BA	a 0.36 (0.00) BC	a 0.17 (0.00) FG	a 54.37 (1.86) BA	a 0.99 (0.02) D	a 115.89 (5.67) BC	a 31.33 (2.34) BAC	a 55.56 (2.32) BDC	a 13.11 (1.18) ED
1	1.20–1.50	a 1.23 (0.01) A	a 0.36 (0.01) BC	a 0.16 (0.00) GH	a 58.32 (1.73) A	a 0.93 (0.02) EF	a 113.33 (5.66) DC	a 25.00 (2.34) BC	a 61.22 (2.32) BA	a 11.78 (0.85) E
2	0–0.30	a 1.16 (0.02) DC	a 0.30 (0.01) E	a 0.17 (0.01) FGH	ab 41.31 (3.05) EGDF	a 2.73 (0.09) A	ab 52.20 (3.16) FE	a 29.80 (3.13) BAC	a 53.20 (3.12) DC	a 17.00 (1.61) CBD
2	0.30–0.60	a 1.13 (0.02) D	a 0.37 (0.01) BA	a 0.24 (0.01) A	ab 39.76 (2.75) GF	a 1.7 0(0.06) B	ab 120.80 (8.69) BAC	a 31.40 (3.13) BAC	a 38.80 (3.12) E	a 29.80 (1.72) A
2	0.60–0.90	a 1.17 (0.02) DC	a 0.36 (0.01) BA	a 0.21 (0.01) BC	ab 46.23 (2.6) EDC	a 1.19 (0.05) C	ab 134.00 (8.29) BA	a 29.00 (3.13) BAC	a 52.60 (3.12) DC	a 18.40(2.29) CB
2	0.90–1.20	a 1.21 (0.02) BA	a 0.36 (0.01) BA	a 0.19 (0.01) DE	ab 51.57 (2.49) BC	a 0.98 (0.02) ED	ab 135.40 (7.61) A	a 29.60 (3.13) BAC	a 59.60 (3.12) BAC	a 10.80 (1.59) E
2	1.20–1.50	a 1.24 (0.02) A	a 0.36 (0.01) BAC	a 0.18 (0.01) FG	ab 55.26 (2.33) BA	a 0.96 (0.02) EDF	ab 136.80 (7.6) A	a 26.40 (3.13) BAC	a 62.80 (3.12) BA	a 10.80 (1.14) E
3	0–0.30	a 1.14 (0.02) DC	b 0.30 (0.01) E	a 0.17 (0.01) FGH	b 40.99 (2.78) EGF	a 2.64 (0.08) A	b 58.17 (2.88) E	a 25.50 (2.86) BC	a 53.17 (2.85) DC	a 21.33 (1.47) B
3	0.30–0.60	a 1.13 (0.02) D	b 0.35 (0.01) BDC	a 0.23 (0.01) BA	b 35.56 (2.51) G	a 1.67 (0.06) B	b 113.50 (7.93) BDC	a 27.33 (2.86) BAC	a 42.00 (2.85) E	a 30.83 (1.57) A
3	0.60–0.90	a 1.18 (0.02) BC	b 0.34 (0.00) DC	a 0.20 (0.01) DC	b 41.76 (2.38) EDF	a 1.12 (0.05) C	b 123.33 (7.57) BAC	a 25.50 (2.86) BC	a 57.33 (2.85) BAC	a 17.17 (2.09) CBD
3	0.90–1.20	a 1.24 (0.02) A	b 0.34 (0.01) DC	a 0.18 (0.01) FE	b 48.51 (2.28) BDC	a 1.00 (0.02) D	b 126.17 (6.95) BAC	a 24.50 (2.86) C	a 64.33 (2.85) A	a 11.17 (1.45) E
3	1.20–1.50	a 1.23 (0.02) A	b 0.35 (0.01) BDC	a 0.18 (0.01) FE	b 51.03 (2.12) BC	a 0.92 (0.02) F	b 123.50 (6.93) BAC	a 32.00 (2.86) BA	a 56.83 (2.85) BDC	a 11.17 (1.04) E

[a] Soil properties between soil types (i.e., comparing soil types for average 1.5 m soil profile) preceded by same letters are not statistically different ($\alpha = 0.05$).

[b] Soil properties at each depth and soil type (i.e., soil × depth interactions) preceded by same letters are not statistically different ($\alpha = 0.05$).

Bulk density and EC showed an increasing trend with soil depth from 0 to 1.20 m whereas OMC showed a decreasing trend with depth (Table 6). The EC of S1 was significantly lower than S3 and EC of S2 was not significantly different from other two soil types. For all soil depths, the highest EC was observed in S2 and the lowest was observed in S1. The FC of S3 was significantly lower than S1 and S2 whereas no difference was observed in PWP among soil types. The greater variability in FC than PWP among different soil types might be due to the fact that FC is a function of various soil characteristics that vary more than those variables that impact PWP such as soil texture and structure, type and content of clay, OMC, water table, depth of wetting, presence of impeding layers, and other factors (Kirkham, 2014), whereas PWP is more of a function of a combination of plant, soil, and atmospheric factors (Tolk, 2003). The SWHC of S1 was also significantly greater than S3 (Table 6). For all three soil types, SWHC first decreased from 0 to 0.30 m and then generally increased with depth due to a presence of a layer with a high clay content in the 0.20–0.60 m soil layer (Djaman and Irmak, 2012).

The soil particle size distribution at each depth in three soil types is presented on soil textural triangles (Figure 6) to understand the differences that may exist in soil texture which can impact irrigation and N requirements and management, crop yields and water use. In 0–0.30 m soil depth (Figure 6a) in S1 (red dots), the soil texture is mostly the combination of sandy loam, loam and silt loam whereas most of the S2 (black dots) is silt loam and loam; and S3 (yellow dots) is generally a combination of loam, silt loam and silty clay loam. For 0.30–0.60 m soil layer (Figure 6b), 90% of S1 has clay loam texture whereas approximately 90% of S2 and S3 are a mixture of clay loam and silty clay loam. The 0.60–0.90 m of soil layers in all soil types are 90% loam and silt loam (Figure 6c). In the 0.90–1.20 m soil layer, S3 was 100% silt loam whereas S1 and S2 had a combination of loam and silt loam (Figure 6d). Figure 6e represents the soil textural distribution for the last soil layer, i.e., 1.20–1.50 m. In this layer, S3 consists of a small portion of sandy loam and loam whereas most of the soil is silt loam. S1 and S2 have most of the area under silt loam with some portions having loam. From soil textural analysis of each layer under three different soil types, it was observed that S3 has considerable textural differences from S1 and S2.

