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Concurrent Response of Soybean to Fixed (Full and Limited) and Variable Rate Irrigation Management in Three Soil Types: II. Growth, Yield, Evapotranspiration and Water Productivity

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ABSTRACT

Soybean growth, yield, crop evapotranspiration (ETc) and crop water use efficiency (CWUE or crop water productivity, CWP) under different irrigation levels in three different soil types in the same field were investigated concurrently. Treatments in each soil type were: (i) variable rate irrigation (VRI), (ii) fixed rate full irrigation (FR-1″) and (iii) fixed rate limited irrigation (FR-0.75″). There was not enough evidence suggesting the superiority of VRI over FRI-1″ or FRI-0.75″ in terms of improving yield or CWUE. Leaf area index (LAI) and plant height were stronger functions of soil types than irrigation treatments. Growing season cumulative grass-reference evapotranspiration (ETo) and cumulative precipitation were 629 and 489 mm, respectively, in 2018; and 589 and 551 mm, respectively, in 2019. Variations in yield among irrigation treatments for both seasons were not significant ($p > 0.05$). Soil type, rather than irrigation treatments, explained variation in yield with statistical significance ($p < 0.05$). Soil types had substantial impact on ETc and CWUE. Since spatial variability in soil properties has a profound impact on soybean growth, yield, ETc and CWUE, soil variability in horizontal and vertical domain must be considered for developing accurate management zones and prescriptions for VRI, and for in-season VRI, FRI and limited irrigation management for successful and effective operations.

Résumé

La croissance, le rendement, l'évapotranspiration d'un couvert (ETc) et l'efficacité d'utilisation de l'eau des cultures (CWUE) du soja sous différents niveaux d'irrigation dans trois types de sol différents sur le même champ ont été étudiés simultanément. Les traitements pour chaque type de sol ont été les suivants: (i) l'irrigation à taux variable (VRI), (ii) l'irrigation complète à taux fixe (FR-1") et (iii) l'irrigation limitée à taux fixe (FR-0,75"). Il n'y avait pas assez de preuves suggérant la supériorité de VRI par rapport à FRI-1" ou à FRI-0,75" en termes d'amélioration du rendement ou de l'efficacité d'utilisation de l'eau des cultures (CWUE). L'indice de surface foliaire (ISF) et la hauteur des plantes étaient des fonctions plus importantes des types de sol que

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les traitements d'irrigation. L'ETo cumulatif et les précipitations cumulatives de la saison de croissance étaient de 629 et 489 mm respectivement, en 2018; et 589 et 551 mm, respectivement, en 2019. Les variations de rendement entre les traitements d'irrigation pour les deux saisons n'étaient pas significatives ($p > 0,05$). Le type de sol, plutôt que les traitements d'irrigation, expliquait la variation du rendement avec une signification statistique ($p < 0,05$). Les types de sol ont exercé un impact important sur l'ETc et la CWUE. Étant donné que la variabilité spatiale des propriétés du sol exerce un impact profond sur la croissance, le rendement, l'ETc. et la CWUE du soja, il faut tenir compte de la variabilité du sol dans les domaines horizontal et vertical pour élaborer des zones de gestion précises et des prescriptions pour l'irrigation à taux variable (VRI), et pour la VRI en saison, l'irrigation complète à taux fixe (FRI), et la gestion de l'irrigation limitée pour des exploitations réussies et efficaces.

1 | Introduction

Irrigation, which is pertinent for current crop production, is the largest sector for freshwater withdrawals globally. Awareness of conserving and efficient use of freshwater resources is becoming more important than ever before as the allocation needs increase due to several factors, including global climate change, competition for water resources between different sectors, freshwater quality degradation, over-pumping of water resources, suboptimal irrigation management (usually overirrigation) and other factors. Human food demand is expected to double by 2050 and the challenge of meeting the demand with relatively constant or declining cultivable land area and limited water resources necessitate the maximization of the water use efficiency and growing more food, fibre and feed with limited resources. The global land area currently is about 13.2 billion ha, of which only 12% (1.6 billion ha) is used for the cultivation of agricultural crops, 28% (3.7 billion ha) is under forest, and 35% (4.6 billion ha) comprises grasslands and woodland ecosystems (FAO 2013; Ritchie and Roser 2019; Irmak 2023). The world's population has increased stupendously, from 1.52 billion in the early 1800s to almost 8 billion today. The world's population has been increasing at an extraordinary rate until the late 1980s and early 1990s, with a net addition of people per year increasing from about 47 million people per year in 1950 to 93 million people per year in the late 1980s (Irmak 2023). In the year 2050, it is estimated that the world population will reach 10 billion, which will place additional substantial pressure on irrigated agriculture to meet the aforementioned demands and the global climate change will make all these processes and efforts more challenging. Thus, currently available technologies and effective water management strategies need to be implemented in the agricultural production fields or newer technologies must be developed and adopted to enhance production efficiency and productivity to keep pace with the increases in population demands.

Numerous irrigation management technologies are currently available to utilize water resources wisely and improve crop production efficiency. In non-water limiting areas, fixed rate irrigation is usually practiced. Full and fixed rate irrigation (FRI), is the uniform application depth of irrigation water over cropping fields and is the most common irrigation method globally, including in the United States. In water-limiting areas with relatively uniform terrain and soil properties, fixed rate limited irrigation is practiced. The limited FRI is the application of a portion of the full irrigation amount in each irrigation to the crop throughout the growing season (Irmak 2015a, 2015b). This method is usually practiced, or should be practiced, in regions with high water holding capacity soils (e.g. silt loam) with uniform or relatively uniform soil properties. In areas with limited or non-limiting water resources, but with substantial variability in terrain, soil properties, variable rate irrigation (VRI) can be practiced to account for soil variability to determine crop's irrigation requirement. In addition to determine irrigation requirement for spatially variable fields, the VRI system can also be applied to vary nitrogen requirement (Sharma and Irmak 2021a, 2021b) based on several factors, including differences in soil physical and chemical characteristics. Most of the VRI applications have been based on the delineation of management zones to develop either stationary or dynamic irrigation prescription maps using one or multiple proxies of soil properties such as electrical conductivity (ECa) (Brevik et al. 2006; Moral et al. 2010; Hawkins et al. 2017; Maona et al. 2023); electromagnetic induction (Daccache et al. 2015); crop canopy temperature (O'Shaughnessy and Evett 2010; O'Shaughnessy et al. 2015); decision support software and simulation models (Al-Kufaishi et al. 2006; Kim and Evans 2009; McCarthy et al. 2010; Stone et al. 2020; Sui et al. 2020); satellite data (Penzotti et al. 2023); plant water status (Bellvert et al. 2012); *EZZone* management, soil water status, soil-water balance, soil water holding capacity, pan evaporation and weather data (Vellidis et al. 2008; Hedley et al. 2009; Han et al. 2009; de Lara et al. 2017; Li 2017; Li et al. 2018; Li et al. 2021; Vories et al. 2021; Sharma and Irmak 2021a, 2021b), soil-water holding capacity (Hedley and Yule 2009; Zhao et al. 2017; Dennis et al. 2020); artificial intelligence techniques (Gonzalez Perea et al. 2018), *k*-means, ISODATA, Gaussian mixture, natural rupture and fuzzy logic method of soil clustering (Gili et al. 2017; Yari et al. 2017) and site-specific water production functions (Haghverdi et al. 2016).

Adoption of VRI technology in growers' production fields is a complicated matter. Although the VRI technology has been developed in the early 1980s (Evans and King 2012; Evans et al. 2013) [the commercial VRI systems were available since 2004 (Milton et al. 2006)], its implementation in the growers' production field ranges from non-existent to extremely limited. Most of the applications of VRI technology are still in the research settings in academic institutions and in USDA-ARS. Some of the potential reasons for extremely limited adoption of VRI technology in growers' production field include, but not limited to: (i) limited understanding/knowledge of developing management zones and operating the system according to the prescription maps; (ii) since 'dynamic' rather than 'stationary' prescriptions are needed for successful and effective within-season VRI implementation, there is also a significant time investment in building prescription maps due to the needs of frequent update prescription maps using one or more field-measured variables; (iii) lack of simple and practical methods and algorithms for developing VRI prescriptions; (iv) system malfunction and uncertainties in how to proceed with VRI after the system is fixed; (v) system cost as well as uncertainties in economic net return with VRI as compared

