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# Field Research Report: Results from the ENREEC VRI Field for the 2021, 2022, and 2023 Crop Seasons

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**Summary**

Long-term irrigation management research has been conducted from 2014 to 2023 for corn and soybean at the Eastern Nebraska Research, Extension, and Education Center (ENREEC) Variable Rate Irrigation (VRI) Field located in subhumid east-central Nebraska (in the Lower Platte North Natural Resources District). The objective of this report was to present the overall results from the VRI Field for 2021 to 2023. Across the three growing seasons, there were the following irrigation treatments: Best Management Practice (BMP), 50% BMP, 125% BMP, rainfed, Spatial ET Modeling Interface (SETMI), SDD1, SDD2, machine-learning-based Cyber-Physical System (CPS), a student team recommended rate, and industry trials from Irriga Global's *Aluvio*. Results showed that from 2021 to 2023, only 2022 was dry enough to have a significant yield response to irrigation in both corn and soybean. The distribution of precipitation in 2023 resulted in a significant difference in yield for corn but not soybean. Over 9 years of corn production, the mean

seasonal irrigation was 4.4 in (for full irrigation treatments), corresponding to a mean yield of 246 bu/ac compared to a mean rainfed yield of 227 bu/ac. For 8 years of soybean research, the average seasonal irrigation was 4.0 in; the mean irrigated soybean yield was 70 bu/ac compared to 66 bu/ac for rainfed plots. The long-term average increase in gross revenue (from irrigation) was 104 $/ac/yr for corn and 46 $/ac/yr for soybean.


**Figure 1: The ENREEC VRI Field, including the pivot point (top left), soybean planted into corn residue on the south half of the field on June 17, 2019 (top right), aircraft (DJI M300) used for capturing imagery in 2023 (bottom left), and aerial view from the aircraft (looking west with corn on the north half, image courtesy David Heeren) on June 26, 2023 (bottom right).**

## Introduction

The Variable Rate Irrigation (VRI) Field was established in 2014 to develop and assess management strategies for VRI by performing research with a VRI center pivot on a large field (quarter section) representative of typical commercial farm fields in the Great Plains. The VRI Field is part of the UNL Eastern Nebraska Research, Extension, and Education Center (ENREEC) located near Mead, NE (Figure 1). The initial partnership included several faculties in order to combine expertise in irrigation, remote sensing for ET (Christopher Neale), unmanned aircraft systems (UAS) (Wayne Woldt), geophysics (Trenton Franz), precision agriculture (Joe Luck), and related topics. Initial research focused on spatial variability in soils (e.g., Miller et al., 2018), spatial ET and water management using Landsat (e.g., Barker et al., 2018), spatial irrigation utilizing UAS multispectral imagery (e.g., Bhatti et al., 2020), and irrigation with Planet multispectral and UAS thermal imagery (Maguire et al., 2022). The overall field data for 2015 to 2020, along with other specific data sets, have been documented in various publications (Table 1). This report's objective is to present the overall results from the VRI Field for 2021 to 2023. Irrigation research at a nearby ENREEC field, using a Valley 8000 (with a high-speed X-Tec drive, Valmont Industries) and infrared thermometers mounted on the pivot lateral (Bhatti et al., 2023), is not included here.

**Table 1: Previously published data from the ENREEC VRI Field.**

| Crop Season | Publications with Overall Field Data | Other Publications with Field Data |
|---|---|---|
| 2014 | -- | Miller et al. (2018) |
| 2015 | Barker et al. (2018) | Barker et al. (2016), Barker et al. (2017) |
| 2016 | Barker et al. (2018) | Barker et al. (2017) |
| 2017 | Bhatti et al. (2020) | Wilkening et al. (2021) |
| 2018 | Bhatti et al. (2020) | Singh et al. (2020), Singh et al. (2021a); Maguire et al. (2021) |
| 2019 | Maguire et al. (2022) | Singh et al. (2021a); Maguire et al. (2021) |
| 2020 | Maguire et al. (2022) | Singh et al. (2021a), Singh et al. (2021b), Kashyap et al. (2023) |
| 2021 | [this report] | Singh et al. (2022) |
| 2022 | [this report] | Li et al. (2023) |
| 2023 | [this report] | Wilkening (2023), Shi et al. (2023) |

## Materials and Methods

### *Field Site and Soils*

The ENREEC VRI Field (41.165° N, 96.430° W) is located in subhumid east-central Nebraska (Saunders County), in the Lower Platte North Natural Resources District. The field is in the Clear Creek watershed, draining into Wahoo Creek, a tributary to Salt Creek, which finally flows into the Platte River (near Ashland, NE). The field is in a corn-soybean rotation, with soybean in the north half and corn in the south half on even-numbered years. This allows research to be performed on both corn and soybean each year. Also, corn typically reaches its peak crop water use rate before soybean; during a week with a very high atmospheric demand for water, irrigation management can prioritize the crop with the highest crop water use and/or the crop in the most sensitive growth stage.

Based on gSSURGO (Soil Survey Staff, 2014), the soils in the field are approximately half silt loam and half silty clay loam (Figure 2). Wilting point (WP) for each plot, based on thermocouple psychrometer measurements, ranged from 0.175 to 0.205 $cm^3/cm^3$ throughout the field (mean 0.19 $cm^3/cm^3$). Neutron probe readings after a large rainfall event were used to determine the field-observed field capacity, $FC_{obs}$ (Lo et al., 2017) for each plot, which ranged from 0.37 to 0.45 $cm^3/cm^3$ (mean 0.42 $cm^3/cm^3$). Topsoil organic matter was approximately 3 to 4%. Additional soil data are presented in Singh et al. (2020) and Barker et al. (2017).

### *Irrigation System*

The irrigated field site was equipped with a seven-span model 8500 Zimmatic (Lindsay Corporation, Omaha, NE) variable rate center pivot with their Precision VRI individual nozzle control system, which was installed in 2014 for an irrigated area of 130 ac (53 ha). A Zimmatic Boss control panel in conjunction with a Zimmatic Precision Growsmart VRI control panel are located on the system, with remote LTE access available through Lindsay's FieldNET online interface to manage and upload VRI prescription maps and initiate irrigation events from locations beyond the field. The zone-control VRI both accommodates rectangular plots for irrigation treatments and allows prescription maps to account for spatial variability in soils or crop water use. For 2014 to 2022, Nelson A3000 Accelerator sprinklers (with navy plates and 10-psi regulators) were mounted on top of the pivot lateral with a 45-ft (14-m) wetted diameter. The design flow rate of the groundwater well was 740 gpm, resulting in a gross system capacity of 5.7 gpm/ac (0.89 L/s/ha) for the field. After each annual harvest, the wheel ruts from the pivot were filled with a Patriot pivot track closer (Minden Machine Inc., Minden, NE) and, as of 2021, a TracPacker (TracPacker LLC, Kearney, NE).

In July 2019, due to a hole in the PVC well casing as well as a hole in the pump column, a liner was installed along the well casing and the pump column was replaced (steel for the upper portion and fiberglass for the lower portion of the column). The pump was replaced with a three-stage Borer 11RKMC pump with closed impellers, which maintained a pumping rate of 740 gpm. In 2023, the sprinkler package was replaced with Senninger I-Wob-2 sprinklers (with blue plates and 10-psi regulators) on drops at truss-rod height, approximately 10 ft (3 m) above the ground with a 40-ft (12-m) wetted diameter. A catch can uniformity test was performed in May 2023 to evaluate system performance before any irrigation applications occurred; the Christiansen Uniformity coefficient (CU) was 90%, the application efficiency was 0.87, and the application efficiency of the lower quartile ($E_{LQ}$) was 0.75.

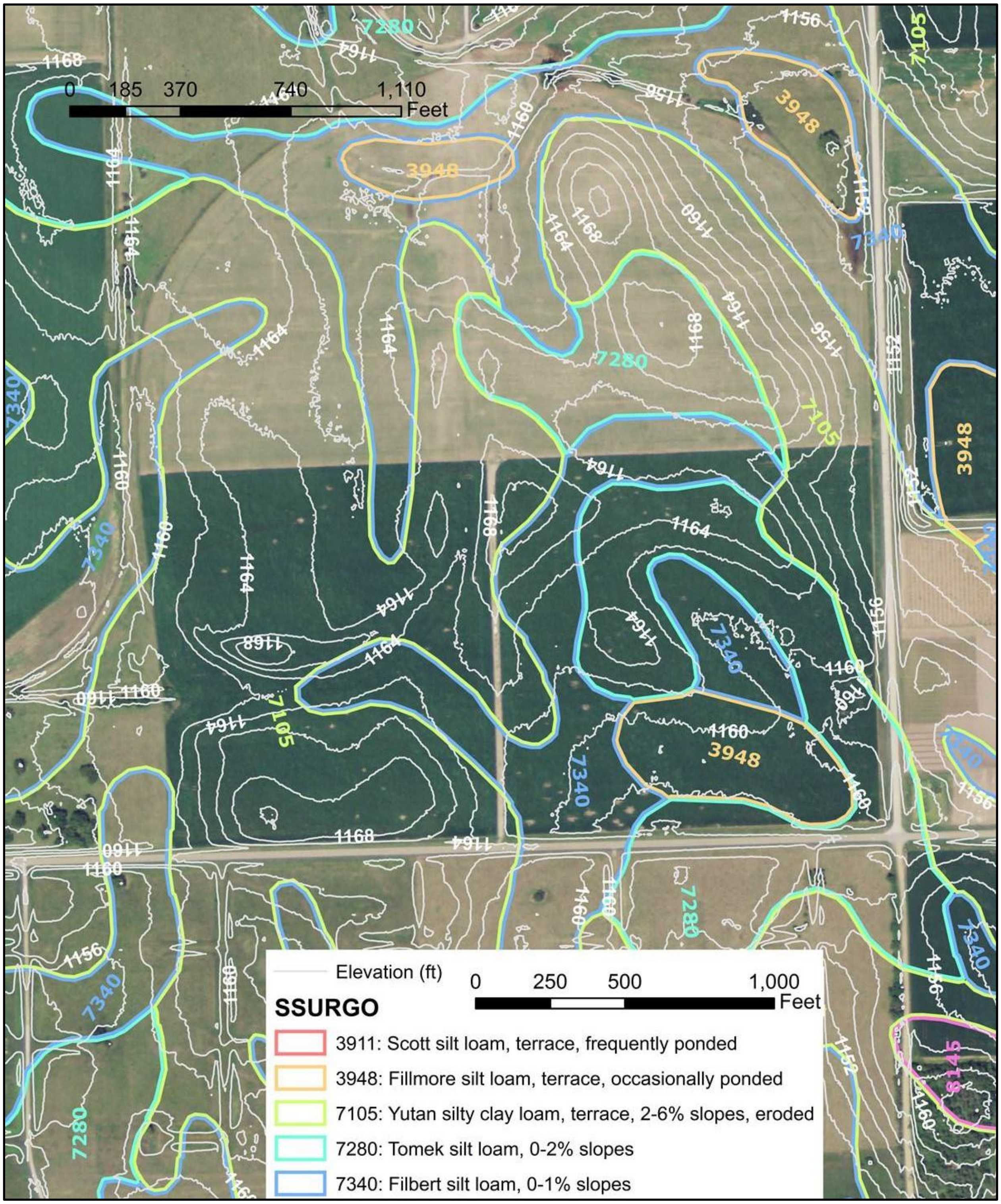



**Figure 2. Soil classification and 2-ft contour lines for elevation (ft) from USDA gSSURGO data for the ENREEC VRI Field. Courtesy of Himmy Lo.**

### *Field Operations*

All activities for crop production at the VRI Field (except irrigation management) were performed by ENREEC Farm Operations. Since 2014, corn and soybean were planted in rows running approximately east-to-west at 30-in spacing, with no-till soil management and controlled wheel traffic. Besides irrigation, optimum agronomic practices (fertilizer, herbicide, etc.) were selected for maximum profit (which would occur with yield being close to the maximum yield) in order that water would be the primary factor for limiting yield. For nitrogen (N) fertilizer, uniform anhydrous ammonia injections occurred in a single application prior to all corn plantings (except in 2022 and 2023 when limited-N treatments were introduced). The soybean did not receive fertilizer. Hybrid, planting date, and harvest date are in Tables 2 and 3.