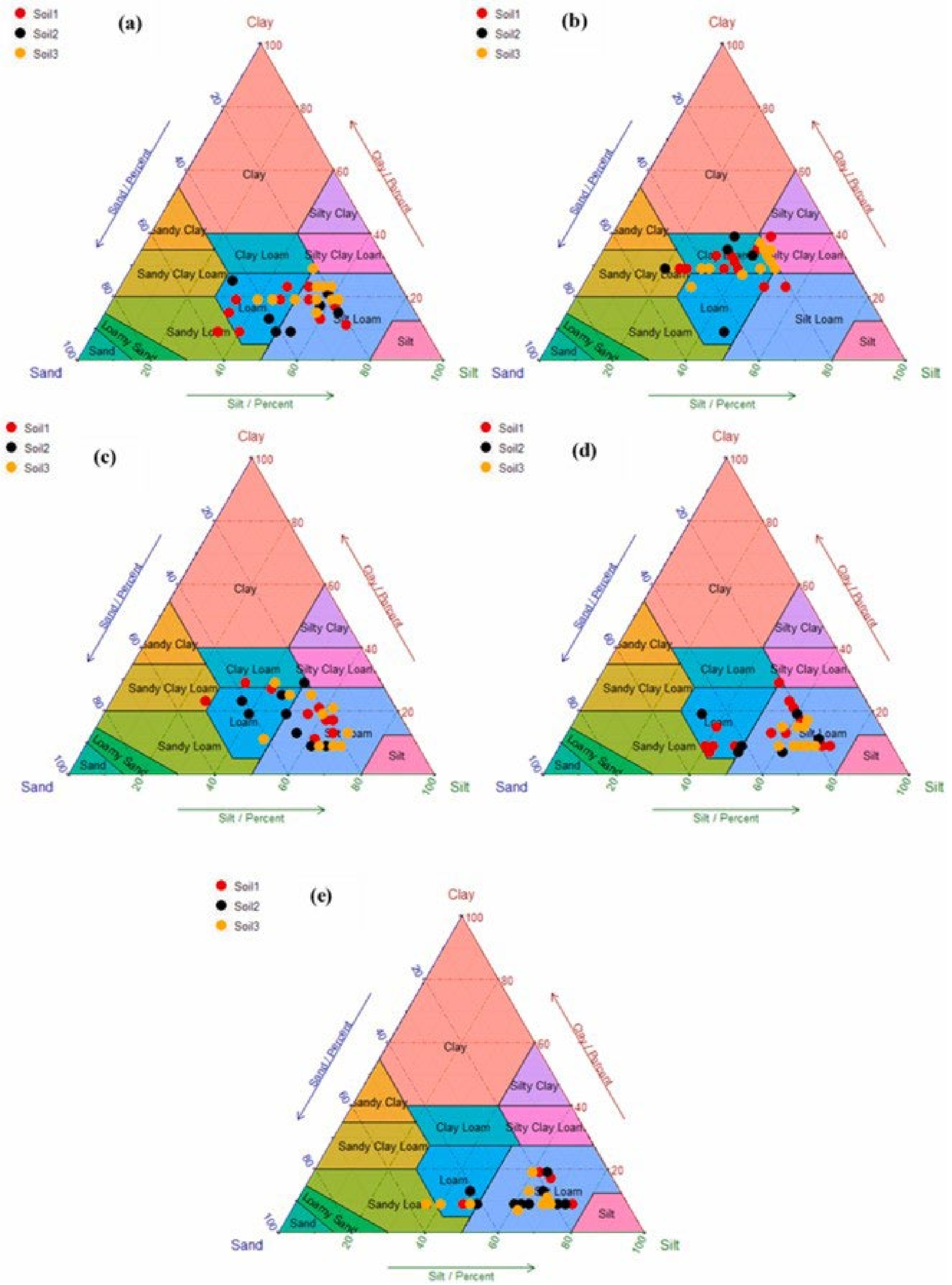

Figure 6. Soil textural triangles at (a) 0.30 m, (b) 0.60 m, (c) 0.90 m, (d) 1.2 m, and (e) 1.5 m soil depth at the research site.

3.3. Treatment effects on soil moisture and available water dynamics

Available water (AW) in the 1.20 m soil profile in various nitrogen treatments under FRI, VRI and NI treatments for three soil types in 2015, 2016 and 2017 growing seasons are presented in Figure 7, Figure 8, & Figure 9, respectively. Typical for the research field, the soil profile was at or above full level (above or close to FC) at the beginning of the growing season in all three years (Figure 7, Figure 8, Figure 9). The initial soil water content in the 2015 growing season for all treatments and soil types was greater than the initial soil water content in 2016 and 2017 growing seasons and greater than the FC due to the greater spring precipitation in 2015. This was also one of the major reasons for late planting in 2015 as compared with 2016 CE 2017 growing seasons. In the 2015 growing season, due to greater precipitation at the beginning of the growing season (Table 5) and more uniform distribution of rainfall throughout the growing season, the availability of soil-water in the root zone was not affected considerably by the type of irrigation and nitrogen applications. During this season, the total precipitation was 353 mm and total irrigation amount for FRI and VRI plots on average was 25.4 and 15.2 mm, respectively, for S1; 25.4 and 24.6 mm, respectively, for S2; and 25.4 and 30.1 mm, respectively, for S3. Thus, in comparison to precipitation which was distributed equally in all plots and soil types, irrigation amounts were less and, in general, the differences in soil-water patterns in all treatments, including NI, were similar. The AW remained above MAD (40–50% TAW) for all treatments, including NI, throughout the growing season, indicating no crop water stress (Figure 7, Figure 8, Figure 9), except for NI treatment at VRF level in S3 (Figure 7i). The AW started approaching MAD around August 17 (R2 growth stage) and September 1 (R3 growth stage), coinciding with the periods of minimal precipitation. Since no irrigation was applied before the R3 growth stage (1 September), the differences in soil moisture dynamics prior to the irrigation application (between 17 August and 1 September) were due to N fertilizer application type and rate. Significant interaction effect ($P < 0.05$) of irrigation and nitrogen treatment on average AW in 1.20 m soil profile was observed in 2015 in reproductive period. Under FRI, average AW in VRF and FRF treatments was significantly greater ($P < 0.05$) than PP treatment, whereas under VRI, average AW in VRF