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with fixed rate irrigation practice; (vi) uncertainties or lack of data and information as whether the grower's field is spatially variable enough to justify adopting a VRI system; (vii) uncertainties in operating the system in wind conditions and impact(s) on spatially soil-water status in the field as operating the VRI system in windy conditions can make the spatial water application almost impossible and can defeat the purpose of using VRI system. Furthermore, in relation to growers and the commercial market, uncertainty of the claimed benefits from new technology is a major impediment. According to a 2018 USDA Irrigation and Water Management Survey (USDA-NASS 2018), data on barriers obstructing improvements to irrigation to conserve water or energy suggested that a major impediment was the concern that technology-driven improvements will not be sufficient to breakeven installation costs (represented 15.3 million ac-ft = 18.9 billion m^3 = 18.9 km^3). Additionally, the risk of a reduced yield or poorer quality crop was another major impediment. While the survey data are not directly regarding the VRI adoption, considering the purpose of VRI, it is justified that it would be one component of improvements to irrigation. The financial implications of irrigation improvements, especially for VRI systems, can add up. VRI system monitors can cost $2000 and individual sprinkler controls can reach $20,000 and over (Kranz et al. 2012). To justify these improvements, proportional or higher returns are necessary. Knox et al. (2012) found that growers perceive irrigation in terms of maximizing profit, rather than water conservation. Potential returns of VRI, when compared to FRI are, but not limited to lowering water application, lower drainage and runoff losses, decreased nitrogen leaching, lower energy use per season and higher water use efficiency (Hedley and Yule 2009). However, these benefits are not ubiquitous. Adoption of VRI technology will result in varying degrees of beneficial and non-beneficial outcomes for each field (Pokhrel et al. 2018) because the type and degree of variability is different in each field, and the return on investment depends on a number of factors, including crop type, useful life of the equipment, cost of water and the cost to pump the water (Marek et al. 2013). Scientific literature is lacking in terms of a concrete understanding of quantitative outcomes of VRI and thus, demonstrating the improved water management or increased net returns of VRI will be a long-term challenge (Evans et al. 2013). As mentioned earlier, the current conditions are such that the VRI infrastructure and technology are available, but the means of effectively implementing VRI management are lacking, and yet to be demonstrated to be actually superior to FRI or limited irrigation.

Literature in terms of VRI's impact on reduction in water application, crop yield, uniformity and crop water use efficiency reveal diverse or inconclusive findings. O'Shaughnessy et al. (2019) reviewed the VRI literature and concluded that the advantages of VRI technology are demonstrated in the areas of agronomic improvement, greater economic returns, environmental protection and risk management, while the main drawbacks of VRI technology include the complexity to successfully implement the technology and the lack of evidence that it assures better performance in net profit or water savings. However, based on the literature, the advantages of this technology, even for agronomic productivity improvement, greater economic returns than fixed rate irrigation strategy, environmental protection and risk management also have mixed findings. Only a very limited number of studies have shown the advantage in water saving of these systems for crops including winter wheat, maize, soybean and cotton (Vories et al. 2017; Li et al. 2019; Sui et al. 2020; Li et al. 2023). However, the definition of water saving in production fields is an extremely complex process. Thus, adopting the term 'reduction in water withdrawal' with VRI as compared with other irrigation strategies may be a more realistic, practical and beneficial description. Furthermore, quantification of water saving with VRI as compared with other irrigation management strategies itself is an extremely difficult task as, in most cases, the VRI system is compared with other irrigation strategies in different fields that may have different soil physical (and chemical) properties, management, topography and other variables which may make comparisons of different irrigation methods for water saving extremely difficult or invalid. The field delineation method used can also impact the comparisons between VRI and FRI as different delineation methods can result in different VRI performance. Yari et al. (2017) utilized variability in soil physical and chemical properties and in field elevation to define site-specific management zones using a stepwise multivariate regression approach to investigate how multiple measured parameters affect wheat yield. An unsupervised clustering algorithm, fuzzy c-means, was used to delineate the irrigation management zones. They found that ECa and field elevation were better suited for management zone delineation. Three management zones were identified based on the verification criteria using ECa and field elevation variables. Measured crop yield differences corresponding to the three noncontiguous management zones were significant. Haghverdi et al. (2015) used different clustering methods, including *k*-means, ISODATA and Gaussian Mixture to investigate the performance of multiple irrigation zoning scenarios on a 73-ha centre pivot-irrigated field. They used soil water content as the main attribute for zoning while ECa, space-borne satellite images and yield data were required as ancillary data. A good agreement was observed among delineated zones by different clustering methods. The new zoning method explained up to 40% of available water content variance. The ECa achieved the highest kappa coefficient (0.79) among ancillary attributes, hence exhibited a considerable potential for irrigation zoning.

The experimental design and set up as well as management can also influence VRI performance and can result in varying results. Vories et al. (2017) investigated irrigation scheduling for sprinkler irrigated rice using two irrigation timings based on management allowed depletion (MAD) (MAD1: 10 mm application at a 12 mm estimated soil water deficit (SWD); MAD2: 15 mm application at a 19 mm estimated SWD). For each MAD treatment, three VRI settings represented 75, 100 and 125% of the target applications. Seven fewer irrigations were applied to MAD2 plots in 2013 and 11 fewer in 2014, but larger applications resulted in similar total application amounts. Neither treatment main effect was significant for yield in 2013, but there was a significant interaction, with differences among the % application treatments for MAD2. The % application's main effect was significant for irrigation water use efficiency and there was a significant interaction. Soil moisture data were inconsistent, and variability among the sensors led to few significant differences. Yield was significantly greater than the field average for only one treatment combination (MAD1–100%) and significantly lower for two (MAD2–75, 100%). Irrigation water use efficiency of two of the treatment combinations was significantly greater than the field average (MAD1–75%, MAD2–75%) while two were significantly lower (MAD1–125%, MAD2–125%). Li et al. (2023)

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compared VRI with uniform rate irrigation (URI) for sudangrass and alfalfa using ECa to develop management zones (MZ). The feasibility of considering the ECa as an MZ delineation approach was supported by the fact that significant differences in yields existed among MZs in each cutting and annual of sudangrass. No significant differences existed between the VRI and URI with regards to the yield, WUE or IWUE in the 3 years of study. Compared to URI, VRI had a better water-conservation performance, especially in the rainy season, with average reductions of 22.2% and 12.6% (only in 2020) for sudangrass and alfalfa, respectively. Li et al. (2021) quantified and compared the deep percolation (DP) of three irrigation strategies, including soil water balance (SWB), measured soil water content and a combination of SWB and rain forecasting for the next 3 days (RF). They observed that RF method exhibited promise for reducing DP, and the zone-specific crop coefficients values were helpful to enhance the water savings of the SWB method for VRI. While VRI technology has been developed in the early 1980s (Evans et al. 2013), the investigation of this technology in terms of its effectiveness for crop growth (i.e. leaf area index [LAI] and plant height), grain yield, crop evapotranspiration (ETc) and crop water use efficiency (CWUE) as compared with the full and limited FRI, especially in different soil types simultaneously does not exist. To address these important knowledge gaps, and answer the fundamental question of viability of VRI as compared with full and limited FRI when used to manage soybean production, this research was designed to realize the following specific objectives: (i) investigating the impact of full and fixed rate, limited and fixed rate and VRI on soybean growth (e.g. plant height and leaf area index), grain yield, ETc and WUE. The addressal of each of these indicators of the soil-crop-atmosphere continuum and grain yield were accomplished considering both variability among the three soil textures, as well as implementing VRI, full fixed rate irrigation (FRI-1″ or [FRI-25.4 mm]) and limited fixed rate irrigation (FRI-0.75″ or [FRI-19 mm]) within each soil type independently and simultaneously, which is one of the novelties of the research. This research is a continuation of the research results reported by Irmak et al. (2025; companion paper, this issue) who investigated the soil water dynamics response to VRI, FRI-1″ and FRI-0.75″ in the same experimental field.

2 | Materials and Methods

2.1 | General Field Experimental Procedures

Field research was conducted in 2018 and 2019 growing seasons in a 2.3 ha field that had substantial spatial variability in soil properties and topography. Then, field research was a part of the Irmak Research Laboratory's advanced irrigation engineering, evapotranspiration, plant physiology and climate science facilities at the University of Nebraska-South Central Agricultural Laboratory. Detailed experimental procedures and processes, including the research site description; VRI system description and infrastructure and agronomic management practices; experimental design and determination of plot-specific soil properties; variable and fixed rate irrigation management protocols; soil-water status measurements and instrumentation; measured meteorological variables (maximum and minimum air temperatures, relative humidity, incoming shortwave radiation, wind speed and vapour pressure deficit) and growing degree days during the experimental periods as compared with the long-term averages; root-zone total soil water; irrigation applications across irrigation treatments and soil types; spatial distribution of soil water characteristics at critical times: water holding characteristics: field capacity, permanent wilting point and total available water and other experimental details were presented in Irmak et al. (2025; companion paper, this issue) and will not be repeated here. Only the materials and methods that pertain to the objectives of this paper are presented. Three distinct soil types existed in the research field: Crete silt loam, 0 to 1% slopes (soil type 1 or S1); Hastings silty clay loam, 3 to 7% slopes (soil type 2 or S2); and Hastings silt loam, 1 to 3% slopes (soil 3 or S3). There are six different soil textures across the horizontal and vertical domains in the research field: silt loam, silty clay loam, clay loam, loam, sandy clay loam and sandy loam. Irrigation was applied using a two-span 75-m-long 7000SL variable rate linear-move sprinkler irrigation system (T-L Irrigation Co., Hastings, Nebraska). System capabilities included a maximum of 48 watering channels, composed of 12 irrigation zones and 4 sprinklers per zone. Irrigation application rates are controlled using solenoid actuated ON/OFF sprinklers spaced 1.2-m apart and were mounted on drop tubes at approximately 2-m above ground level. The wetting diameter of each sprinkler was 6 m. Application maps were created using 'Irrigation Manage' software of the VRI irrigation system and were then uploaded to the 7000SL VRI controller. Irrigation rates from 10 to 90% were achieved by shutting water off and 120 to 200% watering rates were achieved by slowing down the lateral (linear)-move system. In both growing seasons, Golden Harvest GH3324X maize seed was sown at a population of 150,543 seeds/acre (372,000 seeds/ha) at a depth of 0.04–0.05 m. The soybean row spacing was 0.762 m. The entire field was uniformly managed for fertilizer, weeds, disease and soil management, and thus, the management did not vary across different plots.

