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MAIZE CROP COEFFICIENTS UNDER VARIABLE AND FIXED (UNIFORM) RATE IRRIGATION AND CONVENTIONAL AND VARIABLE RATE FERTILIZER MANAGEMENT IN THREE SOIL TYPES

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ABSTRACT

Maize (*Zea mays* L.) evapotranspiration crop coefficients (Kc) that are needed to estimate crop evapotranspiration (ETc) using the two-step approach for variable rate irrigation and nitrogen management under different soil types have not been investigated or quantified. In this research, alfalfa- and grass-reference crop coefficients (Kcr and Kco) curves were developed for fixed rate or uniform rate fertigation (FRF), variable rate fertigation (VRF) and pre-plant nitrogen (PP) management under fixed rate or uniform rate irrigation (FRI) and variable rate irrigation (VRI) for three soil types [Crete silt loam (S1), Hastings silty clay loam (2) and Hastings silt loam (S3)] in 2015, 2016 and 2017 growing seasons. Irrigation and nitrogen management strategies, as well as soil type, all influenced the Kcr and Kco values, which exhibited inter-annual variation. On average, greater variation in Kc curves between FRF, VRF and PP nitrogen treatment were observed under VRI treatments as compared with FRI. Results showed that Kc values are more dependent on the amount rather than the timing of the nitrogen application. In all three seasons, higher Kc values were observed in the FRI treatment than VRI with Kcr, ranging from 0.07 to 1.30 in FRI and 0.07 to 1.20 in VRI. Kc curves also differed between nitrogen treatments and the difference was more prominent in the VRI treatments than in the FRI in all years. In general, maximum Kc was observed in PP nitrogen treatment, followed by FRF and VRF. On a monthly average basis, maximum Kc values were observed in July and August in all soil types and minimum Kc values were observed in June. When soil types are considered, overall, the maximum Kcr value was observed in FRI-PP treatment in S1 (1.02), FRI-VRF treatment in S2 (1.06) and FRI-VRF treatment in S3 (1.02). The Kcr and Kco equations as a function of growing degree days were developed and monthly average Kcr and Kco values were tabulated for practical applications. To the best of the authors' knowledge, this research is the first that investigated and quantified the impact of VRI and VRF strategies under FRF, VRF and PP fertilizer management strategies on maize Kc values. The Kcr and Kco values quantified in this research can aid irrigators, state agencies and other water management and agricultural professionals for more accurate crop water use determinations under different irrigation and nitrogen management strategies and different soil types.

1. Introduction

With increasing competition for freshwater resources between agricultural, domestic, and industrial sectors, improved strategies for efficient use of available water resources in agriculture is required for feeding the increasing population, especially with the change in climatic conditions. Approximately 90% of global freshwater resources during the past century were withdrawn for irrigation (Shiklomanov, 2000; Jury and Henry., 2005). In the United States, agriculture accounts for approximately 80% of consumptive water use, with California, Nebraska, Texas, Arkansas and Idaho amongst the highest irrigation water withdrawal states (USDA ERS, 2018). Approximately 60% of the area under irrigation in the United States use groundwater as a source, resulting in groundwater depletion rates greater than the recharge in many areas, including Ogallala Aquifer, which is one of the world's largest aquifers that underlies an area of approximately 450.660 km^2 in

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portions of eight states (South Dakota, Nebraska, Wyoming, Colorado, Kansas, Oklahoma, New Mexico and Texas), comprising of approximately 80% of the USA High Plains region, with extensive water withdrawal for irrigation. Between 1960 and 2000, groundwater depletion in irrigated regions of the United States, including the heavily irrigated areas such as the High Plains and the California Central Valley aquifers has been doubled (Wada et al., 2010). Efficient irrigation management strategies that use less water without impacting the crop yields need to be developed or existing methods should be further evaluated, improved and implemented, especially in water-limiting regions to increase crop water productivity (CWP) and protect the sustainability of water resources.

CWP in irrigated agriculture can be increased by reducing the unbeneficial use of freshwater through development of efficient management strategies and advancing irrigation technologies at the farm or field level (Irmak, 2015a, 2015b). In certain conditions, precision agricultural technologies such as variable rate irrigation (VRI) systems and microirrigation systems have the potential to enable the growers/farmers to apply water and agrochemicals site-specifically and variably within a field to match soil and plant needs (Evans and Sadler, 2008). In some (or most) cases, variable rate technology is assumed to improve crop yield, CWP and reduce nitrogen leaching. For instance, Hedley and Yule, (2009) compared VRI and fixed (uniform) rate irrigation (FRI) scenarios for three years of climate data on 156 ha pasture and 53 ha maize field sites in New Zealand and reported 23 to 26% of irrigation water savings with VRI when compared with FRI. Hedley, et al., (2009) on 40 ha pasture, 24 ha potato and 22 ha maize sites in New Zealand, evaluated irrigation water use, drainage water use and nitrogen leaching between VRI and FRI. They reported an annual water use reduction of 9 to 19% under VRI when compared with FRI. These studies have used computer simulations to compare conventional and advanced VRI technology; however, the water and/or energy saving and other assumed benefits of VRI such as increasing yield or CWP have not been independently and sufficiently or even conclusively verified through field-based research.

Sadler et al. (2002) emphasized the importance and need of site-specific crop production functions for strategic decision making for site-specific management. In a three-year field study, Sadler et al. (2002) measured the mean response of maize to irrigation and compared variation in crop response within and among soil map units. The water treatments had consistently significant main effects in the analysis of variance (ANOVA) in both linear and quadratic forms at the 1% level, and the variation within soil map units was significant at the 5% level in the latter two years and at the 1% level in the first year. They observed variation in yield among soil map units at any point on the response curves being approximated 25% of the maximum yield in all three years. Variations in the mean irrigation amount to produce a maximum yield in the eight most common map units were 61, 61 and 120% of the base rate amount. They suggested that this information and data would have significant implications for the design, management and economic profitability of irrigation in spatially varying soils. They concluded that spatial variation in crop response to irrigation by year, soil type, and among soil types makes it essential to derive the site-specific crop response data to accurately simulate crop growth models for VRI for any economic analysis.

Evans and Sadler, (2008) stated that appropriately localized and real-time estimates of crop water demand are either unaffordable or not available. Their assessments that were made in 2008 are still valid today in terms of the absence of practical methodologies for determining and deploying site-specific crop coefficients for variable water applications. Whether crop production is practiced under deficit, limited or full irrigation settings, the crop evapotranspiration (ETc) and associated crop coefficients (Kc) values can be impacted by these management practices, especially when irrigation strategies are coupled with different nitrogen management strategies. For example, Sharma and Irmak, 2020a and 2020b), Xu et al. (2020) and Li et al. (2019) investigated the differences in grain yield, ETc and CWP between FRI and VRI management under fixed rate fertigation (FRF), variable rate fertigation (VRF) and pre-plant (PP) nitrogen. Sharma and Irmak, 2020a and 2020b) reported that soil properties and field topography played an important role in deciding the irrigation and nitrogen management strategies at field level and that the crop response in terms of yield, ETc and CWP to FRI and VRI under FRF, VRF and PP strategies within a field differed significantly. The spatial dependence of grain yield and ETc on irrigation and nitrogen management are reported in other studies as well. Tardieu and Katerji, (1991) reported a reduction in maize grain yield due to the increase in soil mechanical resistance because of reduced water uptake by the root system under water deficit conditions. Djaman and Irmak, (2013) represented the differences in ETc values between different irrigation regimes in south central Nebraska. They reported a reduction in seasonal ETc relative to full irrigation treatment (FIT) to be 22, 9, 7 and 2% for the rainfed, 50% FIT, 60% FIT and 75% FIT, respectively, in 2009 and reductions of 9, 4, 2 and 1% in 2010 for the same treatments, respectively. Liu et al. (2010) reported significant impacts of different water management practices on maize ETc, crop coefficients, grain yield and CWP in the same field in Loess Plateau, China. Payero et al. (2008) reported a difference of 75 mm of ETc between lowest irrigation and maximum irrigation treatments in 2005 and a difference of 187 mm in 2006. Payero et al. (2009) reported a variation in ETc of 7.2 and 18.8% among treatments and indicated that irrigation timing could have a considerable effect on ETc and Kc.

Borsato et al., (2019) compared the impacts of drip irrigation and two sprinkler (center pivot and hose-reel) systems on environmental, economic and energetic performance under irrigated and non-irrigated maize cropping. They combined impact and efficiency indicators, addressing a sustainability analysis for the irrigation practice under the three different irrigation systems. The sustainability for the irrigation systems was assessed using water-related indicators (water use efficiency, irrigation water use efficiency, and water footprint), biomass (crop growth rate, relative growth rate, harvest index, and yield response factor), and energy indicators (energy footprint, performance, and energy cost footprint) for the environmental aspect; and the economic-based indicators (water productivity and economic water footprint) for the economic aspect. The results showed that center pivot system was the best solution for irrigation practice since it demonstrated higher economic and environmental performance. They also observed that maize under the pivot system had higher biomass production, economic benefits and WUE.

To achieve the most effective and efficient within season irrigation scheduling for different water and nitrogen application strategies such as VRI and fertigation, accurate quantification of ETc under each management strategy is essential. While extensive irrigation management research and automated weather monitoring networks have advanced over time that resulted in improving FRI applications, such advances in developing crop coefficients and associated spatial ETc for variable rate water and fertilizer applications for site-specific water use determinations are significantly lacking. While Kc and ETc values are critical variables that are needed to manage VRI (and FRI) irrigation management strategies, there is a significant lack of data and information on the Kc and ETc values for VRI-managed cropping systems under different soil types and nitrogen management. Sadler et al. (2000) compared variation in water use and stress of maize within and among soil map units. In one field, at two sites in each of four map units, they measured site-specific effects of soil variation on crop water use from 40 days after planting until after maturity in the southeastern USA Coastal Plain. They observed that maize appears to be particularly susceptible to soil variation, especially during periods of drought. On the 4th day during vegetative growth, drought stress was evaluated on eight transects using infrared thermometer measurements of canopy temperature. They reported that maize at the eight sites arrived at final water use via fundamentally different paths. Further, variation between sites within soils was significant, indicating that soil map units are not homogenous with respect to water relations. These findings indicate the need for developing site-specific crop coefficients to determine spatial water use for VRI management. Stone and Sadler, (2015) utilized a Bayesian semiparametric model to spatially estimate irrigated yield, rainfed yield, maximum yield, and irrigation at maximum yield and provide credible intervals (measures of uncertainty) around these estimates for comparing with the previous analysis. They also examined whether the conclusions from this rigorous re-analysis were different from the prior analysis and if the results would force any modifications to the conclusions obtained with the prior analyses. The model simultaneously accounted for spatial correlation and relationships within the treatments and had the ability to contribute information to nearby neighbors. The model-based yield estimates were in excellent agreement with the observed spatial maize yields and were able to estimate the high and low yields more accurately than did the previous analysis. Their conclusions supported the original analysis in identifying significant spatial differences in crop responses across and within soil map units in spatially variable water management applications. These spatial differences were great enough to be considered in irrigation system design and management, emphasizing the need to experimentally determine variables (such as crop coefficients) to determine spatial ETc.

Some studies have reported the impact of coupled irrigation management and nitrogen management on seasonal and daily ETc that resulted in differences in Kc during the growing season for the same crop at the same location. Djaman and Irmak, (2013) developed grass-reference (Kco) and alfalfa-reference (Kcr) crop coefficient values under rainfed, limited, and fully irrigated settings as a function of the thermal unit and days after emergence. They reported the midseason average Kco values to be 1.26, 1.20, 1.11, 1.08 and 1.10 for the FIT, 75% FIT, 60% FIT, 50% FIT and rainfed treatments, respectively, and midseason average Kcr values to be 1.05, 1.00, 0.97, 0.95 and 0.92 for the same treatments, respectively.

With the prevalent interest in the variable rate management for improving crop productivity, it is essential to develop site specific, local crop coefficients for variable rate management (both irrigation and nitrogen). However, at this point, minimal, if any, studies have investigated the effects of VRI combined VRF on Kc of the same crop in comparison to FRI and FRF as well as pre-plant fertilizer management (PP). Furthermore, it is not well understood as to how Kc values under different water (FRI and VRI) and nitrogen (VRF, FRF and PP) management practices can be potentially impacted by soil types. The main objective of this research was to develop ET crop coefficients for maize under fixed (uniform) rate (FRI), and variable rate irrigation (VRI) and fixed (uniform) rate fertigation (FRF), variable rate fertigation (VRF) and pre-plant nitrogen (PP) management in three typical soil types. To the best of our knowledge, this research is the first to quantify the aforementioned variables under three different soil types in the same environment and soil and crop management practices. Furthermore, the research aimed to develop Kcr to Kco ratios (K values) to enable crop coefficients developed for one reference surface to be used with the other surface.