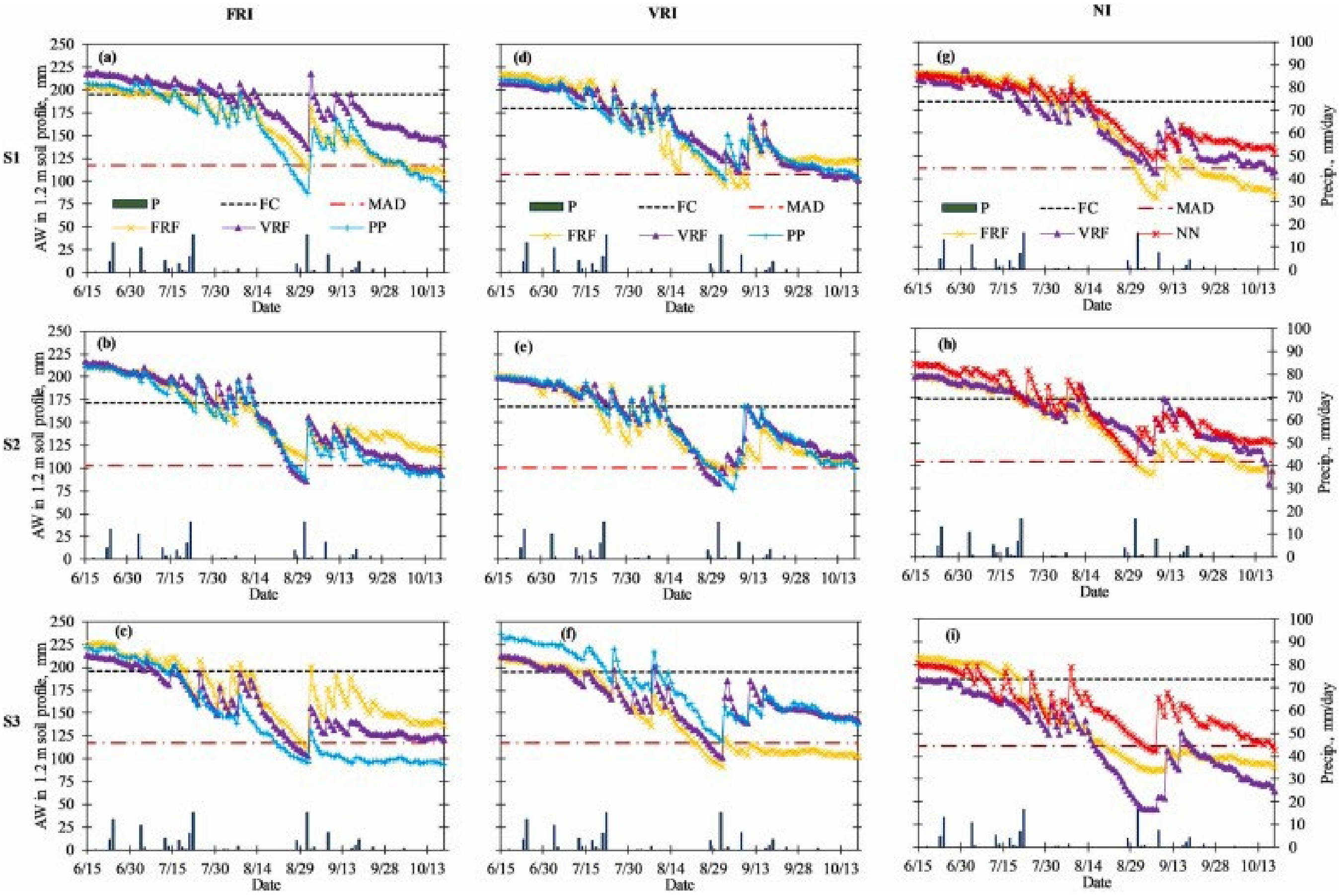

Figure 7. Total soil profile (1.2 m depth) available water (AW, mm) trends for different nitrogen application and irrigation treatments in three soil types in 2015. Daily precipitation, total water at field capacity (FC) and maximum allowable depletion (MAD) at 40% of FC are also included. (FRF: Fixed (uniform) rate fertigation; VRF: Variable rate fertigation; PP: Pre-plant nitrogen; NN: No Nitrogen; FRI: Fixed (uniform) rate irrigation; VRI: Variable rate irrigation; NI: No irrigation).

and PP treatment was significantly greater ($P < 0.05$) than FRF. Though the amount of nitrogen in both PP and FRF was same, lower AW could be due to higher plant water uptake and deeper roots in those treatments (Lenka et al., 2009, Benbi, 1989). The decline in AW after September 16, 2015 in all irrigated treatments (Figure 7a–f) was due to lack of precipitation toward the end of the growing season as well as no irrigation application. The irrigation was not applied after the R4 growth stage, because there was enough water in the soil profile to meet the crop water requirements until physiological maturity.

