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Economic comparisons of variable rate irrigation and fertigation with fixed (uniform) rate irrigation and fertigation and pre-plant fertilizer management for maize in three soils

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Abstract
Extensive field research for data collection to conduct economic comparisons of variable rate irrigation (VRI) with fixed (uniform) rate irrigation (FRI) and no irrigation (NI) in combination with three nitrogen application strategies of fixed (uniform) rate fertigation (FRF), variable rate fertigation (VRF) and pre-plant nitrogen (PP) management for maize (*Zea mays* L.) were conducted. Research was conducted in three soil types [(i) Crete silt loam (S1); (ii) Hastings silty clay loam (S2); and (iii) Hastings silt loam (S3)] for three growing seasons (2015, 2016 and 2017) in Nebraska, USA. For the economic analyses, the average initial investment of the irrigation system and necessary VRI technology, salvage value of the system, total capital investment, total fixed cost, net present value (NPV) and internal rate of return (IRR) were quantified by considering numerous factors/variables, including

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interest rate, production input cost, longevity of the system, insurance cost, ownership cost and salvage value. Soil types and irrigation management strategies (treatments) had significant impact on grain yield and thus on profitability, NPV, IRR and irrigation system payback period. Net income from FRI management was significantly higher than VRI management in all soil types. The nitrogen treatments did not affect net income in any of the growing seasons. The FRI management strategy had a positive NPV in all soil types whereas VRI management in S2 and S3 had negative NPVs. The negative NPV indicates that the present value of the costs exceeds the present value of future profits at the assumed discount rate (5%). Averaging all three years and three soils, FRI had a substantially higher net income than VRI in most cases. The maximum NPV of $4,882.07 per ha and maximum IRR of 18 % was observed in FRI-FRF treatment. A payback period of ≤10 years was determined for all FRI management treatments while the payback period for VRI management, in most cases, was more than 27 years. While the pay-back period in VRI irrigation system was less than ten years in S1, it was still longer than the corresponding FRI management treatments. Results suggest that the VRI and VRF strategies are not economically feasible in current conditions. For these variable irrigation and fertilizer technologies to be competitive with the FRI and FRF, the cost of the VRI and VRF technology will need to be significantly lower than the current investment costs. While there could be some environmental benefits of VRI and VRF technology, with the current high investment cost of VRI technology and the fact that the grain yields are not improved sufficiently to offset the investment cost, it is not possible for VRI technology to be an economically viable technology for profitable economic net return. This may explain, in part, extremely limited adoption of these technologies by producers currently in large scale production fields.

Keywords: Economics of irrigation, Fertilizer management, Net present value, Internal rate of revenue, Payback period, Variable rate technology

1. Introduction

Irrigated agriculture has abetted in stabilizing many communities of the world by permitting human habitation and providing opportunities for economic advancements (Evans and Sadler, 2008; Irmak and Mutiibwa, 2009a). Out of the world's total cultivated lands, approximately 20 % are irrigated farmlands, which produce approximately 40 % of world's food and fiber (Fereres and Connor, 2004; Evans et al., 2013; Irmak and Mutiibwa, 2009a, 2009b). Despite its vitality, irrigated agriculture is facing important challenges due to meeting the food and fiber demand of rapidly increasing human population and competition for freshwater resources. According to the United Nations estimation, to meet the increasing population's food demands, land under cultivation must increase by 40 % and the amount of water allocated to irrigation must increase by 14 % by 2030. However, land area under irrigated agriculture and water needed for irrigation are being depleted or reallocated which is creating a dire and unbalanced situation for crop production. Therefore, there is a pressing need for some significant changes and novel approaches in agricultural water management to address the issue of water shortages in agriculture. One of the solutions to this problem is the effective irrigation management strategies that use water and other inputs (i.e., fertilizers) efficiently and increase crop productivity at the same time (Irmak and Mutiibwa, 2009a, 2009b).

The invention of the center pivot irrigation systems in the 1950s was one of the most significant mechanical innovations in agriculture. After 70 years of its innovation, the center pivot or linear-move sprinkler irrigation systems and associated management practices have advanced substantially and is continuously being evolved to better meet the current requirements of effective agricultural crop production in terms of irrigation needs with an overall goal of uniform and economic irrigation across the field with a specific application depth. In addition to irrigation, center pivot and linear-move systems have also been used for fertilizer applications (fertigation) over the years. With the advent of precision agriculture (PA) technology, the knowledge and understanding about the variability that may exists within a field has increased. Now, the challenge is how to address this variability in terms of irrigation water and fertilizer applications to improve crop productivity. The PA technology has been adapted to a variety of field practices, including planting, fertilizer application, pest management/ herbicide application with a basic characteristic of site-specific treatment to separate portions of a field through the advent and merging of several technologies, including Global Positioning Systems (GPS), Geographical Information Systems (GIS), automatic controls, proximal and remote-sensing, telecommunications and advanced computer knowledge (Zhang et al., 2002). These innovations have facilitated the implementation of variable water application methods with sprinkler irrigation systems for site-specific management. The interest in the concept of variable rate management, especially variable rate irrigation (VRI) and variable rate fertigation (VRF) (Sharma and Irmak, 2020a) to manage spatial and temporal variabilities within an agricultural field has increased due to its expected and/or assumed potential of improving the crop water productivity. Most of this interest, however, remain within the research community and private industry as adoption of VRI technology by farmers in production fields is extremely limited. Adoption of VRF technology is even less than VRI. For any new technology to be adopted by the producers, the benefits, including management and environmental benefits, as well as costs and profit associated with the technology requirements must be investigated and presented and covered from the incremental revenue from crop yields.

Extremely limited research has been carried out to investigate the cost-effectiveness of VRI and VRF as compared with traditional fixed (uniform) rate irrigation (FRI) and fixed (uniform) rate fertilizer management (FRF) and pre-plant (PP) nitrogen management using measured field data. Most of the currently available limited studies focused on using modeling approach for such analyses, which may not provide reasonable or realistic estimates as models may not be able to account for real world challenges involved in investigating the economics and relationships between VRI, VRF, FRI, FRF and PP nitrogen management practices. Furthermore, how such economic analyses may exhibit variations for different soil types is essentially unknown. Nijbroek et al. (2003) used a crop model to compare gross margin of spatially variable irrigation management and uniform irrigation management for a soybean field (9.94 ha) in the Coastal Plain area. The simulation process was applied to 25 years of weather data to determine the feasibility of spatially variable irrigation management. They reported that spatially variable irrigation resulted in the best management option with \$16 ha^{-1} greater gross margin. However, they did not include the cost of equipment associated with spatially variable irrigation in computing the gross margin which could be much greater than \$16 ha^{-1}, resulting in more economic returns from uniform irrigation. King et al. (2006) studied the potential of site-specific irrigation management (SSIM) to increase crop yield, quality and economic returns in potatoes. In a two-year field study, it was found that the gross income was \$159 ha^{-1} greater for SSIM than in conventional uniform irrigation management (CUIM). Potato tuber yield was also 4% and 6% greater under SSIM in 2001 and 2002, respectively, than in CUIM. DeJonge et al. (2007) simulated three irrigation scenarios (no irrigation, uniform irrigation and precision irrigation) to determine the potential yield improvements with irrigation method and to compare the economic benefits of improved yield with capital costs of irrigation systems in Iowa. Their results showed lower yields and lower economic benefits with precision irrigation as compared with uniform irrigation.

In addition to irrigation, studies reported profits ranging from none to marginal and substantial when site-specific nitrogen management is practiced. Yang et al. (2001) examined the differences in yield and economic returns between uniform and variable rate fertilizer applications. The variable rate treatment resulted in significantly higher yields than the uniform nitrogen (N) and phosphorus (P) treatment for both years (400 kg/ha higher in 1997 and 338 kg/ha higher in 1998). Also variable rate treatment had positive relative economic returns over the uniform N and P treatment ($27/ha in 1997 and $23/ha in 1998). However, they did not take into consideration the equipment, control units, management, soil sampling and other costs associated with variable rate treatment. The returns would be much lower or even negative if all these costs, including soil sampling (and soil analyses), equipment, and data analysis associated with variable rate application were considered. Bronson et al. (2006) conducted a 3 year experiment on a 14 ha area within a 48 ha center pivot-irrigated field in a terminated- rye conservation tillage cotton system to assess lint yield response to irrigation levels and to compare the effects of variable rate N, blanket-rate N and zero N on lint yields at varying irrigation levels and landscape positions. Their results indicated more consistent lint yield response in variable-rate N than blanket-rate N in all years. However, when considering the costs of implementing variable-rate N management, the dollar returns to N fertilizer were not favorable for variable-rate fertilization in 2 out of 3 years. Thus, while in some of the studies variable management was proven to increase the yield, the variable management was unable to produce greater economic returns than uniform management.