**Table 2: Corn agronomic data for the VRI Field at ENREEC for the past decade.**

| Year | Subfield (north or south half) | Preplant N (lb/ac) | Hybrid | Maturity Rating (days) | Planting | Emergence | Harvest |
|---|---|---|---|---|---|---|---|
| 2014 | S | 180 | Pioneer P33D53 | -- | May 6 | -- | Nov 5 |
| 2015 | N | 170 | Pioneer P1257AM | -- | May 18 | ~May 27 | Nov 3 |
| 2016 | S | 150 | Pioneer P1151AM | 111 | May 4 | May 13 | Oct 31<br>Nov 1 |
| 2017 | N | 185 | Pioneer P0801AM | -- | Apr 23 | -- | Sep 28 |
| 2018 | S | 185 | Dekalb DK62-53 | 112 | May 14 | -- | Oct 3 |
| 2019 | N | 185 | Dekalb DK60-88RIB | 110 | Apr 20 | -- | Oct 31 |
| 2020 | S | 185 | Pioneer P1366AM | 113 | May 11 | May 28 | Oct 16 |
| 2021 | N | 210 | Pioneer P1185Q | 111 | May 5 | May 15 | Nov 2 |
| 2022 | S | 180 | Pioneer P1359AM | 113 | May 12 | May 23 | Oct 21 |
| 2023 | N | 170 | Dekalb DK62-89 | 112 | Apr 24 | May 9 | Oct 23 |

For equipment used during field operations, in 2023 anhydrous ammonia was applied with a 30-ft John Deere 2510H high-speed anhydrous applicator pulled by a John Deere 8R 370 tractor. Seed was planted with a John Deere 1795 16/31-row planter (40 ft wide) pulled by a John Deere 8R 370 tractor. Spraying was performed with a Rogator RG1100C with a 100-ft boom. The crop was harvested with a John Deere S650 combine using a 20-ft JD 620F flex grain head (for soybean) or a JD 708C eight-row corn head (20 ft wide).

### *Plot Design and Yield Data*

Experimental plots were 48 rows wide (120 ft, 36.6 m) and 200 ft (61 m) long with an area of 0.55 ac (0.22 ha). Plots were sized to account for a 30-ft (9.1-m) buffer zone (for transition in irrigation application depth between plots). After the buffer, the remaining area was 60 ft (3 combine passes) by 140 ft (Barker et al., 2016). The crop yield was measured using a calibrated yield monitor installed on the combine. The plot length was designed to provide a long enough pass with the combine that plot edge effects in the yield monitor data (i.e., the lag time between grain entering the combine head and arriving at the mass flow sensor) would be minimal (based on input provided by Joe Luck). In 2023, the plot layout was updated in order to increase the number of plots in the field and accommodate for changes in machine logistics through the field. The plot dimensions remained the same, although, with the new sprinklers (smaller wetted diameter), the buffer was reduced to 20 ft. This resulted in a remaining area of 80 ft (4 combine passes) by 160 ft.

**Table 3. Soybean agronomic data for the VRI Field at ENREEC for the past decade.**

| Year | Subfield (north or south half) | Hybrid | Maturity Group | Planting | Emergence | Harvest |
|---|---|---|---|---|---|---|
| 2014 | N | Pioneer P 35T58R | 3 | May 6 | -- | Oct 16 |
| 2015 | S | Pioneer P31T11R | 3 | May 21 | -- | Oct 14 |
| 2016 | N | Husker Genetics U03-825124 | 2 | May 18-19 | May 26 | Oct 18 |
| 2017 | S | Pioneer P27T59R | 2 | May 14 | -- | Oct 18 |
| 2018 | N | Pioneer P28T71X | 2 | May 9 | -- | Oct 24 |
| 2019 | S | Pioneer P27A17X | 2 | May 3 | -- | Oct 16 |
| 2020 | N | Pioneer P31A95X | 3 | May 1 | May 15 | Sept 29 |
| 2021 | S | Pioneer P31T64E | 3 | May 5 | May 24 | Oct 5 |
| 2022 | N | Croplan CP2920E | 2 | May 17 | May 29 | Oct 5 |
| 2023 | S | Stein 32EE21 | 3 | May 3 | May 13 | Oct 9 |

Assuming a grain moisture content (wet basis) of 15.5% (corn) or 13% (soybean), a wet bulk density of 56 lb/bu (corn) or 60 lb/bu (soybean) was used to convert the wet weight of the grain to a volume (bu). Yield data were filtered and cleaned with Yield Editor Software version 2.0 (USDA ARS). The filtered yield data (bu/ac) were checked against the total yield obtained from the grain carts. Finally, yield was converted to SI units of metric tons of dry mass per hectare (t/ha); 1 t/ha = 18.9 bu/ac for corn, and 1 t/ha = 17.1 bu/ac for soybean (Eisenhauer et al., 2021).

### *Irrigation Scheduling*

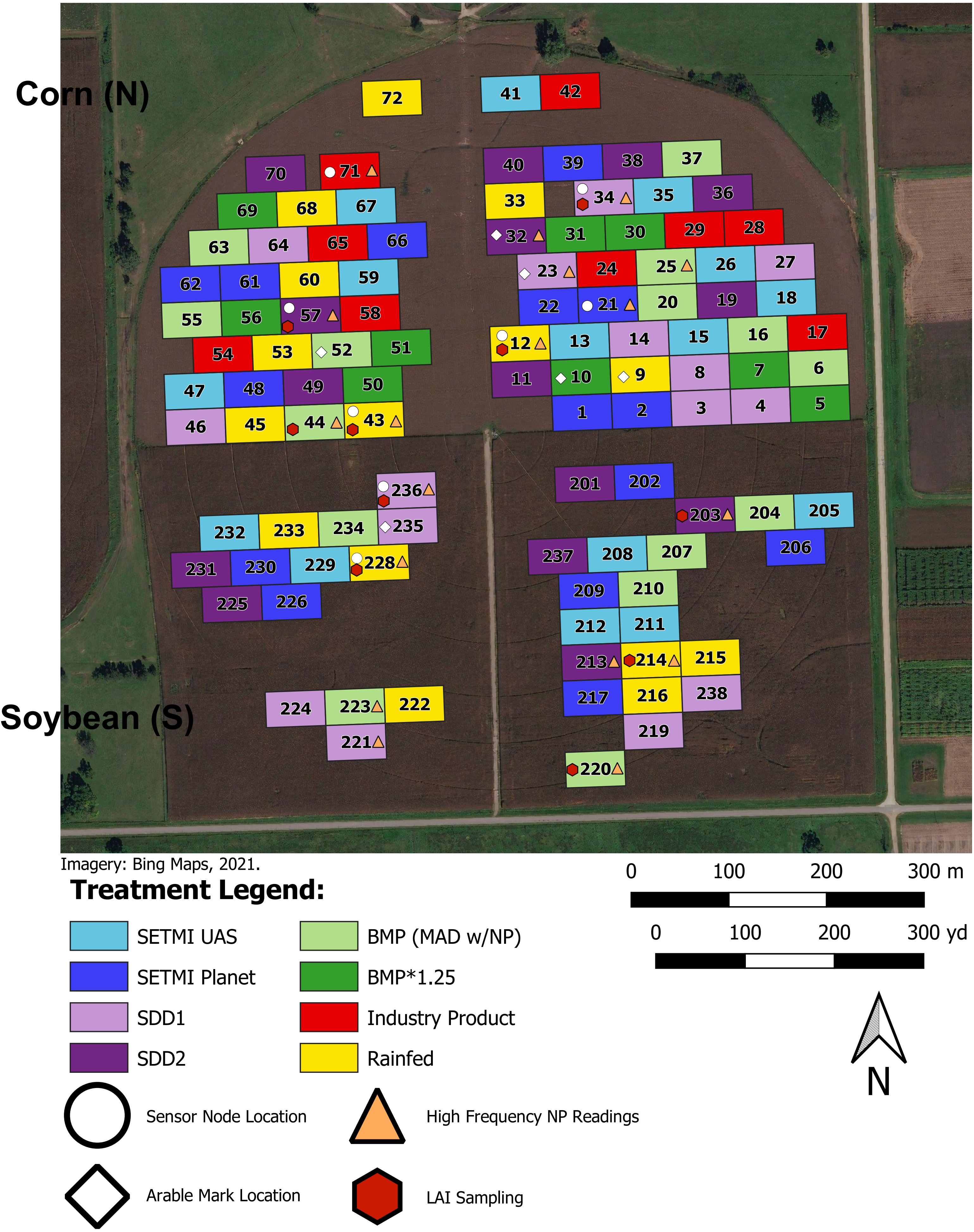
Of the irrigation treatments, the baseline was the Best Management Practice (BMP) treatment, in which irrigation was scheduled using a daily soil water balance in an Excel spreadsheet (developed by Barker et al., 2018). Soil water content was monitored with aluminum access tubes (installed with a Giddings probe) and a neutron probe (CPN 503 ELITE Hydroprobe, InstroTek Inc., Research Triangle Park, NC) to a depth of 48 in (1,200 mm), with readings taken at the midpoint of each 12-in layer of soil. The soil water balance tracks the Soil Water Depletion (SWD), starting with $FC_{obs}$ (SWD = 0) determined from soil sensor data (in this case, neutron probe readings), and subsequently updating the soil water balance approximately biweekly with SWD determined from neutron probe readings. For irrigation scheduling, this method of using soil sensor data to determine $FC_{obs}$, and then tracking the change in SWD, results in lower uncertainty compared to a soil water balance that tracks the actual volumetric water content and uses soil sensor data to update the water content (Singh et al., 2020). The soil water balance generally followed FAO56 and the ASCE Standardized Reference ET Equation, with crop ET being estimated using single crop coefficients and daily reference ET calculated as the sum of hourly reference ET for each 24-hr period. Weather data were retrieved from the Nebraska Mesonet station approximately 5 miles north of Memphis, NE ("Memphis 5N" in the AWDN); the station is one mile east of the VRI Field on the ENREEC Agronomy Farm. Recognizing the spatial variability in rainfall, data from other tipping bucket rain gauges near the field site were also monitored, especially when isolated storms moved through the area in late summer.

Following ET and the soil water balance, irrigation scheduling was guided by the principles of Eisenhauer et al. (2021). The maximum applied irrigation depth was determined based upon soil conditions; it was found that 1.2 in (30 mm) was sufficient both to prevent runoff under the last span of the center pivot and allow irrigation events to occur in an adequate timeframe. The net application depth was calculated using an application efficiency ($E_a$) of 0.85, interpreted from annual catch-can uniformity tests. The managed root zone increased linearly from 4 in (100 mm) at emergence to a maximum depth of 40 in (1,000 mm) at the date of maximum canopy coverage. A critical fraction depleted ($f_{dc}$) of 0.5 was used for both corn and soybean. For example, a plot with a WP of 0.19 $cm^3/cm^3$ and an $FC_{obs}$ of 0.42 $cm^3/cm^3$ (i.e., available water capacity of 0.23 $cm^3/cm^3$), this $f_{dc}$ corresponds to a Management Allowable Depletion (MAD) of 115 mm at the maximum root depth. Irrigation events were initiated with a goal of preventing the SWD from reaching the MAD, with a target SWD being the depth of one irrigation event (maximum net depth) wetter than MAD. A rainfall allowance ($r_a$) was used to keep space in the soil profile to be able to store infiltration from an unexpected rainfall (i.e., irrigation did not refill the root zone up to FC). Often, practical intervention from the irrigation manager's experience was necessary to ensure MAD was not exceeded for the multitude of irrigation treatments and two crop types under one irrigation system.

### *SETMI and Unmanned Aircraft Imagery*

The Spatial ET Modeling Interface (SETMI), developed by Neale et al. (2012), uses the soil-adjusted vegetation index (SAVI) from remote sensing imagery to calculate ET and crop coefficient spatially; it also has a two-source energy balance as a second method to estimate ET. SETMI was adapted to include a spatial soil water balance (which tracks SWD) and spatial irrigation recommendations (Barker et al. 2018), and it has been employed as a primary treatment at the VRI Field since the 2015 cropping season (Bhatti et al., 2020; Maguire et al., 2022, Wilkening 2023). The soil water balance in SETMI has an option to update the SWD during the crop season with neutron probe or in-situ soil water data if desired.