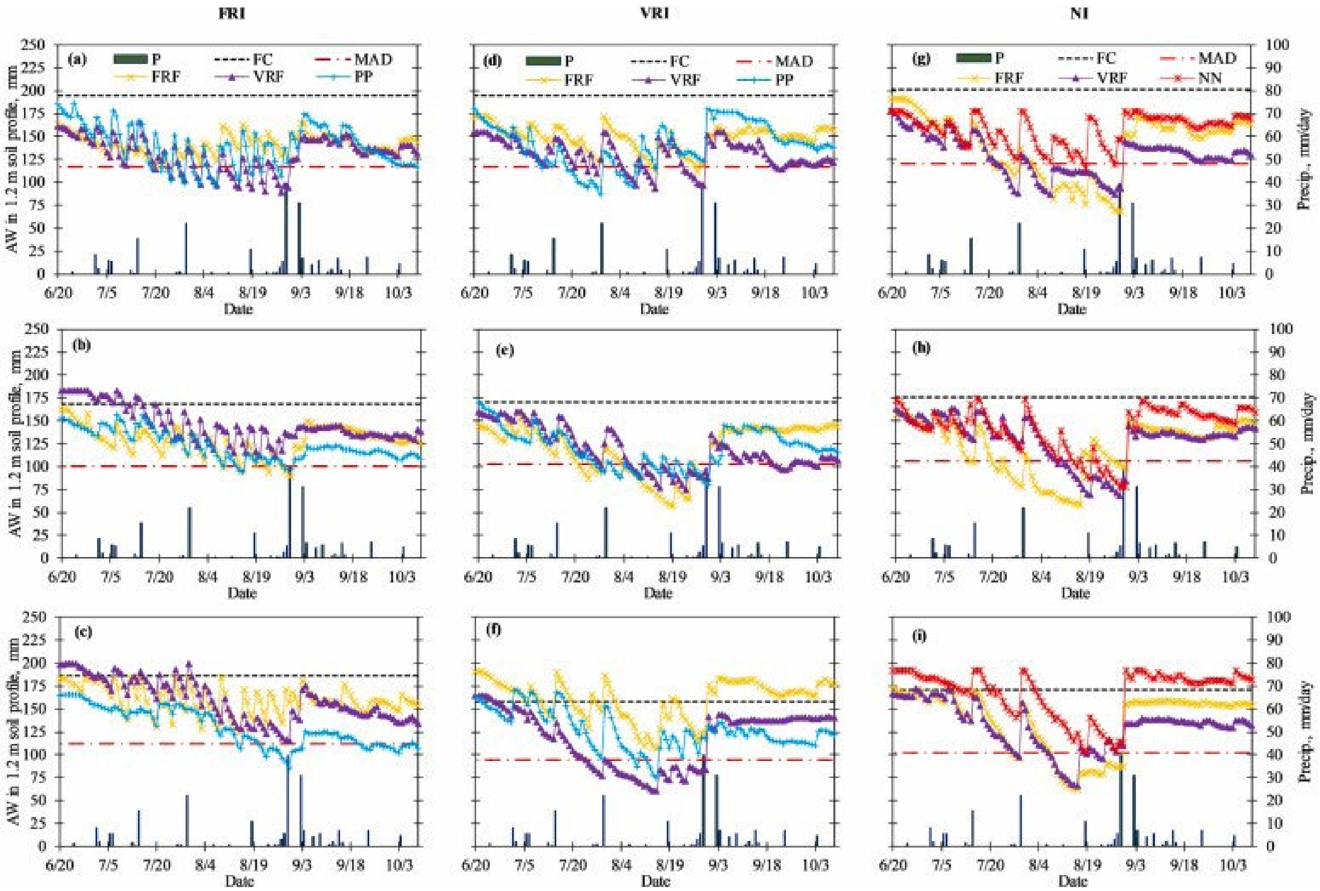

Figure 8. Total soil profile (1.2 m depth) available water (AW, mm) trends for different nitrogen application and irrigation treatments in three soil types in 2016. Daily precipitation, total water at field capacity (FC) and maximum allowable depletion (MAD) at 40% of FC are also included. (FRF: Fixed (uniform) rate fertigation; VRF: Variable rate fertigation; PP: Pre-plant nitrogen; NN: No Nitrogen; FRI: Fixed (uniform) rate irrigation; VRI: Variable rate irrigation; NI: No irrigation).

Greater differences in soil-water fluctuations and depletion among irrigation and nitrogen treatments were observed in 2016 and 2017 than in 2015 growing season. This could mainly be due to very low precipitation of 5 mm and 23 mm in the month of June in 2016 and 2017, respectively, as compared with 226 mm in June of 2015. A total of 7 irrigations were applied to FRI plots in 2016 and 10 in 2017. The total growing season precipitation was 375 mm and 463 mm and the total irrigation amount for FRI was 191 mm and 254 mm, in 2016 and 2017, respectively. Though, for each VRI plot, irrigation timing and amounts were different and, on average, the total irrigation amount for VRI was

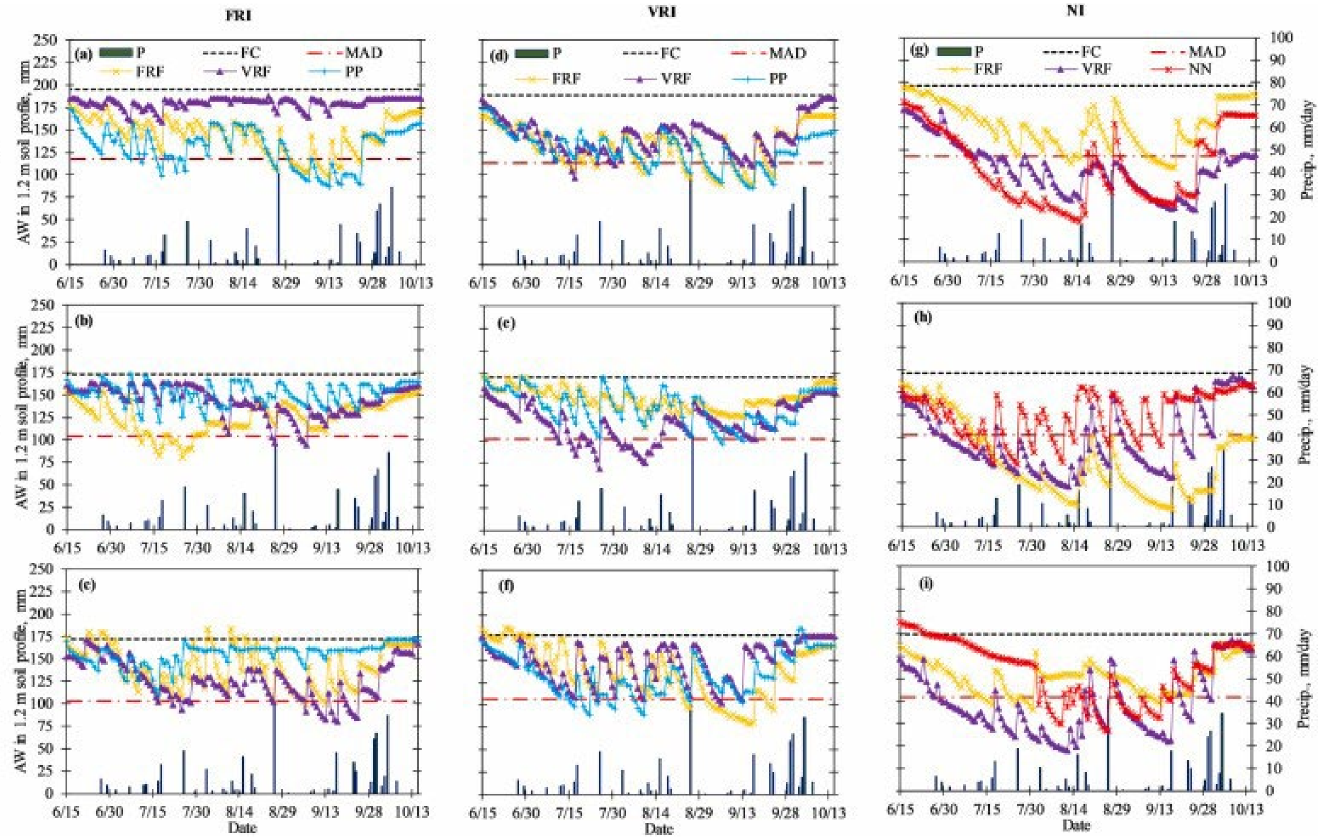

Figure 9. Total soil profile (1.2 m depth) available water (AW, mm) trends for different nitrogen application and irrigation treatments in three soil types in 2017. Daily precipitation, total water at field capacity (FC) and maximum allowable depletion (MAD) at 40% of FC are also included. (FRF: Fixed (uniform) rate fertigation; VRF: Variable rate fertigation; PP: Pre-plant nitrogen; NN: No Nitrogen; FRI: Fixed rate irrigation; VRI: Variable rate irrigation; NI: No irrigation).