Babcock and Pautsch (1998) developed a model based on the yield potential of various soil types in 12 Iowa counties and estimated the potential value of switching from uniform to variable fertilizer rates for maize production. Results indicated only modest increases in the gross returns over fertilizer costs, ranging from $7.43 to $1.52 per

0.404 ha. They found that the net profitability of variable-rate technology is sensitive to the per area costs of moving to a variable rate technology. Under the assumptions of the model, applying variable rates increased yield only by 3–31 kg per 0.404 ha, and would reduce fertilizer costs by $1.19 to $6.83 per 0.404 ha. When the variable rate technology systems' initial cost and other associated application and maintenance costs are considered, these increases in grain yield and minimal reduction in fertilizer application would not result in any financial benefit to the farm net income from variable rate technology.

In Midwestern states, extensive nitrogen management and irrigation is practiced in a very large land area. In Nebraska, around 90 % of total land area (77,421 mi^2 or 200,520 km^2) is under agriculture, of which 44 % is under irrigation (USDA-NASS, 2014), or approximately 3.5 million ha. With such a large area dedicated to agriculture and irrigation, crop production is a critical part of Nebraska's economy. Thompson et al. (2012) reported an economic impact of agriculture as high as 42 % of Nebraska's economy with irrigated crops contributing more than 50 % of that percentage. In addition to water, crops substantially rely on N fertilizers for higher yields, thus heavily influencing the economic results for most crops, including maize (Thompson et al., 2000). About 80–85 % of the irrigated land area in Nebraska is irrigated with center pivot systems, which should make this area suitable for the development and adoption of VRI technology, because of already existing platforms (extensive irrigated land area, four major center pivot manufacturers being located in Nebraska as well as the existence of all other irrigation-related industry such as irrigation pump, motor, well, pipe, control, automation, etc.). However, adoption of site-specific irrigation and nitrogen management technologies and strategies requires quantification, analyses and understanding of such technologies' and strategies' economic feasibility, which is a significant knowledge gap in irrigation science and engineering discipline. It is very important and necessary to understand the economics of variable rate management of water and nitrogen fertilizer application in comparison with currently dominant conventional fixed (uniform) water and fertilizer application. Thus, carefully designed and carried out field research is critical to more accurately determine the economics of these management practices. The specific objectives of this research were to conduct economic comparisons of maize production under fixed (uniform) rate irrigation (FRI) with variable rate irrigation (VRI) and no-irrigation (NI) settings with fixed (uniform) rate fertigation (FRF), variable rate fertigation (VRF) and pre-plant (PP) fertilizer management in different soil types.

2. Materials and methods

2.1. Research site description, experimental design and general crop management practices

This project is part of a larger and ongoing long-term field research project in the Irmak Research Laboratory advanced field research facilities at the University of Nebraska-Lincoln (UNL) that has been investigating the effect of VRI and FRI with VRF, FRF and PP N management on soil-water dynamics in different soils (Sharma and Irmak, 2020a); crop evapotranspiration, irrigation- and evapotranspiration-yield production functions and crop water productivity (Sharma and Irmak, 2020b); and effect of VRI and FRI under VRF, FRF and PP nitrogen management on grass- and alfalfa evapotranspiration crop coefficients in different soil types (Irmak et al., 2020). 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) and Irmak et al. (2020) overlap. The field experiments with maize (Zea mays L.) were conducted in the Irmak Research Laboratory at UNL's South Central Agricultural Laboratory (SCAL), located near Clay Center, Nebraska, in 2015, 2016 and 2017 growing seasons (**Fig. 1**). The research laboratory is located at latitude 40° 34′ N and longitude 98° 8′ W with an elevation of 552m above mean sea level. The research site is in the transition zone between the sub-humid and semi-arid zones (Irmak et al., 2012). The long-term average annual precipitation at the research site is 680 mm. The long-term annual maximum and minimum air temperatures at the research site are 25 °C, and −5 °C, respectively. The growing season precipitation in 2015, 2016 and 2017 was 353, 375 and 467 mm, respectively. The research was conducted on a 2.3 ha field with a west to east elevation gradient in the field ranging from 550.9m to 552.1m

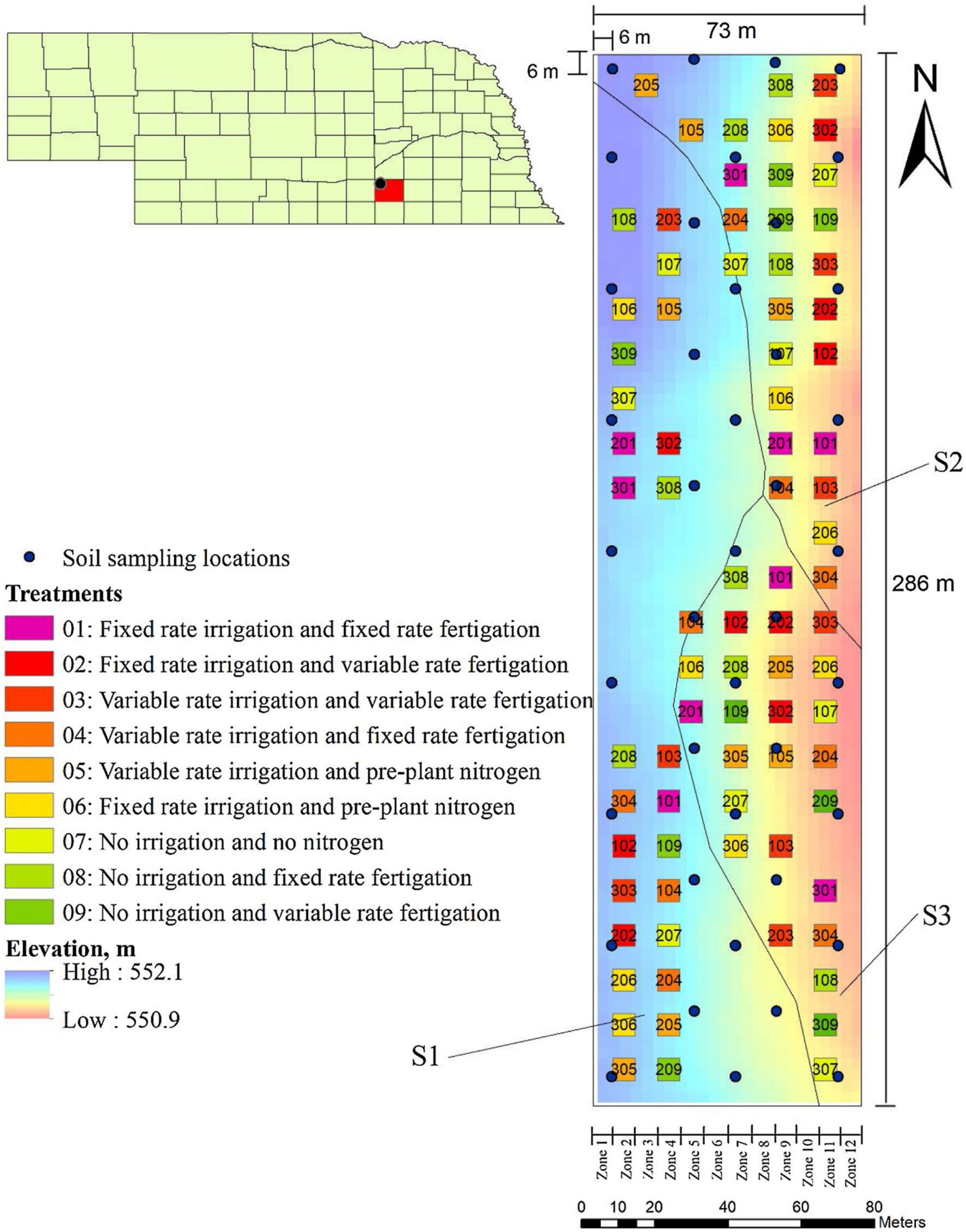

Fig. 1. The research site in the Irmak Research Laboratory advanced field research facilities at the South Central Agricultural Laboratory (SCAL) near Clay Center, Nebraska. The field map shows plot layout and soil sampling locations for three soil types (S1: Crete silt loam, S2: Hastings silty clay loam and S3: Hastings silt loam) with the elevation map on the background.