# 2021 Plot Map (ENREEC VRI Field)



Remote sensing imagery was collected with UAS flights during each season by the Nebraska Unmanned Aircraft Innovation Research and Education (NU-AIRE) Lab (https://nuaire.unl.edu/). The NU-AIRE Lab was founded by Wayne Woldt, and procedures for mission planning and flights are presented in Woldt et al. (2014), Barker et al. (2020) and Maguire et al. (2021). Aircraft included multispectral (green, blue, red, red-edge, and NIR) and thermal cameras. After each flight, individual images were stitched together with Pix4D.

### *2021 Treatments*

The corn in 2021 (north half the field) had eight treatments: BMP, 125% BMP, SETMI-UAS, SETMI-Planet, SDD1, SDD2, rainfed, and an unnamed industry product. The 125% BMP represented over-irrigation and received 25% more water than the BMP treatment. The SETMI-UAS used multispectral imagery from UAS flights, while SETMI-Planet used satellite multispectral imagery from Planet (San Francisco, CA). The two-source energy balance module in SETMI was not used, and the soil water balance in SETMI was not updated with soil sensor data. The SDD (supply-demand dynamics) treatments utilized irrigation scheduling from a research project that is not reported here.

The soybean had six treatments: BMP, SETMI-UAS, SETMI-Planet, SDD1, SDD2, and rainfed.

### *2022 Treatments*

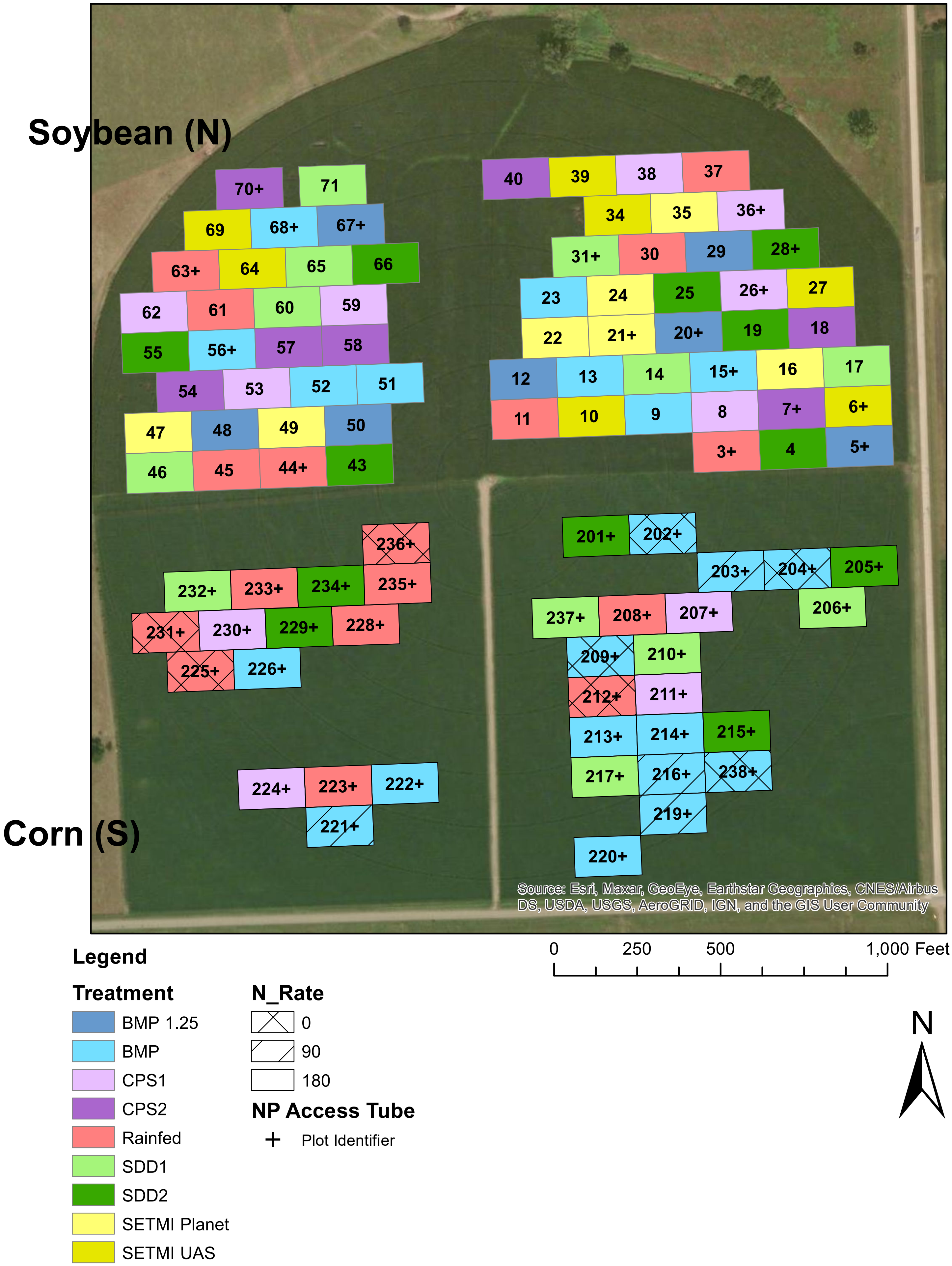
The corn in 2022 (south half the field) had five irrigation treatments: BMP, SDD1, SDD2, CPS1, and rainfed. The Cyber-Physical System (CPS) treatments were for a decision support system utilizing machine learning (with input from Yeyin Shi and Kuan Zhang) for irrigation management (Wilkening, 2023). While most of the corn field received full N (180 lb/ac preplant); some of the plots in the BMP and rainfed treatments received half N (90 lb/ac preplant) or no N.

The soybean had nine treatments: BMP, 125% BMP, SETMI-UAS, SETMI-Planet, SDD1, SDD2, CPS1, CPS2, and rainfed. The SETMI treatments were identical to the SETMI treatments in 2021.

### *2023 Treatments*

The corn in 2023 (north half the field) had seven treatments: BMP, SETMI, CPS1, CPS2, Aluvio-1, Aluvio-2, and rainfed. The SETMI treatment used a combination of multispectral imagery from the UAS (5 dates), Landsat (2 dates), and Planet (1 date). The two-source energy balance module in SETMI was not used, and the soil water balance in SETMI was not updated with soil sensor data. The Aluvio-1 and Aluvio-2 treatments used the Alivio product (Irriga Global, La Conversion, Switzerland) for irrigation scheduling. Aluvio-1 used in-situ sensors in the field along with other data sources, while Aluvio-2 did not use any sensors at the field site. The northwest quadrant of the field received full N (170 lb/ac preplant), with the research focused only on irrigation management.

# 2022 Plot Map (ENREEC VRI Field)



The corn in the northeast quadrant of the field had no-N, limited-N, and fertigation treatments along with irrigation treatments. Nitrogen fertilizer was injected into the center pivot mainline with a ReflexCONNECT™ MacRoy G110 (Agri-Inject, Yuma, CO). Design of the fertigation treatment included input from Yeyin Shi, Laila Puntel, Joe Luck, Guillermo Balboa, and Tyler Smith. Results from the northeast quadrant are not included in this report.

The soybean had ten treatments: BMP, 125% BMP, 50% BMP, SETMI, CPS1, CPS2, Aluvio-1, Aluvio-2, a student team, and rainfed. The 50% BMP received half of the amount prescribed by the BMP (i.e., deficit irrigation).

***Economic Analysis***

We performed a preliminary economic analysis to understand the changes in the yield and revenue due to irrigation as compared to non-irrigated farming using long-term yield data. The estimates in gains in yield and revenue were based on rainfed and irrigated yields, and did not consider profit maximization. The analysis presented is preliminary in nature and does not consider the annual operating costs or depreciation costs associated with the irrigation system. The irrigated acreage of the field was 130 acres (typical for a standard center pivot in the Great Plains). Commodity price data (2015-2023) were obtained from the USDA-NASS database and average annual prices ($/bu) were used for the analysis. The long-term yield and irrigation dataset was used to estimate the changes in yield and gross revenue.

The difference in gross revenue achieved due to irrigation was calculated as:

$$Difference\ in\ Gross\ Revenue = (Y_i - Y_{ni}) \cdot cp_a$$

where $Y_i$ = irrigated crop yield (bu/ac), $Y_{ni}$ = non-irrigated crop yield (bu/ac), and $cp_a$ = average annual commodity price ($/bu). To calculate the relative change in crop yields or revenue due to irrigation, we calculated the fractional irrigated yield gains (FIYG) as:

$$Fractional\ Irrigated\ Yield\ Gains = \frac{(Y_i - Y_{ni})}{Y_{ni}}$$

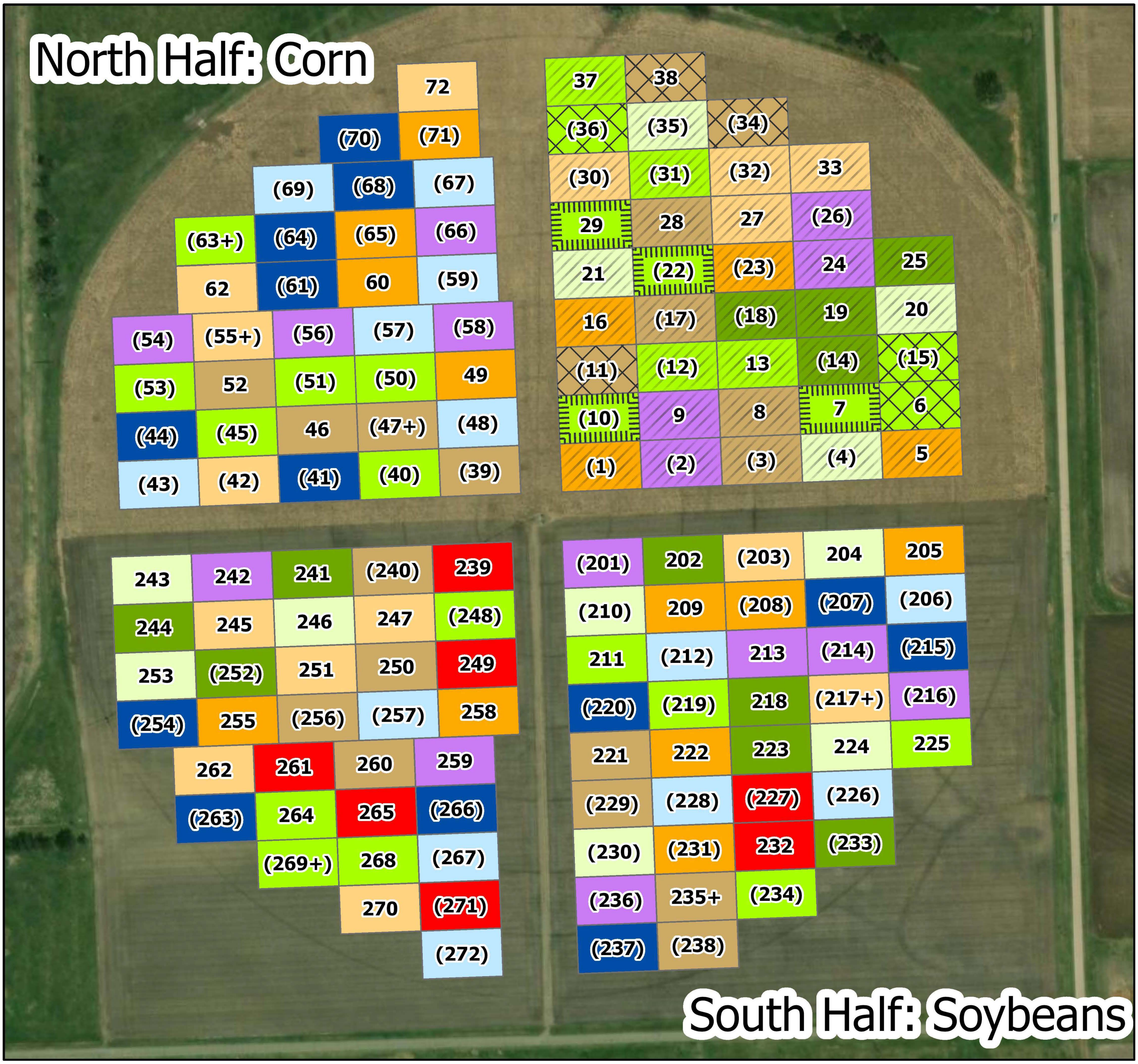
In this case, the Fractional Gross Revenue Gains was identical to the FIYG since the $cp_a$ is the same for both the irrigated yield and non-irrigated yield within a given year. However, to show the impact of the $cp_a$ each year, we also calculated a scaled fractional change in revenue which was normalized for the commodity price over time. The Scaled Fractional Revenue Gains (SFRG) used the ratio of annual commodity price to the long-term average commodity price and was estimated as:

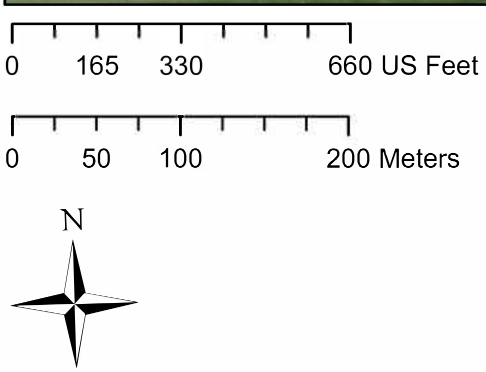
$$Scaled\ Fractional\ Revenue\ Gains = FIYG \cdot \phi_{cp}$$

$$\phi_{cp} = \frac{cp_a}{\sum_{i=1}^{n} \frac{cp_i}{n}}$$

where $\phi_{cp}$ was the price adjustment factor.

# 2023 Plot Map (ENREEC VRI Field)




## Legend

**Irrigation**

- 0.5 BMP
- 1.25 BMP
- Aluvio 1
- BMP
- CPS 1
- CPS 2
- Aluvio 2
- Rainfed
- SETMI
- Student Team

**FertLevel,N_Rate**

- 170 lbs-N/ac Pre-Plant, No Fertigation
- 85 Lbs-N/ac Pre Plant, No Fertigation
- 85 Lbs-N/ac Pre-Plant, Full Fertigation
- 0 Lbs-N/ac Pre-Plant, No Fertigation

() Indicates Plot Has Neutron Probe Access Tube

+ Indicates Plot Has CPS Sensor Node Station

## Results and Discussion

### *Precipitation*

The 2021 growing was relatively wet (404 mm for May-Aug), while the 2022 growing season was dry. The 2023 growing season started very dry, to the point that irrigation was needed to ensure germination and water stress was visible in the corn canopy early in the season (Figure 3); however, rain started on July 4 and occurred regularly through August.

**Figure 3. Data collection with a leaf area index (LAI) meter in 2021 (left), and visible water stress in the <u>corn</u> canopy (at a location with adequate N) on June 22, 2023 (right).**

The 2022 and 2023 precipitation data were analyzed in detail; most of the high precipitation events occurred during July, August, and beginning October (Figure 4). The total growing season (May-Oct) precipitations were 317 and 410 mm for 2022 and 2023, respectively. The precipitation increased by approximately 29% from 2022 to 2023.

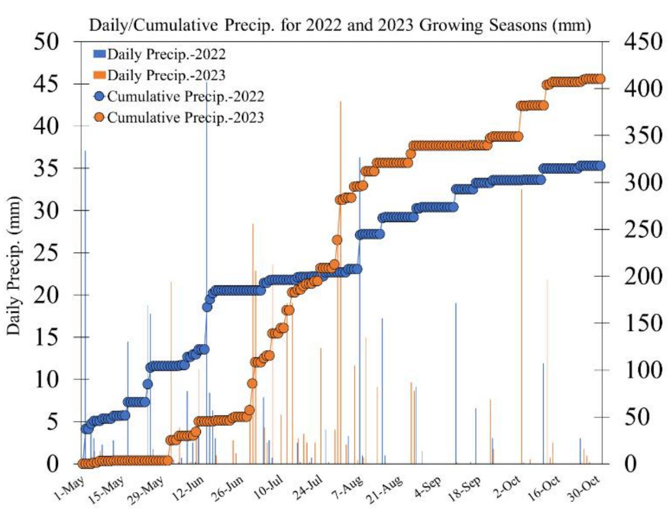



**Figure 4. Daily and cumulative precipitation for the 2022 and 2023 growing seasons.**

***2021 Results***

The 2021 crop season was relatively wet resulting in irrigation being lower than normal (Tables 4 and 5). Mean yields were not statistically different from each other except for corn between the SDD1 (229 bu/ac) and SDD2 (241 bu/ac) treatments with $p = 0.03$. It is unclear whether this difference is due to random variation or an actual effect of the treatment.

**Table 4. Grain yield and gross seasonal irrigation for corn in 2021. Parentheses show the minimum and maximum irrigation among the plots in the SETMI treatments. Other treatments had uniform irrigation among the plots within each treatment. All treatments had full N fertilizer.**

| Irrigation Treatment | n (plots) | Irrigation Applied (in) | Mean Yield (bu/ac) | Mean Yield (t/ha) |
|---|---|---|---|---|
| Rainfed | 9 | 1.0 | 237 | 12.6 ab† |
| SDD1 | 9 | 2.9 | 229 | 12.1 a |
| SDD2 | 9 | 3.7 | 241 | 12.8 b |
| BMP | 9 | 2.9 | 234 | 12.4 ab |
| 125% BMP | 9 | 3.8 | 237 | 12.6 ab |
| SETMI-UAS | 9 | 3.5 (3.1 – 4.1) | 240 | 12.7 ab |
| SETMI-Planet | 9 | 3.7 (3.1 – 4.1) | 242 | 12.8 ab |
| Industry Product | 9 | 3.6 | 234 | 12.4 ab |

†Means with the same letter are not statistically different ($p > 0.05$).

**Table 5. Grain yield and gross seasonal irrigation for soybean in 2021. Parentheses show the minimum and maximum irrigation among the plots in the SETMI treatments. Other treatments had uniform irrigation within each treatment.**

| Irrigation Treatment | n (plots) | Irrigation Applied (in) | Mean Yield (bu/ac) | Mean Yield (t/ha) |
|---|---|---|---|---|
| Rainfed | 6 | 0 | 65.8 | 3.9 a† |
| SDD1 | 6 | 1.8 | 67.7 | 4.0 a |
| SDD2 | 6 | 2.0 | 63.6 | 3.7 a |
| BMP | 6 | 2.9 | 63.6 | 3.7 a |
| SETMI-UAS | 6 | 4.0 | 63.3 | 3.7 a |
| SETMI-Planet | 6 | 4.1 | 66.3 | 3.9 a |

†Means with the same letter are not statistically different ($p > 0.05$).

*2022 Results*

With 2022 being a dry year, irrigation applied was more than normal and significant differences in yield were observed. Results for the corn and soybean are shown in Tables 6 and 7. The soybean treatments had a wide range in yield making it possible to fit a yield production function to the data (Figure 5), which is not common in east-central Nebraska.

**Table 6. Nitrogen applied, gross seasonal irrigation, and grain yield for corn in 2022. All treatments had uniform irrigation among the plots within each treatment.**

| Irrigation Treatment | Nitrogen (lb/ac) | n (plots) | Irrigation Applied (in) | Mean Yield (bu/ac) | Mean Yield (t/ha) |
|---|---|---|---|---|---|
| Rainfed | 0 | 4 | 0.0 | 115 | 6.1 a† |
| Rainfed | 180 | 5 | 0.0 | 149 | 7.9 ab |
| SDD1 | 180 | 5 | 4.3 | 212 | 11.2 c |
| SDD2 | 180 | 5 | 5.8 | 214 | 11.3 c |
| BMP | 0 | 4 | 9.6* | 147 | 7.8 b |
| BMP | 90 | 4 | 9.6* | 214 | 11.3 c |
| BMP | 180 | 5 | 9.6* | 242 | 12.8 d |

*The prescribed seasonal irrigation was 9.6 in. However, plots received additional irrigation (2.4 in) late in the season (Aug 30 to Sept 5) due to a system error.
†Means with the same letter are not statistically different ($p > 0.05$).

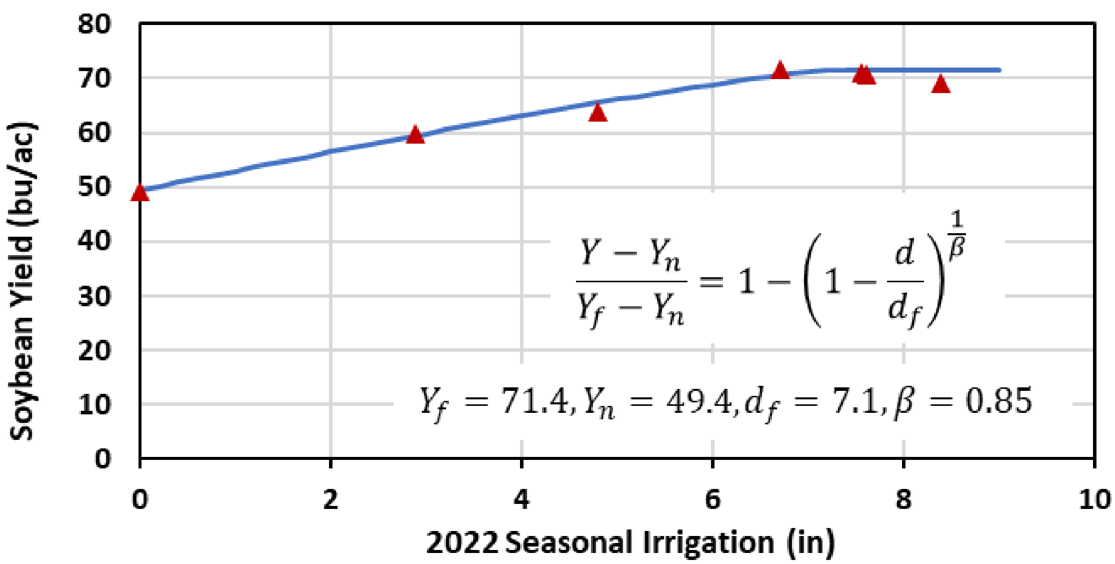



**Figure 5. Yield response to irrigation (red triangles) for soybean in 2022 at the ENREEC VRI Field. The blue curve is the Cobb-Douglas yield-water production function (Wilkening et al., 2021).**

The decision support system for the CPS1 and CPS2 treatments was not available in time for the irrigation season, so these plots received the same irrigation as prescribed by the BMP. Unfortunately, at the end of the season, there was a system error resulting in additional irrigation being applied from Aug 28 to Sept 7 on the BMP, 125% BMP, SETMI-UAS, SETMI-Planet, CPS1, and CPS2 treatments. Since it was late in the season and these treatments were for full or over-irrigation, it was assumed that this system error had a negligible impact on yield. The SDD1, SDD2, and rainfed plots did not receive irrigation from the system error.

**Table 7. Grain yield and gross seasonal irrigation for soybean in 2022. Parentheses show the minimum and maximum prescribed irrigation among the plots in the SETMI treatments. Other treatments had uniform irrigation among the plots within each treatment.**

| Irrigation Treatment | n (plots) | Irrigation Applied (in) | Mean Yield (bu/ac) | Mean Yield (t/ha) |
|---|---|---|---|---|
| Rainfed | 8 | 0.0 | 49.4 | 2.9 a[†] |
| SDD1 | 6 | 2.9 | 59.9 | 3.5 b |
| SDD2 | 8 | 4.8 | 63.8 | 3.7 b |
| BMP | 8 | 6.7* | 71.7 | 4.2 c |
| 125% BMP | 7 | 8.4* | 69.4 | 4.1 bc |
| SETMI-UAS | 7 | 7.6* (7.2 - 7.9) | 71.2 | 4.2 c |
| SETMI-Planet | 7 | 7.6* (7.4 - 8.1) | 70.8 | 4.1 c |

*Prescribed seasonal irrigation. Plots received additional irrigation (2.9-3.6 in) late in the season (Aug 28 to Sept 7) due to a system error.
[†]Means with the same letter are not statistically different (p > 0.05).