136 mm and 116 mm for 2016 and 2017 respectively. The timing and amount of irrigation for VRI plots is presented in Table 2. In 2016, out of 7 irrigation events in FRI treatment, 6 irrigations occurred from July 15 to August 24 (V16 to R4 growth stage), which was the most active soil-water extraction period and the most sensitive stages to water stress. Due to only 37 mm precipitation in this period, the effect of amount and type of irrigation management (FRI vs. VRI) was most prominent in this period. The greatest soil-water depletion from July 2 to August 28 (i.e., the higher crop water uptake period for maize growth due to high atmospheric evaporative demand) was observed in NI treatment (73 mm) followed by VRI (54 mm) and FRI (50 mm). Similarly, for 2017

growing season, for all treatments, the greatest soil-water depletion occurred from June 12 to September 13 (V6 to R5 growth stage) period. On average, the greatest water depletion in this period was in NI treatment (102 mm) followed by VRI (67 mm) and FRI (47 mm). Similar results were obtained by Djaman et al., 2013, Irmak, 2015a, Irmak, 2015b where full irrigation treatment showed lower soil-water depletion as compared with limited irrigation treatments and rainfed condition. Overall, the AW between VRI and FRI treatments demonstrated little or no difference regardless of the timing and amount of irrigation. However, in the VRI treatment at all levels of nitrogen and soil type, soil-water was depleted below MAD on several occasions when crop water demand was high. Whereas, when FRI of 25.4 mm was applied, soil-water always remained within the allowable limit. This shows that irrigation timing and amount decisions based on site-specific soil moisture measurement sometimes delays the irrigation because of which applied amount of irrigation may not be able to keep up with the crop water uptake (Bucks et al., 1988). This could be due to the reason that irrigation scheduling based on soil-water status considers only the changes in bulk soil water content and does not account for changes in water status in the plant tissues. The actual tissue water is not only dependent on soil-water status alone, but also on the rate of water flow through the plant and corresponding hydraulic flow resistances between plant tissues and soil. Therefore, in many cases plant response to soil-water varies as a function of evaporative demand (Jones, 2004).

To understand how various irrigation and nitrogen treatments affect water uptake at different depths and growth stages, average AW of three growing seasons at the vegetative and reproductive growth stages were also analyzed separately and are presented in Table 7, Table 9, respectively. Since irrigation was initiated after or at the end of vegetative growth period, Table 7 shows only the effect of nitrogen treatment on AW in different soil types. During the vegetative period, effect of nitrogen treatment and interaction of soil type and nitrogen treatment was statistically insignificant ($P > 0.05$) at all depths in all soil types, thus Table 7 shows only statistical difference between soil types (soil type main effect). During this period, the minimum AW or maximum soil-water depletion was observed near the soil surface (0–0.30 m) in all treatments and growing seasons due to high surface evaporation losses. During the reproductive growth period, minimum AW or maximum depletion was observed in both 0–0.30 m and 0.60–0.90 m soil depths due to plant water uptake as roots has progressed to 0.90 m depth coupled with evaporative losses from the surface. In both vegetative and reproductive periods maximum AW (i.e., minimum depletion) was observed at either 0.30–0.60 m soil depth or below 0.90 m soil depth. The reason behind high AW in 0.30–0.60 m soil profile is the presence of high clay content layer (argillic layer) at 0.30–0.60 m depth (Figure 3c). This resulted in high AW and consequently insufficient aeration, thus low plant water uptake. Similar results were observed by Djaman and Irmak (2012) at the same location. They indicated around 51% of soil-water extraction from 0 to 0.30 m soil profile and only 10% from 0.30 to 0.60. High AW below 0.90 m can be attributed to low root density at that depth thus less plant water uptake. During the vegetative growth period, no significant effect ($P > 0.05$) of any treatment (irrigation and nitrogen) and soil type on AW was observed at 0–0.30 m and 0.60–1.2 m soil depths; however, significant effect ($P < 0.05$) of soil type on AW was observed at 0.30–0.60 m (clay layer). At 0.30–0.60 m depth, the AW in S1 was significantly greater ($P < 0.05$) than S2, whereas S3 was not significantly different ($P > 0.05$) from either S1 or S2 (Table 7) and can be attributed to significantly greater SWHC in 0.30–0.60 m soil profile in S1 (Table 6).

Table 7. Average available water (AW, mm) at different soil depth during vegetative growth period in pooled 2015, 2016 and 2017.

Soil	*Nitrogen*	*Soil depth (m)*			
		0–0.30	*0.30–0.60*	*0.60–0.90*	*0.90–1.20*
S1	FRF	37.4	48.8	44	41.6
	VRF	40.2	48.2	43.3	43.8
	PP	34.9	49.2	42.7	46
	Mean	37.5a	48.7a	43.3a	43.8a
S2	FRF	31.2	44.2	41.7	42.3
	VRF	40	46.3	41.4	42.4
	PP	36	45.5	42.8	42.7
	Mean	35.7a	45.3b	42.0a	42.5a
S3	FRF	41.5	49.1	44.5	45.6
	VRF	39	45.1	44.5	44.7
	PP	38.2	47.5	44.1	44.8
	Mean	39.6a	47.2ab	44.4a	45.0a

AW between soil types (i.e., comparing soil types at each depth) followed by same letters are not statistically different ($\alpha = 0.05$).

Abbreviations: S1 is Soil 1; S2 is Soil 2; S3 is Soil 3; FRF is Fixed Rate Fertigation; VRF is Variable Rate Fertigation; PP is Pre-Plant Nitrogen.