2. Materials and Methods

2.1. Experimental site

This project is part of a larger and ongoing long-term field research project in the Irmak Research Laboratory that is also investigating crop evapotranspiration, grain yield, irrigation-yield production functions, evapotranspiration-yield production functions and crop water productivity (Sharma and Irmak, 2020b) and the effect of VRI, FRI and no irrigation (NI) under VRF, FRF and PP N management on soil-water dynamics in different soils (Sharma and Irmak, 2020a). Thus, the materials and methods, including experimental details and cultural practices, soil moisture measurements, irrigation and nitrogen management practices, etc. reported in this work and those reported by Sharma and Irmak, 2020a and 2020b). As reported by Sharma and Irmak, 2020a and 2020b), extensive and comprehensive field research campaigns were conducted at the UNL-South Central Agricultural Laboratory (SCAL) research facility, near Clay Center, Nebraska, in 2015, 2016 and 2017 maize growing seasons. SCAL is located at latitude 40° 34′ N and longitude 98° 8′ W with an elevation of 552 m above mean sea level. The long-term average annual precipitation, maximum and minimum temperatures at the research site is 680 mm, 25 °C, and −5 °C, respectively. The research was conducted on a 2.3 ha field with a west to east elevation gradient ranging from 550.8 m to 552.1 m above mean sea level. The research site is in the transition zone between subhumid and semiarid zones with strong winds and a high vapor pressure deficit during summer. Fixed and variable rate water and nitrogen applications were achieved using a two-span 75 m long 7000SL variable rate linear-move sprinkler irrigation system. Three soil types existed in the research field: (1) Crete silt loam, 0 to 1% slopes (S1); (2) Hastings silty clay loam, 3 to 7% slopes (S2); and (3) Hastings silt loam, 1 to 3% slopes (S3) Fig. 1). Soil samples were collected from 42 locations before planting in each growing season to facilitate the quantification of spatial variation in soil properties. The research field was sampled to determine the existing conditions of the soil to determine soil fertilizer recommendations as well as determining irrigation management variables. Soil cores collected from 42 locations in the field showed average sand, silt and clay content ranging from 15 to 57%, 20 to 74% and 7 to 39%, respectively. Measured volumetric water content at field capacity for soil 3 (S3) was significantly lower than soil 1 (S1), and soil 2 (S2). Soil water holding capacity (SWHC) of S1 was also significantly higher than soil 3. Other soil physical characteristics were also significantly different ($p < 0.05$) between the soils, which provided a unique opportunity to investigate soil type impact on Kc values under FRI, VRI with FRF, VRF and PP management practices, which has not been documented before. The electrical conductivity (EC) of S1 was significantly lower than S3 and EC of S2 was not significantly different from the other two soil types. The range in FC and PWP was 26% to 43 % and 11.5% to 30%, respectively (Sharma and Irmak, 2020a).

The research was designed and implemented as completely randomized design with three levels of irrigation (FRI, VRI and NI) and three levels of nitrogen (N) fertilizer management of FRF, VRF and PP nitrogen on three soil types with a total of 9 treatments (Fig. 1). The treatment combination of no irrigation (NI) and pre-plant N application (PP) was not studied in this research, instead, no irrigation and no nitrogen combination treatment was evaluated. Each treatment was replicated 3 times in each soil type, resulting in a total of 81 plots (Fig. 1). Treatments were randomly assigned to the plots in each growing season. The plots were aligned with the linear-move system's zones in the direction of the travel of the system (south-north). Each plot was 6 m x 6 m in size with a 6 m buffer plot on all four sides of each plot (Fig. 1). The buffer plots were established in order to prevent/eliminate sprinkler wetting overlap between the plots. Table 1 summarizes some of the agronomic operations/management practices for three growing seasons. The research field was disk-tilled before planting each season. Maize seed was planted in rows at a depth of 0.06 m. Row spacing was 0.76 m and the seeding rate in all three growing seasons was 84,500 plants/ha.

2.2. Irrigation and fertilizer management

The volumetric water content (VWC) for all irrigation treatments was determined by measuring soil matric (SMP) values. SMP was measured using Watermark Granular Matrix sensors (WGMS, Irrometer, Co., Riverside, CA) installed at four depths (0.30, 0.60, 0.90 and 1.20 m) in two replications in each soil type. WGMS were installed in the middle of each plot. The instrumentation was installed immediately following the crop emergence each year and was removed from the field at the end of each growing season for harvesting. WGMS were used to monitor soil matric potential (SMP, kPa) on an hourly basis, which was then

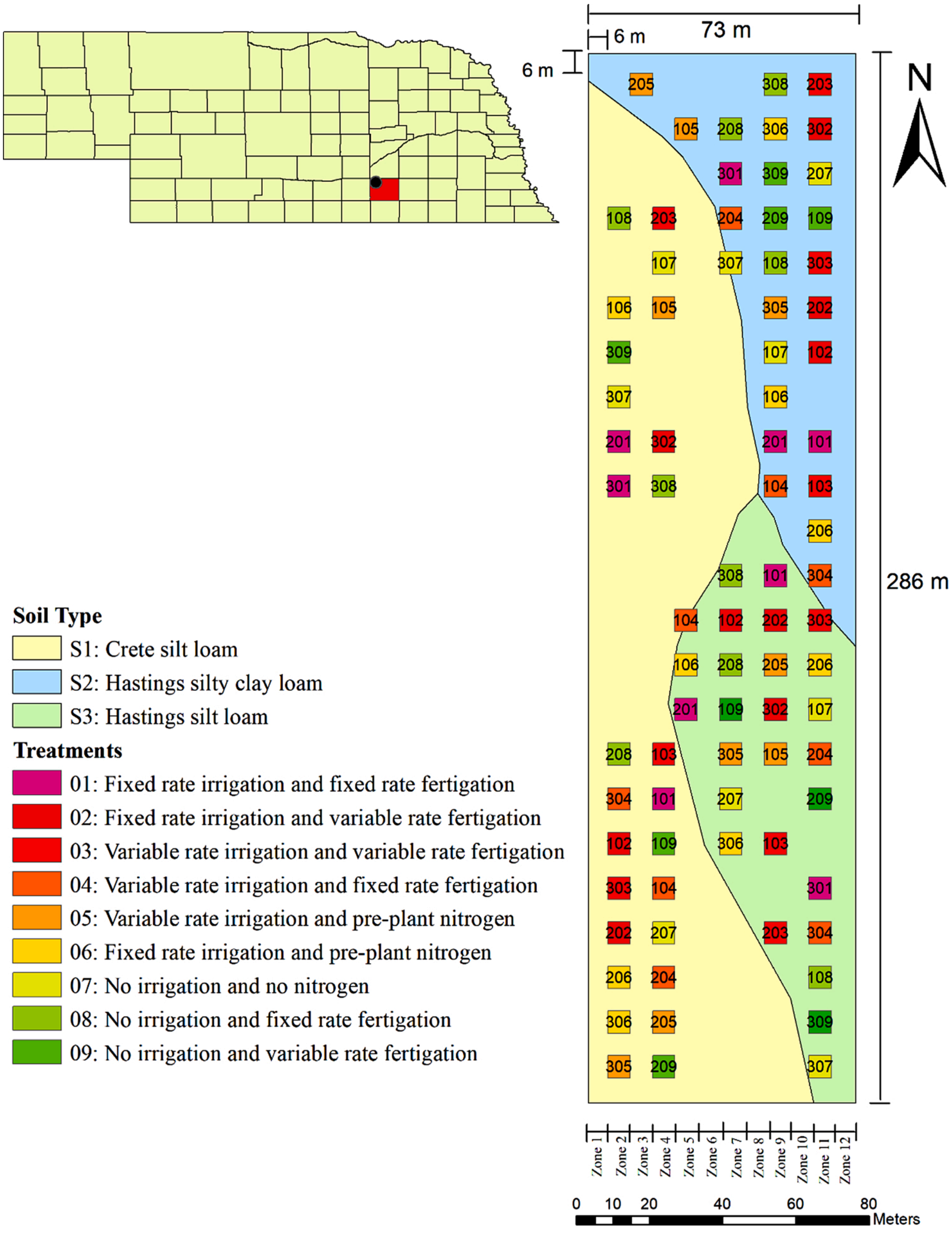

Fig. 1. Experimental plot layout in three soil types in the Irmak Research Laboratory at the South Central Agricultural Laboratory, near Clay Center, Nebraska. Small boxes are the treatment plots. Each plot is designated by a three-digit number, where the first digit indicates the replication number (1 to 3) and the last two digits are the treatment numbers.

converted to VWC using pre-determined soil water retention curves for each soil type and for individual soil layers for the research site developed by Irmak (2019). Since soil textures varied at different depths at the same point in the field, different soil water retention curves developed by Irmak (2020) were used for each depth at the same location, depending on the measured soil texture. Thus, when VRI applications were made, the soil heterogeneity/spatial variability in both horizontal and vertical domains in the soil profile were considered for determining irrigation requirements. This is critical for successfully and properly implementing VRI strategy, but to the best of the knowledge of the authors, this required management strategy (accounting for horizontal and vertical domain spatial variability for determining spatial irrigation requirements) has not been considered by other researchers. When both horizontal and vertical domains spatial variability is considered, in total, there were six soil types in the research field. These soil types were silt loam, silty clay loam, clay loam, loam, sandy clay loam and sandy loam. The VWC estimated from the soil-water retention curves (Irmak, 2019) were then multiplied by the representative depth intervals to determine the total soil water stored in each soil layer (with a 0.30 m increments) and then summed up to obtain total soil water for the 0-1.20 m soil profile for each plot.

Soil water holding capacity (SWHC) was calculated by subtracting soil water at PWP from soil water at FC for each plot. Approximately a 40% depletion in available SWHC was allowed and irrigation was triggered whenever the total soil water stored in 1.20 m profile as measured from WGMS fell just below this 40% threshold. This threshold is called management allowable depletion (MAD). The timing of irrigation for both VRI and FRI was decided in this manner. However, for FRI plots, the irrigation amount for each irrigation event was fixed to be 25.4 mm. Each time any of the FRI plots needed irrigation, all plots for this treatment were irrigated with 25.4 mm depth of water, considering no variability in the field and assuming that crop responds in the same

Table 1

Description of some of the field 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			8 May
Emergence	7 June	19 May	16 May
Pre-plant N in treatment 05 and 06			
UAN* 32-0-0	27 May	13 April	19 April
In season FRF*			
UAN* 32-0-0	13 July 16 July	30 May 28 June	5 June 23 June
In season VRF*			
UAN* 32-0-0	19 July	31 May 27 June	6 June 22 June
Herbicide			
Lexar + Roundup + AMS	28 May		
Roundup + AMS	29 June		
Acuron + Roundup		18 May	11 May
Pesticide			
Quilt Excel	17 Aug.	22 July	
Force 3G			8 May
Lorsban + Brigade+Headline Amp			4 Aug.
Tasseling	25 July	19 July	17 July
Physiological maturity	15 Sep.	20 Sep.	13 Sep.
Harvest	19 Oct.	13 Oct.	25 Oct.

manner at all locations in the field. This is the common practice that producers follow in Nebraska and other midwestern regions where center pivot irrigation is practiced. A total of 1, 7 (5 irrigations of 25.4 mm each and 2 irrigations of 31.7 mm each) and 10 irrigations were applied to FRI plots in 2015, 2016 and 2017 growing seasons, respectively. For VRI plots, irrigation amounts were applied to replenish the soil moisture to approximately 90% of the FC. The detailed timing and amount of irrigation in each treatment is presented in Table 2 which is adapted from Sharma and Irmak, 2020a. Measured soil moisture readings from WGMSs were used to trigger irrigation for variable irrigation plots. Thus, the number and amount of irrigation events for each VRI plot are different from FRI. The irrigation amounts were estimated by taking the average of two replications of each VRI treatment. For this research, irrigation amounts and timing in each experimental plot was needed prior to irrigation to calculate the irrigation amounts for FRI and VRI irrigation. To accomplish this, the WGMS data were downloaded from each plot every other day and put into a plot specific irrigation scheduling worksheet that was developed in the Irmak Research Laboratory. Computed irrigation values were then used to develop spatial irrigation control maps for irrigation to each experimental unit. The final map was then uploaded to the linear-move control panel and VRI was practiced.

Three N fertilizer treatments were investigated in this research: fixed (uniform) rate fertilizer (FRF), variable rate fertilizer (VRF) and pre-plant fertilizer (PP) management. For the PP treatment, a 246 kg/ha of urea ammonium nitrate (UAN 32-0-0) in 2015, 2016 and 2017 was applied before planting. In-season fertilizer was applied in VRF and FRF treatments using the linear move sprinkler system. The N fertilizer rate for VRF plots was calculated using N recommendation equation proposed by University of Nebraska-Lincoln fertilizer guidelines (Shapiro et al., 2008):

$$N\ need\left(\frac{lb}{ac}\right) = [35 + (1.2*EY) - (8*NO_3 - Nppm) - (0.14*EY*OMC) - other\ N\ credits\,]*Price_{adj}*Timing_{adj} \tag{1}$$

where, EY is expected yield (bu/ac); NO_3-N (ppm) is average nitrate-N concentration in the crop root zone (0-1.20 m soil depth); OMC is organic matter content in % (other nitrogen credits were assumed to be negligible); $Price_{adj}$ is the adjustment for market price of maize grain and cost of nitrogen, and $Timing_{adj}$ is the adjustment factor for fall, spring and split nitrogen applications. The expected yield was 105 percent of the five-year average yield of the field. Five-year yield for the research field was obtained from the Irmak Research Laboratory field research database depository. Nitrate-N and OMC for each plot were obtained from extensive soil sampling conducted in each spring before planting and N requirement for each VRF plot was determined separately. Price and timing adjustments were calculated using the equation from Shapiro et al. (2008) based on the current maize market price. Procedures and associated values for $Price_{adj}$ * $Timing_{adj}$ are presented in Shapiro et al.

Table 2

Irrigation dates and amounts (mm) for irrigation and nitrogen treatments in three soil types (Sharma and Irmak, 2020a).

	FRI		S1 VRI			S2 VRI			S3 VRI		
Date		Date	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

(2008).

For VRF treatment, on average, 217, 234 and 221 kg ha^{-1} N fertilizer was applied to FRI, VRI and NI treatments, respectively, in 2015. In 2016, these values were 205, 206 and 202 kg ha^{-1}, respectively, and in 2017 they were 172, 161 and 168 kg ha^{-1}, respectively. A constant rate of 246 kg ha^{-1} of N fertilizer was applied to all FRF plots. Since multiple applications of N are generally more efficient than single large doses due to N loss potential, the N fertilizer application was divided into two applications. Half of the required N was applied at the vegetative growth stage of V2 and another application at V8 stage (Shapiro et al., 2008) for both VRF and FRF plots (Table 1).