above mean sea level (Fig. 1). Three soil types exist in the research field: (1) Crete silt loam, 0–1% slopes (S1); (2) Hastings silty clay loam, 3–7 % slopes (S2); and (3) Hastings silt loam, 1–3 % slopes (S3). The primary production systems in the area are continuous maize and maize-soybean rotation, primarily under center-pivot irrigation (~80–85 % of the state's total irrigated land) and some surface irrigation (furrow) (~15–20% of the state's total irrigated land). Fixed and variable rate water and nitrogen applications were achieved using a two-span 75m long 7000SL variable rate linear-move sprinkler irrigation system (T-L Irrigation. Co, Hasting, Nebraska).

Three levels of irrigation (FRI, VRI and NI) and three levels of nitrogen (N) fertilizer (FRF, VRF and PP) and their interactions were studied on three soil types. The treatment combination of no irrigation (NI) and pre-plant N application (PP) was not included, instead no irrigation and no nitrogen combination treatment was evaluated. Therefore, there are total 9 treatments (irrigation and nitrogen combination treatments) which are replicated 3 times in each soil type making 27 plots in each soil type (Fig.1). Each plot was 6m×6m in size with 6m×6m buffer plot in all four sides of each plot. Maize was planted on May 27 with population densities of 84,500 plants ha^{-1} and was harvested after 146 of planting on October 19 in 2015. In 2016 and 2017 earlier planting occurred due to warmer temperature in the month of May as compared to 2015. The maize was planted on May 6 and May 5 in 2016 and 2017, respectively, with population densities of 84,500 plants ha^{-1}. Maize was harvested on October 13 (161 days after planting, DAP) and October 25 (174 DAP) in 2016 and 2017, respectively. Herbicides, insecticides and fungicides were applied uniformly to all plots as required (**Table 1**). To determine the soil properties and nitrogen amount of all soil properties for each plot, extensive soil sampling was conducted from 42 locations within the 2.3 ha experimental field in April (before planting) of each year to create spatially interpolated maps for various soil properties in ArcGIS. Extract by Mask tool was used to extract the soil physical properties [i.e., field capacity (FC), permanent wilting point (PWP), organic matter content (OMC), soil texture and soil nitrate-N for each plot was determined based on which irrigation and nitrogen amounts should be applied were determined (Sharma and Irmak, 2020a).

Table 1. Agronomic products, including seed (80,000 kernels per bag), fertilizer, herbicide, additives, and fungicides, application dates, types, costs and methods of application for 2015, 2016 and 2017 growing seasons.

Year	*Description*	*Date*	*Type*	*Amount/ha*	*Product cost($/ha)*	*Method of application*
2015	Planting	5/27/2015	P1151AMX corn	84,158 seeds	$276.11/bag	8-row planter
	Fertilizer	5/27/2015	32−0-0	246.5 kg	$360/Mg	In-Furrow Injection/Fertigation
	Herbicide	5/27/2015	Lexar	7 L	$9.39/L	Spray
	Herbicide	5/27/2015	Roudup	2.3 L	$5.05/L	Spray
	Additive	5/27/2015	AMS	7.7 kg	$0.57/kg	Spray
	Herbicide	6/29/2015	Roundup	2.3 L	$5.05/L	Spray
	Additive	6/29/2015	AMS	4 kg	$0.57/kg	Spray
	Fungicide	8/17/2015	Quilt Excel	0.8 L	$63.45/L	Chemigation
2016	Planting	5/6/2016	G07F23−3111	84,911 seeds	$273.9/bag	8-row planter
	Fertilizer	3/14/2016	11−52-0	112 kg	$450/Mg	Broadcast
	Fertilizer	5/6/2016	10−34-0	47 L	$530/Mg	In-Row Starter
	Fertilizer	4/13/2016	32−0-0	246.5 kg	$270/Mg	In-Furrow Injection/Fertigation
	Herbicide	5/18/2016	Acuron	5.9 L	$11.90/L	Spray
	Herbicide	5/18/2016	Roundup	2.3 L	$4.89/L	Spray
	Fungicide	7/22/2011	Quilt Excel	1 L	$60.85/L	Chemigation
2017	Planting	5/8/2017	Channel 209−53STXRIB	84,911 seeds	$336.00/bag	8-row planter
	Fertilizer	2/9/2017	11−52-0	246.5 kg	$400/Mg	Broadcast
	Fertilizer	5/8/2017	10−34-0	47 L	$400/Mg	In-Row Starter
	Fertilizer	4/19/2017	32−0-0	246.5 kg	$260/Mg	In-Furrow Injection/Fertigation
	Herbicide	5/11/2017	Acuron	4.7 L	$11.49/L	Spray
	Herbicide	5/11/2017	Roundup	3.5 L	$5.02/L	Spray
	Insecticide	8/4/2017	Lorsban	1.2 L	$9.43/L	Aerial Spray
	Insecticide	8/4/2017	Brigade	0.5 L	$30.51/L	Aerial Spray
	Fungicide	8/4/2017	Headline Amp	1.2 L	$66.78/L	Aerial Spray
	Insecticide	5/8/2017	Force 3G	6.1 kg	$9.92/kg	Banded w/Planter

2.2. Irrigation and nitrogen management

The Watermark Granular Matrix sensors (WGMS, Irrometer, Co., Riverside, CA) installed at four depths (0.30, 0.60, 0.90 and 1.20 m) in 20 plots (two replications of each treatment) in each soil type were used for irrigation management. WGMS were used to monitor SMP (kPa) on an hourly basis and hourly data were then converted to volumetric soil water content (VSWC) using pre-determined soil water retention curves for each soil type (by accounting for vertical variability in soil layers for all soil types) for the research site that were developed by Irmak (2019). When horizontal and vertical soil variability is considered, in total, there were six soil types in the research field: silt loam, silty clay loam, clay loam, loam, sandy clay loam and sandy loam. Thus, the experimental field provided a unique opportunity to truly investigate VRI and VRF management impacts on crop productivity and associated economic implications. Many of the VRI studies reported in the literature were not carried out in fields that have spatial variability, which may result in incomplete analyses and conclusions in terms of crops' productivity and economic response to VRI. The VSWC was then multiplied by the representative depth intervals to determine the total soil water stored in each depth and then summed up to obtain total soil water for the 0–1.2m 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. Management allowable depletion (MAD) for all plots was taken as 40 % of SWHC. Irrigation for both FRI and VRI treatments was triggered whenever total soil water stored in the 0−0.90m profile as measured by Watermark sensors fell below this 40 % threshold. However, the amount of irrigation per irrigation event for FRI plots was fixed to be 25.4 mm. Each time any of the FRI plots needed irrigation based on soil moisture sensor information, all FRI plots were irrigated with 25.4mm of irrigation depth considering no variability in the field and assuming that crops in FRI plots respond in the same manner at all locations in the field. This is the most common operation that producers practice in Nebraska and other Midwestern states in the United States. A total of 1, 7 and 10 irrigations were applied to FRI plots in 2015, 2016 and 2017 growing seasons, respectively. The total seasonal irrigation amounts for all growing seasons are presented in **Table 2**.

Table 2. Seasonal irrigation and nitrogen (N) amounts applied to 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 growing seasons (Sharma and Irmak, 2020a).