In the reproductive period, effect of nitrogen and irrigation treatment on AW at each depth in each soil type was analyzed separately. In this period, no significant effect ($P > 0.05$) of irrigation and nitrogen treatment and their interaction was observed on AW in S2 and S3 at any depth. However, in S1, significant effect of irrigation and nitrogen treatments and their interaction existed except at 0.30–0.60 m soil depth (Table 8, Table 9). In S2 and S3, even though the amount of irrigation in VRI was lower than FRI, no significant difference in AW between VRI and FRI showed that excess water in FRI treatment was either lost to deep percolation and runoff or translated to ETc. In S1, there was a significant main effect of nitrogen treatment at 0–0.30 m, significant main effect of irrigation and nitrogen at 0.60–0.90 and significant interaction effect of irrigation and nitrogen at 0.90–1.2 m soil depth on AW (Table 9). In general, there was a lower AW under VRI treatment than in FRI. The possible explanation is that the frequent irrigations in the FRI treatment helped with frequent replenishment of water which prevented cyclical water stress that can occur with longer irrigation intervals as in VRI treatment even if the total amount of seasonal irrigation is the same (Bucks et al., 1988, Radin et al., 1989). Comparing nitrogen treatments, significantly lower AW in PP treatment as compared with VRF at 0–0.30 m and as compared to VRF and FRF at 0.60–0.90 m, was observed under FRI in S1 (Table 9). In general, in S1, lowest AW was observed in either PP or FRF. Even though, the nitrogen amount in both FRF and PP treatment was same, and was greater than VRF, it can be suggested that higher rates of nitrogen (246 kg ha^{-1}) can have higher soil-water extraction due to deeper roots in those treatments (Lenka et al., 2009, Benbi, 1989). No trend of nitrogen application on AW was observed in S2 and S3. Overall, results indicated that effect of irrigation and nitrogen application on AW was significant only in S1 whereas no significant effect of any treatment was observed in S2 and S3. The difference in effect of treatments on AW between soils could be related to the elevation and slope in that soil type which determines the flow and accumulation of soil-water in different positions of the landscape (Ruffo et al., 2006, Kanwar et al., 1988). Lower elevation and higher slopes in S2 and S3 could have resulted in poor conditions for plant growth (excessive water for prolonged period in the root zone) in all treatments.

Table 8. Analysis summary (*p*-value) for available water (AW) response to irrigation and nitrogen fertilizer in three soil types at reproductive growth stage in pooled 2015, 2016 and 2017.

Soil	*Effect*	*Soil depth (m)*			
		0–0.30	*0.30–0.60*	*0.60–0.90*	*0.90–1.2*
S1	Irrigation	0.27	0.58	0.03*	0.56
	Nitrogen	0.02*	0.46	0.01*	0.56
	Irrigation × Nitrogen	0.78	0.98	0.78	0.05*
S2	Irrigation	0.44	0.78	0.43	0.18
	Nitrogen	0.54	0.73	0.98	0.78
	Irrigation × Nitrogen	0.40	0.98	0.55	0.85
S3	Irrigation	0.82	0.18	0.78	0.88
	Nitrogen	0.93	0.77	0.18	0.98
	Irrigation × Nitrogen	0.78	0.99	0.35	0.94

Abbreviations: S1 is Soil 1; S2 is Soil 2; S3 is Soil 3.
p values followed by * indicate significance at the 5% level.

Table 9. Average available water (AW, mm) at different soil depths during reproductive growth period.

Soil	*Irrigation*	*Nitrogen*	*Soil depth (m)*			
			0–0.30	*0.30–0.60*	*0.60–0.90*	*0.90–1.20*
S1	FRI	FRF	31.4 ab	37.6 a	38.2 a	36.3 ab
	FRI	VRF	38.8 a	41.4 a	36.9 a	43.1 a
	FRI	PP	30.4 b	41.7 a	25.7 b	39.1 ab
	VRI	FRF	28.4 b	35.5 a	30.3 ab	38.8 ab
	VRI	VRF	34.8 ab	39.2 a	28.6 ab	34.3 b
	VRI	PP	30.0 b	40.8 a	21.9 b	41.7 ab
S2	FRI	FRF	36.6	37.9	30.5	37.6
	FRI	VRF	34.8	30.8	33.3	39.0
	FRI	PP	28.0	34.7	29.4	39.9
	VRI	FRF	28.7	30.4	26.7	35.4
	VRI	VRF	27.2	30.7	25.0	33.1
	VRI	PP	26.7	33.3	30.1	36.7
S3	FRI	FRF	34.4	37.0	38.9	40.5
	FRI	VRF	32.0	34.6	30.6	40.1
	FRI	PP	30.7	35.8	26.4	39.2
	VRI	FRF	31.1	32.8	30.9	39.6
	VRI	VRF	30.2	28.8	34.2	38.4
	VRI	PP	33.4	30.7	37.8	40.2

AW within a soil type and depth (i.e., comparing irrigation-nitrogen combination treatments under each soil type and depth) followed by same letters are not statistically different ($\alpha = 0.05$).

Abbreviations: S1 is Soil 1; S2 is Soil 2; S3 is Soil 3; FRI is Fixed Rate Irrigation; VRI is Variable Rate Irrigation; FRF is Fixed Rate Fertigation; VRF is Variable Rate Fertigation; PP is Pre-Plant Nitrogen.