2.3. Crop evapotranspiration

Maize evapotranspiration (ETc) was calculated using a general soil-water balance equation:

$$ETc = P + I + U - Runoff \pm \Delta SWS - DP \tag{2}$$

where, ETc is crop evapotranspiration (mm); P is precipitation (mm); I is irrigation (mm); U is upward water flux (mm); Run-off is surface runoff from individual treatments (mm), ΔSWS is the change in soil water storage (mm) in the soil profile between the beginning and the end of the calculation 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. From hourly soil water storage data, an hour of the day was selected, which was considered to be showing the soil water present in the profile at that particular day. Then, the growing season was divided into the soil water depletion periods (weekly or bi-weekly to few days) such that all the days with precipitation events remain inside these periods. There was no precipitation at the start of the period and this period ends 1-2 days after the precipitation. This was done because on the day of precipitation, soil water in the profile is dynamic, resulting in fluctuations in the sensor readings. Change in soil water storage (ΔSWS) was calculated by subtracting SWS at the beginning of the period from SWS value at the end of the period (week to a few days depending upon the precipitation). Deep percolation was estimated using the daily soil water balance computer program (Payero et al., 2009; Bryant et al., 1992;Djaman and Irmak, 2013); Irmak, 2015a; and 2015b).

The surface runoff was estimated using the USDA Natural Resources Conservation Service (NRCS, formerly known 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 each year. The SCS curve number method relates runoff curve number (CN) to runoff, accounting for initial abstraction losses and the soil infiltration rate. The following equation was used to estimate runoff from each treatment:

$$\mathrm{RO} = \frac{(\mathrm{P} - \mathrm{I_a})^2}{(\mathrm{P} - \mathrm{I_a}) + \mathrm{S}} \text{ for } \mathrm{P} > 0.2\ \mathrm{S} \tag{3}$$

where, Ia is initial abstraction (mm) and S is the potential maximum retention after run-off begins (mm) and was calculated as:

$$\mathrm{S} = \frac{25400}{(CN)} - 254 \tag{4}$$

Initial abstraction (Ia) represents the water loss before run-off begins and includes water retained in surface depressions, water intercepted by vegetation, evaporation and infiltration. The Ia value is usually well correlated with soil and surface residue cover parameters. From many small agricultural watershed studies (USDA-NRCS, 1985), Ia is approximated by the following empirical equation:

$$I_a = 0.2\mathrm{S} \tag{5}$$

The Curve Number used in this method is dependent on the surface cover type, hydrological soil group, treatment and hydrologic condition. According to the silt loam (S1 and S3) and silty clay loam (S2) soil at the site and known row cropping in all soil types, curve numbers were determined as 78 and 89, respectively, for average antecedent run-off condition, from the USDA-NRCS (1985) tables.

2.4. Grass and alfalfa reference evapotranspiration

One of the commonly used approaches to quantify ETc is to use experimentally developed crop-specific coefficients (Kc) and reference evapotranspiration (ETref), typically alfalfa or grass-reference ET (ETr and ETo, respectively) to estimate ETc. This method is called the two-step approach that relates Kc to ETref (i.e., ETc = Kc x ETref) assuming simplifications of several surface energy balance principles. ETr and ETo values were calculated using the standardized Penman-Monteith equation (ASCE-Environmental and Water Resources Institute (EWRI), 2005), which is a derivation of Penman-Monteith (1965) equation with a fixed canopy resistance (Irmak et al., 2012) on a daily time step (equation 6). The ETref is the reference (potential) evapotranspiration from either the short grass (ETo) or alfalfa (ETr) without water stress and represent the weather and climate potential for evapotranspiration in a given region. The High Plains Regional Climate Center (HPRCC) automated weather station-measured climate variables were used as input data to calculate ETr and ETo. The standardized ETref equation is:

$$ET_{ref} = \frac{0.408\ \Delta\ (R_n - G) + \gamma \left(\frac{C_n}{T+273}\right) u_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)} \tag{6}$$

where, reference ETref is, grass-reference ET (ETo) or alfalfa-reference ET (ETr) (mm d^{-1}); Δ is slope of saturation vapor pressure vs. air temperature curve (kPa ^{o}C^{-1}); Rn is net radiation at the surface (MJ m^{-2} d^{-1}); G is soil heat flux density (MJ m^{-2} d^{-1}) and assumed to be zero for daily time step; T is mean daily air temperature (^{o}C); u2 is mean daily wind speed at 2 m height (m s^{-1}); es is saturation vapor pressure (kPa); ea is actual vapor pressure (kPa); ea-es is vapor pressure deficit (kPa); γ is psychrometric constant (kPa ^{o}C^{-1}); Cn is numerator constant that changes with reference type and calculation time step; Cd is denominator constant that changes with reference type and calculation time step. Both Cn and Cd are functions of the time step and aerodynamic roughness of the surface (i.e., reference type). The value of Cd depends on bulk surface resistance and daytime/nighttime. Cd and Cn values on a daily time step for grass and alfalfa-reference surfaces were 900 and 0.34, and 1600 and 0.38, respectively (ASCE-Environmental and Water Resources Institute (EWRI), 2005; Irmak et al., 2003). Daily values of Δ, Rn, ea and es were calculated (for albedo = 0.23) using equations given in ASCE-Environmental and Water Resources Institute (EWRI), 2005 and Food and Agricultural Organization of the United Nations (FAO), 1998. The Stefan-Boltzman constant (σ) to calculate Rnl was taken as 4.901 × 10-9 MJ K^{-4} m^{-2} d^{-1} (Irmak et al., 2003).

2.5. Grass- and alfalfa-reference crop coefficients, growing degree days calculation and statistical analysis

The ETc values calculated from the soil-water balance approach over the three growing seasons were used to calculate grass-reference and alfalfa-reference single (normal) Kco and Kcr crop coefficients. The Kco and Kcr accounts for difference in the crop canopy and aerodynamic resistance relative to reference crop (grass and alfalfa, respectively). The Kc serves as an aggregation of the physical and physiological difference between crops. For all treatments, cumulative ETc for each soil water depletion period was calculated. The corresponding ETref for each soil water depletion period was also calculated for each treatment. The crop coefficients (Kco and Kcr) were calculated as the ratio of soil water balance-determined ET and ETref from the Penman-Monteith equation as described in FAO-56 (Food and Agricultural Organization of the

United Nations (FAO), 1998):

$$K_c = \frac{ET_c}{ET_{ref}} \tag{7}$$

where, ETc and ETref are in mm, and Kc is the single (normal) crop coefficient (unitless). The Kco and Kcr data were plotted against cumulative growing degree days (CGDD) and third order polynomial equations were fitted to the data. Detailed information on GDD calculation is presented in Irmak (2015a, b). ETc data were statistically analyzed using Proc Glimmix procedure in SAS (SAS Institute Inc., Cary, NC) to compare the effects of irrigation treatment, nitrogen (N) treatment and soil type on maize grain yield and ETc. The means were separated using the least significant difference (LSD) test at 95% level of significance to identify any potential significant differences in ETc between treatments. When no significant interactions occurred between the treatments, the main effects were evaluated. The strength of the developed Kc and CGDD relationships were measured using the coefficient of determination (R^2).

3. Results and Discussion

3.1. Weather conditions and reference evapotranspiration (ETr and ETo)

Monthly average weather variables for 2015, 2016 and 2017 growing seasons as well as long-term average values (1983-2017) are presented in Table 3. A total of 42, 47 and 49 precipitation events occurred in 2015, 2016 and 2017 growing seasons (planting to harvesting), respectively. The total growing season precipitation in 2015, 2016 and 2017 were 353, 375 and 467 mm, respectively. The total growing season precipitation in 2015 was lower than in 2016 and 2017. The 2015 growing season experienced very heavy rainfall in June (226 mm) which was 131 mm higher than the long-term average. On average, the 2015 growing season was warmer than 2016 and 2017 with mean air temperature in 2015 to be 20.3 °C whereas 19.8 °C and 19.1 °C in 2016 and 2017, respectively. The highest monthly average temperature in all years occurred in July (Table 3). On average, greater wind velocity existed in 2016 as compared with 2015 and 2017. Also, greater wind speeds were observed in the early growing season in all three years from May to June, which is common for the research area. The 2017 growing season experienced below-normal wind velocities late in the growing season in August and September. Because of the minimal precipitation amounts in June in 2016 and 2017 growing seasons as compared with 2015, large differences in relative humidity (RH) were observed between the seasons. 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.

Distribution of Penman-Monteith (PM) equation-estimated daily ETo and ETr and GDD values from mid-April to mid-October in three growing seasons are presented in Fig. 2a, b and c, respectively. The ETr values ranged from 1.1 to 10.6 mm in 2015, from 0.8 to 11.5 mm in 2016 and 0.5 to 10.5 mm in 2017. The ETo values ranged from 1.0 to 7.5 mm in 2015, from 0.70 to 8.4 mm in 2016 and from 0.5 to 7.8 mm in 2017. Maximum ETr and ETo values were observed on June 28 in 2015 (32 DAP), on June 21 in 2016 (46 DAP) and again on June 21 in 2017 (44 DAP). The corresponding average weather conditions on these days included wind speed of 3.78, 4.62 and 4.64 $m\ s^{-1}$, Rs of 304, 323 and 306 $W\ m^{-2}$, average air temperature (Tavg) of 23.0, 27.3 and 27.1 °C, VPD of 1.42, 1.99 and 1.78 kPa, and RHmean of 53.5, 52.0 and 55.4% in 2015, 2016 and 2017, respectively. Greater variability and higher values of ETo and ETr were observed in the initial growing season, generally from mid-May to mid-July which is typically the vegetative growth period for maize in all three growing seasons (~65–75 DAP). Less variations were observed in both ETo and ETr in the maize reproductive stages, which is generally between mid-July to mid-October in all three growing seasons. Maximum daily GDD values occurred in the middle of the season (from late June to mid-July) and followed a quadratic distribution over the growing seasons. There were substantial differences in the GDDs from planting to harvest between 2015, and 2016 and 2017. Due to differences in climatic conditions between the years, maize reached its physiological maturity at different GDDs. The seasonal cumulative GDD from planting to harvest was 1,640 °C (DAP 145) in 2015;

Table 3
Monthly average weather conditions during the 2015, 2016 and 2017 growing seasons and long-term (1983-2017) averages at the research site in south central Nebraska.

Year	Month	Tmax (°C)	Tmin (°C)	RHmean (%)	Wind Speed (m s^{-1})	Precip. (mm)	Rs (W m^{-2})	VPD (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

Weather data were obtained from the High Plains Regional Climate Center—Automated Weather Data Network (HPRCC-AWDN) near Clay Center, Nebraska; Rs: incoming solar radiation; Tmax and Tmin: maximum and minimum air temperature, respectively; RHmean: mean relative humidity; VPD: vapor pressure deficit; Precip: precipitation.

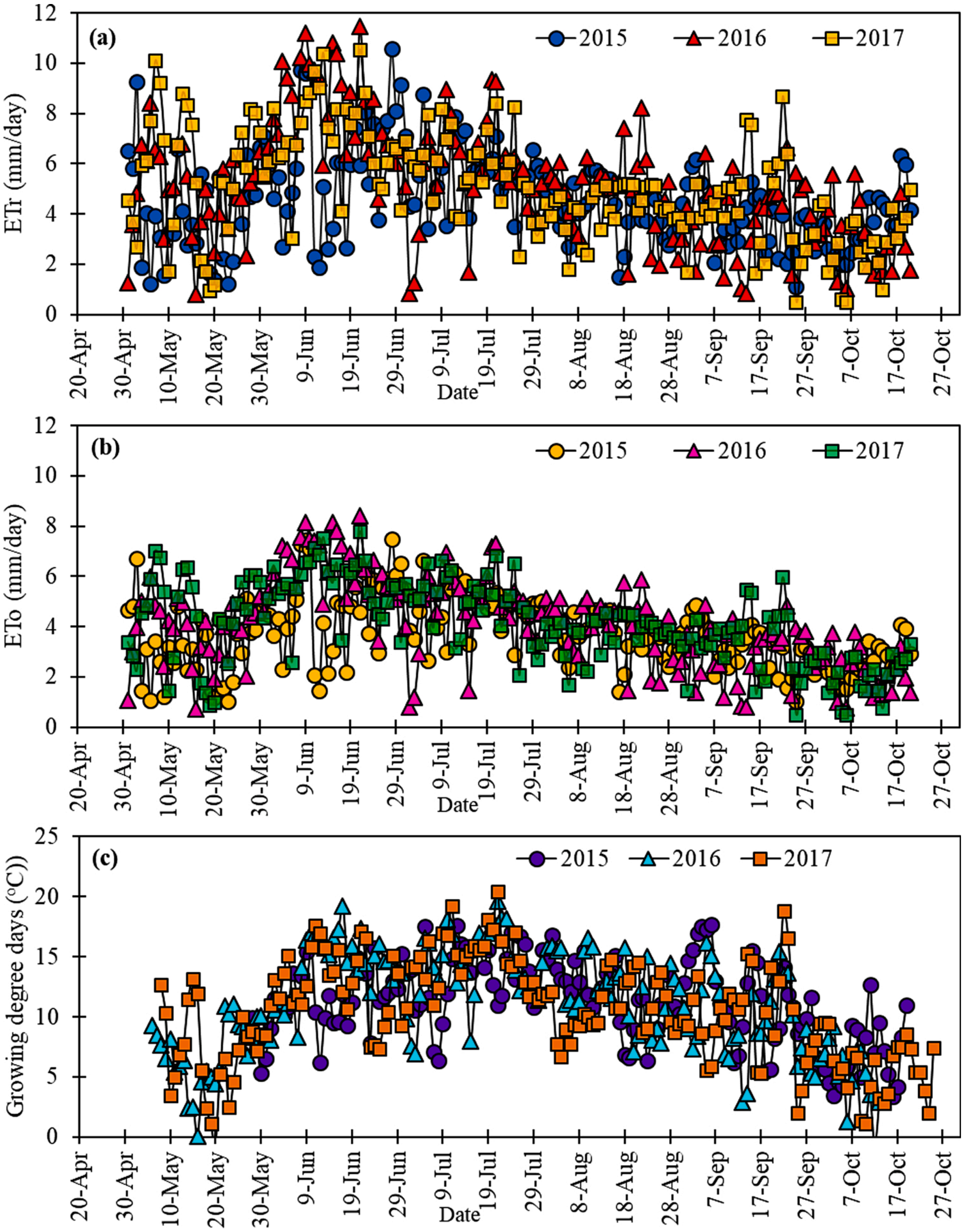

Fig. 2. Daily (a) alfalfa-reference ET (ETr); (b) grass-reference ET (ETo); (c) growing degree days (GDDs) from planting to harvest for 2015, 2016 and 2017 growing seasons at the research site.