### *2023 Results*

The soil water balance for the BMP treatment is shown in Figures 6 and 7. At the corn field, irrigation events were varied among the treatments, with seasonal irrigation ranging from 0.0 in at rainfed to 4.9 in at the SETMI treatment (Table 8). Similarly, irrigation events were varied at the soybean field, ranging from 0.0 in at rainfed to 4.8 in of seasonal irrigation (Table 9). Corn grain yield data indicated that the rainfed treatment had a significantly lower grain yield than the other irrigation treatments ($p<0.05$). The soybean grain yield did not have significant differences in mean yield.

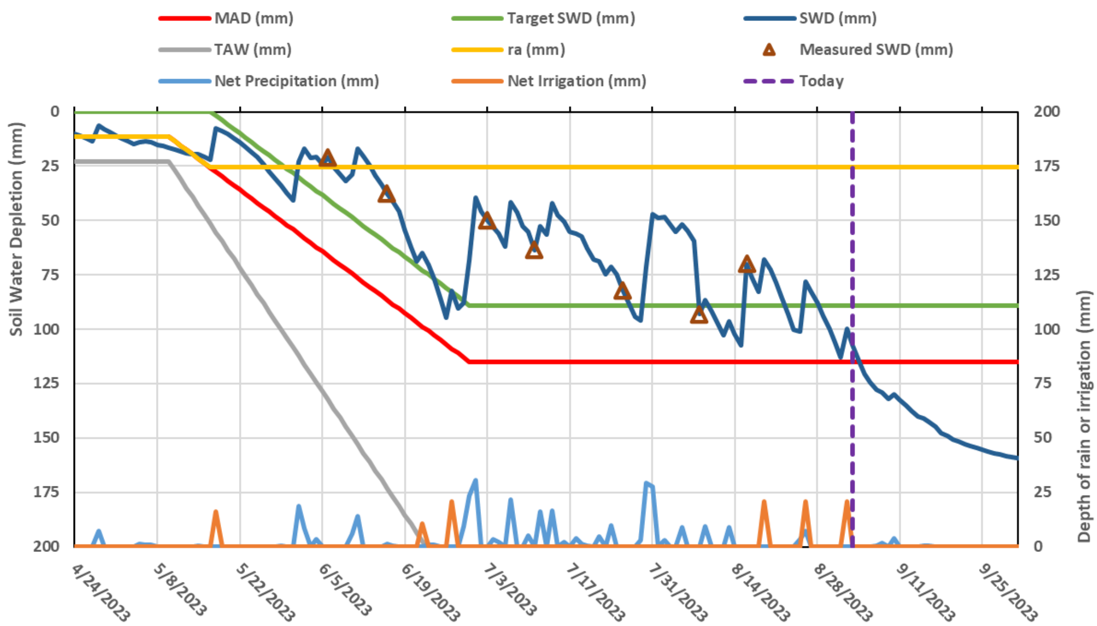



**Figure 6. Soil water balance for corn in the BMP treatment (plot 63).**

**Table 8. Grain yield and gross seasonal irrigation in 2023 for corn in the northwest quadrant of the field. Parentheses show the minimum and maximum prescribed irrigation among the plots in the SETMI treatments. (Results from corn in the northeast quadrant are not included in this report.)**

| Irrigation Treatment | n (plots) | Irrigation Applied (in) | Mean Yield (bu/ac) | Mean Yield (t/ha) |
|---|---|---|---|---|
| Rainfed | 4 | 0 | 221 | 11.7 a† |
| BMP | 6 | 4.4 | 236 | 12.5 b |
| Aluvio-1 | 6 | 4.3 | 239 | 12.7 ab |
| Aluvio-2 | 6 | 4.3 | 243 | 12.9 b |
| CPS1 | 4 | 4.3 | 245 | 13.0 b |
| CPS2 | 4 | 4.5 | 227 | 12.0 ab |
| SETMI | 4 | 4.9 (4.6 - 5.2) | 247 | 13.1 b |

†Means with the same letter are not statistically different ($p > 0.05$).

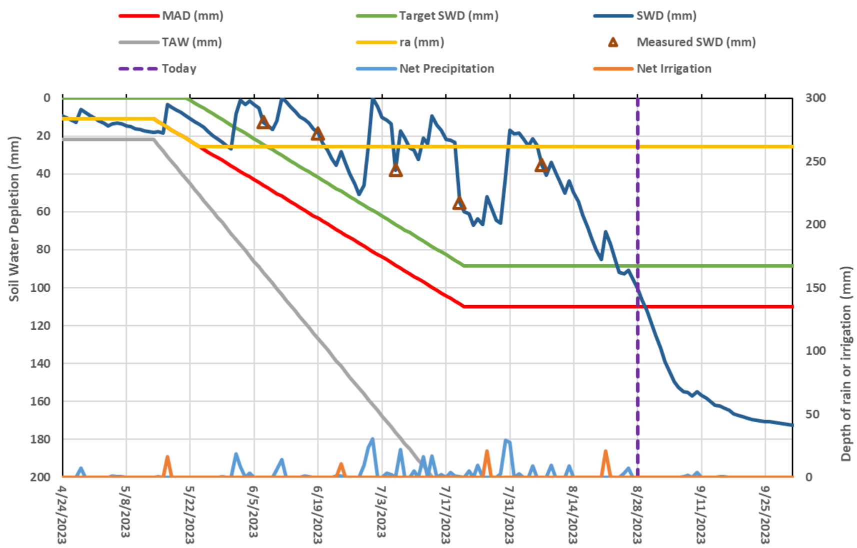



**Figure 7. Soil water balance for soybean in the BMP treatment (plot 269).**

**Table 9. Grain yield and gross seasonal irrigation for soybean in 2023. Parentheses show the minimum and maximum prescribed irrigation among the plots in the SETMI treatments. Other treatments had uniform irrigation within each treatment.**

| Irrigation Treatment | n (plots) | Irrigation Applied (in) | Mean Yield (bu/ac) | Mean Yield (t/ha) |
|---|---|---|---|---|
| Rainfed | 8 | 0 | 59.8 | 3.5 a[†] |
| 50% BMP | 7 | 1.9 | 55.9 | 3.3 a |
| BMP | 7 | 3.8 | 61.6 | 3.6 a |
| 125% BMP | 7 | 4.8 | 57.2 | 3.3 a |
| Aluvio-1 | 7 | 3.2 | 58.5 | 3.4 a |
| Aluvio-2 | 7 | 3.2 | 57.4 | 3.4 a |
| CPS1 | 7 | 3.8 | 53.7 | 3.1 a |
| CPS2 | 7 | 3.8 | 59.3 | 3.5 a |
| SETMI | 7 | 2.5 (1.9 – 3.5) | 54.1 | 3.2 a |
| Student team | 7 | 3.3 | 60.0 | 3.5 a |

[†]Means with the same letter are not statistically different ($p > 0.05$).

### *Long-Term Yield and Irrigation*

Tables 10 and 11 present the yield response to irrigation treatments and total seasonal precipitation for corn and soybean from 2015 to 2023. Yield response varied between years and among the irrigation treatments. Precipitation events and their distribution within the season minimized the effect of irrigation treatments on crop production for most years, especially for wet seasons (when the total seasonal precipitation amounts were higher than historical total precipitation). For instance, during the wet seasons of 2015 (May-Aug precipitation of 22.1 in), 2016 (precipitation of 21.5 in), and 2021 (precipitation of 16.5 in), the yield for both corn and soybean were not significantly affected ($p<0.05$) by irrigation treatments. The largest differences in yield occurred in years when the May-Aug rainfall was less than 14 in (2019, 2020, 2022, and 2023).

**Table 10. Long-term precipitation, seasonal irrigation (for a full irrigation treatment), irrigated yield, and rainfed yield for the VRI Field (USCS units). Yield and irrigation data for 2015-2020 are from Barker et al. (2018), Bhatti et al. (2020), and Maguire et al. (2022).**

| | | Corn | | | Soybean | | |
|---|---|---|---|---|---|---|---|
| Year | Rainfall (May-Aug) (in) | Full Irrigation (in) | Full Irrigation Yield (bu/ac) | Rainfed Yield (bu/ac) | Full Irrigation (in) | Full Irrigation Yield (bu/ac) | Rainfed Yield (bu/ac) |
| 2015 | 22.1 | 1.5 | 251 | 251 | -- | -- | -- |
| 2016 | 21.5 | 0.8 | 262 | 253 | 0.9 | 75 | 77 |
| 2017 | 16.8 | 3.0 | 226 | 219 | 2.0 | 70 | 69 |
| 2018 | 14.8 | 2.6 | 230 | 228 | 3.6 | 56 | 58 |
| 2019 | 13.5 | 6.1 | 281† | 266 | 4.9 | 82 | 79 |
| 2020 | 8.1 | 8.4 | 251† | 219 | 7.2 | 80† | 72 |
| 2021 | 16.5 | 2.9 | 234 | ~237 | 2.9 | 64 | 66 |
| 2022 | 10.0 | 9.6 | 242† | 149 | 6.7 | 72† | 49 |
| 2023 | 13.1 | 4.4 | 236† | 221 | 3.8 | 62 | 60 |
| Average | 15.2 | 4.4 | 246 | 227 | 4.0 | 70 | 66 |

†Full irrigation yield is statistically different than rainfed yield ($p < 0.05$).

**Table 11. Long-term precipitation, seasonal irrigation (for a full irrigation treatment), irrigated yield, and rainfed yield for the VRI Field (SI units). Yield and irrigation data for 2015-2020 are from Barker et al. (2018), Bhatti et al. (2020), and Maguire et al. (2022).**

| | | Corn | | | Soybean | | |
|---|---|---|---|---|---|---|---|
| Year | Rainfall (May-Aug) (mm) | Full Irrigation (mm) | Full Irrigation Yield (t/ha) | Rainfed Yield (t/ha) | Full Irrigation (mm) | Full Irrigation Yield (t/ha) | Rainfed Yield (t/ha) |
| 2015 | 561 | 39 | 13.3 | 13.3 | -- | -- | -- |
| 2016 | 546 | 20 | 13.9 | 13.4 | 24 | 4.4 | 4.5 |
| 2017 | 427 | 76 | 12.0 | 11.6 | 51 | 4.1 | 4.1 |
| 2018 | 376 | 66 | 12.2 | 12.1 | 91 | 3.3 | 3.4 |
| 2019 | 343 | 155 | 14.9† | 14.1 | 124 | 4.8 | 4.6 |
| 2020 | 206 | 213 | 13.3† | 11.6 | 183 | 4.7† | 4.2 |
| 2021 | 419 | 73 | 12.4 | 12.6 | 73 | 3.7 | 3.9 |
| 2022 | 254 | 244 | 12.8† | 7.9 | 171 | 4.2† | 2.9 |
| 2023 | 333 | 112 | 12.5† | 11.7 | 97 | 3.6 | 3.5 |
| Average | 385 | 111 | 13.0 | 12.0 | 102 | 4.1 | 3.9 |

†Full irrigation yield is statistically different than rainfed yield ($p < 0.05$).

### *Crop Yield and Revenue Gains from Irrigation*

Our analysis shows that the greatest difference in corn yield (93 bu/ac) and gross revenue ($632/ac) occurred in 2022 (Table 12). If the entire field had been in fully irrigated corn, the increase in gross revenue would have been $82k for the field. In terms of the difference in irrigated and non-irrigated gross revenue generated over the 9 years of data, a field on irrigated acres would earn an average of 104 $/ac/yr more ($13.5k for 130 ac) compared to dryland yield. In 2022, irrigated corn generated 62% more yield and 96% more revenue (scaled for trends in crop price) due to irrigation compared to non-irrigated fields (Figure 8). In 2023, irrigated corn showed a 7% increase in yield and 9% scaled gain in revenue due to irrigation compared to non-irrigated fields. The spike in gross revenue in 2022, attributed to irrigation, was favored by the low rainfall, large irrigation application and jump in commodity prices. The corn prices peaked from 3.6 $/bu in 2020 to 6.8 $/bu in 2022 (Figure 8). Commodity prices surged in 2022 due to supply chain disruptions from wars, increased energy and fertilizer costs, higher transportation costs, and drought in the US, among other economic factors.