3.4. Treatment effects on maize evapotranspiration during vegetative and reproductive period

To understand how different irrigation and nitrogen treatments in different soil types affect plant water use, ETc between FRF, VRF and PP nitrogen treatments under FRI and VRI in three soil types were compared in maize vegetative and reproductive growth periods (Table 10, Table 11, Table 12). In 2015, no irrigation was applied whereas only 1 irrigation was applied in 2016 in the vegetative period. In 2017, more irrigations were applied in the vegetative period as compared to 2015 and 2016 due to higher crop water demand that can be attribute to higher incoming solar radiation and higher VPD in vegetative period of 2017 (Table 5). On average, 76.2 mm of irrigation in FRI and 26, 17 and 0 mm of irrigation in VRI in S1, S2 and S3, respectively, was applied in 2017 (Table 2). Because of no to very little irrigation in vegetative period of 2015 and 2016, any difference in ETc in 2015 and 2016 among treatments during vegetative period were due to soil type or nitrogen treatment or their interaction (Table 10). In 2015, vegetative ETc in S3 was 15 and 14 mm greater than ETc in S1 and S2, respectively. The greater vegetative ETc in S3 was most likely due to greater surface evaporation due to incomplete canopy cover (LAI < 2) (Sharma and Irmak, 2020). The sparse crop leaf canopy (LAI < 2) can result in considerable surface evaporation as compared with full canopy cover (Ogola et al., 2002). The effect of nitrogen treatments on ETc was also significant ($P < 0.05$) in 2015 with 9 and 10 mm greater ETc in PP nitrogen treatment as compared with FRF and VRF, respectively (Table 11). In 2016, the effect of interaction of soil and nitrogen treatment on ETc was significant ($P < 0.05$) (Table 10). No statistical impact of irrigation treatments on vegetative ETc was observed in 2016 which indicates that there was enough soil water in the root zone to meet the crop water requirements in the plots where no irrigation was applied in the vegetative period as compared to the plots where irrigation was applied (Table 2). The ETc in PP nitrogen treatment was 54 mm greater than FRF in S1 whereas no significant difference between PP and FRF existed in S2 and S3 ($P > 0.05$). The ETc in FRF was 43 mm greater than VRF in S2 whereas no significant difference occurred between FRF and VRF in S1 and S3 ($P > 0.05$). Comparing the VRF and PP nitrogen treatments, no significant difference existed in any soil type in 2016. Overall, in 2016, greater ETc was observed in S1 as compared with S2 and S3. The nitrogen treatments had a significant impact ($P < 0.05$) which could be attributed to soil type, environmental conditions (impact of soil type and environment on N mineralization) and timing of nitrogen application rather than the amount. Further research is needed to assess the comprehensive impact of nitrogen fertilizer timing and soil chemical properties on vegetative ETc. In 2017, effect of irrigation and soil type on ETc was significant ($P < 0.05$); however, nitrogen treatment did not significantly impact ETc (Table 10). The ETc in FRI treatment in 2017 was 47 mm greater than VRI that can be attributed to higher irrigation amount in FRI in that period as compared to VRI. Also, similar to 2016, S1 had significantly higher ($P < 0.05$) ETc (244 mm) than S2 (179 mm) and S3 (198 mm) in 2017. It could be argued that lower ETc in S2 and S3 as compared with S1 was due to lower irrigation, but in this research there was enough soil water in the root zone (Figure 9) to meet crop water requirements because of which no irrigation was recommended for some plots under VRI. It is likely that the greater AW and lower ETc in those plots where no irrigation was recommended in S2 and S3 was due to the lower elevation (Sharma and Irmak, 2020). Because of lower elevation, soil pores were filled with water for an appreciable length of time that restricted the growth of roots, thus impacted ETc (Kanwar et. al., 1988).

Table 10. Analysis summary (*P*-value) for the maize evapotranspiration (ETc) response to irrigation, nitrogen fertilizer and soil type at vegetative and reproductive growth stages.

Effect	*Vegetative period*			*Reproductive period*		
	2015	*2016*	*2017*	*2015*	*2016*	*2017*
Irrigation	0.478	0.304	0.002*	0.778	0.018*	< 0.001*
Nitrogen	0.049*	0.611	0.282	0.860	0.058	0.290
Irrigation × Nitrogen	0.759	0.760	0.181	0.426	0.773	0.122
Soil	0.002*	0.006*	0.011*	0.258	0.640	0.040*
Irrigation × Soil	0.132	0.540	0.535	0.804	0.839	0.038*
Nitrogen × Soil	0.499	0.014*	0.933	0.132	0.549	< 0.001*
Irrigation × Nitrogen × Soil	0.481	0.943	0.753	0.779	0.931	0.164

P values followed by * indicate significance at the 5% level.

Table 11. Crop evapotranspiration (ETc, mm) during the vegetative (emergence to tassel) period for FRF, VRF and PP nitrogen treatments under FRI and VRI irrigation treatments in three soil types in 2015, 2016 and 2017 growing seasons.

Soil Treatment		*2015*				*2016*				*2017*			
	Irrig./Nitrogen	*FRF*	*VRF*	*PP*	*Mean*	*FRF*	*VRF*	*PP*	*Mean*	*FRF*	*VRF*	*PP*	*Mean*
S1	FRI	151.9	147.4	159.3	152.9	206.1	215.9	242.3	221.4	272.5	247.4	225.7	248.5
	VRI	158.9	156.2	176.5	163.9	165.9	197.8	238.7	200.8	217.5	246.8	193.4	219.2
	Mean	155.4	151.8	167.9	158.4b	186.0bc	206.8ab	240.5a	211.1	245.0	247.1	209.6	233.9a
S2	FRI	162.1	152.7	160.3	158.4	203.2	162.9	180.7	182.3	235.0	183.9	186.8	201.9
	VRI	160.6	159.2	164.0	161.3	209.4	164.4	180.7	184.9	134.0	198.3	135.9	156.1
	Mean	161.4	156.0	162.1	159.8b	206.3ab	163.6c	180.7bc	183.6	184.5	191.1	161.3	179.0b
S3	FRI	166.6	172.8	191.6	177.0	175.6	194.7	166.6	179.0	244.2	232.5	215.8	230.8
	VRI	166.2	174.9	170.2	170.5	159.0	186.7	165.5	170.4	158.2	164.8	170.4	164.5
	Mean	166.4	173.9	180.9	173.7a	167.3c	190.7bc	166.1c	174.7	201.2	198.6	193.1	197.6b
Avg. Soil	FRI	160.2	157.6	170.4	162.8	195.0	191.2	196.5	194.2	250.6	221.2	209.4	227.1a
	VRI	161.9	163.5	170.2	165.2	178.1	183.0	195.0	185.4	169.9	203.3	166.6	179.9b
	Mean	161.1b	160.5b	170.3a	164.0	186.6	187.1	195.8	189.8	210.2	212.3	188.0	203.5

Crop ETc within a year followed by same letters are not significantly different ($P > 0.05$) from each other. Statistical significance is only shown for the effects that are significant.

Abbreviations: S1 is Soil 1; S2 is Soil 2; S3 is Soil 3; FRI is Fixed Rate Irrigation; VRI is Variable Rate Irrigation; FRF is Fixed Rate Fertigation; VRF is Variable Rate Fertigation; PP is Pre-Plant Nitrogen.

Table 12. Crop evapotranspiration (ETc, mm) during the reproductive (silking to maturity) period for FRF, VRF and PP nitrogen treatments under FRI and VRI irrigation treatments in three soil types in 2015, 2016 and 2017 growing seasons.