				2015		*2016*		*2017*	
Soil	*Irr. level*	*N level*	*Trt. No.*	*Irr. amount (mm)*	*N amount (Kg ha⁻¹)*	*Irr. amount) (mm)*	*N amount (Kg ha⁻¹)*	*Irr. amount (mm)*	*N amount (Kg ha⁻¹)*
S1	FRI	FRF	1	25.4	246.4	190.5	246.4	254	246.4
	FRI	VRF	2	25.4	225.7	190.5	240.9	254	195.0
	FRI	PP	6	25.4	246.4	190.5	246.4	254	246.4
	VRI	FRF	4	27.9	246.4	31.8	246.4	244	246.4
	VRI	VRF	3	0.0	229.0	102.9	238.1	111	190.7
	VRI	PP	5	17.8	246.4	288.3	246.4	128	246.4
	NI	FRF	9	0.0	246.4	0.0	246.4	0	246.4
	NI	VRF	10	0.0	224.6	0.0	221.3	0	192.4
	NI	No	7	0.0	0.0	0.0	0.0	0	0.0
S2	FRI	FRF	1	25.4	246.4	190.5	246.4	254	246.4
	FRI	VRF	2	25.4	234.6	190.5	205.1	254	161.6
	FRI	PP	6	25.4	246.4	190.5	246.4	254	246.4
	VRI	FRF	4	10.2	246.4	186.8	246.4	19.1	246.4
	VRI	VRF	3	48.3	225.1	105.0	191.3	116	139.2
	VRI	PP	5	15.2	246.4	183.6	246.4	86	246.4
	NI	FRF	9	0.0	246.4	0.0	246.4	0	246.4
	NI	VRF	10	0.0	230.7	0.0	196.3	0	155.2
	NI	No	7	0.0	0.0	0.0	0.0	0	0.0
S3	FRI	FRF	1	25.4	246.4	190.5	246.4	254	246.4
	FRI	VRF	2	25.4	191.5	190.5	169.1	254	159.2
	FRI	PP	6	25.4	246.4	190.5	246.4	254	246.4
	VRI	FRF	4	34.3	246.4	62.2	246.4	0	246.4
	VRI	VRF	3	36.8	225.7	154.9	188.0	0	152.4
	VRI	PP	5	19.1	246.4	106.7	246.4	122	246.4
	NI	FRF	9	0.0	246.4	0.0	246.4	0	246.4
	NI	VRF	10	0.0	208.3	0.0	188.4	0	154.9
	NI	No	7	0.0	0.0	0.0	0.0	0	0.0

For VRI plots, irrigation amounts were applied to bring the soil water to maintain approximately 90 % of SWHC. Only those plots which needed irrigation calculated according to the measured soil moisture readings from WMGS were irrigated for VRI plots by considering each soil layer's physical properties for each soil type. Thus, the number and amount of irrigation events for each VRI plot differed substantially (Sharma and Irmak, 2020a). Such VRI practice is extensive, but it is important to account for soil's vertical variability in irrigation requirements calculations to ensure proper practice of VRI management. Most studies reported in the literature did not account for this critical aspect of VRI.

Three N fertilizer treatments were imposed under each irrigation management in each soil type: (i) FRF, VRF and (iii) PP N fertilizer management. For the PP treatment, a total of 246 kg/ha of urea ammonium nitrate (UAN 32–0-0) was applied in 2015, 2016 and 2017 before planting. In-season fertilizer was applied to VRF and FRF treatments using a linear-move sprinkler irrigation system that is equipped with advanced variable rate irrigation and fertilizer management technologies. The N fertilizer rate requirement for each VRF plot was calculated every growing season from soil samples data using N recommendation procedure proposed by (Shapiro et al., 2008). These fertilizer requirements for maize were based on the expected/targeted yield, organic matter content and current soil nitrate-N levels. Based on this procedure, for VRF treatment, on average, 217, 234 and 221 kg ha^{-1} N fertilizer were applied in FRI, VRI and NI treatments, respectively, in 2015. In 2016, these values were 205 kg ha^{-1}, 206 kg ha^{-1} and 202 kg ha^{-1}, respectively. In 2017, they were 172 kg ha^{-1}, 161 kg ha^{-1} and 168 kg ha^{-1}, respectively. A constant rate of 246 kg ha^{-1} of N fertilizer was applied to all FRF plots. The N fertilizer application was divided in two applications in 2016 and 2017 growing season. Half of the required N was applied at the vegetative growth stage of V2 and the other half was applied at V8 stage (Shapiro et al., 2008) for both VRF and FRF plots.

2.3. Economic analyses

Economic analyses of different irrigation and fertilizer management treatments were conducted based on net present value (NPV), internal rate of return (IRR), gross income and net farm return (income) on a per hectare (ha) basis. A full scale 7-span center pivot irrigation system generally used in a 65 ha field was considered for calculating the fixed cost per ha of the irrigation system. Calculations were based mainly on the final grain yield, the market price for maize, irrigation and fertilizer application/management costs, other management and product (such as herbicides, pesticides, fuel type and amount for irrigation water withdrawal, etc.) application costs. Economic analyses

Table 3. Market maize grain price for 2015, 2016 and 2017.

Year	*Market Grain Price (per Mg)*
2015	$138.58
2016	$120.08
2017	$124.80

were conducted for each year separately. Gross income and net income for all irrigation and nitrogen combination treatments in three soil types for three growing seasons were calculated. Gross income was calculated using the market maize grain price for each growing season in the research area (**Table 3**). Net income was calculated by subtracting the operational costs from the gross income. Operational costs for each treatment was calculated by considering the individual cost of each product that was applied to each treatment plots (replications) (Table 1) throughout each growing season plus the application/equipment and machinery cost averaged over the research period, assuming diesel price of $0.57 per liter (**Table 4**). An irrigation cost of $4.96 per ha-cm was used, which was calculated using the Nebraska Pumping Plant Performance Criteria (NPPPC) (Martin et al., 2011) with an outlet pressure of 138 kPa, a lift (depth to groundwater) of 32m and repair and maintenance cost of $2.11 per ha-cm. The electricity cost used for the calculations was taken as $0.123 per kWh. The net income analysis did not consider the hauling and drying costs of the grain due to substantial variability in these processes. The costs of irrigation systems were them compared with the net incomes from

Table 4. Average application/equipment cost for 2015, 2016 and 2017 growing seasons.

Management practice	*Cost*
Planter (per ha)	$47.67
Cultivating (per ha)	$44.31
Fertilizer (11−52-0) (per ha)	$16.06
Fertilizer (UAN 32 %) (per ha)	$30.28
Herbicide (per ha)	$25.75
Aerial Application (per ha)	$17.29
Irrigation (per ha-mm)	$0.50
Combine (per ha)	$71.41

each of the irrigation treatment (FRI and VRI) under different nitrogen management treatments (FRF, VRF and PP nitrogen). All costs and profits were compared on a US dollar per ha basis.

Another financial analysis was carried out in which capital costs of linear move irrigation systems with and without VRI technology was compared in terms of the payback period. The calculated net income for each irrigation management was further utilized to calculate the payback period for two irrigation systems, especially if the investment could be recovered within the lifespan of the irrigation system. Since VRF in FRI treatment is not feasible with a typical center pivot or linear move irrigation system that is not equipped with a VRI technology, the FRI-VRF combination was not considered in the economic analyses. For the economic analysis, several assumptions that were made and considered in the calculations are shown in **Table 5**. To determine the net income per ha, a moving average approach of actual net income for three experimental years was considered. This was also done to accommodate the seasonality throughout the assumed lifespan of the equipment and irrigation system. For the economic analyses, the average initial investment of the irrigation system and necessary VRI technology, salvage value of the system, total capital investment, total fixed cost and net present value were calculated by considering numerous factors/variables, including interest rate, production input cost, longevity (life) of the system, insurance cost, ownership cost, salvage value, etc. The input variables include planting, harvesting, irrigation and nitrogen management, cultivation, pesticide applications, etc. The average initial investment cost of the irrigation system per ha was calculated by dividing the total initial investment by average farm size. It was assumed that the equipment would salvage for 10 % its value at the end of its longevity. The

Table 5. Assumptions for the economic analysis.

Assumption	*Value*
Life of the Equipment	20 Years
Salvage Value	10 % of the Initial Investment
Average Interest Rate	5%
Average Insurance	0.5 %
Average Farm Size (NE)	65 ha

Table 6. Fixed costs for fixed (uniform) rate irrigation (FRI) and variable rate irrigation (VRI) systems.