Detailed descriptions of the irrigation management decisions are presented in Table 1 in Irmak et al. (2025; companion paper, this issue). The two main experimental factors in this research were irrigation management (fixed rate irrigation FRI-1″ [FRI-25.4 mm] depth, fixed rate irrigation FRI-0.75″ [FRI-19 mm] depth and variable rate irrigation [VRI]) and soil type (S1, S2 and S3). Each irrigation management treatment was imposed and evaluated under each of the three soil types. Irrigation management was a function of soil moisture, plot-specific soil physical properties and the imposed irrigation treatment. For each of the growing seasons, the maximum allowable depletion (MAD) was set at 40% of the TAW (MAD = 0.40 × TAW). MAD was calculated with the average TAW for the 0 to 0.60-m soil profile when the crop was at vegetative stages and 0 to 0.90 m when plants were at reproductive stages to account for the effective rooting depth for soybean (Mayaki et al. 1976). Three irrigation treatments replicated four times in each of the three soil types, resulting in 36 plots in the research field. Irrigation depth and frequency were a function of the treatment imposed on each plot. Soil moisture was measured in the 0–0.30, 0.30–0.60, 0.60–0.90, 0.90–1.20 and 1.20–1.50-m soil depths bi-weekly throughout the growing seasons with a Troxler Model 4302 neutron probe (NP) soil moisture gauge (Troxler Electronic Laboratories Inc., Research Triangle Park, North Carolina, United States). NP access tubes were installed post emergence in the crop row between healthy plants in the centre of the plots in the field using

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TABLE 1 | Maximum and mean leaf area index (LAI) across irrigation treatments and soil types during the 2018 and 2019 growing seasons.

		2018 LAI				2019 LAI			
		Soil 1	Soil 2	Soil 3	Trt. avg.	Soil 1	Soil 2	Soil 3	Trt. avg.
VRI	Max	7.3	6.3	5.9	6.5	4.9	3.5	3.8	4.1
	Mean	4.1	3.6	3.8	3.8	2.6	2.6	2.5	2.6
FRI 1″ (25.4 mm)	Max	7.2	6.2	6.6	6.7	4.2	3.2	2.8	3.4
	Mean	4.4	3.7	4.0	4.0	2.5	2.4	2.0	2.3
FRI 0.75″ (19 mm)	Max	6.7	6.7	6.1	6.5	4.3	3.4	—	3.9
	Mean	4.1	4.1	3.8	4.0	2.6	2.6	—	2.6
Soil Avg.	Max	7.1	6.4	6.2	6.7	4.5	3.4	3.3	3.2
	Mean	4.2	3.8	3.9	5.3	2.6	2.5	2.3	4.1

Giddings probe (Giddings Machine Co., Windsor, Colorado, United States).

2.2 | Plant Height, Leaf Area Index and Grain Yield Measurements

Plant height measurements were taken every 2 weeks during both growing seasons. Measurements were taken from the ground surface to the top of the canopy to the tip of the tallest leaf. Six plants were measured for plant height in each replication of all treatments. All plant height measurements were taken near the centre of the plot: with two measurements south of the centre, two measurements in the centre and two measurements slightly north of the centre. The plant height measurements were conducted until August 10 and September 26 in 2018 and 2019, respectively. Five leaf area index (LAI) measurements were taken from each plot, bi-weekly, in both seasons. Measurements were taken using a model LAI-2200 plant canopy analyser (Li-Cor Biosciences, Lincoln, Nebraska, United States). The LAI measurements were taken near the centre of the plot. All measurements were taken from north to south to avoid any shadows cast by the researcher or equipment. Soybean plants were harvested on October 4, 2018, and October 15, 2019. In both years, the centre four rows were harvested in each plot with a two-row plot combine. Harvest data were recorded with a grain yield monitor. Grain yield was adjusted to 13% standard moisture content and expressed as t/ha.

2.3 | Seasonal Crop Evapotranspiration, Deep Percolation, Surface Runoff and Water Use Efficiency

A general soil-water balance equation was used to determine the crop evapotranspiration (ETc) of soybean throughout the growing season:

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

where ETc is the crop evapotranspiration (mm); P is precipitation (mm); I is irrigation (mm); U is upward water flux (mm); Runon is surface runon within the field (mm); Runoff is runoff from individual treatments (mm); ΔSWS is change in soil water storage (mm) in the profile between the beginning and end of the growing season; and DP is the deep percolation from the crop root zone (mm). Due to vegetative buffer strips between fields, runon was assumed to be negligible and was given a value of 0. Upward water flux, or U, was also assumed to be negligible and was assigned a value of 0 because the water table is 30 m below the field surface. Using a program written in Microsoft Visual Basic, deep percolation was estimated by the daily soil water balance approach. Estimating the daily soil water balance required daily weather data (maximum and minimum values of air temperature (°C) and relative humidity (%), wind speed ($m\,s^{-1}$), incoming shortwave irradiance ($W\,m^{-2}$), and precipitation (mm), planting and harvest dated, and irrigation amount (mm) and dates. Minimum root depth was set to 0.10 m and maximum was 0.90 m for soybean. MAD values were constant throughout the growing season and set at 40%. Due to the spatial variability of the soil, FC and WP for 0.30, 0.60 and 0.90 m depths were adjusted for each plot based on previously described soil physical properties. Daily ETc and crop root-zone water balance were computed using the Penman equation's two-step process, which involves (i) determining reference evapotranspiration (ETref) for either clipped grass or alfalfa and (ii) multiplying by the crop coefficient (Kc), which is used to adjust reference evapotranspiration to the crop for a given location and growth stage (Task Committee on Revision of Manual 70 2005):

$$ET_c = Kc\ x\ ETref \quad (2)$$

Deep percolation (D_j) was calculated using the daily soil-water balance equation:

$$D_j = Max\left(P_j - R_j - I_j - ET_{cj} - CD_{j-1}\right) \quad (3)$$

where subscript j refers to specific days, making the variables daily specific. P_j is precipitation on day j with the same context for: precipitation or irrigation runoff R_j, irrigation depthI_j, actual crop evapotranspiration using the two-step approach ET_{cj}, and CD_{j-1} for root zone cumulative depletion depth at the end of the previous day (i.e. $_{j\text{-}1}$). Using the curve number

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procedure and equations from the USDA Natural Resources Conservation Service (USDA-NRCS, 1985), surface runoff was estimated. These services and methods were formerly known as the Soil Conservation Service (SCS). Each treatment's daily runoff was estimated using the relevant curve number (CN) from the SCS. CN are dependent on hydrological conditions and soil group as well as surface cover type and treatment. For row cropping and the research plot's soil types of silt loam (S1 and S3) and silty clay loam (S2), CN values of 78 and 89, respectively, were used. Antecedent runoff conditions (ARCs) are important scalers used to represent the soil moisture prior to precipitation events, which can affect runoff. CN values were scaled by the prior 5-day ARC. Three levels of ARC exist: ARC I, which is dry, and is represented by values less than 1, reducing the adjusted CN and the potential of runoff. ARC II, which has a value of 1 and represents the average soil moisture. CN values are represented at ARC II, hence the scalar of 1. AMC III represents wet soil and has values greater than 1, resulting in a larger adjusted CN and larger potential for runoff. Daily runoff was calculated using proper CN and the following equations: S, which is the potential maximum retention after runoff begins (mm), was calculated using the CN and the following equation:

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

Solving for S, the initial abstraction (I_a) (mm) can be obtained through:

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

Runoff was determined as:

$$RO = \frac{(P - I_a)^2}{(P - I_a) + S} \; for \; P > 0.2S \tag{6}$$

where RO is daily runoff (mm) and P is rainfall (mm). Daily RO values are summed for seasonal plot totals. Plot totals are sorted into their respective treatments and averaged again for seasonal treatment means. To understand the response of soybean to the irrigation treatments, CWUE was calculated as:

$$CWUE = \frac{Y}{ETc} \tag{7}$$

where CWUE is expressed in kg m^{-3}, Y is grain yield (kg m^{-2}) and ETc is crop evapotranspiration (mm).