**Table 12. Difference between irrigated and rainfed yield and gross revenue for 2015-2023. Soybean was assumed to have no difference in yield or revenue in 2015 which was a wet year.**

| | Corn | | Soybean | |
|---|---|---|---|---|
| **Year** | **Difference in Yield (bu/ac)** | **Difference in Gross Revenue ($/ac)** | **Difference in Yield (bu/ac)** | **Difference in Gross Revenue ($/ac)** |
| 2015 | 0 | 0 | -- | 0 |
| 2016 | 9 | 32 | -2 | -19 |
| 2017 | 7 | 24 | 1 | 9.4 |
| 2018 | 2 | 7 | -2 | -18 |
| 2019 | 15 | 56 | 3 | 25 |
| 2020 | 32 | 115 | 8 | 72 |
| 2021 | -3 | -16 | -2 | -26 |
| 2022 | 93 | 632 | 23 | 343 |
| 2023 | 15 | 90 | 2 | 25 |

For soybean, our analysis shows that in 2022, irrigated soybean generated 47% more yield and a 65% scaled gain in gross income due to irrigation compared to non-irrigated fields (Figure 8). In 2023, irrigated soybean showed a 3% increase in yield and a Scaled Fractional Revenue Gain of 4% due to irrigation. Similar to corn, the spike in gross revenue in 2022 was favored by the dry season and significant price jump in soybean prices. The prices jumped from 9 $/bu in 2020 to 15 $/bu in 2022. If the entire field had been irrigated soybean in 2022, the total increase in gross revenue for the field would have been $45k. In terms of the difference in gross revenue generated over the 9 years of data (Table 12), irrigated soybean would earn an average of 46 $/ac/yr more ($6k for 130 ac) compared to dryland yield.

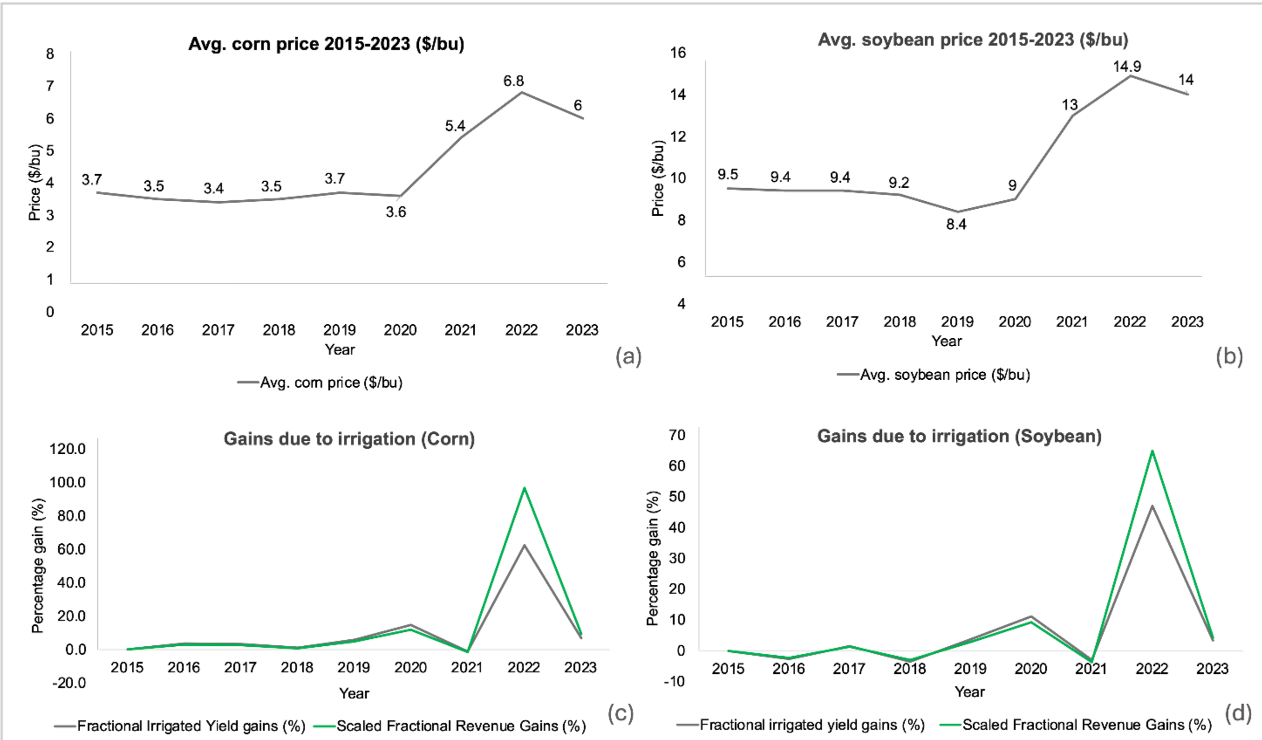



**Figure 8. Panels (a) and (b) show average annual corn (left) and soybean (right) prices from 2015-2023. Panels (c) and (d) show Fractional Irrigated Yield Gains and Scaled Fractional Revenue Gains due to irrigation for corn (left) and soybean (right).**

## <u>Conclusion</u>

From 2021 to 2023, only 2022 was dry enough to have a significant yield response to irrigation in both corn and soybean. The rainfed yield was 38% lower than the full irrigation yield for corn and 31% lower than the full irrigation yield for soybean. 2023 began very dry, but rain started on July 4 and then occurred regularly; only corn had a significant difference in yield. Over 9 years of corn production, the mean seasonal irrigation was 4.4 in (for full irrigation treatments), corresponding to a mean yield of 246 bu/ac compared to a mean rainfed yield of 227 bu/ac. For 8 years of soybean research, the average seasonal irrigation was 4.0 in; the mean irrigated soybean yield was 70 bu/ac compared to 66 bu/ac for rainfed plots.

The findings of the economic analysis are consistent with our economic intuition. Fractional yield and revenue gains due to irrigation in corn and soybean were positive in dry years, such as 2020, 2022, and 2023. Over 9 years, the average increase in gross revenue (from irrigation) was 104 $/ac for corn and 46 $/ac for soybean. The economic analysis is preliminary in nature, as we have not considered profit maximization or optimization.

Prior research at the VRI Field focused on sensor-based irrigation management and using VRI to account for spatial variability in crop water demand. Ongoing research focuses on UAS for canopy thermal stress detection (Kashyap et al., 2023), development of a machine learning model for irrigation (Wilkening, 2023), and application of machine learning to irrigation and fertigation management (which will be documented in future publications).

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## Appendix

The following pages include field spatial variability and topography (Figures 9 to 13), imagery from 2022 (Figure 14), the irrigation application chart for the sprinkler package installed in 2023 (Figure 15), and imagery from 2023 (Figures 16 and 17).

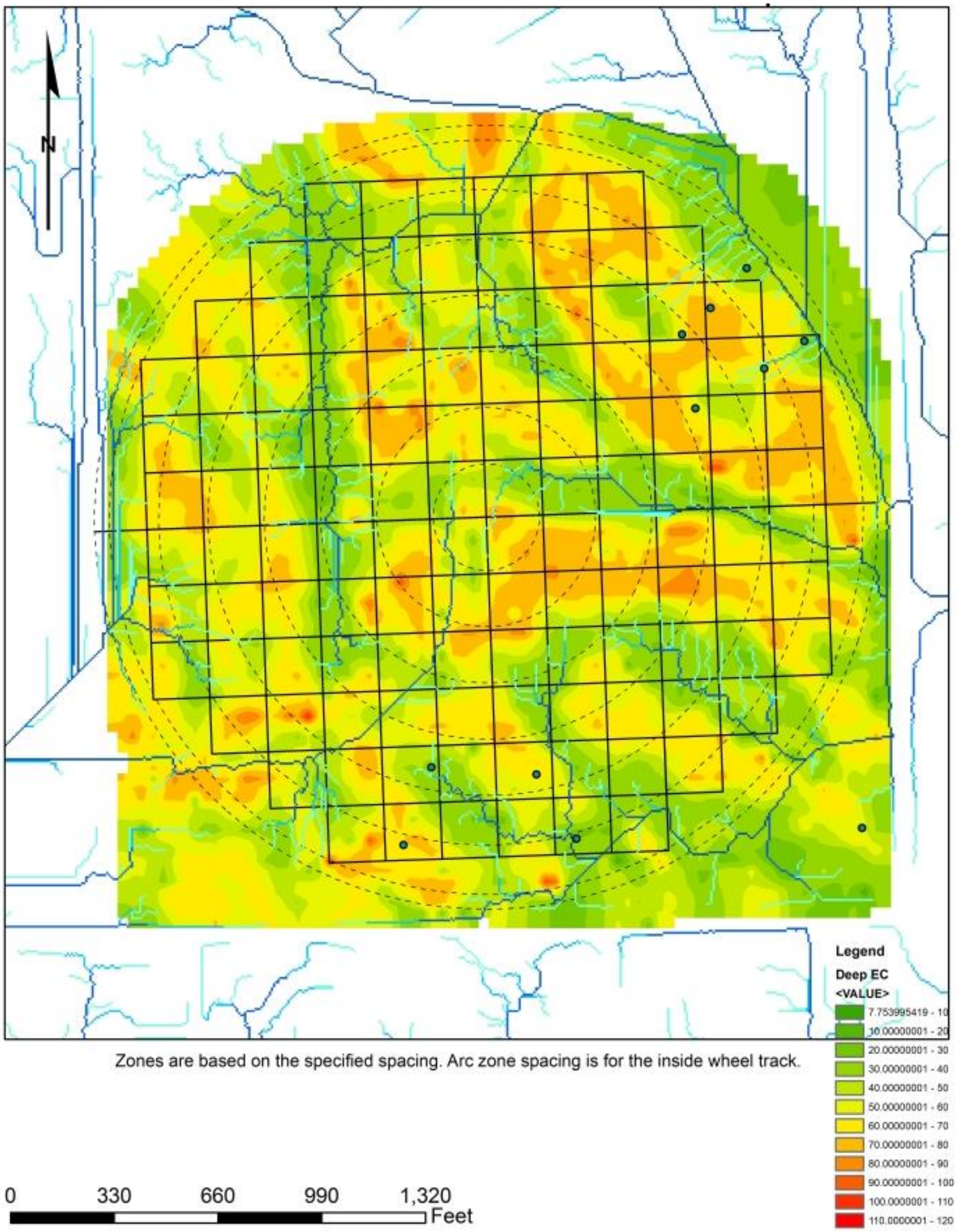


**Figure 9. Deep apparent electrical conductivity (ECa) at the VRI Field collected with a Veris MSP (Salina, KS) in November 2014, along with surface flow paths based on a digital elevation model. Courtesy of Joe Luck, Himmy Lo, and Burdette Barker.**