	FRI	*VRI*
Capital Cost		
Initial Investment	$(102,449.80)	$(130,129.80)
Initial Investment/ha	$(1,576.15)	$(2,002.00)
Salvage Value	10 %	10 %
End of Life Salvage Value /ha	$157.62	$200.20
Total Capital Cost	$(1,418.54)	$(1,801.80)
Ownership Cost		
Average Interest Rate	5% 5%	
Annual Interest Payment / ha	($113.19)	($143.78)
Insurance Rate	0.50 %	0.50 %
Annual Insurance Cost	$(7.09)	$(9.01)
Total Annual Ownership Cost	($120.29)	($152.79)
Total Ownership Cost [Life of Machine (i.e., 20 years)]	$(2,405.75)	$(3,055.73)
Total Fixed Cost	$(3,824.28)	$(4,857.53)

total capital cost per ha for each equipment (**Table 6**) was calculated by subtracting per ha average salvage value from the initial investment using the following steps:

(i) Average Initial Investment per ha=initial investment / average farm size
(ii) Salvage Value=10 % x Initial Investment
(iii) Total Capital Investment per ha=Average Initial Investment per ha – Salvage Value
(iv) Total Fixed Cost=Total Capital Cost+Total Ownership Cost

The annual ownership cost was calculated by including interest and equipment insurance cost, which were calculated by assuming an annual compound interest and insurance rate at 5% and 0.5 %, respectively (Table 6). Sum of the total capital cost and total cost of ownership provided the total fixed cost for respective equipment (Table 6). The NPV, discounted at 5% annual compound rate, of the respective equipment was calculated for each soil type under different treatments. Net present value was then determined as the difference between the present values of cash inflows and outflows of the operation. A positive NPV indicates that the investment in equipment proved profitable within the life span of the equipment. A negative

NPV indicates that the investment will result in a net loss. NPV was calculated using the standard financial formula:

$$NPV = -C_o + \frac{C_1}{1+r} + \frac{C_2}{(1+r)^2} + \ldots + \frac{C_T}{(1+r)^T} \quad (2)$$

where, $-C_o$ is initial investment, C is cash flow, r is discount rate and T is time. In general, increase in grain prices can increase the probability of NPV being positive for irrigation investment, regardless whether the irrigation system has a VRI technology or not, due to substantial increase in grain yield as a result of irrigation as compared with rainfed crop production. While irrigation, in most cases, can result in substantial grain yield increase, this increase can vary substantially depending on numerous factors, including soil and crop management, climatic conditions (especially in-season precipitation timing and amount), nitrogen management and other factors, which can all influence the economic benefits of investment in irrigation technology (both VRI and FRI). To complement the NPV values, IRR was calculated for various treatments. The IRR represents the rate of return at which NPV of the investment would become zero. A higher IRR helps identifying best investments out of all the investments with positive NPV.

3. Results and discussion

3.1. Effect of irrigation and nitrogen treatments on maize grain yield

The grain yield responses to irrigation and nitrogen management strategies under different soil types were used as critical components of the economic analyses. Maize grain yields for 2015, 2016 and 2017 growing seasons for each treatment are presented in **Table 7** and were discussed in (Sharma and Irmak, 2020b). Briefly, Sharma and Irmak (2020b) reported that maize grain yield (adjusted to 15.5 % grain moisture content) ranged from 5.8 tons ha^{-1} to 11.6 tons ha^{-1} in 2015, 5.6 ton ha^{-1} to 14.8 ton ha^{-1} in 2016 and 7.1 ton ha^{-1} to 15.4 ton ha^{-1} in 2017. Grain yields were significantly different ($p < 0.05$) between soil types in 2015 and 2016 growing seasons and VRI had greater variability in grain yield, crop water use and crop water productivity

Table 7. Maize grain yield (Sharma and Irmak, 2020a) (tons ha^{-1}) 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 for the 2015, 2016 and 2017 growing seasons that were used in the economic analyses (Sharma and Irmak, 2020b).

Soil	*Irrigation treatment*	*Nitrogen treatment*	*Grain Yield (ton ha^{-1})*		
			2015	*2016*	*2017*
S1	FRI	FRF	9.4	14.6	14.1
	FRI	VRF	8.1	13.8	14.5
	FRI	PP	8.5	14.0	15.4
	VRI	FRF	8.9	11.1	13.8
	VRI	VRF	11.6	13.2	14.4
	VRI	PP	9.9	14.6	10.7
	NI	FRF	9.7	11.5	11.6
	NI	VRF	7.6	8.7	11.3
	NI	No	7.2	9.4	7.7
S2	FRI	FRF	7.5	14.8	13.0
	FRI	VRF	6.7	11.8	14.8
	FRI	PP	7.6	12.8	14.0
	VRI	FRF	7.9	10.1	8.3
	VRI	VRF	7.5	8.3	11.2
	VRI	PP	9.1	10.3	9.5
	NI	FRF	7.3	6.0	9.2
	NI	VRF	6.6	7.1	9.2
	NI	No	5.9	5.6	8.2
S3	FRI	FRF	6.8	9.2	14.5
	FRI	VRF	6.3	12.2	14.7
	FRI	PP	7.5	12.5	13.7
	VRI	FRF	7.7	6.5	10.1
	VRI	VRF	5.8	9.2	7.5
	VRI	PP	7.5	8.6	10.1
	NI	FRF	7.1	7.4	7.1
	NI	VRF	7.0	6.3	8.4
	NI	No	7.8	6.3	7.8

as compared with FRI. Soil type S1 had the highest grain ($p < 0.05$) yield followed by S2 and S3. There was no significant yield difference among irrigation treatments in 2015 in any of the soil type. In 2016, FRI in S1 had the highest grain yield (14.1 tons ha^{-1}) and the lowest yield occurred in S2 the NI treatment (6.2 ton ha^{-1}). A significant effect ($p < 0.05$) of soil type was observed in 2016 growing season. Yield in S1 was significantly higher ($p < 0.05$) than S2 and S3 in 2016. Comparing irrigation levels in each soil type, yield in FRI was not significantly different ($p > 0.05$) from VRI in S1. However, significantly higher than

VRI and NI in S2 and S3 (Table 7). Similar results were obtained in 2017 where FRI treatment had the highest grain yield (14.3 ton ha^{-1}) followed by VRI (10.6 ton ha^{-1}) and NI (9.4 ton ha^{-1}) averaged over three soil types. Grain yield was not significantly different between FRI and VRI treatment in S1; however, in S2 and S3, yield in FRI was 43 % and 55 % higher than VRI ($p < 0.05$), respectively. All these different responses of grain yield to treatments within a growing season as well as their inter-annual variations were accounted for when determining the economics of different irrigation and nitrogen management practices as all analyses were done on a growing season basis.

3.2. Economics of irrigation and nitrogen management treatments

The operational cost, gross income and net income for each irrigation and fertilizer management treatment are presented in **Tables 8, 9, 10 and 11** for 2015, 2016 and 2017 growing seasons and for the pooled data for all years, respectively. Since gross income was calculated from maize grain yield, the effect of various treatments on gross income would be the same as the effect on grain yield; therefore, nitrogen treatment had no significant effect on gross income. However, there was an interacting effect of irrigation and soil type on gross income. In 2015, the gross income ranged from $802 ha^{-1} in S3-VRI-VRF

Table 8. Operational cost (Opt., $/ha), gross income (Gross, $/ha) and net income (Net, $/ha) 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) in Crete silt loam (S1), Hastings silty clay loam (S2) and Hastings silt loam (S3) for 2015 growing season.