3 | Results and Discussion

3.1 | Soil Type and Irrigation Treatment Impacts on Crop Growth (LAI and Plant Height)

LAI, defined as the total one-sided area of leaf tissue per unit ground surface area (Bréda 2003), is a representation of vegetation's ability to intercept light and water, transpire and perform photosynthesis (Viña et al. 2011). Stand productivity would be modified by any change in canopy LAI due to the abundance of interactions and processes LAI is representative of (Bréda 2003). Table 1 presents the impacts of the imposed irrigation treatments and soil types on maximum and mean LAI. Overall, little distinction between irrigation treatments exists for either growing season. S1 had the largest average LAI for the 2018 growing season, being 10% greater than S2 and 8% greater than S3. S1 also had the greatest average for 2019, being 4% greater than S2 and 12% greater than S3. FRI-0.75″ treatments were omitted for 2019 due to the irrigation scheduling error. Sharma and Irmak (2021a, 2021b) also observed similar trends in maize growth (represented by LAI) with either S1 or S2 demonstrating the maximum mean LAI, and S3 having the lowest LAI. The timing of attainment of the maximum LAI can be influenced by soil water conditions and thus were investigated for differences among soil types and irrigation treatments. The maximum LAI was reached on different dates for different soil types. For the 2018 growing season, maximum LAI values for S1 occurred 95 DAP (1211 °C CGDD-after planting (AP), August 10, 2018) S2 maximum LAI values were reached between 79 and 95 DAP (1008–1211 °C CGDD-AP, July 25–August 10, 2018) while S3 maximum LAI values were reached 66 DAP (836 °C CGDD-AP, July 12,2018). The 2018 and 2019 varied significantly in terms of LAI. The likely cause of this is due to extreme precipitation and delayed planting as compared with 2018. A light hail event occurred on August 7, 2019. Although the research field was affected much less than other cropped fields in the area, evidence of impact existed in crop measurements (Figure 1).

Plant heights for the 2018 growing season had little variance among irrigation treatments and soil types (Figure 2). Plant heights were nearly linear until the second to last data collection, 129 DAP (1591 °C CGDD-AP, September 13, 2018), when all plant heights had reductions in growing rates. Maximum plant height in 2019 was substantially lower than those measured in 2018, for similar reasons as LAI, and peaked at 81 DAP (941 °C CGDD-AP, August 6, 2019). The 2019 mean plant height, however, was higher than those in 2018. This may be explained by the dates the data was observed. The 2019 plant height measurements were delayed due to weather events, neglecting early season plant heights (smaller values), and may not be most accurately representative of the growing season. Similar to the LAI data, variation in 2019 plant heights was a stronger function of soil types than irrigation treatments. Considering the differences in seasonal irrigation amounts for both growing seasons, there is little evidence that suggests plant height differences among irrigation treatment. Nearly all average plant heights are within the standard deviation bars of the other treatments. There was also no evidence of differences in plant heights between the soil types. In VRI research to quantify within-field variation in alfalfa LAI using UAV visible vegetation indices, Hammond et al. (2023) reported that regardless of irrigation treatments, the difference in the LAI between management zones was not above a 15% threshold, which was considered to be the practical level needed to justify the use of VRI. Zhao et al. (2017) investigated the influences of soil properties on winter wheat and summer maize using VRI. In the two-year study, they observed that the seasonal irrigation amounts were basically equivalent among management zones for both winter wheat and summer maize. Differences in crop growth parameters were detected in plant height and LAI for winter wheat. They demonstrated

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that AWC is an effective parameter for zone identification in VRI, and differences in AWC and the layered-textural soils in a field may influence the crop growth, yield and water productivity of winter wheat and summer maize.

3.2 | Soybean Grain Yield Impacted by Irrigation Treatments and Soil Types

In addition to investigating soybean growth and morphological impacts, soybean grain yield was analysed to understand the effects of irrigation treatments and soil types on soybean productivity. Figure 3 represents soybean grain yield measured under each irrigation treatment in each soil type, individually for the 2018 and 2019 growing seasons and mean across the two growing seasons. Bars in Figure 3 are treatment means in each soil type, and the vertical error bars represent standard deviation across replications. The yield comparison for soil types in 2018 resulted with S1 having the largest average yield of 5.6 t/ha, with S2 and S3 having an average of 5.2 t/ha. Yields among irrigation treatments resulted with FRI-1″ having the highest average yield of 5.5 t/ha, VRI had the second highest at 5.3 t/ha, and FRI-0.75″ treatment had the lowest with 5.2 t/ha. Irrigation depths for each treatment for the 2018 growing season were 58 mm for VRI, 229 mm for FRI-1″ and 114 mm for FRI-0.75″. Comparisons of irrigation treatments' application depth and yield are as follows: VRI required 75% less water than FRI-1″, resulting in a 3% loss in yield and required 49% less water than FRI-0.75″ with a 1% increase in yield. FRI-0.75″ required 98% more water than VRI, resulting in a 1% decrease in yield. FRI-0.75″ also required 50% less water than FRI-1″, resulting in a 4% increase in yield. There was less uniformity among soil type and treatment types from visual analysis of the 2019 growing season. The largest average yield for the season was again, in S1, with an average of 4.4 t/ha. S2 had the second largest average yield as 4.2 t/ha, and S3 had the lowest yield as 3.6 t/ha. Irrigation treatments, however, were more uniform with VRI and FRI-0.75″ having the same average yield at 4.2 t/ha, as FRI-1″ average yield was 4.02 t/ha. Irrigated depths for irrigation treatments for the 2019 growing season were 45 mm for VRI, 0 mm for FRI-1″ and 76 mm for FRI-0.75″. In comparison of irrigated depths and irrigation treatment yields, VRI required 100% more irrigation than FRI-1″, resulting in a 4% increase in yield. VRI required 41% less irrigation than FRI-0.75″ with no difference in yield between the two treatments. The FRI-0.75″ treatment required 70% more water than VRI for no difference in yield and FRI-0.75″ was irrigated 100% more than FRI-1″ with a 4% increase in yield. Mean grain yields across 2018 and 2019 growing seasons exhibited trends observed in both years, however, pooled data had a much greater standard deviation than the two growing seasons. This is likely due to differences in growing season conditions and weather conditions affecting plant growth and productivity. It is not believed that the pooled data accurately represents soil type or irrigation effects on yield, and the observations of the individual season are better representations.

Ultimately for the two growing seasons, the decrease in irrigation amounts did not result in decreased yield. Bohman

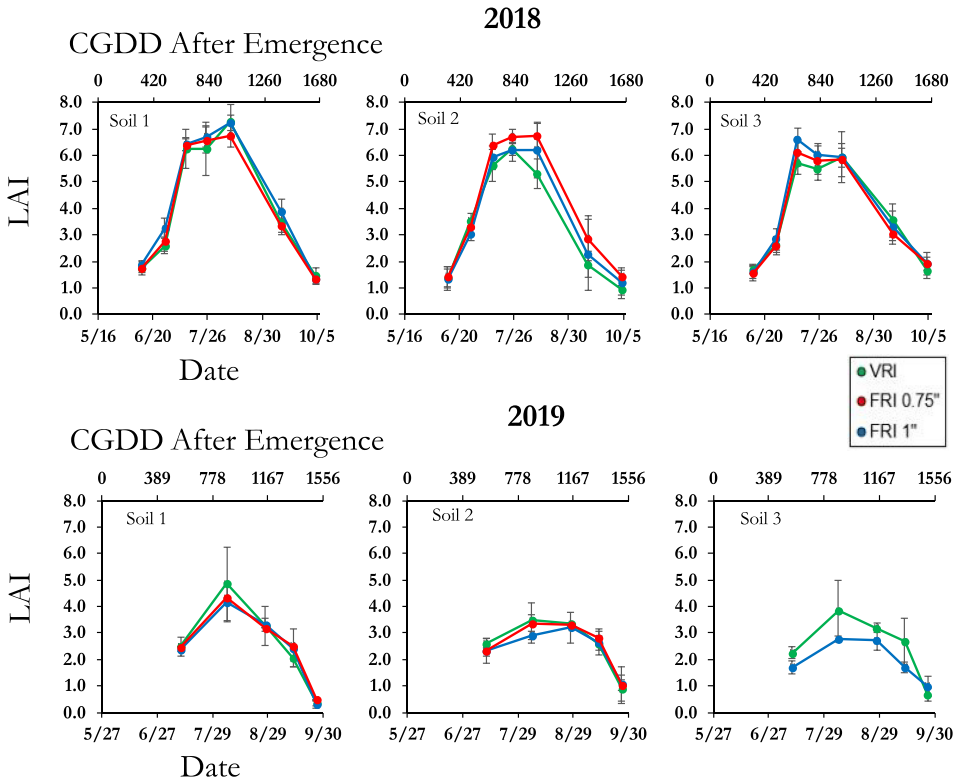

FIGURE 1 | Observed leaf area index (LAI) for each irrigation treatment in each soil type during 2018 and 2019 growing seasons with both date and cumulative growing degree days (CGDD) for comparison between the seasons Each data point represents an average of four replications. Vertical bars indicate standard deviation.