Table 4
Maize seasonal evapotranspiration (ETc) determined using the soil water balance approach for fixed (uniform) rate fertigation (FRF), variable rate fertigation (VRF), and pre-plant nitrogen application (PP) under fixed (uniform) rate irrigation (FRI), variable rate irrigation (VRI) and no irrigation (NI) in Crete silt loam (S1), Hastings silty clay loam (S2) and Hastings silt loam (S3) soil types in 2015, 2016 and 2017 maize growing season.

Soil	Nitrogen level	2015			2016			2017		
		FRI	VRI	NI	FRI	VRI	NI	FRI	VRI	NI
S1	FRF	342	378	374	525	356	395	603	605	409
	VRF	330	344	349	510	474	426	513	500	448
	PP	389	372	-	649	614	-	614	576	-
S2	FRF	337	338	332	487	493	381	556	362	464
	VRF	382	372	356	518	411	343	565	538	388
	PP	364	376	-	500	485	-	511	408	-
S3	FRF	349	345	324	480	364	357	605	427	403
	VRF	345	368	363	581	466	369	634	401	422
	PP	365	341	-	499	481	-	523	503	-

1,781 °C (DAP 160) in 2016 and 1,783 °C (DAP 170) in 2017.

3.2. *Crop evapotranspiration (ETc)*

Seasonal maize ETc under different irrigation and nitrogen levels, determined using the soil-water balance approach, is presented in Table 4. In 2015, ETc ranged from 324 mm in S3-NI-FRF treatment to 389 mm in S1-FRI-PP treatment. The ETc values for all soil types and treatments were higher in 2016 and 2017 than in 2015 due to higher seasonal rainfall and higher VPD. Due to very heavy rainfall at the beginning of the growing season and more uniform temporal distribution of rainfall until DAP 100 in 2015, there were fewer irrigation events (three) in 2015 than in 2016 (nine) and 2017 (ten). ETc ranged from 343 mm in S2-NI-VRF to 649 mm in S1-FRI-PP treatment in 2016 whereas in 2017 it ranged from 362 mm in S2-VRI-VRF treatment to 634 mm in S3-FRI-VRF treatment. In 2015, no significant difference ($p > 0.05$) in ETc was observed between soil types, irrigation or nitrogen treatments. This was expected since irrigation amounts for this season were very low and were similar in all treatments. In 2016, no significant interaction between soil type, irrigation or nitrogen treatment was observed; however, irrigation had a significant effect on ETc. In 2016, plots under FRI had maximum ETc, which was significantly higher than ETc in VRI and NI. On a three-year average, ETc was 528, 460 and 378 mm in FRI, VRI and NI treatments, respectively. In the 2017 growing season, the soil and nitrogen management interactions were significant ($p < 0.05$) and irrigation level had a significant effect on ETc. In this season, ETc in VRF treatment was significantly lower than FRF and PP treatment in S1 and S2. This means that applying in-season nitrogen variably and uniformly might have different impacts on crop growth and development as well as associated ETc values, which in turn, can impact

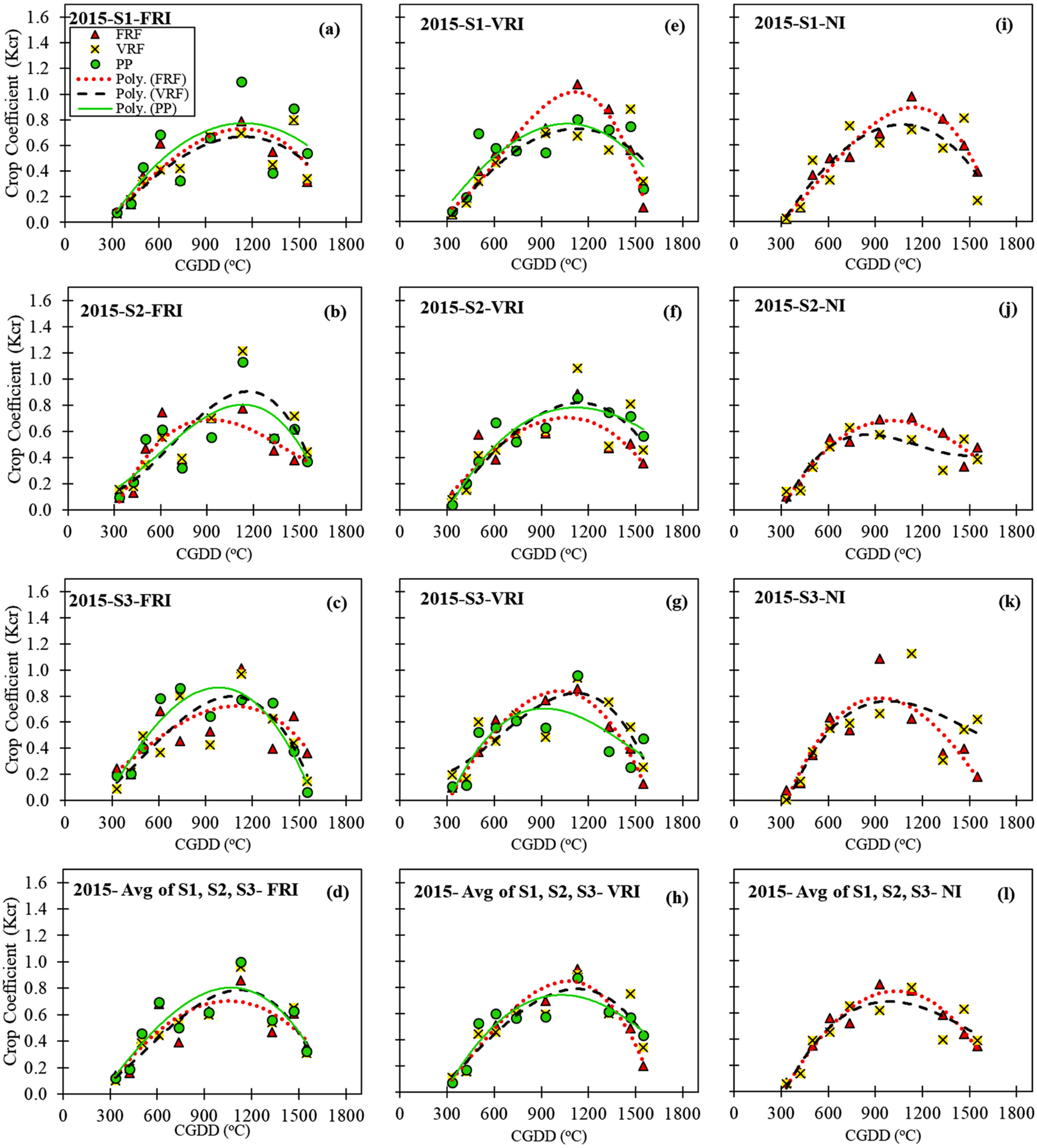

Fig. 3. Alfalfa-reference crop coefficient (Kcr) curves for fixed (uniform) rate fertigation (FRF) (red line), variable rate fertigation (VRF) (black line) and pre-plant (PP) (green line) nitrogen treatments under (a-d) fixed (uniform) rate irrigation (FRI), (e-h) variable rate irrigation (VRI), and (i-l) no-irrigation (NI) conditions in 2015 for Crete silt loam (S1), Hastings silty clay loam (S2), Hastings silt loam (S3) and average of S1, S2 and S3.

Kc values in different soil types. Similar to 2016, ETc in FRI treatment (577 mm) was significantly ($p < 0.05$) higher than VRI treatment (560 mm) in the 2017 growing season.

Similar weekly or biweekly (soil moisture depletion period) trends (data not shown) of ETc were observed for all irrigation and nitrogen treatments within a year; however, magnitudes varied among the treatments. Maximum measured soil moisture depletion period ETc was from mid-August to late August in 2015, from late July to mid-August in 2016 and 2017 growing seasons. In general, FRI treatment with FRF and PP nitrogen levels had maximum ETc in the mid-growing season (especially during July and August) as compared with other treatments due to higher nitrogen and water availability. Due to higher irrigation and nitrogen amounts in these treatments, LAI and plant height (data not shown) was greater as compared with other treatments, resulting in greater ETc. The ETc results from 2015, 2016 and 2017 growing season indicated that greater differences in ETc existed between irrigation treatments within a nitrogen level as compared to nitrogen treatments within an irrigation level, supporting that irrigation has a greater impact on ETc than nitrogen and that these impacts may also translate into differences in Kc values of maize under different management practices.

3.3. Weekly/bi-weekly alfalfa- and grass-reference crop coefficients (Kcr and Kco)

Alfalfa-reference crop coefficients (Kcr) for all pre-plant N treatment (PP), fixed rate fertigation (FRF) and variable rate fertigation (VRF) under fixed rate irrigation (FRI), variable rate fertigation (VRI) and no irrigation (NI) in three soil types are graphed for the 2015 (Fig. 3), 2016

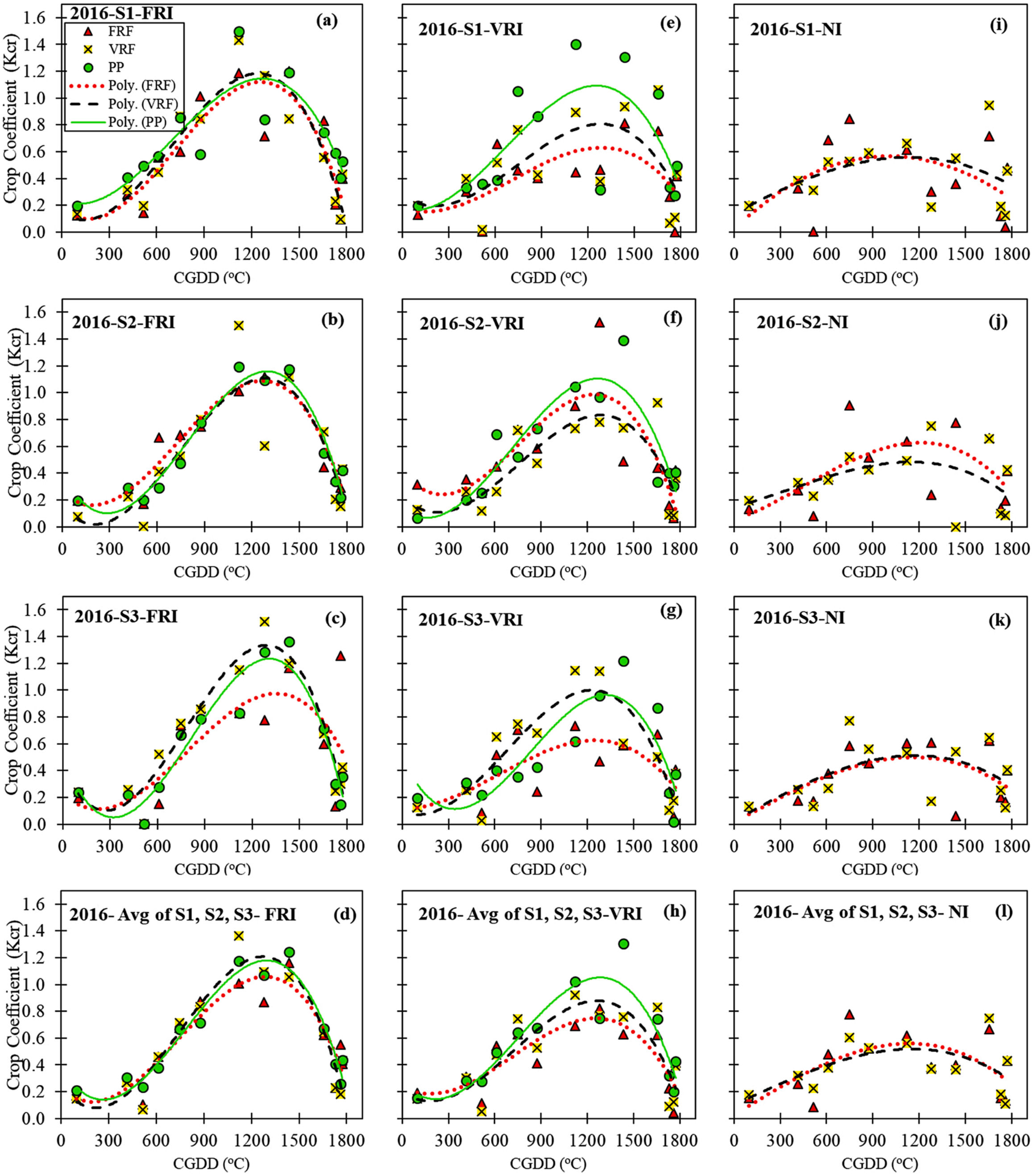

Fig. 4. Alfalfa-reference crop coefficient (Kcr) curves for fixed (uniform) rate fertigation (FRF) (red line), variable rate fertigation (VRF) (black line) and pre-plant (PP) (green line) nitrogen treatments under (a-d) fixed (uniform) rate irrigation (FRI), (e-h) variable rate irrigation (VRI), and (i-l) no-irrigation (NI) conditions in 2016 for Crete silt loam (S1), Hastings silty clay loam (S2), Hastings silt loam (S3) and average of S1, S2 and S3.