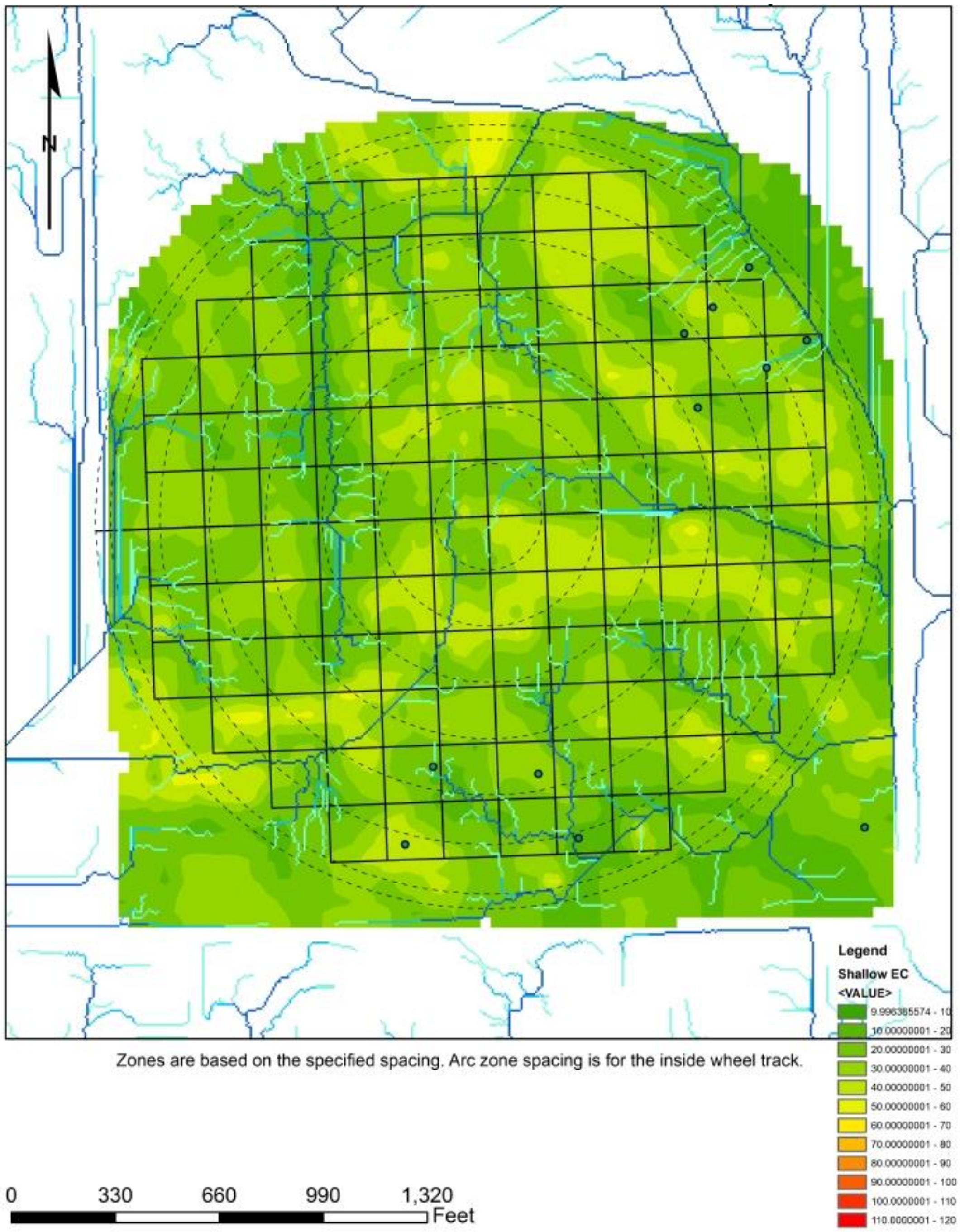


**Figure 10. Shallow apparent electrical conductivity (ECa) collected with a Veris MSP (Salina, KS) in November 2014, along with surface flow paths based on a digital elevation model. Courtesy of Joe Luck, Himmy Lo, and Burdette Barker.**

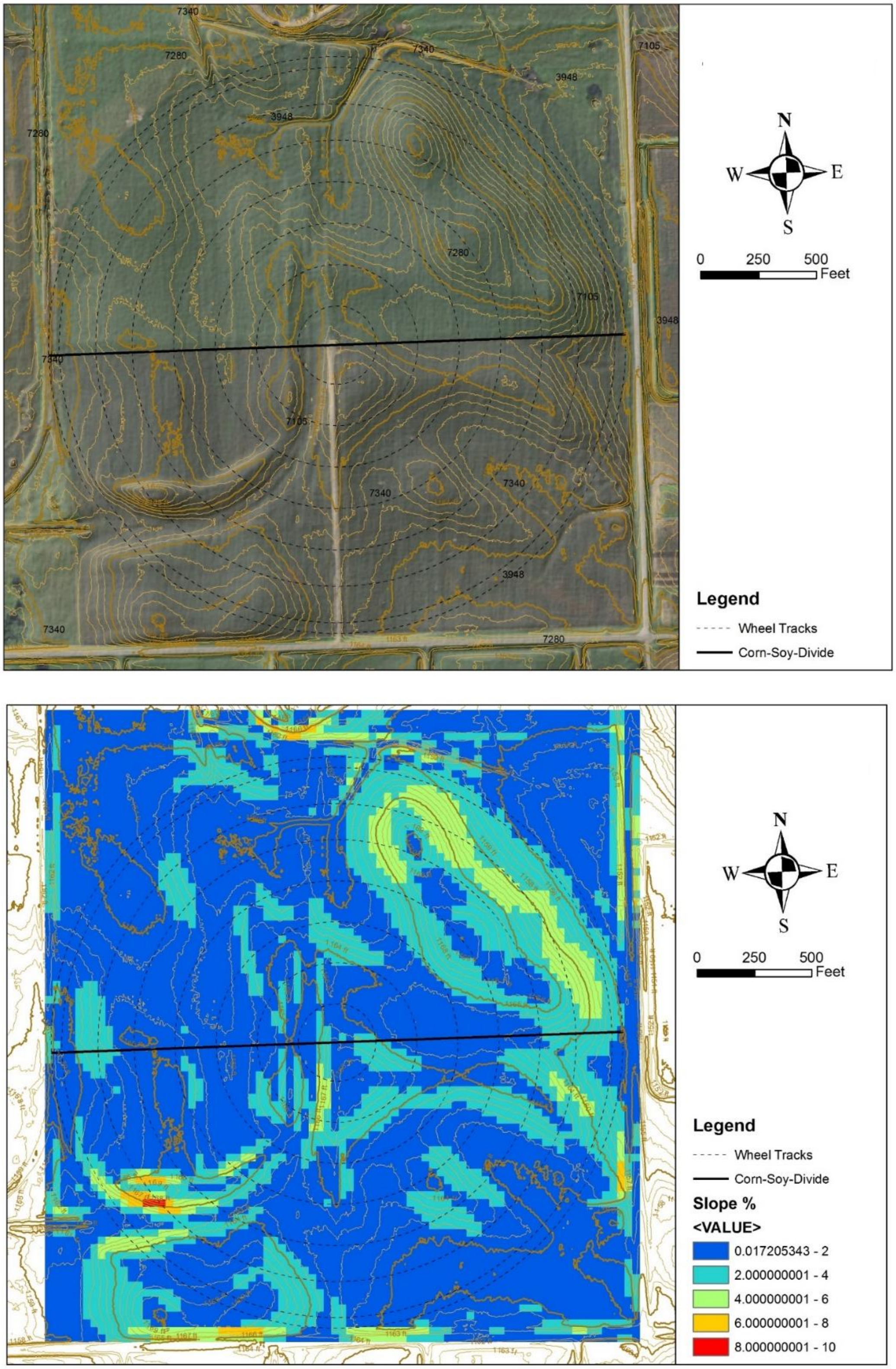


**Figure 11. Shaded topography (1-ft contours) and land slope maps. Courtesy of Burdette Barker.**

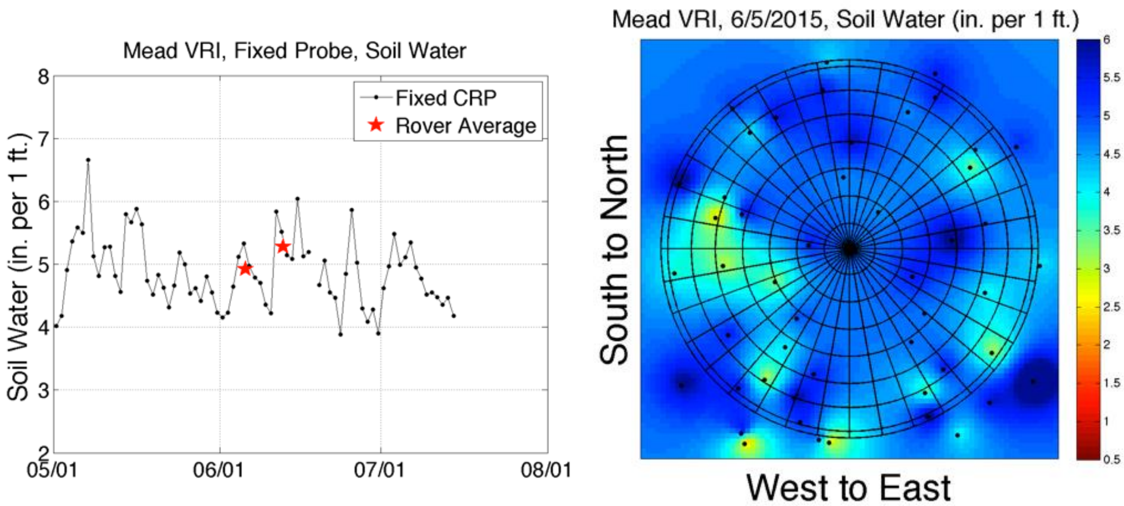


**Figure 12. Volumetric water content (inches of water per foot of soil) in the top ~1 ft of the soil profile measured with a stationary cosmic ray neutron probe (CRP) in 2015 (courtesy Trenton Franz) (left); spatial volumetric water content as measured with a rover CRP survey (as described in Finkenbiner et al., 2019) at the VRI Field on June 5, 2015 (right).**

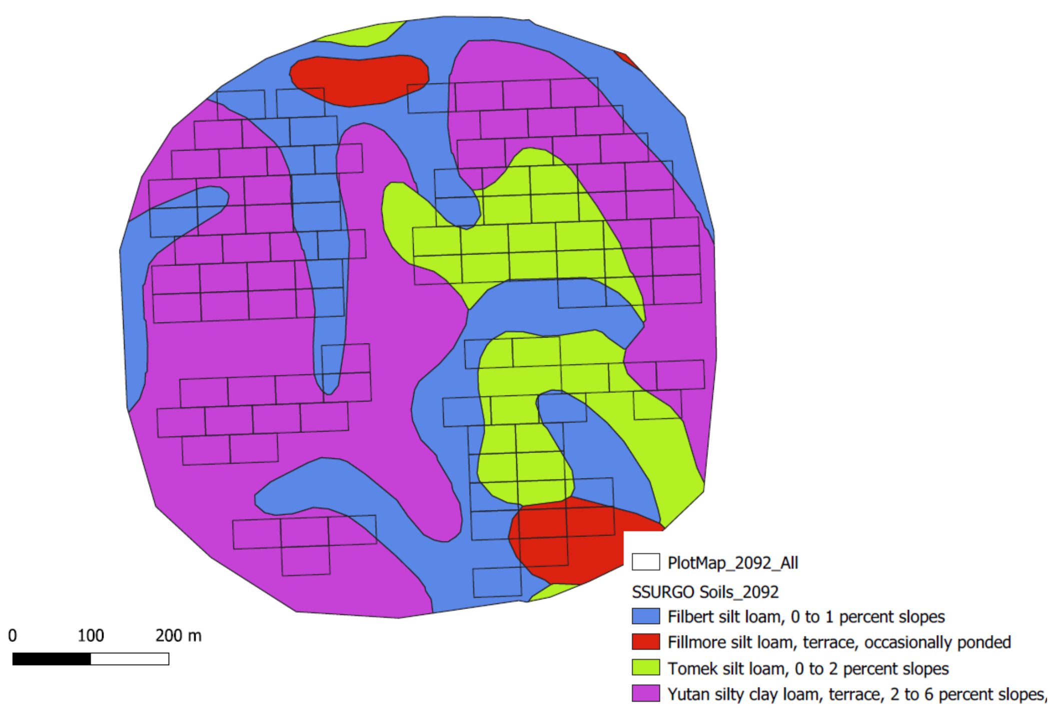


**Figure 13. SSURGO soil types at the ENREEC VRI Field overlaid with the plot layout used in 2021 and 2022. Courtesy of Guillermo Balboa.**