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et al. (2019) also reported that irrigation rate with VRI was reduced by 29–33 mm, but neither variable rate nitrogen management nor reduced irrigation produced significant differences in potato tuber yield or net return as compared with the full rate treatments. The VRI and FRI-0.75″ treatments in the current research exhibited very similar yields to FRI-1″ treatment for 2018 and yields of all three treatments for 2019 were similar, even with FRI-1″ receiving no irrigation for the season. Crop stress was observed in each irrigation treatment in 2018, but was not observed in 2019, which may help to explain similar yields. Considerations of precipitation and soil water dynamics during the 2018 and 2019 growing season as compared with the long-term seasonal average is an important factor for comparing irrigation treatments. Sharma and Irmak (2021a) observed significant differences in crop growth, yield and productivity among irrigation treatments within soil types, interannually. The growing season precipitations were 353 mm in 2015, 375 mm in 2016 and 467 mm in 2017 for the research site. Precipitation for the 2018 and 2019 growing seasons were 592 and 618 mm, for the same site, which is likely to have removed irrigation treatment distinctions from the two growing seasons. Economic evaluations of water savings for FRI and VRI irrigation are not in the scope of the research project and are an important part in transitioning from FRI to VRI irrigation; however, findings of the research suggest that VRI and limited irrigation provided similar yield with reduced irrigation applications. For a statistical understanding of the effects that irrigation treatments and soil types had on soybean yield, a two-way analysis of variation (ANOVA) was conducted. Table 2 presents the composition of p-values for the two-way ANOVA for 2018, 2019 and pooled data for both years. Due to differences in growing season conditions and weather events, it is not believed that pooled data is the best representation of the effects irrigation treatment and soil types had on soybean yield. A two-way ANOVA was conducted on grain yield data from all soil types and all irrigation treatments to provide statistical evidence that variation in yield was not statistically different than variation in irrigation treatments or soil types. Failure to reject the null hypothesis means there was not a statistically significant difference among yields for the selected variable. Rejecting the null hypothesis means that there was a statistically significant difference in yield. Statistical significance was observed when p values ≤ 0.1, and the lower the p value, the greater confidence that mean yield is significant among the variables.

The 'All soils, all irrigation treatments' row in Table 2 represents the p values for the two-way ANOVA for yield among all soil types and yield among all irrigation treatments. This test was used for a general statistical understanding of the effects irrigation treatments and soil types had on yield. From the data, it was determined that variation in yield among irrigation treatments for 2018, 2019, and pooled data was not significant, hence, resulted in failure to reject the null hypothesis. In context, this means that neither of the three irrigation treatments provided any statistical evidence for an increase or decrease in yield. Further investigation showed that there was no significant difference among any of the three irrigation treatments in any of the soil types. From observations of Figure 1, these results are expected as there was noticeable uniformity among irrigation types. Lack of significance in variation among irrigation treatments, however, is an indicator that all three irrigation treatments provided non-significantly different yields. As the three irrigation treatments supplied varying depths of irrigation, using less water without sacrificing yields provides support to limited and variable rate irrigations. Irmak (2015a) similarly found that yield of fully irrigated and 75% of full irrigation treatments resulted in non-statistically significant yields in the same experimental area for maize.

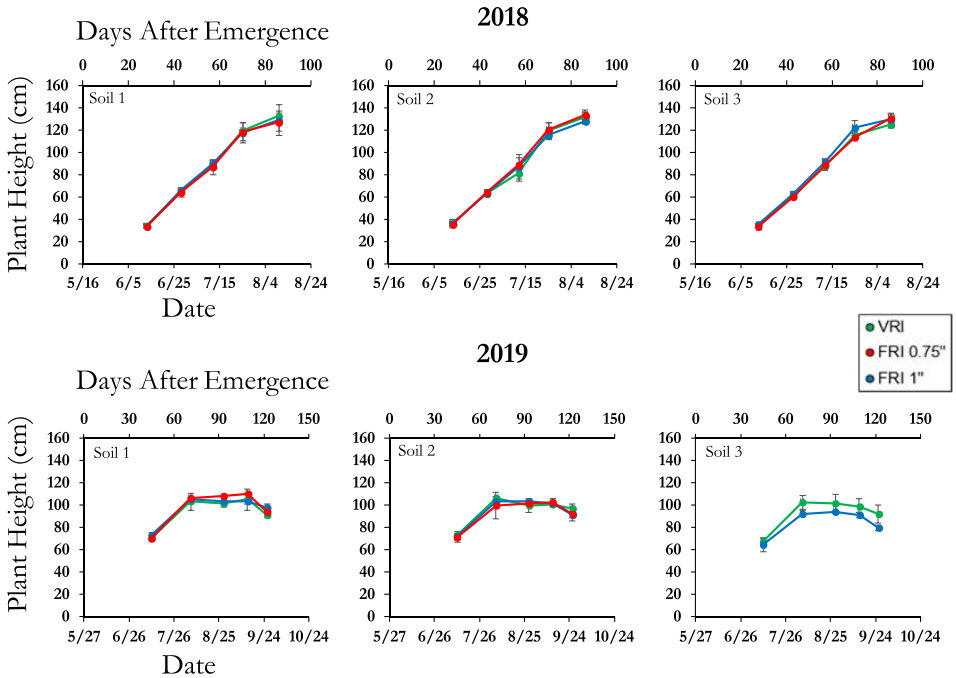

FIGURE 2 | Observed plant height for each irrigation treatment in each soil type during 2018 and 2019 growing seasons with both date and days after emergence for comparison between the seasons. Each data point represents an average of four replications. Vertical bars indicate standard deviation.

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The two-way ANOVA test also revealed that soil type resulted in statistically significant differences in grain yield, hence, rejecting the null hypothesis for 2018, 2019 and pooled data.

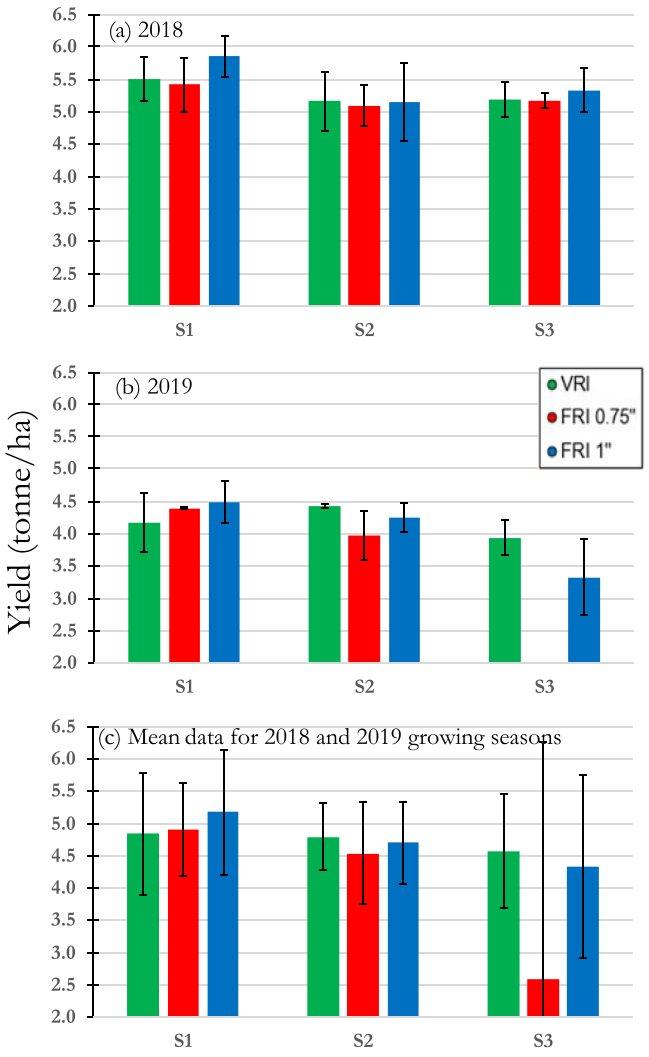

FIGURE 3 | Soybean grain yield during 2018 and 2019 growing seasons and pooled data for both growing seasons under each irrigation treatment and soil type. Each data point represents an average of four replications. Vertical bars indicate standard deviation.