Soil type	*N level→*	*FRF*			*VRF*			*PP*		
	Irr. level ↓	*Opt. ($/ha)*	*Gross ($/ha)*	*Net ($/ha)*	*Opt. ($/ha)*	*Gross ($/ha)*	*Net) ($/ha)*	*Opt. ($/ha)*	*Gross) ($/ha)*	*Net ($/ha)*
S1	FRI	749	1299	550±184	729	1128	389±154	781	1174	378±232
S1	VRI	749	1228	479±193	715	1601	880±117	772	1370	589±145
S1	NI	744	1348	604±253	723	1049	308±117	–	–	–
S2	FRI	776	1038	261±98	758	928	133±207	808	1047	197±193
S2	VRI	767	1093	326±18	761	1033	238±306	798	1260	426±461
S2	NI	771	1015	244±62	749	916	123±138	–	–	–
S3	FRI	803	940	137±153	749	808	−4±158	835	1040	136±145
S3	VRI	806	1062	256±224	783	802	−41±48	827	858	−31±251
S3	NI	798	990	192±97	765	973	137±133	–	–	–

Table 9. Operational cost (Opt., \$/ha), gross income (Gross, \$/ha) and net income (Net, \$/ha) 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) in Crete silt loam (S1), Hastings silty clay loam (S2) and Hastings silt loam (S3) for 2016 growing season.

Soil type	*N level→*	*FRF*			*VRF*			*PP*		
	Irr. level ↓	*Opt. (\$/ha)*	*Gross (\$/ha)*	*Net (\$/ha)*	*Opt. (\$/ha)*	*Gross (\$/ha)*	*Net) (\$/ha)*	*Opt. (\$/ha)*	*Gross) (\$/ha)*	*Net (\$/ha)*
S1	FRI	963	1753	791±166	955	1661	705±137	986	1679	693±104
S1	VRI	883	1336	453±66	908	1580	672±478	1035	1758	722±126
S1	NI	867	1384	517±98	824	709	−101±122	–	–	–
S2	FRI	963	1772	810±97	900	1417	516±60	986	1534	548±49
S2	VRI	961	1208	248±622	851	997	146±294	983	1233	250±233
S2	NI	867	719	−148±275	807	854	46±382	–	–	–
S3	FRI	963	1110	147±32	888	1461	574±154	986	1502	515±65
S3	VRI	898	782	−116±341	872	1105	234±249	944	1038	93±153
S3	NI	867	894	27±502	791	761	−30±382	–	–	–

Table 10. Operational cost (Opt., \$/ha), gross income (Gross, \$/ha) and net income (Net, \$/ha) 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) in Crete silt loam (S1), Hastings silty clay loam (S2) and Hastings silt loam (S3) for 2017 growing season.

Soil type	*N level→*	*FRF*			*VRF*			*PP*		
	Irr. level ↓	*Opt. (\$/ha)*	*Gross (\$/ha)*	*Net (\$/ha)*	*Opt. (\$/ha)*	*Gross (\$/ha)*	*Net) (\$/ha)*	*Opt. (\$/ha)*	*Gross) (\$/ha)*	*Net (\$/ha)*
S1	FRI	1068	1812	744±462	1025	1816	791±92	1092	1918	826±33
S1	VRI	1063	1728	665±124	951	1797	846±58	1029	1335	306±596
S1	NI	941	1445	504±201	897	1408	511±83	–	–	–
S2	FRI	1068	1623	555±161	999	1846	847±196	1092	1936	844±199
S2	VRI	950	1036	85±365	911	1398	486±19	1008	1638	608
S2	NI	941	1151	211±54	865	1149	284±144	–	–	–
S3	FRI	1068	1813	745±181	994	1840	846±329	1092	1714	622±82
S3	VRI	941	1255	314±21	864	683	−181±349	1026	1263	253
S3	NI	941	884	−56±38	870	1050	180±71	–	–	–

treatment to \$1601 ha^{-1} in S1-VRI-VRF treatment (**Table 8**). The lowest and highest values were observed in the same irrigation and nitrogen management combination treatment (VRI-VRF), which was due to soil type having a significant impact on grain yield, and this effect influenced the gross income. Moreover, variability in grain yield was highest in VRI (Sharma and Irmak, 2020b), and this resulted in

Table 11. Average results of operational cost (Opt., $/ha), gross income (Gross, $/ha) and net income (Net, $/ha) for fixed rate fertigation (FRF), variable rate fertigation (VRF) and pre-plant (PP) nitrogen treatments under fixed 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) for 2015, 2016 and 2017 growing seasons.

Soil type	*N level→*	*FRF*			*VRF*			*PP*		
	Irr. level ↓	*Opt. ($/ha)*	*Gross ($/ha)*	*Net ($/ha)*	*Opt. ($/ha)*	*Gross ($/ha)*	*Net) ($/ha)*	*Opt. ($/ha)*	*Gross) ($/ha)*	*Net ($/ha)*
S1	FRI	927	1622	692	903	1535	628	953	1590	632
S1	VRI	898	1431	530	858	1659	799	946	1487	539
S1	NI	851	1392	536	815	1055	240	–	–	–
S2	FRI	936	1478	530	886	1397	499	962	1506	530
S2	VRI	893	1112	208	841	1143	290	930	1377	428
S2	NI	860	962	88	807	973	151	–	–	–
S3	FRI	945	1288	322	877	1370	472	971	1418	425
S3	VRI	882	1033	131	840	863	4	932	1053	105
S3	NI	869	923	31	808	928	96	–	–	–

considerable variation in gross income in VRI treatment within and among soil types as compared with gross income for FRI treatments. In 2016, the gross income varied from \$675 ha^{-1} in S2-NI-No nitrogen treatment to \$1772 ha^{-1} in S1-FRI-FRF treatment (**Table 9**) whereas in 2017 the range was \$683 ha^{-1} in S3-VRI-VRF to \$1936 ha^{-1} S2-FRI-PP (**Table 10**). The lower gross income in 2015 than in 2016 and 2017 was due to the lower grain yields in that growing season than in 2016 and 2017 growing seasons. The operational and soil, crop, irrigation and nitrogen management costs also varied year to year due to differences in the product costs as well as the amount of the products applied due to different insect and disease pressure. The 2017 growing season, had the greatest operational cost ranging from \$734 ha^{-1} in S2-NI-No nitrogen treatment to \$1092 ha^{-1} in S2-FRI-PP treatment. The highest operational cost in 2017 can be attributed to higher irrigation amounts applied as well as the aerial application of insecticide and fungicide. The lower operational cost in all NI treatment in all three years was due to the reduction in cost of pumping of irrigation water from the groundwater source.

Since the grain yield and productivity response to different irrigation and nitrogen management strategies varied and they also exhibited different response in different soil types, the net income from these management practices (treatments) also varied between the years, treatments and soil types. Similar to gross income, nitrogen treatments had no significant impact ($p > 0.05$) on net income; however, there was a soil type and irrigation interaction effect on net income. In 2015, due to similar grain yields in all treatments as well as no to very little amount of irrigation applications in both VRI and FRI treatments, the effect of any treatment on net income was not significant ($p > 0.05$); however, the effect of soil type on on net income was significant ($p < 0.05$) with greatest net income being observed in S1 (silty clay loam soil) (Table 8). In 2016, significant impact of irrigation and soil type was observed on net income. The greatest net income was observed in FRI, which was significantly higher ($p < 0.05$) than VRI and NI; however, NI and VRI were not significantly different. Similar results of net income were obtained in 2017 growing season. The net income ranged from \$19 ha^{-1} to \$886 ha^{-1} in 2015; from \$-148 ha^{-1} to \$810 ha^{-1} in 2016; and from \$-151 ha^{-1} to \$847 ha^{-1} in 2017. On average of three growing seasons, net income was significantly higher in FRI as compared with VRI and NI in all soil types. Although, the results of grain yield revealed that grain yield was not significantly different between FRI and VRI in S1; the net income was significantly lower in VRI in S1 as compared to FRI. Overall, averaging all three years, all treatments had a positive net income at the end of the growing season with FRI having substantially higher income than VRI in most cases.