(Fig. 4), 2017 (Fig. 5) and pooled data for all three growing seasons (Fig. 6) as a function of cumulative GDD (CGDD). Third-order polynomial regression lines in the form of Kcr or Kco = a3 (CGDD)^3 + a2 (CGDD)^2 + a (CGDD) [where, a3 and a2 represent slope and a represents intercept of the polynomial equation and CGDD is cumulative growing degree day (°C)]) were fitted to all treatments for three years as well as for the pooled data and the equations and R^2 values are presented in Table 5–8. While Kco values were also quantified for all treatments in all soil types and for all years, only Kcr values are discussed in detail. Previous studies on Kc have fitted the Kc curves ranging from third to fifth order polynomials (Djaman and Irmak, 2013; Piccinni et al., 2009; Kang et al., 2003). In 2015, Kcr ranged from 0.10 to 1.10, 0.10 to 1.10 and 0.02 to 1.0 for FRI, VRI and NI, respectively in S1. In S2, Kcr ranged from 0.10 to 1.20, 0.03 to 1.10 and 0.10 to 0.80 for FRI, VRI and NI, respectively; and in S3 it ranged from 0.06 to 1.0, 0.10 to 0.95 and 0.01 to 1.10 in FRI, VRI and NI, respectively. Averaged over the soil types, Kcr ranged from 0.10 to 1.0, 0.07 to 0.93 and 0.05 to 0.82 for FRI, VRI and NI, respectively. Maximum Kcr was observed under FRI treatment in S1 and S2, whereas in S3, maximum Kcr was observed in NI. On average of three soil types, maximum Kcr was observed in FRI treatment. When the average of all three soil types for each treatment is considered, the Kcr values under FRI with FRF, VRF and PP treatment were 0.85, 0.96 and 1.0 respectively; under VRI with FRF, VRF and PP treatment maximum Kcr values were 0.94, 0.90 and 0.87, respectively; and under NI with FRF and VRF treatment, maximum Kcr was 0.82 and 0.79, respectively. In general, maximum Kcr was observed in PP nitrogen treatment, followed by FRF and VRF. The maximum values of Kcr in 2015 occurred between GDD values of 900 and 1,200 °C (mid-August), which corresponded to the R2 to R3 growth stages in this season and the minimum values occurred in the early and late season when transpiration rates

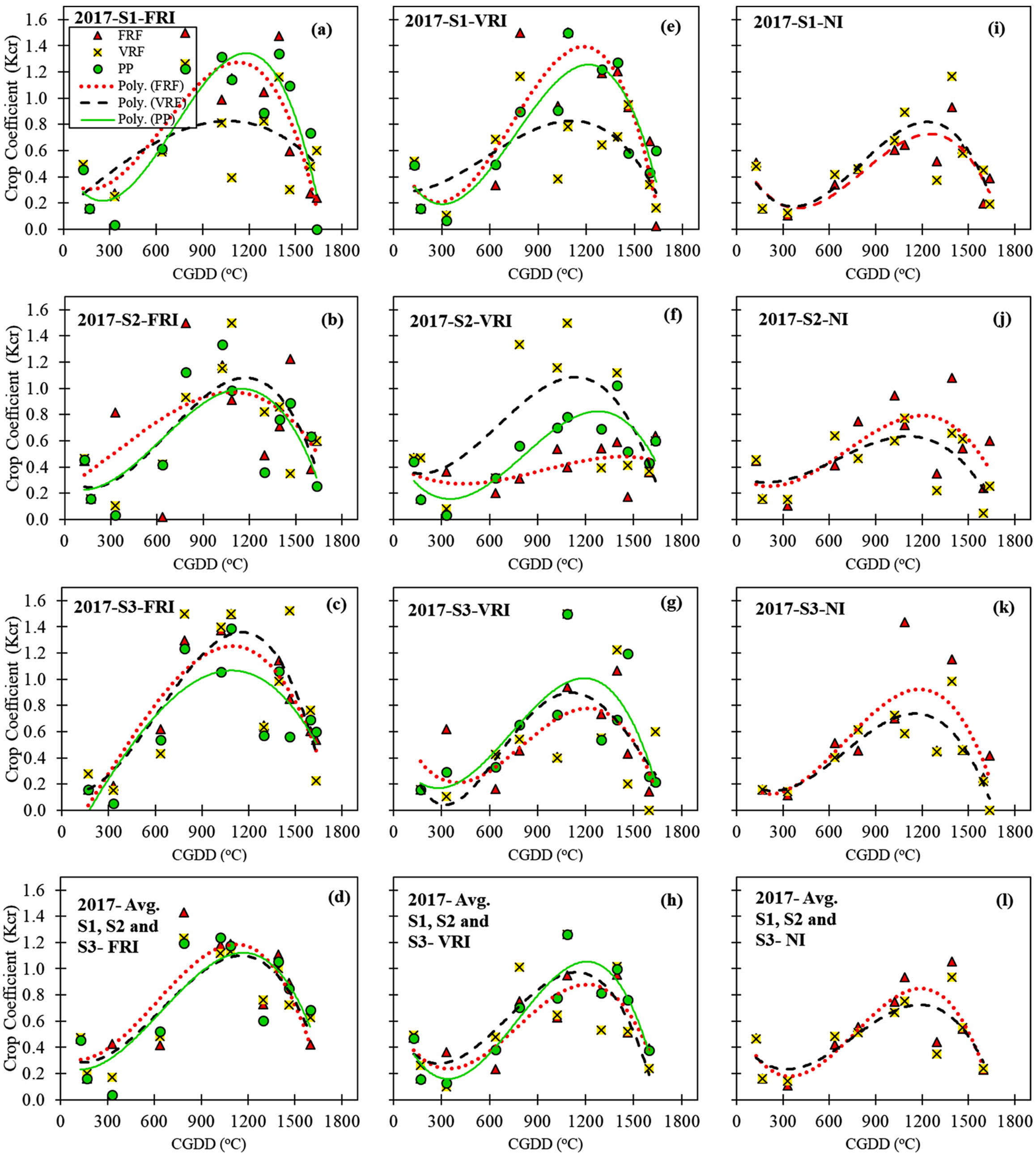

Fig. 5. Alfalfa reference crop coefficient (Kcr) curves for fixed (uniform) rate fertigation (FRF) (red line), variable rate fertigation (VRF) (black line) and pre-plant (PP) (green line) nitrogen treatments under (a-d) fixed (uniform) rate irrigation (FRI), (e-h) variable rate irrigation (VRI), and (i-l) no-irrigation (NI) conditions in 2017 for Crete silt loam (S1), Hastings silty clay loam (S2), Hastings silt loam (S3) and average of S1, S2 and S3.

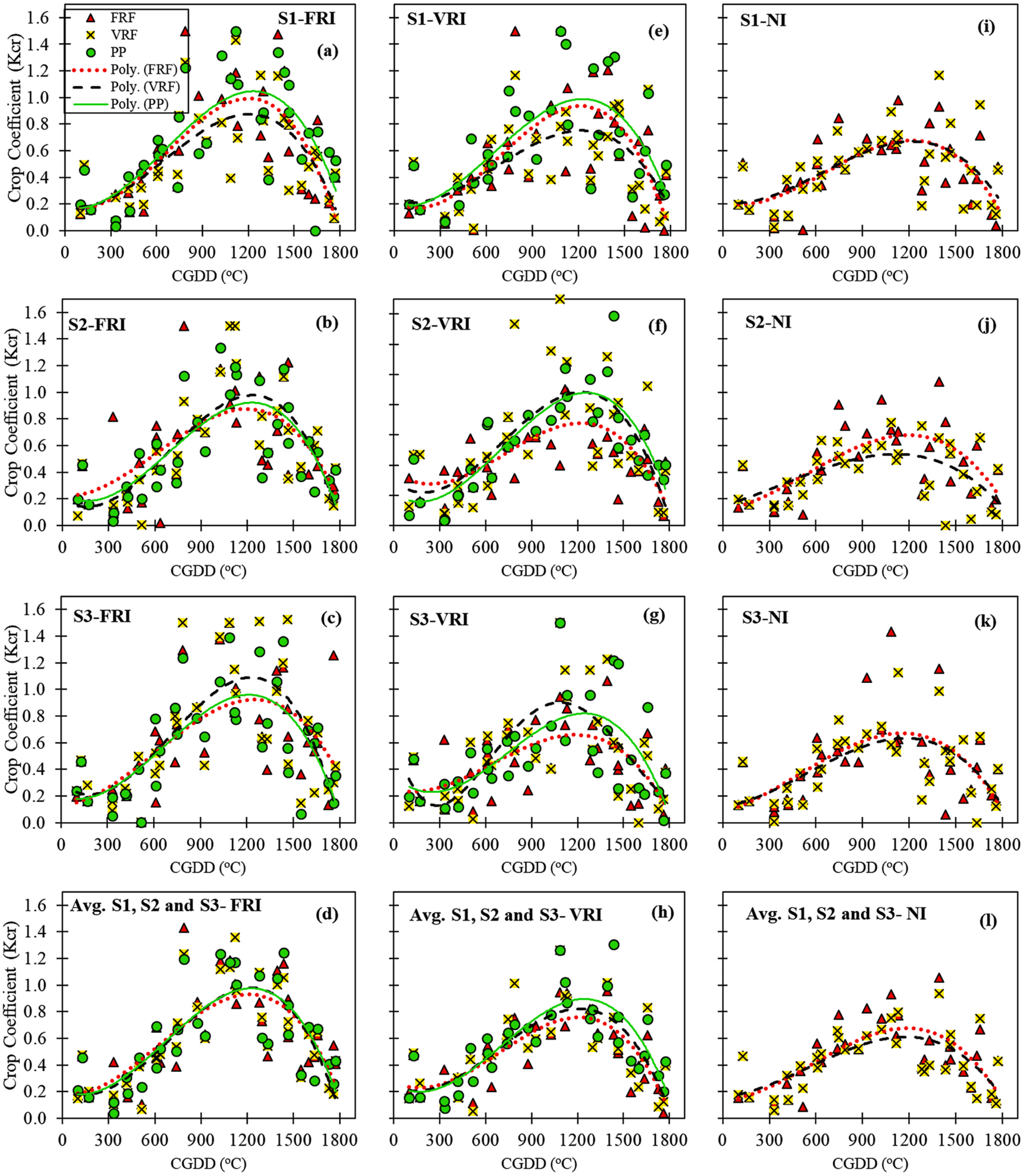

Fig. 6. Alfalfa reference crop coefficient (Kcr) curves for fixed (uniform) rate fertigation (FRF) (red line), variable rate fertigation (VRF) (black line) and pre-plant (PP) (green line) nitrogen treatments under (a-d) fixed (uniform) rate irrigation (FRI), (e-h) variable rate irrigation (VRI), and (i-l) no-irrigation (NI) conditions for pooled data of 2015, 2016 and 2017 for Crete silt loam (S1), Hastings silty clay loam (S2), Hastings silt loam (S3) and average of S1, S2 and S3.

were lowest.

In general, greater Kcr values existed in 2016 and 2017 growing seasons as compared with 2015. In 2016, Kcr ranged from 0.09 to 1.50, 0 to 1.40 and 0 to 0.90 for FRI, VRI and NI, respectively in S1. In S2, Kcr ranged from 0.004 to 1.50, 0.06 to 1.52 and 0 to 0.90 for FRI, VRI and NI, respectively, and in S3 it ranged from 0.002 to 1.50, 0.02 to 1.20 and 0.004 to 0.80 in FRI, VRI and NI, respectively. On average of three soil types, Kcr ranged from 0.07 to 1.40, 0.04 to 1.30 and 0.08 to 0.80 in FRI, VRI and NI, respectively. Similar to 2015, maximum Kcr value occurred in FRI treatment followed by the VRI and NI treatments. However, the nitrogen treatment effect on Kcr was not consistent such that the maximum Kcr within FRI treatment was observed under the VRF treatment (1.36), maximum Kcr within VRI was observed under PP treatment (1.30) and maximum Kcr within NI was observed under the FRF treatment (0.78). The maximum Kcr values in 2016 for FRI and VRI treatment occurred in early August which corresponded to R2 to R4 growth stage (GDD 1119 to 1400 °C) in that season.

In 2017, the Kcr values were in a similar range as in 2016 for FRI and VRI treatment and was slightly lower for NI treatments. On average of three soil types, maximum Kcr for FRF, VRF and PP nitrogen treatment were 1.43, 1.23 and 1.24 under FRI management; 0.95, 1.30 and 1.30 under VRI management; and 1.05 and 0.90 under NI, respectively. Maximum Kcr for all treatments occurred at GDD 800 to 1400 °C (late July to late-August and early September) which corresponded to R1 to R4 growth stage. Similar maximum Kcr peaks were observed by other researchers in the past. For example, Piccinni et al. (2009) reported that

Table 5

Alfalfa reference crop coefficient (Kcr) equations as a function of cumulative growing degree days (CGDD) for fixed (uniform) rate fertigation (FRF), variable rate fertigation (VRF) and pre-plant (PP) nitrogen treatments under fixed (uniform) rate irrigation (FRI), variable rate irrigation (VRI) and no-irrigation (NI) conditions in 2015 for Crete silt loam (S1), Hastings silty clay loam (S2), Hastings silt loam (S3) and average of S1, S2 and S3.