Confidence that grain yield values are significantly different among soil types is 95% for the 2018 growing season, 99% confidence for 2019 and 90% confidence for the pooled data. Further evaluations of Table 2 showed *p* values for the variance in yield among two individual soil types. The yield among S1 and S2 is significantly different at 95% confidence interval for 2018, but the null hypothesis failed to be rejected for 2019 and the pooled data. The null hypothesis failed to be rejected for S2 and S3 for 2018 and pooled data; however, the null hypothesis was rejected for 2019 with a 99% confidence interval. The *p* values were significant with confidence intervals of 95% for 2018, 99% for 2019 and 90% for pooled data for S1 and S3, rejecting the null hypothesis for each data set. Thus, soil type was the only factor with statistical evidence explaining grain yield variability. Sharma and Irmak (2021a) showed significant impacts of maize grain yield by soil type. Significance occurred in all 3 years with S1 having a significantly higher yield than S2 and S3, which follows the findings of the current research in 2018 and 2019. Sadler et al. (2002) also found crop yield's response to irrigation to be significant at the 1% level among soil replications. Jiang and Thelen (2004) concluded for seven site-years out of nine that the combined effect of soil properties and topographic data explained 30 to 85% of grain yield variability.

Although it is not in the scope of this research to determine the exact biophysical properties causing the grain yield variability, yield was regressed against LAI to determine if crop morphology (foliage) can partially explain crop yield, and thus, the differences detected in LAI early in the season due to soil types could be potentially translated to grain yield. As literature (Board et al. 1996; Kumudini et al. 2001) provided evidence of LAI's relationship with and in-season indication of crop yield, these relationships were investigated for the 2018 and 2019 growing seasons (Figure 4). The relationship between maximum LAI and yield was also investigated; however, it was found that the maximum LAI did not explain any of the variability in grain yield. This could be because maximum LAI during the growing season only represents cumulative impacts of influencing variables during vegetative stages and does not convey crop condition during grain-fill period, which is the one of the most sensitive stages that is determinant of grain yield. On the other hand, growing season mean LAI includes the grain-fill period

TABLE 2 | Two-way ANOVA *p* values for grain yield among irrigation treatments and soil types with suffixes denoting; *** indicates significance at 99% confidence interval (CI), ** indicates significance at 95% CI, * indicates significance at 90% CI.

	2018		2019		2018–2019 pooled data	
Two-way ANOVA between:	***p* value of irrig. trts.**	***p* value of soils**	***p* value of irrig. trts.**	***p* value of soils**	***p* value of irrig. Trts.**	***p* value of soils**
All soils, All irrigation trts.	0.351	0.014**	0.131	0***	0.645	0.098*
FRI-1″ vs. FRI-0.75″, all soils	0.178	0.036**	0.054	0***	0.372	0.113
FRI-1″ vs. VRI, all soils	0.335	0.042**	0.942	0.004***	0.701	0.231
FRI-0.75″ vs. VRI, all soils	0.704	0.134	0.084	0.004***	0.574	0.341
S1 vs. S2, all irr. trts.	0.503	0.015**	0.294	0.387	0.607	0.141
S2 vs. S3, all irr. trts.	0.852	0.538	0.004	0***	0.733	0.421
S1 vs. S3, all irr. trts.	0.157	0.012**	0.699	0***	0.753	0.052*

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crop condition, and thus may have a better capability for predicting grain yield. In observation of the 2018 growing season, a linear trendline was fitted for all plots with a slope of 0.51. The coefficient of determination (R^2) of the linear regression was 0.17; hence, LAI explained only 17% of yield variability. R^2 was also investigated for yield data among soil types. Low R^2 values were found, however, each linear regression line was positive and differed between the three soil types. The 2019 LAI and yield data were fitted with a linear regression line with a slope of 1.01 and R^2 of 0.29, indicating that 29% of variation in yield can be explained by LAI. Linear regression lines were also investigated for LAI and yield among soil types. There was significant variation between the soil types in terms of what percentage of grain yield was explained using seasonal average LAI. For example, when individual soil types are considered, S3 explained as much as 32% of yield variability in 2018 and as high as 41% in 2019. The R^2 results indicated variances for all three soil types, with positive slopes for S2 and S3. The S1's slope, however, was negative in 2019, but this weak relationship cannot be relied upon to explain yield variability.

3.3 | Crop Evapotranspiration (ETc)

To understand the effects of VRI, FRI and limited irrigation treatments in three varying soil types on ETc, measured and observed data were input to the soil-water balance equation. Figure 5 presents irrigation treatment average ETc data for each soil type, and Figure 7 provides daily and cumulative precipitation and ETo for 2018 and 2019. In 2018, FRI-1″ irrigation treatment had the largest ETc in all soil types. FRI-1″ irrigation treatments had the largest ETc for each soil type, with FRI-0.75″ having the second greatest, and VRI the least. The average ETc in each soil type were: 553 mm in S3, 543 mm in S2, and 540 mm in S3. Although no statistical analysis was performed on ETc data, there was less variation in ETc among irrigation treatments than soil type given the standard deviation values. ETc similarities among irrigation treatment were unexpected; however, it is plausible given the variables in the soil-water balance equation. Irrigation, runoff, deep percolation and change in soil water storage were the only variables in the soil-water balance equation that were dynamic regarding irrigation treatment and soil type. As the three soil types exhibit contextually similar physical properties among themselves, ETc values are likely to be most dependent on change in water storage and irrigation. In discussion of irrigation treatments, FRI-1″ resulted in the largest ETc, with FRI-0.75″ treatment being the second, and VRI treatment being the lowest. Similar trends in ETc were also represented in irrigation treatments, which also reflected total irrigation quantities. Observations of VRI treatments among soil types are interesting as they received varying rates of irrigation depths for the growing season, but exhibited similar ETc. As there may not have been enough of a difference in irrigation among the treatments and soil types to be apparent in ETc, it is also potential evidence of site-specific management. Sharma and Irmak (2021a) found that differences in maize ETc were not significantly different among soil types or irrigation and nitrogen for the 2015 growing season in the same experimental field. In 2016, statistical significance in ETc for irrigation and nitrogen separately was observed; however, significance among soil type was not. The impacts of irrigation treatments in 2016 showed that FRI-1″ treatment's ETc was 19.3% greater than VRI and 43.9% greater than non-irrigated (NI) treatment, and 2017 resulted in significance among soil types as well as irrigation and nitrogen treatments. FRI-1″ had the maximum ETc among all treatments in all years, except S1 in 2015. The NI treatments had the minimum ETc in soil types in all three years.

For the 2019 growing season, ETc was visually spiritic without uniformity among irrigation treatments or soil types which may result from precipitation events throughout the growing season. There was only a 37.8 mm deficit in ETc and precipitation for the growing season. The seasonal ETc in S1 were 416 mm for FRI-1″; 411 mm for FRI-0.75″ and 411 mm in VRI. ETc values in S2 were 416 mm for FRI-0.75″; 393 mm for FRI-1″ and 387 mm for VRI. ETc was 436 mm and 407 mm for VRI and FRI-1″, respectively, in S3. Considering that FRI-1″ did not receive irrigation in 2019, similar ETc values may be the result of precipitation or the impact of soil physical properties. Variability in both irrigation treatments and soil type are depicted from the growing season of 2019. Averaged data for the growing seasons of 2018 and 2019 appear to follow similar trends among irrigation treatments and soil types.

3.4 | Soybean Crop Water Use Efficiency (CWUE)

CWUE can be used as a powerful indicator to determine the efficiency of irrigation treatments and soil types in terms of producing soybean yield ($kg\,m^{-2}$) per mm of ETc. Figure 6 is the representation of irrigation treatment mean CWUE between the soil types for the 2018, 2019 and averaged data. The 2018 growing season resulted in S1 having the largest mean CWUE at $1.04\,kg\,m^{-3}$ and S2 and S3 had the same mean CWUE at $0.95\,kg\,m^{-3}$. Mean CWUE for VRI was $1.01\,kg\,m^{-3}$; for the FRI-0.75″, it was $0.97\,kg\,m^{-3}$; and for the FRI-1″, it was $0.95\,kg\,m^{-3}$. From visual and analytical observations, VRI had the highest efficiency in yield production per unit of ETc in the 2018 growing season. In relation to the other irrigation treatments and the soil types, VRI CWUE was 5% greater than FRI-1″ and FRI-0.75″ in S1; 4% greater than FRI-1″ and 3% greater than FRI-0.75″ in S2; and 10% greater than FRI-1″ and 3% greater than FRI-0.75″ in S3. Mean CWUE was not statistically investigated, however, variation in standard deviation among soil type was slightly less than that of irrigation treatments. Though VRI appears to have the largest mean CWUE for the 2018 growing season, it is worth noting that the irrigation depths were expected to be the driving factor among soil types. As it was presented earlier, yield was not found to be statistically significant among irrigation treatments. With no statistical significance, variation in CWUE would come from ETc in the denominator of Equation 6. As irrigation is the only dynamic variable for the soil-water balance equation among soil types, ETc is mostly related to irrigation treatments and depth or soil physical mechanisms. As the FRI-1″ treatment had the greatest applied irrigation depth, with FRI-0.75″ treatment second, and VRI treatment the lowest, mean CWUE results adhere to previous findings in the research. In the same experimental field for maize, Sharma and Irmak (2021b), observed that VRI had 15, 54 and 4% greater CWUE than FRI in