Soil		*2015*				*2016*				*2017*			
	Irrigation/Nitrogen	*FRF*	*VRF*	*PP*	*Mean*	*FRF*	*VRF*	*PP*	*Mean*	*FRF*	*VRF*	*PP*	*Mean*
S1	FRI	175.9	162.8	193.2	177.3	289.0	298.6	355.7	314.4	274.2	199.7	299.2	257.68a
	VRI	213.4	173.2	177.0	187.9	176.0	243.0	321.2	246.7	291.3	162.1	292.9	248.76a
	Mean	194.6	168.0	185.1	182.6	232.5	270.8	338.4	280.6	282.74a	180.89c	296.03a	253.2
S2	FRI	153.0	207.9	187.4	182.8	262.9	297.4	289.5	283.3	229.1	272.7	226.0	242.61a
	VRI	160.8	191.6	188.2	180.2	241.6	231.3	263.4	245.5	127.8	235.4	191.1	184.78b
	Mean	156.9	199.7	187.8	181.5	252.3	264.4	276.5	264.4	178.48c	254.04ab	208.57bc	213.7
S3	FRI	167.7	163.7	168.1	166.5	239.0	322.6	290.7	284.1	285.4	301.4	231.2	272.67a
	VRI	171.8	178.9	147.1	165.9	183.4	252.0	254.5	230.0	173.1	153.3	224.2	183.52b
	Mean	169.8	171.3	157.6	166.2	211.2	287.3	272.6	257.0	229.25bc	227.35bc	227.69bc	228.1
Avg. Soil	FRI	165.5	178.1	182.9	175.5	263.6	306.2	312.0	293.94a	262.9	257.9	252.1	257.7
	VRI	182.0	181.2	170.8	178.0	200.3	242.1	279.7	240.72b	197.4	183.6	236.0	205.7
	Mean	173.8	179.7	176.8	176.8	231.98b	274.17ab	295.83a	267.3	230.2	220.8	244.1	231.7

Crop ETc within a year followed by same letters are not significantly different ($P > 0.05$) from each other. Statistical significance is only shown for the effects that are significant.

Abbreviations: S1 is Soil 1; S2 is Soil 2; S3 is Soil 3; FRI is Fixed Rate Irrigation; VRI is Variable Rate Irrigation; FRF is Fixed Rate Fertigation; VRF is Variable Rate Fertigation; PP is Pre-Plant Nitrogen.

Greater variability in ETc among treatments was observed in reproductive period as compared with vegetative period due to the effects of soil type, irrigation, nitrogen and their interaction (Table 10). In 2015, no significant impact ($P > 0.05$) of any treatment and soil type was observed in reproductive period ETc due to lower irrigation amounts in this season. In 2016, significant effect of irrigation and nitrogen treatment existed on reproductive ETc whereas interaction effect of soil and irrigation and soil and nitrogen treatment was significant ($P < 0.05$) in 2017 (Table 10, Table 12). In 2016, reproductive ETc in FRI was 53 mm greater than VRI which could be attributed to 50 mm greater irrigation in FRI. In terms of nitrogen, PP treatment has significantly higher ($P < 0.05$) ETc as compared with FRF which shows the timing of nitrogen application plays an important role in crop water uptake. Similar results were obtained in 2017; however, significant interaction ($P < 0.05$) of irrigation and nitrogen with soil type was also observed. In S1, ETc under PP nitrogen treatment was significantly greater ($P < 0.05$) than VRF, but no statistical difference was observed between PP and FRF. In S2, significant difference occurred between FRF and VRF treatment whereas in S3, no significant difference between nitrogen treatments was observed. In 2017, effect of irrigation treatment on reproductive ETc was not significant in S1, whereas significantly higher ETc under FRI as compared with VRI was observed in S2 and S3 (Table 12). This shows that amount and timing of irrigation had a direct impact on ETc in S2 and S3, but not in S1. Even though significant differences occurred in AW among different irrigation treatments at reproductive growth stage in S1, no difference in ETc between VRI and FRI revealed that the lower AW in VRI was due to higher plant water uptake. As ETc is directly correlated to grain yield (Irmak, 2015), it can be assumed that VRI has a potential in maintaining the optimum grain yield by using less water as compared to FRI in certain soil types like S1. However, additional research is required to understand the potential benefits of VRI and its impact on crop yield. In terms of nitrogen, since the nitrogen rates between the treatments were not different, it would be hard to determine the impact of nitrogen rates on ETc; however, from the pooled data as well as from the individual year, it can be suggested that PP nitrogen treatment resulted in greater ETc than other nitrogen treatments. Details about the impact of ETc under different irrigation and nitrogen treatments on grain yield are presented in the companion paper by Sharma and Irmak (2020).

4. Conclusions

Soil-water dynamics and maize ETc during vegetative and reproductive growth periods for different irrigation and nitrogen application treatments in three soil types for maize was researched in the 2015, 2016 and 2017 growing seasons in the Irmak Research Laboratory in south-central Nebraska. The irrigation treatment did not statistically impact ETc during the vegetative period for the 2015 and 2016 growing seasons; however, the impact of irrigation on vegetative ETc in 2017 was significant due to earlier initiation of irrigation in 2017. No effect of irrigation and nitrogen fertilizer was observed on AW in the vegetative period and differences in the AW between treatments were mainly due to soil type The results indicate that vegetative period ETc was primarily affected by soil type, weather conditions (evaporative demand and soil wetting) and nitrogen fertilizer application timing. In the reproductive growth period, no significant effect ($P > 0.05$) of irrigation and nitrogen treatment and their interaction was observed on AW in S2 and S3 at any depth; however, in S1 significant effect of irrigation and nitrogen treatments and their interaction was observed, except at 0.30–0.60 m soil depth. These results indicate that soil type and topography play important role in determining the impact of irrigation and nitrogen on AW.

The effect of irrigation treatment on reproductive ETc was not significant in S1 in 2017, whereas significantly higher ETc under FRI as compared with VRI was observed in S2 and S3. The fact that significant differences occurred in AW among VRI and FRI at reproductive growth stage in S1, and no significant differences in ETc between VRI and FRI were observed, revealed that the lower AW in VRI was due to higher plant water uptake and that excess irrigation water applied in FRI treatment was either lost to deep percolation or runoff. This indicated the potential benefit of VRI in S1. Significantly lower ETc in VRI as compared with FRI in S2 and S3 in reproductive period in 2017 was likely due to restricted root growth due to excessive water in the root zone for prolonged period due to lower elevation (depression) in S2 and S3. These results show that irrigation scheduling based on soil-water status only, sometimes does not take into account the changes in water status in the plant and root tissues creating plant water stress even though enough water is available in soil profile. In terms of nitrogen fertilizer effect, the nitrogen rates between the treatments were not substantially different, so it would be difficult to determine the impact of nitrogen rates; however, from the pooled data as well as from the individual year data, it can be suggested that PP nitrogen treatment resulted in greater ETc than other nitrogen treatments.

The results of this research indicated that soil-water dynamics is a strong function of not only management practices (irrigation and nitrogen treatments), but is also a strong function of site-specific soil-water holding capacity and AW water in the same treatments (under the same management) varied by soil type. Results of this research can aid in better understanding the relationships between spatial soil properties in relation to FRI and VRI as well as FRF, VRF and PP management and developing more effective and relevant management options under different soil types.

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