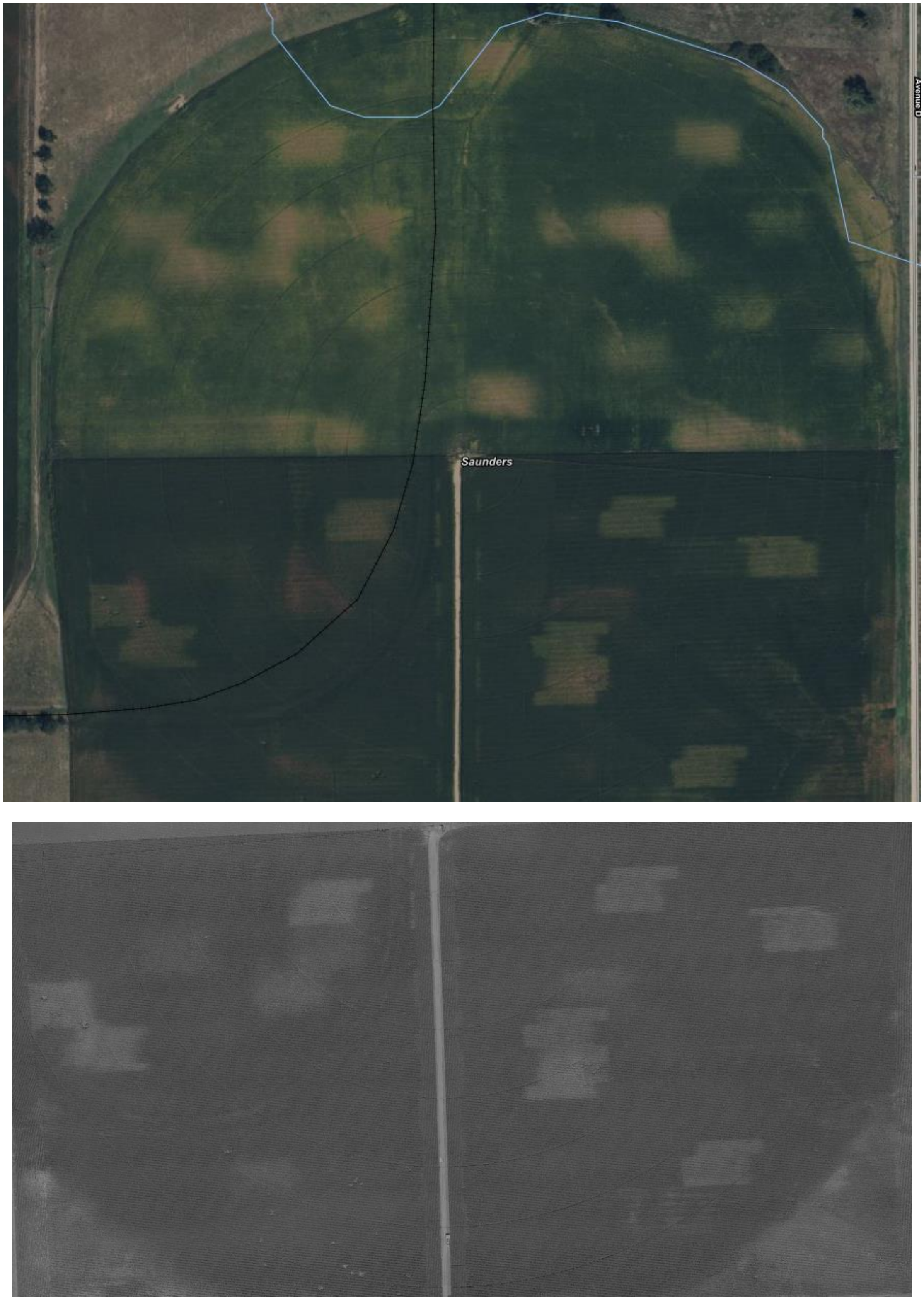


**Figure 14. Satellite imagery from Web Soil Survey in 2022 (top picture) showing limited-water plots in the soybean and no-N plots in the corn (south half); and red edge reflectance (bottom picture) from UAS on August 10, 2022 (courtesy of Jiating Li and Yeyin Shi). [The railroad (no longer present) was used as part of a munitions plant during World War II.]**

**ZIMMATIC** BY LINDSAY

# CENTER PIVOT APPLICATION CHART

UNL / Mead

Dealer Name : **FULL CIRCLE FARM SERVICES**

Sprinkler Chart Number : **EH-6092-23**

Last Tower Tire Size : 14.9x24-12 Lindsay
Last Tower Motor Speed : 59
Feet per Minute @ 100% : 14.00 fpm
Flowrate : 741.25
Pivot Pressure : 30.62
% of Pivot Revolution: 100.00
Length to Last Tower : 1200.59 ft
Overhang : 44.87
Total System Length : 1245.46 ft
Range of End Gun : 125.22
Total Length w/Endgun : 1370.68 ft

Date : April 21, 2023


**Panel Inputs:**

**741.25**

**539 minutes (Circle @ 100%)**

**0.109 min app rate**

**1370.68 ft (Wetted radius)**

| Set specific rate (by inch) | | | Set specific rate (by timer) | | |
|---|---|---|---|---|---|
| Gross Application (Inches) | Main Panel Timer (Percent) | Revolution Time (Hours) | Gross Application (Inches) | Main Panel Timer (Percent) | Revolution Time (Hours) |
| 0.11 | 100.00 | 8.98 | 0.11 | 100.00 | 8.98 |
| 0.11 | 100.00 | 8.98 | 0.11 | 95.00 | 9.45 |
| 0.20 | 54.28 | 16.55 | 0.12 | 90.00 | 9.98 |
| 0.30 | 36.18 | 24.82 | 0.13 | 85.00 | 10.57 |
| 0.40 | 27.14 | 33.09 | 0.14 | 80.00 | 11.23 |
| 0.50 | 21.71 | 41.36 | 0.14 | 75.00 | 11.97 |
| 0.60 | 18.09 | 49.64 | 0.16 | 70.00 | 12.83 |
| 0.70 | 15.51 | 57.91 | 0.17 | 65.00 | 13.82 |
| 0.80 | 13.57 | 66.18 | 0.18 | 60.00 | 14.97 |
| 0.90 | 12.06 | 74.46 | 0.20 | 55.00 | 16.33 |
| 1.00 | 10.86 | 82.73 | 0.22 | 50.00 | 17.96 |
| 1.10 | 9.87 | 91.00 | 0.24 | 45.00 | 19.96 |
| 1.20 | 9.05 | 99.27 | 0.27 | 40.00 | 22.45 |
| 1.30 | 8.35 | 107.55 | 0.31 | 35.00 | 25.66 |
| 1.40 | 7.75 | 115.82 | 0.36 | 30.00 | 29.93 |
| 1.50 | 7.24 | 124.09 | 0.43 | 25.00 | 35.92 |
| 1.60 | 6.78 | 132.36 | 0.54 | 20.00 | 44.90 |
| 1.70 | 6.39 | 140.64 | 0.72 | 15.00 | 59.87 |
| 1.80 | 6.03 | 148.91 | 1.09 | 10.00 | 89.80 |
| 1.90 | 5.71 | 157.18 | 1.55 | 7.00 | 128.29 |
| 2.00 | 5.43 | 165.46 | 2.17 | 5.00 | 179.61 |

This chart is an estimate of the performance of your Zimmatic center pivot system.
Tire inflation, soil conditions, flow fluctuations, and other conditions can cause application and time deviations.
The speed (fpm) is based on average operation. Time the rotation of your center pivot to verify accuracy.
Any questions should be directed to your Zimmatic Dealership.
***This chart should not cover safety decals, warning stickers, or wiring diagrams.***

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**Figure 15. Irrigation application chart for the sprinkler package installed in May 2023. Given that the maximum speed of the last tower is 14 ft/min, setting the percent timer to 9.05% would result in a 1.2-in gross application depth. At this rate, 99 hr would be required to complete a full revolution.**

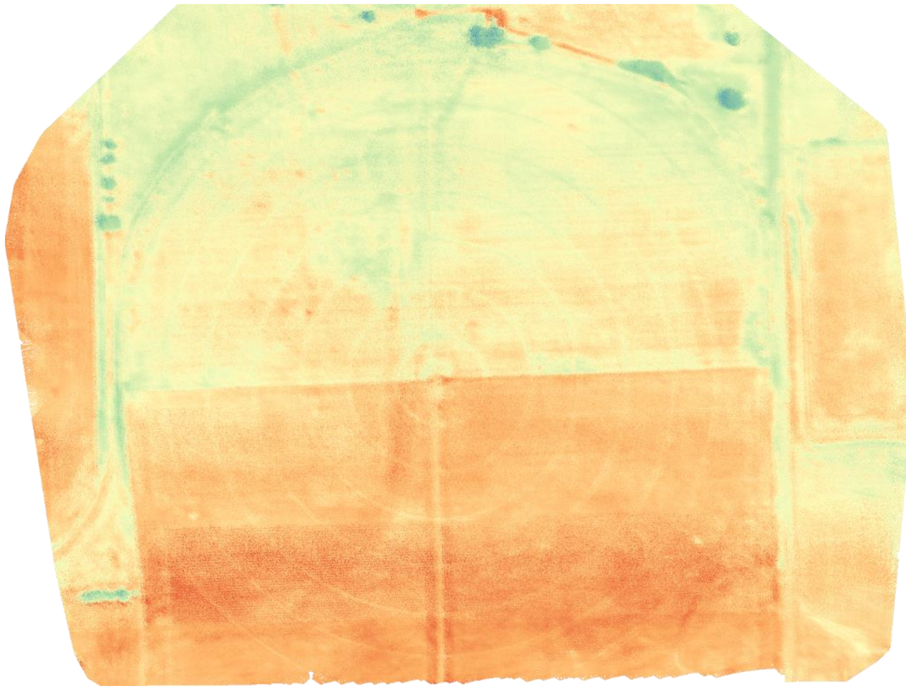

**Figure 16. Thermal imagery for June 13, 2023 at the VRI Field (courtesy David Heeren). There are some broad spatial patterns, but no rectangular patterns from the plots, indicating no substantial impact of the treatments on canopy temperature at that time.**

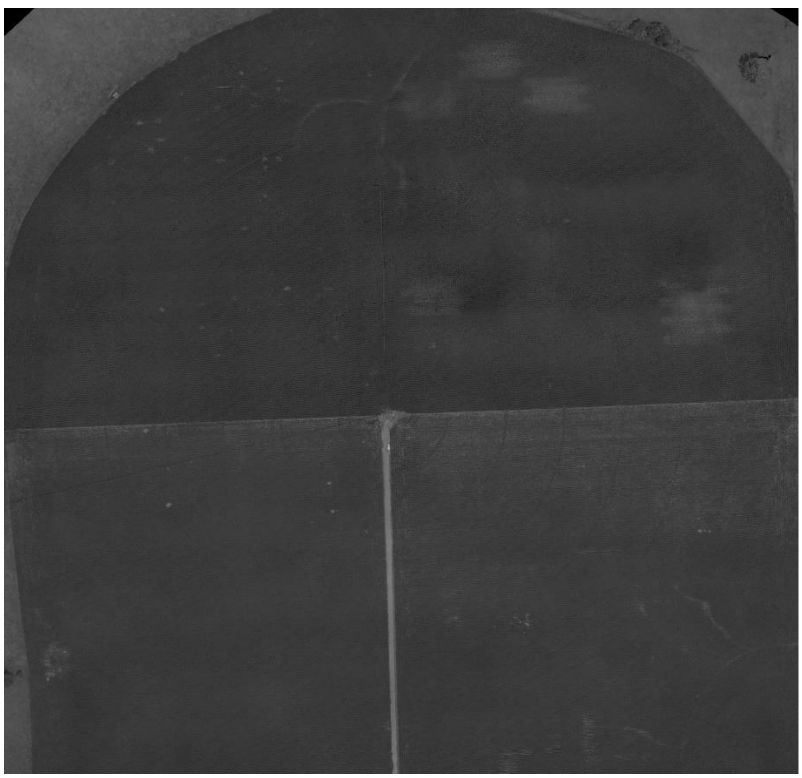

**Figure 17. Green reflectance imagery for August 11, 2023 (courtesy David Heeren). A few rectangular plots are visible in the northeast quadrant, which are no-N plots.**