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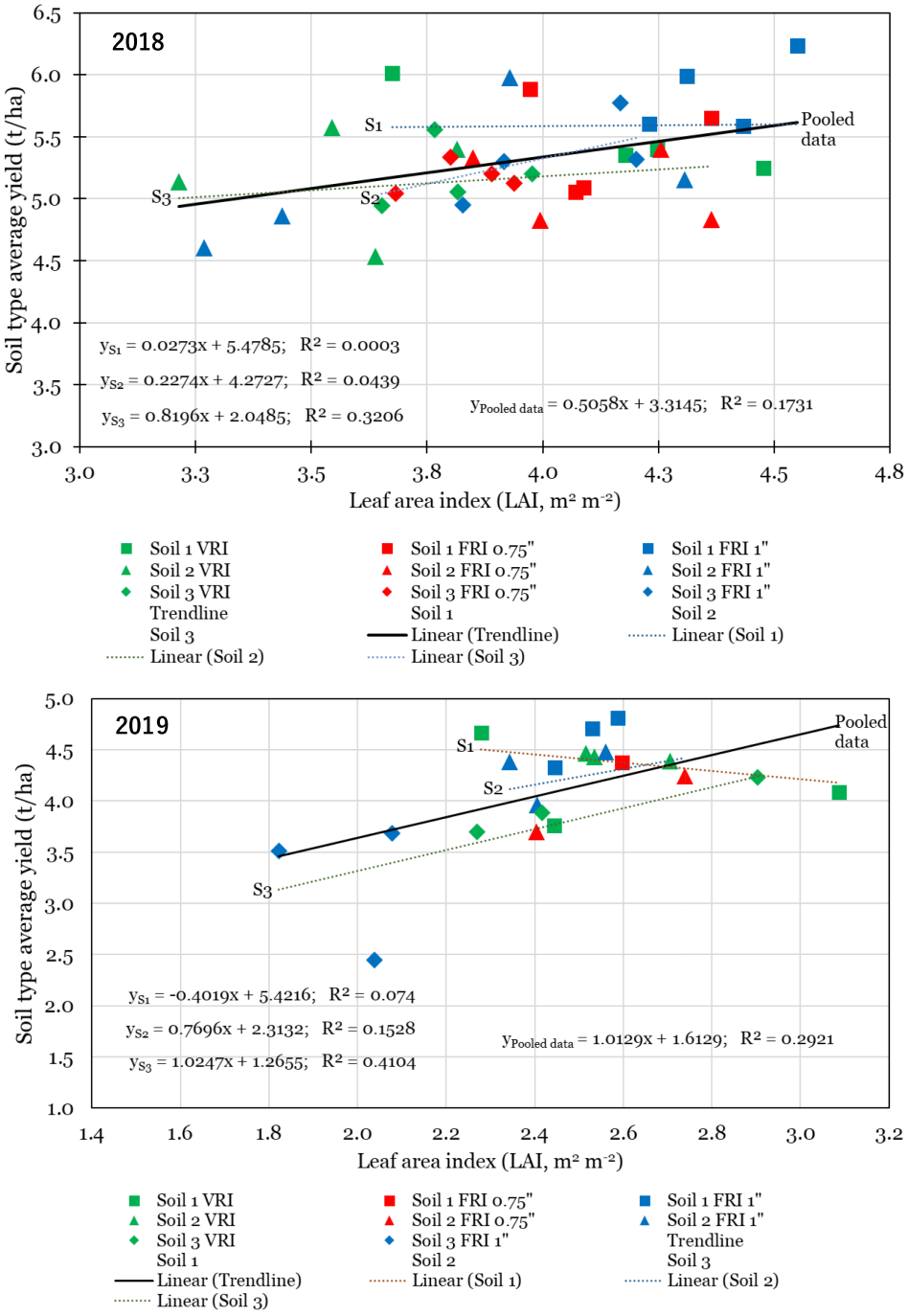

FIGURE 4 | Linear relationships between soil average grain yield and mean leaf area index (LAI) for 2018 and 2019 growing seasons. Each data point represents an average of five measurements, but linear relationships were fitted to all data points.

S1 for all three growing seasons, respectively. Nearly all FRI treatments in S2 and every FRI treatment in S3 had CWUE greater than VRI for the three growing seasons.

The CWUE for the 2019 growing season appeared to have more distinction among irrigation treatments and soil types than the 2018 growing season. The CWUE mean for S1 was 1.05 kg m^{-3} with a standard deviation of 0.03 kg m^{-3}; S2 had 1.06 kg m^{-3} CWUE with a standard deviation of 0.10 kg m^{-3}; and S3 had the lowest CWUE with a mean of 0.86 kg m^{-3} and a standard deviation of 0.06 kg m^{-3}. The VRI mean CWUE for 2019 was 1.02 kg m^{-3} with a standard deviation of 0.12 kg m^{-3}. FRI-0.75″ had a mean CWUE of 1.01 kg m^{-3} with a standard deviation of 0.08 kg m^{-3}. The FRI-1″ treatment had the lowest mean CWUE for irrigation treatments in the 2019 growing season, which was 0.99 kg m^{-3} with a standard deviation of 0.15 kg m^{-3}. In 2019, the mean CWUE standard deviation was less variable among soil types than that of irrigation treatments, which is similar to the findings in 2018. Along with the conclusions of the 2018 growing season, ETc was the main driver of the mean CWUE data as yield was not found to be statistically different among the two growing seasons and irrigation was the only dynamic variable in the soil-water balance among soil types. Irrigation treatments that received larger

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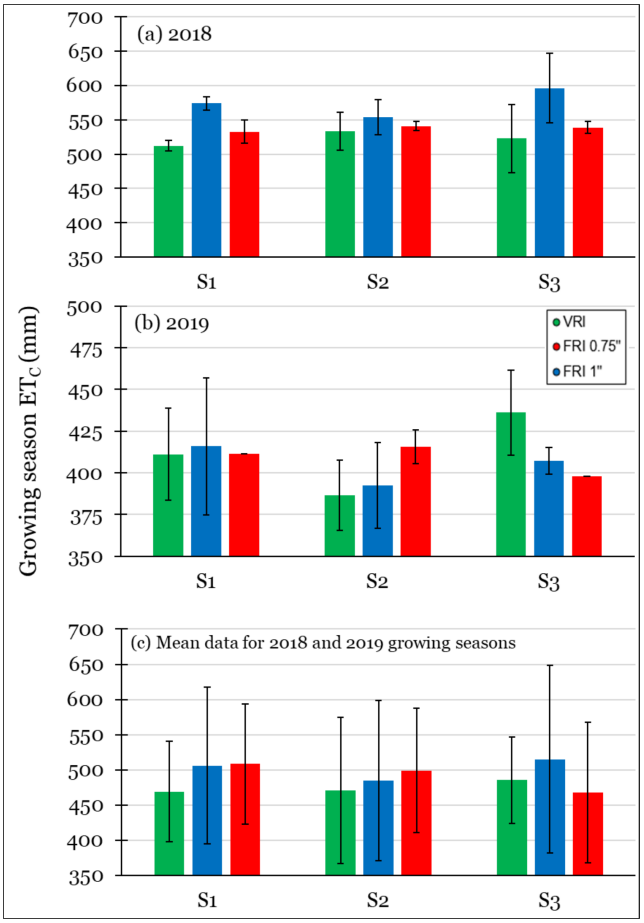

FIGURE 5 | Growing season total crop evapotranspiration (ETc) during 2018 and 2019 growing seasons and mean (2018 and 2019) ETc under each irrigation treatment and soil type. Each data point represents an average of four replications. Vertical bars indicate standard deviation.