The net income values from FRI-FRF, FRI-PP, VRI-FRF, VRI-VRF and VRI-PP treatments were then compared to the fixed capital cost of the irrigation system (Table 6). The NPV for each treatment was evaluated. In economics, the net present value is the measurement of profit calculated by subtracting the present value of cash outflows from the irrigation and nitrogen management as well as other inputs related to crop production, which also includes the initial cost of investment from the present value of all the cash inflows over a period. In addition to NPV, IRR is another indicator of the profitability of the investment. The IRR is a discount rate at which the NPV of all cash flows from a particular investment becomes equal to zero. In this research, the average age of the irrigation system was assumed to be 20 years for which the NPV and IRR were calculated. The other assumptions for this analysis are already presented in Table 5. The NPV and IRR for each treatment in all soil types are presented in **Figs. 2 and 3**, respectively. These values were calculated using the separate total fixed

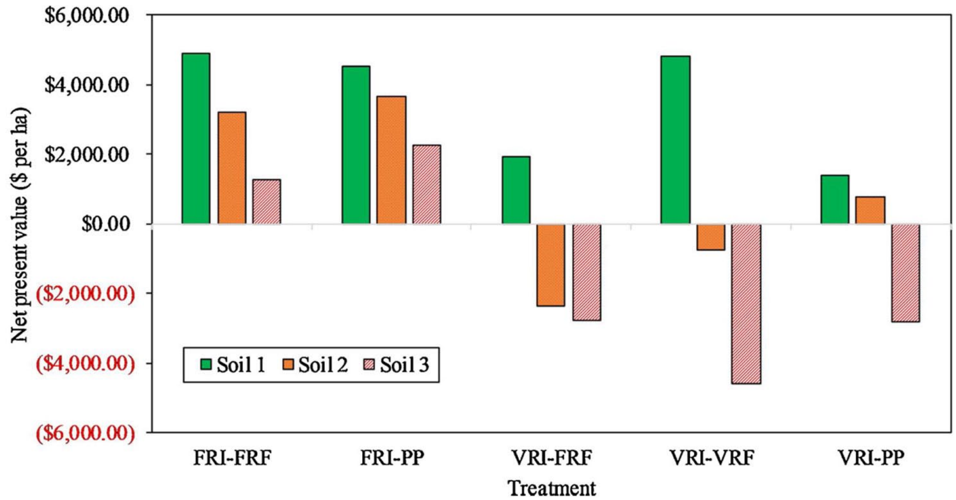

Fig. 2. Net Present Value (NPV, $ per hectare) for the investment in an irrigation system for fixed (uniform) rate irrigation (FRI) and variable rate irrigation (VRI) under fixed (uniform) rate fertilizer (FRF), variable rate fertilizer (VRF) and pre-plant (PP) fertilizer (nitrogen) management for three soil types.

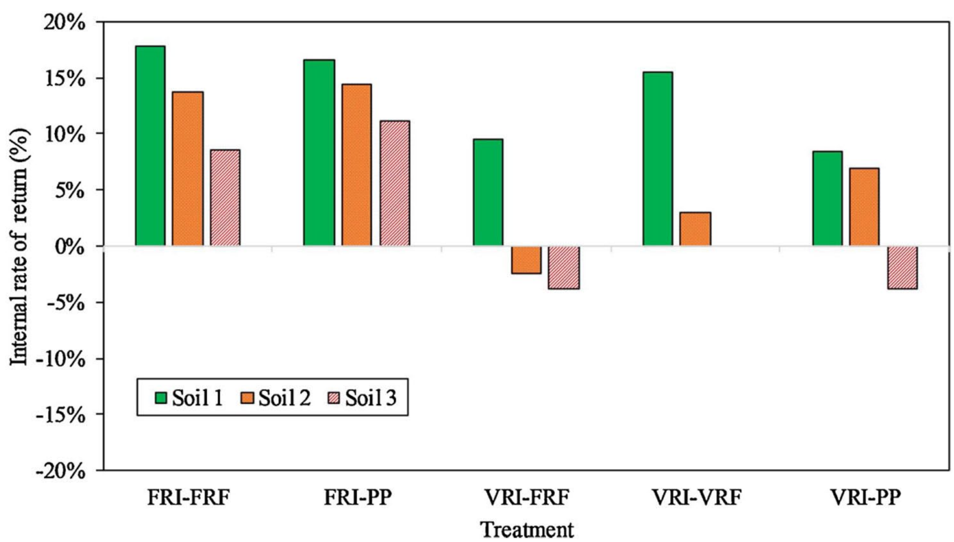

Fig. 3. Internal Rate of Return (IRR, %) for the investment in an irrigation system for fixed (uniform) rate irrigation (FRI) and variable rate irrigation (VRI) under fixed (uniform) rate fertilizer (FRF), variable rate fertilizer (VRF) and pre-plant (PP) fertilizer (nitrogen) management for three soil types.

costs of FRI and VRI systems (Table 6). Since the FRI-VRF combination includes both systems (fixed rate and variable rate technologies), this combination (FRI-VRF) was excluded from NPV calculations in Fig. 2. In real world operations, in most, if not all, cases, under irrigated conditions, there is no reason to practice variable rate fertilizer management if fixed (uniform) rate irrigation management is practiced and most, if not all, fixed rate center pivot and other irrigation methods do not have the VRF capability to solely practice VRF management. The maximum NPV of $4,882.07 per ha was observed in FRI-FRF treatment in S1. A similar NPV of $4,821.5 per ha was observed in VRI-VRF in S1. However, an IRR of 18 % in FRI-FRF in S1 makes it a better investment compared to VRI-VRF in S1. In S2 and S3 the VRI treatments had negative NPV, except for VRI-PP in S2. The negative NPV indicates that the present value of the costs exceeds the present value of future profits at the assumed discount rate (5%). Following Boyer et al. (2015), the discount rate used in this analysis reflects the current common discount rate, but this rate can vary between the regions. If the discount rate increases, the profitability of investment in irrigation for maize production will decrease. Also, energy prices are not likely to decrease in the future and can impact the amount of water pumped by producers (Pfeiffer and Lin, 2014; Boyer et al., 2015). The aforementioned results suggest that maize grain prices will need to remain high and the discount rate will need to remain low for extended periods of time and grain yields for VRI and VRF management will need to produce substantially greater yield with reduced inputs with respect to FRI and FRF for VRI and VRF management practices to be competitive with FRI and FRF management under these experimental conditions. Furthermore, for the VRI and VRF strategies to be competitive with the FRI and FRF, the cost of the VRI and VRF technology will need to be significantly lower than the current investment costs. Comparing the soil types, S1 had the highest NPV followed by S2 and S3. The profitability of VRI was limited by the high capital cost of the irrigation system with VRI technology as well as lower grain yields obtained with VRI treatments. A decrease in the capital cost of the VRI system could possibly help in improving the economic viability of VRI management if VRI technology and management results in increased yields with reduced input costs. Otherwise, while there could be some environmental benefits of VRI technology, with the current high investment and operational cost of VRI technology and the fact that the grain yields are not improved sufficiently, in relation to FRI management, to offset the investment cost, it is almost impossible for VRI technology to be an economically viable technology or

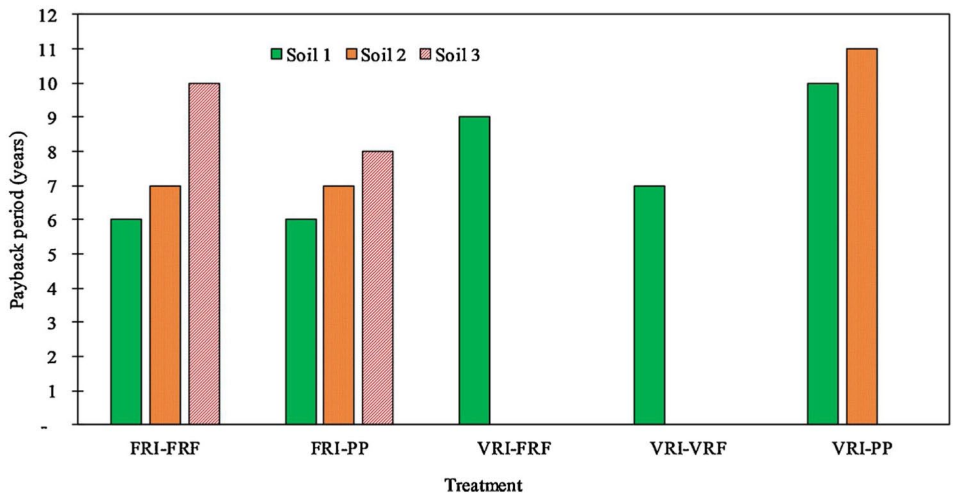

Fig. 4. Payback period (in years) when the initial investment in irrigation system will break even with net income for fixed (uniform) rate irrigation (FRI) and variable rate irrigation (VRI) under fixed (uniform) rate fertilizer (FRF), variable rate fertilizer (VRF) and pre-plant (PP) fertilizer (nitrogen) management for three soil types. No data under VRI treatments indicate that payback period is greater than the assumed lifespan of the irrigation system.

management practice for profitable economic net return, which may explain extremely limited adoption of these technologies by producers in large scale production fields.