				Regression Coefficients*				
Year	Soil	Irrigation	N	a3	a2	a	b	R^2
2015	1	FRI	FRF	−5.62E-10	4.89E-07	1.07E-03	−0.29	0.69
2015	1	FRI	VRF	−2.83E-10	−1.58E-07	1.47E-03	−0.38	0.74
2015	1	FRI	PP	5.61E-12	−1.06E-06	2.39E-03	−0.59	0.54
2015	1	VRI	FRF	−2.36E-09	4.56E-06	−1.37E-03	0.15	0.94
2015	1	VRI	VRF	−1.97E-10	−5.65E-07	2.02E-03	−0.55	0.76
2015	1	VRI	PP	−2.63E-10	−4.64E-07	1.89E-03	−0.40	0.60
2015	1	NI	FRF	−1.38E-09	2.34E-06	7.57E-05	−0.18	0.94
2015	1	NI	VRF	−3.43E-10	−4.65E-07	2.17E-03	−0.62	0.68
2015	2	FRI	FRF	8.16E-10	−3.58E-06	4.51E-03	−1.07	0.68
2015	2	FRI	VRF	−1.74E-09	3.57E-06	−1.20E-03	0.23	0.71
2015	2	FRI	PP	−1.13E-09	1.95E-06	−7.30E-05	0.03	0.56
2015	2	VRI	FRF	−2.97E-10	−3.60E-07	1.76E-03	−0.40	0.71
2015	2	VRI	VRF	−5.64E-10	3.48E-07	1.41E-03	−0.40	0.72
2015	2	VRI	PP	1.94E-10	−1.65E-06	2.97E-03	−0.74	0.89
2015	2	NI	FRF	3.32E-10	−2.14E-06	3.29E-03	−0.80	0.89
2015	2	NI	VRF	1.30E-09	−4.56E-06	4.93E-03	−1.12	0.79
2015	3	FRI	FRF	−5.39E-10	4.77E-07	8.75E-04	−0.10	0.48
2015	3	FRI	VRF	−1.17E-09	1.69E-06	4.10E-04	−0.14	0.69
2015	3	FRI	PP	−4.68E-10	−6.20E-07	2.57E-03	−0.62	0.82
2015	3	VRI	FRF	−6.10E-10	−2.37E-07	2.36E-03	−0.68	0.96
2015	3	VRI	VRF	−1.44E-09	2.76E-06	−7.51E-04	0.23	0.69
2015	3	VRI	PP	7.84E-10	−3.57E-06	4.58E-03	−1.09	0.62
2015	3	NI	FRF	5.66E-10	−3.50E-06	5.02E-03	−1.31	0.78
2015	3	NI	VRF	8.91E-10	−3.91E-06	5.11E-03	−1.33	0.66
2015	Field average	FRI	FRF	−9.50E-11	−8.71E-07	2.15E-03	−0.49	0.66
2015	Field average	FRI	VRF	−1.07E-09	1.70E-06	2.25E-04	−0.10	0.82
2015	Field average	FRI	PP	−5.30E-10	9.01E-08	1.63E-03	−0.39	0.73
2015	Field average	VRI	FRF	−1.09E-09	1.32E-06	9.18E-04	−0.31	0.93
2015	Field average	VRI	VRF	−7.35E-10	8.47E-07	8.91E-04	−0.24	0.81
2015	Field average	VRI	PP	2.39E-10	−1.90E-06	3.14E-03	−0.75	0.81
2015	Field average	NI	FRF	−1.62E-10	−1.10E-06	2.80E-03	−0.77	0.94
2015	Field average	NI	VRF	6.18E-10	−2.98E-06	4.07E-03	−1.02	0.82

*Regression coefficients for the polynomial equation in the form $Kcr = a3\ (CGDD)^3 + a2\ (CGDD)^2 + a\ (CGDD) + b$. R^2 is the coefficient of determination.

maximum Kco values of 1.20 under non-limiting water and N conditions at milk and dough growth stages. Sammis et al. (1985) found a maximum Kcr value of 1.44 for the month of July (GDD 900-1200 °C) for maize grown in New Mexico under FIT and N fertilizer rate of 224 kg ha^{-1}.

3.4. *Monthly Kcr and Kco values*

While Kc values presented as a function of CGDD can be very beneficial for different applications and daily or weekly Kc values can be determined by solving the associated equations for within-season water management, modeling of water resources demand and use, crop modeling, hydrologic modeling and other applications, tabulating Kc values can be useful in practical applications by irrigators, practitioners and other water management professionals. Monthly Kcr values with standard deviations (SD) for all treatments and for the three-year pooled data for each soil type are presented in Table 9. The statistical significance [*t*-test ($\alpha = 0.05$)] of the differences between three-year average Kcr values for all FRI, VRI and NI under FRF, VRF and PP fertilizer management in all three soil types are presented in Table 10. Maximum Kcr values were observed for the month of July and August during peak crop development and maximum water use period in all soil types and minimum Kcr values were observed in June during the early stage of crop growth and development with minimum water use rates for all soil types. Overall, the maximum Kcr value was observed in FRI-PP treatment in S1 (1.02), FRI-VRF treatment in S2 (1.06) and FRI-VRF treatment in S3 (1.02). This indicates that there was no consistent effect of nitrogen treatments on Kcr, which suggests that the Kcr values are more dependent on the amount rather than the timing of the nitrogen application because the amount of nitrogen in both FRF and PP treatment under FRI, averaged over three growing seasons, was 246 kg ha^{-1}, which was similar to the amount applied to VRF treatment (201 kg ha^{-1}). On average of nitrogen treatments, greater Kcr values were observed in FRI treatment, followed by VRI and NI treatments. The monthly Kcr values agreed with the mid-season Kcr values of 1.26 and 1.05, respectively, for the full irrigation treatment obtained by Djaman and Irmak, (2013).

The difference in Kcr values between years indicates that climatic conditions that affect atmospheric evaporative demands strongly influence the Kc value. The results of this research also indicated that Kc values are the function of crop growth and development as well as strongly dependent on the irrigation management strategy. Similar results have been reported in the literature. On average of three soils, in all three growing seasons, greater differences in Kcr curves between FRF, VRF and PP nitrogen treatment were observed under VRI treatments as compared with FRI. Greater variability under VRI treatments can be attributed to lower irrigation amounts and less frequent irrigations that resulted in more variability in water distribution and perhaps uneven soil-water evaporation and plant water uptake. Non-uniform distribution of irrigation in VRI treatment may have affected the uptake of water (ETc) as well as soluble N (nitrate-N), which resulted in more variability in Kcr curves. The variation that could be caused by VRI management has not been investigated. The only research the authors are aware is the research reported by Sharma and Irmak, (2020b) who investigated and compared maize growth and development, grain yield, irrigation-yield production functions (IYPF), evapotranspiration-yield production functions (ETYPF) and crop water productivity (CWP) under VRI, FRI and no-irrigation (NI) with FRF, VRF and PP management in the same environment and management practices. They observed that VRI did not improve maize growth and development, grain yield or CWP as compared with FRI management. They also reported that VRI strategy

Table 6

Alfalfa-reference crop coefficient (Kcr) equations as a function of cumulative growing degree days (CGDD) for fixed (uniform) rate fertigation (FRF), variable rate fertigation (VRF) and pre-plant (PP) nitrogen treatments under fixed (uniform) rate irrigation (FRI), variable rate irrigation (VRI) and no-irrigation (NI) conditions in 2016 for Crete silt loam (S1), Hastings silty clay loam (S2), Hastings silt loam (S3) and average of S1, S2 and S3.

				Regression Coefficients*				
Year	Soil	Irrigation	N	a3	a2	a	b	R^2
2016	1	FRI	FRF	−1.58E-09	3.38E-06	−1.01E-03	0.18	0.77
2016	1	FRI	VRF	−1.65E-09	3.41E-06	−8.63E-04	0.15	0.86
2016	1	FRI	PP	−1.21E-09	2.51E-06	−5.18E-04	0.24	0.73
2016	1	VRI	FRF	−6.46E-10	1.39E-06	−3.61E-04	0.18	0.36
2016	1	VRI	VRF	−9.87E-10	2.21E-06	−7.92E-04	0.27	0.36
2016	1	VRI	PP	−1.13E-09	2.25E-06	−3.12E-04	0.17	0.48
2016	1	NI	FRF	2.48E-11	−5.96E-07	1.12E-03	0.02	0.25
2016	1	NI	VRF	−8.49E-11	−1.37E-07	6.38E-04	0.13	0.19
2016	2	FRI	FRF	−1.50E-09	3.29E-06	−1.10E-03	0.26	0.89
2016	2	FRI	VRF	−1.76E-09	3.92E-06	−1.39E-03	0.15	0.71
2016	2	FRI	PP	−2.04E-09	4.84E-06	−2.26E-03	0.40	0.93
2016	2	VRI	FRF	−1.55E-09	3.49E-06	−1.49E-03	0.42	0.63
2016	2	VRI	VRF	−1.22E-09	2.78E-06	−1.08E-03	0.22	0.64
2016	2	VRI	PP	−1.52E-09	3.24E-06	−9.09E-04	0.14	0.81
2016	2	NI	FRF	−3.75E-10	5.08E-07	4.15E-04	0.05	0.34
2016	2	NI	VRF	−2.03E-10	2.10E-07	3.21E-04	0.15	0.19
2016	3	FRI	FRF	−1.19E-09	2.82E-06	−1.09E-03	0.23	0.46
2016	3	FRI	VRF	−2.36E-09	5.55E-06	−2.52E-03	0.43	0.91
2016	3	FRI	PP	−2.46E-09	6.02E-06	−3.12E-03	0.51	0.89
2016	3	VRI	FRF	−5.37E-10	1.01E-06	−1.53E-05	0.12	0.42
2016	3	VRI	VRF	−1.30E-09	2.60E-06	−4.99E-04	0.10	0.76
2016	3	VRI	PP	−1.81E-09	4.52E-06	−2.45E-03	0.50	0.70
2016	3	NI	FRF	−1.45E-10	−2.14E-08	6.43E-04	0.01	0.32
2016	3	NI	VRF	−1.32E-10	−4.20E-08	6.48E-04	0.02	0.28
2016	Field average	FRI	FRF	−1.42E-09	3.16E-06	−1.06E-03	0.22	0.83
2016	Field average	FRI	VRF	−1.92E-09	4.30E-06	−1.59E-03	0.24	0.90
2016	Field average	FRI	PP	−1.90E-09	4.46E-06	−1.96E-03	0.38	0.94
2016	Field average	VRI	FRF	−9.09E-10	1.96E-06	−6.23E-04	0.24	0.65
2016	Field average	VRI	VRF	−1.17E-09	2.53E-06	−7.91E-04	0.20	0.68
2016	Field average	VRI	PP	−1.49E-09	3.34E-06	−1.22E-03	0.27	0.81
2016	Field average	NI	FRF	−1.65E-10	−3.65E-08	7.26E-04	0.02	0.36
2016	Field average	NI	VRF	−1.40E-10	1.03E-08	5.36E-04	0.10	0.30

*Regression coefficients for the polynomial equation in the form $Kcr = a3\,(CGDD)^3 + a2\,(CGDD)^2 + a\,(CGDD) + b$. R^2 is the coefficient of determination.

increased the variation in grain yield, ETc and CWP as compared with FRI management. Increased variation in ETc in VRI treatments as compared with FRI treatments in the same field and crop and soil management and same climatic conditions would result in increased variation in Kc values in VRI in comparison with FRI management. They determined that soil type had a significant impact on the variation in yield, ETc, IYPF, ETYPF and CWP under their experimental conditions. For example, S1 had the lowest grain yield variability as compared with S2 and S3. The coefficient of variation (CV) of grain yield ranged from 8% in Crete silt loam soil under FRI management to as high as 35.3% in Hastings silt loam soil under VRI management. FRI treatments in all soil types and years had less variation in maize grain yield as compared with VRI, suggesting that the increased variation in VRI Kc values is not random and caused by increased variation in ETc under VRI management, which was manifested into variation in Kc values. Djaman and Irmak, (2013) reported greater variability in maize Kco and Kcr values under rainfed and limited irrigation levels as compared with FIT. The difference in Kcr curves between nitrogen treatments at each irrigation level as well as between irrigation levels is also evident from the pooled data graphs (Fig. 6). The strong dependence of Kcr and Kco on CGDD was also observed in pooled data for all treatments and years. The lowest Kcr and Kco values were obtained for NI treatment and the FRI treatments had the highest values. Similar temporal trends existed between Kcr and Kco, therefore a discussion on Kco was not included; however, monthly Kco values are presented in Table 9. The results indicated that considerable differences in estimated ETc exist between different irrigation and nitrogen management strategies and Kc values for the same treatments differed between the soil types. Therefore, the Kc curves presented in this research for various nitrogen and irrigation management strategies in three different soil types can aid irrigators, state agencies and others to make decisions on in-season irrigation management and can aid in better understanding of how different irrigation and nitrogen management strategies can influence Kcr and Kco values in different soil types. This would, in turn, enable ETc estimations that can account for these influences by using different sets of Kcr or Kco values, depending on the soil types investigated.

There were significant differences ($p < 0.05$) (approximately 50% of the time) in monthly average Kc values between the treatments (Table 10). Under VRI with FRF and PP fertilizer management, all Kcr values were significantly different in soil types whereas under FRI with FRF and PP management, the Kcr values were significantly different only in S1. Soil 2 had significantly different Kcr values under VRI with FRF and VRF, under VRI with FRF and PP and under NI with FRF and VRF. Out of 21 statistical analyses that were conducted, S1, S2 and S3 had 27, 10 and 14% of the time significant difference in Kcr values between the treatments with most differences occurring in S1 for irrigated treatments. In NI treatment (FRF and VRF) only S2 had significantly different Kcr values.