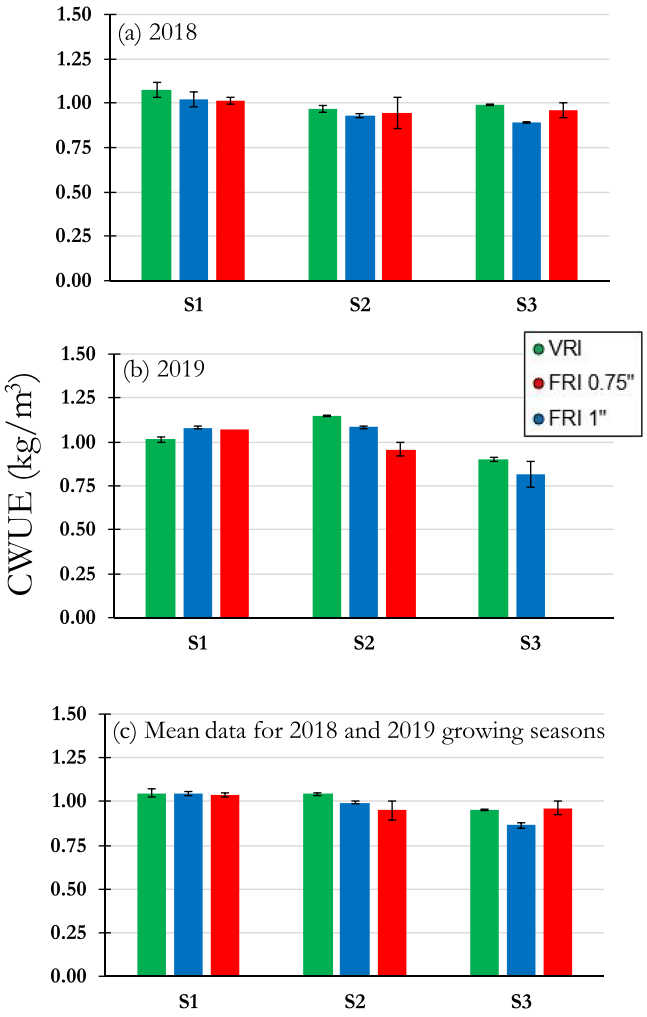

FIGURE 6 | Crop water use efficiency (CWUE) in 2018 and 2019 growing seasons and mean data (2018 and 2019) under each irrigation treatment and soil type. Each data point represents an average of four replications. Vertical bars represent standard deviation.

irrigation depths also had a greater mean CWUE, which is why it was proposed that mean CWUE was related to irrigation depths. Similar conclusions, however, cannot be drawn from 2019 results. The FRI-1″ treatments did not receive any irrigation for the 2019 growing season. As no statistical variation among yield was observed for irrigation treatments, ETc would dictate the mean CWUE. Because no irrigation was applied, ETc was expected to be smaller for FRI-1″, resulting in the largest mean CWUE. This was observed in S1 in the 2019 growing season with FRI-1″ mean CWUE being 6% greater than VRI and 1% greater than FRI-0.75″. VRI, however, had the largest mean CWUE in both S2 and S3. The CWUE for VRI was 5 and 17% greater than FRI-1″ and FRI-0.75″, respectively, in S2 and 10% greater than FRI1″ in S3. Again, no claims are to be made from 2019 data, though the results are peculiar comparative to 2018 results. Averaged CWUE for the 2018 and 2019 growing season are presented in Figure 6c. Initial observations of the averaged data show uniformity among irrigation treatments in S1. The mean CWUEs in S1 were 1.04 $kg\,m^{-3}$, 0.99 $kg\,m^{-3}$ for S2 and 0.93 $kg\,m^{-3}$ for S3. Among irrigation treatments, VRI had the greatest mean CWUE at 1.01 $kg\,m^{-3}$, FRI 0.75″ had the second largest mean CWUE at 0.98 $kg\,m^{-3}$, and the lowest mean CWUE for the averaged data was in FRI-1″ with 0.97 $kg\,m^{-3}$. In both seasons, irrigation treatment and soil type lacked the definitive evidence of irrigation treatments or soil type having more impact than the other (Figure 7).

4 | Summary and Conclusions

The VRI technology was introduced to 'potentially' enhance CWUE and crop yields through delivery of irrigation water variably by accounting for spatial variability in soil physical properties. However, the effectiveness and benefits of VRI application in comparison with fixed rate full and limited irrigation with respect to enhancing crop growth, yield, ETc and CWUE have not been investigated in multiple spatially variable soil types 'concurrently' in the same field. Through the research conducted for quantifying and understanding the soybean response to VRI, FRI-1″ and FRI-0.75″ irrigation treatments in three different soil types concurrently during the 2018 and 2019 growing seasons, it was concluded that soil type had profound impacts on soybean growth and development,

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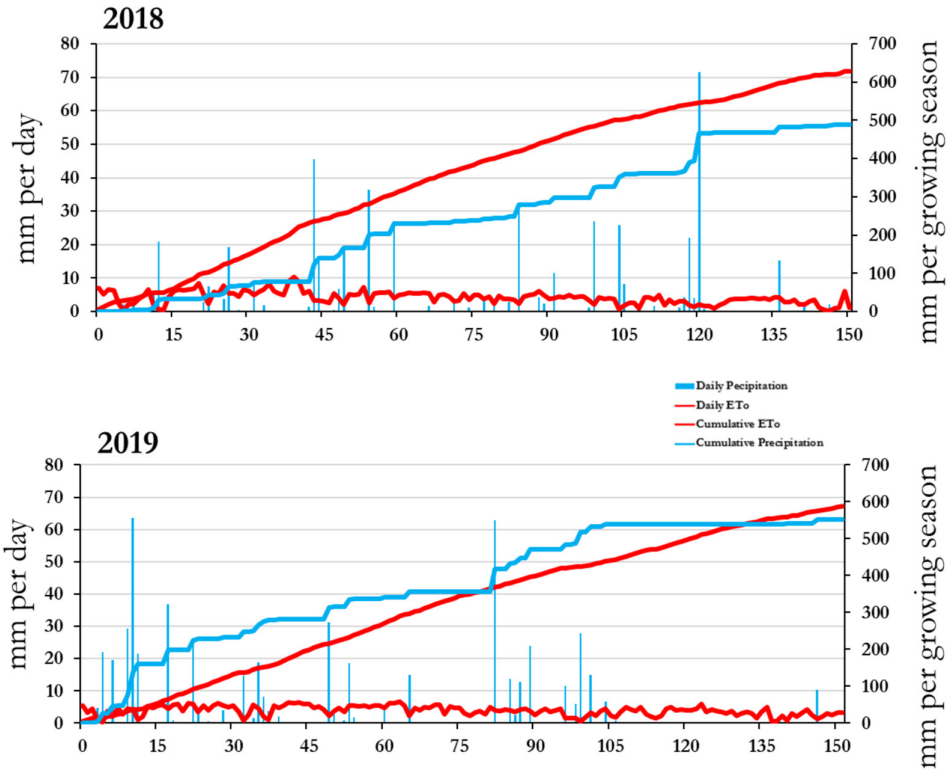

FIGURE 7 | Daily and cumulative precipitation and grass-reference evapotranspiration (ETo) for the 2018 and 2019 growing seasons.

grain yield, ETc and CWUE. The largest seasonal mean and maximum LAI values were S1, S2 and S3, respectively, which coincides with S1 having the greatest total soil water of the three soils. Grain yield followed the trend with the largest yield occurring in S1, second in S2 and third was in S3. It was found that soil type had a statistically significance effect on grain yield, which contrasted with irrigation treatments, as irrigation treatments did not have any statistical significance on grain yield. As yield was not statistically significant among irrigation treatments, irrigation depths applied, and ETc became significantly important for comparisons. VRI required 75% less water than FRI-1″ and 49% less water than FRI-0.75″ in 2018. During the 2019 growing season, VRI required 100% more irrigation water depth than FRI-1″ and 41% less than FRI-0.75″ treatment.

While ETc varied between the treatments, yield was not statistically significant. FRI-0.75″ limited irrigation treatments received less water than FRI-1″ full irrigation in 2018 with non-significant differences in yield. The FRI-1″ treatment required significantly more water than the other two treatments during the 2018 growing season, but it was not irrigated in the 2019 growing season. Statistically non-significant differences in yield for the 2019 growing season with FRI-1″ being essentially a rainfed treatment could be a challenge in terms of the validity of concluding that VRI and FRI-0.75″ treatments were effective at requiring less irrigation water for similar productivity. It is not in the best interest to conclude whether the results of yield and irrigation applied were causes of irrigation treatments or periodic precipitation. It cannot be precisely determined that VRI and FRI-0.75″ irrigation treatments provided non-statistically significant yields while requiring less water than conventional FRI-1″ as both growing seasons experienced irregular weather conditions. In general, VRI resulted in a reduction of ETc with similar yields as other irrigation strategies, which can be a significant contribution to this technology. As soil type was most responsible for variability among yield, crop growth, ETc and CWUE, it is suggested that further investigation of soil variability is necessary. Intra-soil variability can explain observations in 2018 and 2019, but the investigation of soil properties was extensive for this research. A grater resolution in soil data collection may result in increased water savings, but this would theoretically increase the time dedicated to irrigation management. Soil type was continuously prevalent in data and should be carefully and comprehensively explored and implemented in the theory and management of VRI and limited irrigation strategies before their adoption.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data for this research can be made available by the senior author (S. Irmak; sfi5068@psu.edu) upon a reasonable request.

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