As it is the case with all other farm machinery and investment in large equipment, the payback period of any irrigation system is also an important economic consideration for any farm operation. The payback period (when investment cost breaks even) was estimated for each irrigation and nitrogen treatment for all soils and years (**Fig. 4**). A payback period of less than or equal to 10 years was evaluated for FRI management. There were substantial differences in payback period between the irrigation methods (FRI and VRI) in the same soil type and for the same irrigation and/or fertilizer management method between the soil types. For example, the payback period for FRI-FRF is 6 years in S1 whereas it is 9 years in VRI-FRF and 10 years in VRI-PP management. For FRI-FRF management, the payback period was 6 years in S1 and this increased to 10 years in S3, indicating substantial impact of soil type (through its impact on irrigation requirement and grain yield production) on economics and payback period of the irrigation and fertilizer management strategy. For the VRI management, the payback period was in most cases more than 27 years, which is more than the assumed lifespan of the irrigation system (20 years). In S3, none of the VRI treatments at any fertilizer management resulted in a reasonable payback period. The pay-back period in VRI irrigation system was less than 10 years for S1; however, it was longer than the corresponding FRI management. It should be noted that NPV of the equipment and the payback period could vary depending upon the field size under consideration. To the best of the authors' knowledge, these are the first information and data from extensive research comprehensively investigated the soil type impact on economics and payback period of FRI and VRI under different fertilizer management strategies under different soil types for three years. The results clearly suggest that soil type impact on grain yield and, in turn, its impact on economic feasibility of VRI technology should be taken into account when considering investment into VRI technology to be able to make more comprehensive farm economy/net return analyses and for long- and (short)-term planning of investment vs. return analyses.

Other researchers reported similar findings in terms of lower or no profitability of VRI technology as compared with traditional fixed (uniform) rate irrigation and nitrogen management in other states for different crop management, climatic and soil conditions and management practices. For example, Yao-Chi et al. (2005) evaluated the economic feasibility of variable rate applications (VRA) of irrigation water in maize production using data collected through field experiments in Florence, SC. The net returns from VRA applications were compared with fixed (uniform) rate irrigation applications. Their results indicated that the VRA applications yielded larger net returns than the uniform applications. However, the variable rate technologies (VRT) applications require additional equipment and control. They reported that the benefits of reduced irrigation water costs plus the value of increased yields must be greater than the additional costs associated with the VRT applications for VRT to be a viable option. For the commercial VRA system, the additional costs of VRT are more than the benefits of using VRT. They concluded that at present, the VRT application of irrigation water is not profitable as compared with uniform applications for South Carolina. They further suggested that the costs of these equipment and controls are declining over time. Furthermore, the costs would be much smaller when VRT is widely adopted by producers and these equipment and controls are mass-produced. King et al. (2006) evaluated the potential for site-specific irrigation management (SSIM) in terms of increasing yield and quality of potatoes relative to conventional uniform irrigation management (CUIM) for two years in Idaho. Tuber yield distributions trended 4% greater under site-specific irrigation management, but were not significantly different ($p > 0.05$). Total tuber yield per unit of water applied from irrigation and precipitation was 4% greater in 2001 and 6% greater in 2002 under SSIM. Based on a local tuber quality adjusted potato processing contract price structure, the trend in gross income averaged across the field site was $159/ha ($65/ acre) greater with SSIM. However, they reported that this increase in gross income is likely about half the actual cost of commercial site-specific irrigation technology. They concluded that the economic benefit of SSIM needs to be increased or realized for other crops in the rotation for it to be an economically viable technology in potato production systems.

The economic analyses presented in this research and others can vary between the years, cropping systems, region, climatic conditions, field size, fuel source used for irrigation water withdrawal and other factors. For example, in a comprehensive research, Boyer et al. (2015) investigated the NPV of investing in a center-pivot irrigation system for maize production in western Tennessee using experimental data and input variables as well as cost from field research conducted near Milan, Tennessee. While the authors did not compare FRI and VRI practices and did not study soil type impact, they comprehensively accounted for three different field sizes and two energy sources (diesel and electric) for irrigation water withdrawal and evaluated how change in maize prices impact the profitability of irrigated maize as compared with rainfed production for long-term (2006–2013). They estimated yield response functions to N for rainfed and irrigated maize and used the estimated optimal yields and N fertilization rates for rainfed and irrigated maize to estimate the economic returns from investing in irrigation. They observed that maize yield increased and stabilized with irrigation in their experimental conditions. On average, irrigation increased maize yield by 4.14 ton ha^{-1}. Prior to 2006, the expected NPV for irrigating maize was negative across all field sizes and energy sources. However, post-2006, the expected NPV was positive for fields of 50 ha or larger that used either diesel or electric power.

The probability of NPV being positive for fields of 50 ha or larger, which used either diesel or electric power, ranged between 3% and 31 % for prices prevailing before 2006 and increased to between 87 % and 100 % for prices prevailing from 2006 to 2013. The expected NPV for using electric power was higher than for diesel power for all fields of 50 ha or larger. They suggested that if the maize grain price follows Food and Agricultural Policy Research Institute (FAPRI, 2012) projections in Tennessee and other humid regions of the United States, producers will likely continue investing in irrigation systems for maize production. However, they also suggested that maize prices will need to stay high for extended periods of time for irrigated production to remain profitable after investment in center-pivot irrigation under Tennessee growing conditions. Thus, investment in center-pivot irrigation may be a risky proposition for Tennessee producers if maize prices do not remain high.

4. Summary and conclusions

Economic analyses of FRI and VRI under different nitrogen management practices were conducted using field research-measured data, input cost, grain price and other variables and factors. Overall, both irrigation treatments (VRI and FRI) increased the grain yield as compared with no irrigation. Significant differences in the grain yield between VRI and FRI management were observed in S2 and S3 soil types with FRI being greater than VRI. However, in S1, grain yield between VRI and FRI management was not significantly different. In 2016 and 2017 growing seasons, net income from FRI management was significantly greater than VRI management in all soil types. Also, pooled data for three growing seasons showed significantly greater net income in FRI management than VRI. Nitrogen treatments had no effect on net income in any of the growing seasons. Comparing the soil types, S1 (Create silt loam) resulted in maximum net income for all treatments as compared with S2 (Hastings silty clay loam) and S3 (Hastings silt loam). In terms of NPV and IRR, the maximum values of $4,882.07 per ha and 18 %, respectively were observed for FRI-FRF treatment in S1. The VRI treatments had negative NPV in S2 and S3, except for VRI-PP in S2 which means that the present value of the costs under these treatments exceeded the present value of profits at the assumed discount rate (5%). A payback period of less than or equal to 10 years was determined for all FRI management treatments whereas for VRI management, payback period was, in most cases, more than 27 years, which is more than the assumed lifespan of an irrigation system (20 years). While the pay-back period for the VRI irrigation system was less than 10 years for S1, it was still much longer than the corresponding FRI management treatments in the same soil. In conclusion, the results of this research indicate that soil types as well as irrigation and nitrogen management practices play a critical role in overall farm economics. With no evidence of increased grain yield and reduction in input variables coupled with high capital costs associated with VRI technology may constitute impediments of its economic feasibility and profitability as well as its adoptability in production fields for maize production under these experimental conditions. Our results suggest that maize grain prices will need to remain high and the discount rate will need to remain low throughout the lifespan of the irrigation system and grain yields for VRI and VRF management will need to produce substantially greater yield with reduced inputs with respect to FRI and FRF for VRI and VRF management practices to be competitive with FRI and FRF management. The research results can be beneficial in aiding growers and their advisors, managers and other agricultural and irrigation professionals in terms of assessing, evaluating and even forecasting the profitability and economic viability of different irrigation management practices, especially for variable rate irrigation management, under different nitrogen management conditions in different soil types.

Competing Interests The authors declare no conflict of interest.

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