3.5. Impact of irrigation and fertilizer management and soil type on Kcr to Kco ratios

The Kcr values sometimes need to be converted to Kco, or vice versa, to enable crop coefficients developed for one reference surface to be used with the other surface. For example, in the midwestern United States, ETr and Kcr values are much more commonly used than ETo and Kco. In eastern, southern, western, southwestern and southern US, ETo and Kco are most commonly used. ETo and Kco also are most commonly used globally. Thus, practical approaches to convert Kc values developed for one surface to another surface are needed to make this

Table 7
Alfalfa-reference crop coefficient (Kcr) equations as a function of cumulative growing degree days (CGDD) for fixed (uniform) rate fertigation (FRF), variable rate fertigation (VRF) and pre-plant (PP) nitrogen treatments under fixed (uniform) rate irrigation (FRI), variable rate irrigation (VRI) and no-irrigation (NI) conditions in 2017 for Crete silt loam (S1), Hastings silty clay loam (S2), Hastings silt loam (S3) and average of S1, S2 and S3.

				Regression Coefficients*				
Year	Soil	Irrigation	N	a3	a2	a	b	R^2
2017	1	FRI	FRF	−2.20E-09	4.29E-06	−1.27E-03	0.41	0.72
2017	1	FRI	VRF	−2.46E-10	−8.11E-08	1.01E-03	0.14	0.31
2017	1	FRI	PP	−2.82E-09	6.06E-06	−2.53E-03	0.51	0.79
2017	1	VRI	FRF	−3.25E-09	7.15E-06	−3.27E-03	0.63	0.76
2017	1	VRI	VRF	−9.43E-10	1.65E-06	−1.88E-04	0.29	0.42
2017	1	VRI	PP	−2.81E-09	6.40E-06	−3.10E-03	0.62	0.79
2017	1	NI	FRF	−1.80E-09	4.44E-06	−2.66E-03	0.63	0.66
2017	1	NI	VRF	−1.99E-09	4.78E-06	−2.71E-03	0.62	0.56
2017	2	FRI	FRF	−5.60E-10	6.07E-07	6.66E-04	0.25	0.26
2017	2	FRI	VRF	−1.66E-09	3.35E-06	−1.00E-03	0.33	0.62
2017	2	FRI	PP	−1.39E-09	2.62E-06	−5.33E-04	0.25	0.54
2017	2	VRI	FRF	−4.22E-10	1.18E-06	−7.93E-04	0.43	0.21
2017	2	VRI	VRF	−1.64E-09	3.21E-06	−9.58E-04	0.43	0.43
2017	2	VRI	PP	−1.69E-09	4.13E-06	−2.28E-03	0.52	0.75
2017	2	NI	FRF	−1.13E-09	2.41E-06	−8.84E-04	0.34	0.45
2017	2	NI	VRF	−9.04E-10	1.76E-06	−5.68E-04	0.33	0.45
2017	3	FRI	FRF	−1.52E-09	2.63E-06	−1.01E-04	0.21	0.72
2017	3	FRI	VRF	−2.34E-09	4.83E-06	−1.67E-03	0.46	0.60
2017	3	FRI	PP	−1.08E-09	1.78E-06	1.78E-04	0.16	0.59
2017	3	VRI	FRF	−2.12E-09	5.15E-06	−3.13E-03	0.77	0.47
2017	3	VRI	VRF	−2.12E-09	4.90E-06	−2.58E-03	0.59	0.34
2017	3	VRI	PP	−2.49E-09	5.74E-06	−3.01E-03	0.67	0.56
2017	3	NI	FRF	−2.12E-09	4.84E-06	−2.43E-03	0.55	0.51
2017	3	NI	VRF	−1.86E-09	4.24E-06	−2.24E-03	0.55	0.66
2017	Field average	FRI	FRF	−1.43E-09	2.51E-06	−2.34E-04	0.29	0.68
2017	Field average	FRI	VRF	−1.42E-09	2.70E-06	−5.56E-04	0.31	0.73
2017	Field average	FRI	PP	−1.76E-09	3.49E-06	−9.61E-04	0.31	0.70
2017	Field average	VRI	FRF	−1.93E-09	4.50E-06	−2.40E-03	0.61	0.73
2017	Field average	VRI	VRF	−1.57E-09	3.26E-06	−1.24E-03	0.44	0.54
2017	Field average	VRI	PP	−2.33E-09	5.42E-06	−2.80E-03	0.60	0.83
2017	Field average	NI	FRF	−1.69E-09	3.90E-06	−1.99E-03	0.51	0.59
2017	Field average	NI	VRF	−1.58E-09	3.59E-06	−1.84E-03	0.50	0.61

*Regression coefficients for the polynomial equation in the form Kcr = a3 (CGDD)3 + a2 (CGDD)2 + a (CGDD) + b. R^2 is the coefficient of determination.

conversion instead of re-calculating or re-measuring Kc values, which can be extremely difficult given the needed research, instrumentation, time and other resources required. Irmak et al. (2003) and Irmak et al. (2008) developed ETr to ETo ratios (Kr values) for several climatic regions, ranging from tropical/humid to semi-arid, to make conversions between Kcr and Kco for growing and non-growing (dormant) seasons. They determined the seasonal behavior of Kr values between the locations and in the same location for different seasons. Monthly average Kr values from daily values were developed for Bushland, Texas; Clay Center, Nebraska; Davis, California; Gainesville, Florida; Phoenix, Arizona and Rockport, Missouri for the calendar year and for the growing season (May–September) using several different ET methods. Their approach is robust and beneficial for making conversions in areas where detailed climate data are available to solve the Penman-Monteith equation for ETr or ETo estimations to make the conversions. However, to the best of authors' knowledge, the impact of irrigation (FRI, VRI and NI) and nitrogen (FRF, VRF and PP) management practices on Kcr to Kco ratios in different soil types have not been studied and the potential impact of nitrogen management strategies on Kcr to Kco ratios has not been investigated. Here, we propose another method to determine Kcr to Kco ratios (K values) to be able to make conversions between Kcr and Kco. This conversion (K values) would also be beneficial to be able to use Kcr or Kco values developed for a region in another region for irrigation management, ET estimations and other purposes where Kc values are not available.

Monthly (June, July, August and September) K values for each growing season individually as well as for a three-year average for all treatments for each soil type were developed (Table 11). The standard deviations between K values for each treatment were calculated to determine variations. While the K values were determined for a portion of the growing season (June-September), this period covers most of the period in which irrigation is practiced. The K values ranged from 0.78 to 0.98 and they were at their lowest during June, increased in July and August and decreased in September. Unlike significant differences observed between the Kc values between the treatments and between the soil types for the same treatment, differences in K values between the treatments as well as for the same treatment in different soil types were small for the same month, which indicates that the ratios are independent of the nature of irrigation and nitrogen management practices. For example, in S1 the K values for all irrigation and nitrogen treatments were within 0.79 and 0.80, 0.83 and 0.86, 0.85 and 0.88 and within 0.80 and 0.83 for June, July, August and September, respectively. However, K values for the same treatment differed considerably between the months for the same soil type. In general, SD values were higher for NI and VRI treatments than FRI treatments; and VRF SD values were higher than FRF treatments. Conversions between Kcr and Kco is a straightforward process. For example, the three-year average Kcr value in June for FRI-FRF treatment in S1 is 0.35 (Table 9) and the Kco value needs to be determined. The Kcr to Kco ratio for the same treatment in the same soil is 0.80 (Table 11). Since Kcr / Kco = K; 0.35 / Kco = 0.80; then Kco = 0.44 (the same value in Table 11 for that treatment in S1). Similar to the ETr to ETo ratios (Kr values) developed by Irmak et al. (2003) and Irmak et al. (2008), the Kcr to Kco ratios (K values) developed in this research can be useful for making conversions from Kcr to Kco or vice versa, to enable using crop coefficients developed for one reference surface with the other to determine crop water use for locations, with similar climatic characteristics of this research when locally measured K values are not available.

Table 8
Alfalfa reference crop coefficient (Kcr) equations as a function of cumulative growing degree days (CGDD) for fixed (uniform) rate fertigation (FRF), variable rate fertigation (VRF) and pre-plant (PP) nitrogen treatments under fixed (uniform) rate irrigation (FRI), variable rate irrigation (VRI) and no-irrigation (NI) conditions for pooled data of three years for Crete silt loam (S1), Hastings silty clay loam (S2), Hastings silt loam (S3) and average of S1, S2 and S3.

				Regression Coefficients*				
Year	Soil	Irrigation	N	a3	a2	a	b	R^2
Pooled	1	FRI	FRF	−1.27E-09	2.52E-06	−5.36E-04	0.20	0.55
Pooled	1	FRI	VRF	−9.87E-10	1.91E-06	−3.06E-04	0.19	0.50
Pooled	1	FRI	PP	−1.13E-09	2.21E-06	−3.13E-04	0.18	0.55
Pooled	1	VRI	FRF	−1.28E-09	2.62E-06	−7.11E-04	0.22	0.47
Pooled	1	VRI	VRF	−7.87E-10	1.57E-06	−3.17E-04	0.23	0.37
Pooled	1	VRI	PP	−1.04E-09	2.04E-06	−2.78E-04	0.19	0.49
Pooled	1	NI	FRF	−7.29E-10	1.45E-06	−3.01E-04	0.22	0.43
Pooled	1	NI	VRF	−6.04E-10	1.16E-06	−1.46E-04	0.21	0.35
Pooled	2	FRI	FRF	−8.25E-10	1.52E-06	−9.51E-05	0.22	0.38
Pooled	2	FRI	VRF	−1.34E-09	2.80E-06	−7.77E-04	0.20	0.60
Pooled	2	FRI	PP	−1.21E-09	2.51E-06	−7.10E-04	0.24	0.56
Pooled	2	VRI	FRF	−8.50E-10	1.86E-06	−7.40E-04	0.36	0.34
Pooled	2	VRI	VRF	−1.20E-09	2.55E-06	−8.42E-04	0.29	0.45
Pooled	2	VRI	PP	−1.11E-09	2.38E-06	−7.04E-04	0.21	0.69
Pooled	2	NI	FRF	−5.30E-10	8.73E-07	1.84E-04	0.12	0.42
Pooled	2	NI	VRF	−2.92E-10	3.39E-07	3.33E-04	0.15	0.30
Pooled	3	FRI	FRF	−7.62E-10	1.39E-06	8.54E-05	0.13	0.39
Pooled	3	FRI	VRF	−1.55E-09	3.27E-06	−1.05E-03	0.30	0.51
Pooled	3	FRI	PP	−1.16E-09	2.31E-06	−4.64E-04	0.20	0.52
Pooled	3	VRI	FRF	−6.95E-10	1.36E-06	−2.86E-04	0.25	0.36
Pooled	3	VRI	VRF	−1.05E-09	2.08E-06	−4.53E-04	0.21	0.46
Pooled	3	VRI	PP	−1.19E-09	2.66E-06	−1.10E-03	0.35	0.43
Pooled	3	NI	FRF	−5.28E-10	7.78E-07	3.18E-04	0.08	0.34
Pooled	3	NI	VRF	−5.20E-10	8.54E-07	1.50E-04	0.12	0.37
Pooled	Field average	FRI	FRF	−9.52E-10	1.81E-06	−1.82E-04	0.19	0.53
Pooled	Field average	FRI	VRF	−1.29E-09	2.66E-06	−7.09E-04	0.23	0.66
Pooled	Field average	FRI	PP	−1.16E-09	2.34E-06	−4.96E-04	0.21	0.62
Pooled	Field average	VRI	FRF	−9.41E-10	1.95E-06	−5.79E-04	0.28	0.61
Pooled	Field average	VRI	VRF	−1.01E-09	2.07E-06	−5.37E-04	0.24	0.56
Pooled	Field average	VRI	PP	−1.12E-09	2.36E-06	−6.93E-04	0.25	0.66
Pooled	Field average	NI	FRF	−5.95E-10	1.03E-06	6.70E-05	0.14	0.48
Pooled	Field average	NI	VRF	−4.72E-10	7.86E-07	1.12E-04	0.16	0.42

*Regression coefficients for the polynomial equation in the form Kcr = a3 $(CGDD)^3$ + a2 $(CGDD)^2$ + a (CGDD) + b. R^2 is the coefficient of determination.

Table 9
Monthly average alfalfa- and grass-reference evapotranspiration crop coefficients (Kcr and Kco) for fixed (uniform) rate fertigation (FRF), variable rate fertigation (VRF) and pre-plant (PP) nitrogen treatments under fixed (uniform) rate irrigation (FRI), variable rate irrigation (VRI) and no-irrigation (NI) conditions for pooled data of three years for 2015, 2016 and 2017 growing seasons. Values that follow ± indicate standard deviations. S1: Crete silt loam, S2: Hastings silty clay loam and S3: Hastings silt loam.

			Irrigation	Fixed (uniform) rate irrigation (FRI)			Variable rate irrigation (VRI)			No irrigation (NI)	
			Nitrogen	FRF	VRF	PP	FRF	VRF	PP	FRF	VRF
		Month	Soil								
Kcr	3-yr average	June	S1	0.35 ± 0.15	0.34 ± 0.15	0.37 ± 0.23	0.30 ± 0.16	0.32 ± 0.19	0.33 ± 0.20	0.31 ± 0.17	0.34 ± 0.18
		July	S1	0.73 ± 0.34	0.69 ± 0.31	0.72 ± 0.33	0.60 ± 0.28	0.57 ± 0.19	0.74 ± 0.23	0.52 ± 0.18	0.50 ± 0.07
		Aug	S1	0.95 ± 0.20	0.81 ± 0.29	1.02 ± 0.15	0.94 ± 0.39	0.71 ± 0.03	1.02 ± 0.35	0.61 ± 0.21	0.59 ± 0.11
		Sep	S1	0.57 ± 0.07	0.52 ± 0.12	0.69 ± 0.09	0.58 ± 0.11	0.56 ± 0.02	0.66 ± 0.08	0.52 ± 0.09	0.56 ± 0.04
	3-yr average	June	S2	0.45 ± 0.07	0.28 ± 0.20	0.29 ± 0.21	0.37 ± 0.13	0.33 ± 0.15	0.32 ± 0.20	0.29 ± 0.18	0.32 ± 0.18
		July	S2	0.68 ± 0.23	0.62 ± 0.24	0.67 ± 0.27	0.47 ± 0.16	0.64 ± 0.27	0.53 ± 0.09	0.60 ± 0.18	0.48 ± 0.09
		Aug	S2	0.84 ± 0.21	1.06 ± 0.10	0.89 ± 0.24	0.73 ± 0.25	0.85 ± 0.10	0.87 ± 0.23	0.60 ± 0.09	0.49 ± 0.07
		Sep	S2	0.51 ± 0.19	0.55 ± 0.08	0.53 ± 0.10	0.40 ± 0.08	0.57 ± 0.06	0.56 ± 0.17	0.49 ± 0.11	0.44 ± 0.09
	3-yr average	June	S3	0.27 ± 0.20	0.33 ± 0.16	0.26 ± 0.22	0.40 ± 0.11	0.32 ± 0.20	0.35 ± 0.14	0.28 ± 0.16	0.28 ± 0.16
		July	S3	0.78 ± 0.33	0.80 ± 0.32	0.74 ± 0.19	0.42 ± 0.07	0.55 ± 0.14	0.47 ± 0.09	0.50 ± 0.07	0.55 ± 0.13
		Aug	S3	0.92 ± 0.15	1.02 ± 0.30	0.95 ± 0.23	0.75 ± 0.13	0.90 ± 0.17	0.90 ± 0.13	0.74 ± 0.28	0.61 ± 0.25
		Sep	S3	0.54 ± 0.22	0.58 ± 0.26	0.54 ± 0.17	0.43 ± 0.06	0.44 ± 0.12	0.50 ± 0.12	0.43 ± 0.13	0.45 ± 0.04
Kco	3-yr average	June	S1	0.44 ± 0.18	0.43 ± 0.19	0.46 ± 0.29	0.38 ± 0.20	0.40 ± 0.24	0.41 ± 0.25	0.39 ± 0.21	0.43 ± 0.22
		July	S1	0.86 ± 0.37	0.83 ± 0.36	0.86 ± 0.37	0.70 ± 0.29	0.68 ± 0.21	0.89 ± 0.27	0.62 ± 0.21	0.60 ± 0.08
		Aug	S1	1.11 ± 0.23	0.95 ± 0.36	1.18 ± 0.18	1.07 ± 0.40	0.82 ± 0.04	1.16 ± 0.37	0.71 ± 0.24	0.68 ± 0.11
		Sep	S1	0.70 ± 0.05	0.64 ± 0.13	0.86 ± 0.11	0.72 ± 0.13	0.70 ± 0.03	0.81 ± 0.10	0.63 ± 0.09	0.69 ± 0.06
	3-yr average	June	S2	0.57 ± 0.09	0.36 ± 0.25	0.36 ± 0.26	0.47 ± 0.15	0.42 ± 0.19	0.40 ± 0.25	0.36 ± 0.22	0.41 ± 0.22
		July	S2	0.79 ± 0.24	0.74 ± 0.26	0.80 ± 0.30	0.57 ± 0.19	0.77 ± 0.30	0.64 ± 0.11	0.72 ± 0.20	0.58 ± 0.09
		Aug	S2	0.98 ± 0.27	1.21 ± 0.09	1.03 ± 0.31	0.83 ± 0.29	0.96 ± 0.07	1.02 ± 0.29	0.69 ± 0.11	0.56 ± 0.08
		Sep	S2	0.64 ± 0.22	0.68 ± 0.08	0.66 ± 0.11	0.48 ± 0.09	0.70 ± 0.05	0.69 ± 0.19	0.60 ± 0.12	0.54 ± 0.11
	3-yr average	June	S3	0.34 ± 0.25	0.42 ± 0.20	0.33 ± 0.28	0.50 ± 0.14	0.41 ± 0.25	0.44 ± 0.18	0.35 ± 0.2	0.35 ± 0.20
		July	S3	0.93 ± 0.37	0.93 ± 0.33	0.89 ± 0.21	0.51 ± 0.09	0.61 ± 0.24	0.57 ± 0.10	0.51 ± 0.11	0.66 ± 0.14
		Aug	S3	1.05 ± 0.15	1.16 ± 0.35	1.10 ± 0.28	0.87 ± 0.14	1.03 ± 0.18	1.03 ± 0.14	0.85 ± 0.31	0.71 ± 0.29
		Sep	S3	0.66 ± 0.26	0.70 ± 0.27	0.67 ± 0.21	0.52 ± 0.08	0.54 ± 0.13	0.63 ± 0.15	0.53 ± 0.15	0.56 ± 0.06

Table 10

Statistical analyses for alfalfa-reference crop coefficients (Kcr) between fixed (uniform) rate irrigation (FRI), variable rate irrigation (VRI) and no irrigation (NI) treatments under fixed (uniform) rate fertilizer (FRF), variable rate fertilizer (VRF) and pre-plant fertilizer (PP) management in three soil types at the 5% significance level [$p_{(0.05)}$]. Var. 1: variable 1 and Var. 2: variable 2. The bold *p* values followed by asterisks indicate statistically significant difference in Kcr values. S1: Crete silt loam, S2: Hastings silty clay loam and S3: Hastings silt loam.

Soil	Fixed (uniform) rate irrigation (FRI)														
	FRF vs VRF					FRF vs PP					VRF vs PP				
	Mean		Variance		$p_{(0.05)}$	Mean		Variance		$p_{(0.05)}$	Mean		Variance		$p_{(0.05)}$
	Var. 1	Var. 2	Var. 1	Var. 2		Var. 1	Var. 2	Var. 1	Var. 2		Var. 1	Var. 2	Var. 1	Var. 2	
S1	0.7138	0.6513	0.0661	0.0444	**0.0087***	0.7138	0.7700	0.0661	0.0731	**0.0167***	0.6513	0.7700	0.0444	0.0731	**0.0051***
S2	0.6825	0.6875	0.0319	0.1016	0.4664	0.6825	0.6538	0.0319	0.0647	0.2200	0.6875	0.6538	0.1016	0.0647	0.1669
S3	0.6863	0.7425	0.0815	0.0846	**0.0022***	0.6863	0.6850	0.0815	0.0879	0.4567	0.7425	0.6850	0.0846	0.0879	**0.00004***

Soil	Variable rate irrigation (VRI)														
	FRF vs VRF					FRF vs PP					VRF vs PP				
	Mean		Variance		$p_{(0.05)}$	Mean		Variance		$p_{(0.05)}$	Mean		Variance		$p_{(0.05)}$
	Var. 1	Var. 2	Var. 1	Var. 2		Var. 1	Var. 2	Var. 1	Var. 2		Var. 1	Var. 2	Var. 1	Var. 2	
S1	0.6613	0.5950	0.0671	0.0282	0.0647	0.6613	0.7525	0.0671	0.0806	**0.0009***	0.5950	0.7525	0.0282	0.0806	**0.0045***
S2	0.5400	0.6550	0.0261	0.0449	**0.0084***	0.5400	0.6288	0.0261	0.0539	**0.0247***	0.6550	0.6288	0.0449	0.0539	0.1401
S3	0.5500	0.6000	0.0287	0.0602	0.1001	0.5500	0.6113	0.0287	0.0558	**0.0365***	0.6000	0.6113	0.0602	0.0558	0.2874

Soil	No irrigation (NI)				
	FRF vs VRF				
	Mean		Variance		$p_{(0.05)}$
	Var. 1	Var. 2	Var. 1	Var. 2	
S1	0.5388	0.5488	0.0178	0.0145	0.2281
S2	0.5438	0.4775	0.0233	0.0074	**0.0187***
S3	0.5238	0.5213	0.0361	0.0225	0.4713

Table 11

Alfalfa-reference crop coefficient (Kcr) to grass-reference crop coefficients (Kco) ratios (K values) for fixed (uniform) rate irrigation (FRI), variable rate irrigation (VRI) and no irrigation (NI) treatments under fixed (uniform) rate fertilizer (FRF), variable rate fertilizer (VRF) and pre-plant fertilizer (PP) management in three soil types all treatments in three soil types for individual years and average three years. S1: Crete silt loam, S2: Hastings silty clay loam and S3: Hastings silt loam. SD: standard deviation.

K value	Month	Irrigation	FRI			VRI			NI	
		Nitrogen Soil	FRF	VRF	PP	FRF	VRF	PP	FRF	VRF
3-yr average K values	June	S1								
	July	S1	0.85	0.83	0.84	0.86	0.84	0.83	0.84	0.83
	Aug	S1	0.86	0.85	0.86	0.88	0.87	0.88	0.86	0.87
	Sep	S1	0.81	0.81	0.80	0.81	0.80	0.81	0.83	0.81
3-yr average K values	June	S2	0.79	0.78	0.81	0.79	0.79	0.80	0.81	0.78
	July	S2	0.86	0.84	0.84	0.82	0.83	0.83	0.83	0.83
	Aug	S2	0.86	0.88	0.86	0.88	0.89	0.85	0.87	0.88
	Sep	S2	0.80	0.81	0.80	0.83	0.81	0.81	0.82	0.81
3-yr average K values	June	S3	0.79	0.79	0.79	0.80	0.78	0.80	0.80	0.80
	July	S3	0.84	0.86	0.83	0.82	0.90	0.82	0.98	0.83
	Aug	S3	0.88	0.88	0.86	0.86	0.87	0.87	0.87	0.86
	Sep	S3	0.82	0.83	0.81	0.83	0.81	0.79	0.81	0.80
3-yr average K values	June	All soils	0.79	0.78	0.80	0.79	0.79	0.80	0.80	0.79
	July	All soils	0.85	0.84	0.84	0.84	0.86	0.83	0.88	0.83
	Aug	All soils	0.86	0.87	0.86	0.87	0.88	0.87	0.87	0.87
	Sep	All soils	0.81	0.82	0.80	0.82	0.81	0.81	0.82	0.81
3-yr average SD of K values	June	All soils	0.003	0.007	0.010	0.007	0.010	0.005	0.005	0.010
	July	All soils	0.011	0.015	0.003	0.019	0.039	0.003	0.083	0.003
	Aug	All soils	0.011	0.015	0.0001	0.010	0.010	0.014	0.006	0.008
	Sep	All soils	0.011	0.011	0.002	0.015	0.008	0.011	0.007	0.006

4. Summary and Conclusions

This research quantified ETc, Kcr and Kco curves and algorithms as a function of CGDD for maize under different irrigation (FRI, VRI and NI) under different nitrogen management practices (FRF, VRF and PP) in three soil types for maize for three growing seasons. On average, the 2015 growing season was warmer than 2016 and 2017 and growing season precipitation in 2015, 2016 and 2017 was 353, 375 and 467 mm, respectively. Our results showed that soil type, irrigation management and nitrogen management strategies all had an impact on Kc values. In 2015, the maximum Kcr occurred between CGDD values of 900 and 1200 °C (mid-August), which corresponded to the R2 to R3 growth stages in the FRI-PP treatment. Inter-annual variations were observed in Kc values. Greater Kcr values were observed in 2016 and 2017 as compared with 2015. The maximum Kcr values in 2016 for the FRI and VRI treatments occurred in August, which was also at the R2 to R4 growth stages (CGDD 1119 to 1400 °C) in that season. Similar to 2015, the maximum Kcr values were observed in the FRI treatment in 2016 as well. In 2017, Kcr values were in a similar range as in 2016 for the FRI and VRI treatments and, on average, maximum Kcr was observed in the FRI treatment. Maximum Kcr for all treatments occurred at CGDD 800 to 1400 °C (late July to early September) which was at the VT to R4 growth stages. On a monthly average basis, maximum Kcr and Kco values were observed in July and August in all soil types and minimum Kc values were observed in June. Overall, the maximum Kcr value was observed in the FRI-PP treatment in S1 (1.02), the FRI-VRF treatment in S2 (1.06) and the FRI-VRF treatment in S3 (1.02). The results of this research indicated that the magnitude of Kcr and Kco depends on the irrigation management strategies (amount and timing of water). In general, the maximum Kcr and Kco values were observed in FRI. The difference between the Kcr curves at different nitrogen levels were observed, which was more pronounced in the VRI and NI treatments than in FRI for all years. Kcr to Kco ratios (K values) were quantified and tabulated for each irrigation and nitrogen management strategy in each soil type. This conversion (K values) would be beneficial in terms of using Kcr or Kco values developed for a region in another region for irrigation management, ETc estimations and other purposes where Kc values are not available.

With increasing interest in variable rate technology and due to increasing nitrogen application restrictions and decline in water resources, it is critical to understand the impact of various irrigation and nitrogen management strategies on crop water use to plan and manage water and fertilizers efficiently. To the best of our knowledge, this research is the first to investigate the impact of variable rate irrigation and nitrogen management strategy on crop coefficients for maize under different soil types. The crop coefficient curves presented in this research can aid irrigators, state agencies and others for accurate crop water use estimates under different irrigation and nitrogen management strategies and soil types to make field level and larger scale irrigation management decisions and water resources assessments, planning, management and allocation decisions for the climate, soil and cropping systems conditions similar to those presented in this research. Further research to investigate the applicability/transferability of the crop coefficients developed in this research in other regions with similar characteristics is needed.

Declaration of Competing Interest

The authors declare no conflict of interest.

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