QUANTIFYING THE EFFECTS OF IRRIGATION AND FERTIGATION ON NUTRIENT USE EFFICIENCY IN CORN

Final Report submitted to DNREC by:

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ABSTRACT

Expansion of irrigation in Delaware has helped growers stabilize crop yields and increase profitability, especially in years where rainfall is deficient. However, inefficient irrigation management can create significant economic and environmental problems (e.g., reduced crop yields and inefficient use of applied nutrients if crops are under-irrigated; wasted water and energy, and increased nutrient losses if crops are over-irrigated). Similarly, inefficient nutrient applications can lead to excess nutrient losses from agricultural fields. The overall goal of this proposed project was to quantify differences in water use efficiency (WUE) and nitrogen use efficiency (NUE) for a variety of advanced soil moisture-based irrigation, subsurface drip irrigation, and fertigation techniques for irrigated corn (*Zea Mays* L.) grown on sandy Coastal Plain soils. Two replicated field trials were conducted at the University of Delaware (UD) Warrington Irrigation Research Farm near Harbeson, DE. Briefly, we evaluated corn yields, WUE, and NUE for corn receiving eight soil moisture based irrigation schedules, two evapotranspiration (ET)-based irrigation schedules, and a non-irrigated control in 2013-2016. In addition, we evaluated corn yields, WUE, and NUE under various N rates, methods, and timings for dryland and irrigated corn.

Overall, the 2013, 2014, and 2015 seasons were ideal corn production years with little natural moisture stress, while 2016 was less conducive to high-yield corn production (but still did not represent true drought conditions). As such, we reported only few statistical differences in crop yield when various irrigation treatments were applied, and in 2013 and 2014, yields achieved with no irrigation were not statistically different than irrigated yields (regardless of treatment). In general, treatments that allowed for the soil to stay wetter (e.g., 20 kPa) or replaced 100% of ET often received the most water and had the lowest WUE. However, we only reported significant irrigation treatment effects on WUE in 2014 and 2016, which is another indicator that the study years were at or above average for precipitation. When NUE was calculated based on crop N

uptake per unit of fertilizer applied, we generally saw excellent efficiencies (except in 2013). However, when NUE was evaluated using a mass balance approach, the efficiency of fertilizer N recovery (e_f) values were typically lower than 0.6 (60%) for irrigated plots receiving in-season N applications across all rates, suggesting that 40% or more of the N available to growing crops was at risk for loss to the environment.

We also compared WUE and NUE for corn grown under irrigated and dryland conditions in Bucks Branch watershed, Sussex County, DE. Water use efficiency was slightly higher (3.04 kg m^{-3}) for the irrigated field than the dryland field (2.77 kg m^{-3}). The amount of yield obtained per unit of fertilizers was similar for the two Bucks Branch fields (46.0 and 48.5 kg kg^{-1} [0.97 and 1.03 lb N/bu] for the irrigated and dryland fields, respectively). As reported for the UD Warrington Irrigation Research Farm plots, the irrigated field at Bucks Branch had reduced e_f (0.61) and increased amount of “unaccounted” for fertilizer/manure N (UA_N; 107 kg ha^{-1}) when compared to the dryland field (0.79 and 37.8 kg ha^{-1}), which was due to lower N application rates to the dryland field and significant applications of irrigation water N and differences in estimated soil N mineralization potential between the two fields.

Nitrogen use efficiency results from the UD Warrington Irrigation Research Farm fertilizer trials and Bucks Branch fields highlight the importance of accurate accounting for ancillary sources of N (e.g. atmospheric, soil N, and irrigation) when determining the appropriate fertilizer rate. The ability to accurately estimate these “other” N inputs will be key to increasing NUE within the region.

The fact that we received adequate to excessive rainfall over the course of this study makes it difficult to make definitive claims about the benefits of irrigation on WUE and NUE. It is also important to recognize that this work was conducted 1) on one farm with many small plots or 2) on a cooperating farm with no replication. As such, we recommend expanding WUE and NUE trials to additional farms, with differing soils and larger scale production. Data should be collected from paired fields (dryland and irrigated) at each site over multiple years to further evaluate yield, WUE, and NUE responses to irrigation during periods with intensive rainfall and extended dry periods, as improvements in NUE with irrigation are expected to be best in drought years.

BACKGROUND AND SITUATION

Drought is a persistent, long-standing problem for farmers on the Delmarva Peninsula and many other Atlantic Coastal Plain states. Regional weather, crop, and soil conditions often result in periods of prolonged drought, leading to significant crop yield reductions, economic losses to farmers, and reduced nutrient use efficiency. On five occasions in the past 25 years, dry-land (non-irrigated) corn [*Zea Mays* (L.)] yields averaged <5 Mg ha^{-1}, which was much lower than the realistic, profitable yield goals farmers established and fertilized to attain (Sims et al., 2012). In recent years, the amount of irrigated cropland has been steadily increasing in Delaware as growers seek to buffer their operations from the effects of repeated droughts and historically low crop yields. Irrigation helps farmers to stabilize yields and increase profitability; to prevent serious economic losses due to crop failure; and to use fertilizers and manures more efficiently (Hergert, 1986; Irmak and Rathje, 2008; Oberle and Keeney, 1990; Wendt et al., 1976).

While expansion of irrigation is generally considered beneficial to growers and the environment, inefficient irrigation management can create significant economic and environmental problems (e.g., reduced crop yields and inefficient use of applied nutrients if crops are under-irrigated; wasted water and energy, and increased nutrient losses if crops are over-irrigated). Recent advances in soil moisture sensor technology, data communication systems, weather monitoring networks, and irrigation scheduling models allow farmers and crop consultants to optimize crop water use efficiency (WUE) and nutrient use efficiency and mitigate the effects of drought by basing irrigation decisions on actual real-time soil moisture and climate data (Hanson et al., 2000; Sample et al., 2016).

In addition, nitrogen (N) loss from agricultural fields has been implicated as a source of pollution in our local waters. Field corn has a large requirement for both water and N and is the largest crop grown under irrigation in Delaware. Irrigated corn in Delaware typically receives N with applications of poultry manure, starter fertilizer (at plant), and sidedress N (in-season). A small percentage of Delaware growers fertigate to provide the N to the crop in the mid- to late-stages of the rapid growth phase of corn. Sidedressing consists of making a single N application just before the rapid growth phase begins in order to supply the remaining balance of N needed for the crop over the growing season. In contrast, fertigation provides N in smaller, targeted applications through the irrigation system as needed by the crop throughout the rapid growth phase, essentially allowing growers to "spoon feed" the crop. If done correctly, fertigation should allow for more efficient use of N than can be achieved by sidedressing alone, particularly during a spring or an early summer where heavy rainfall could potentially leach N out of the crop root zone. In addition, maintaining adequate soil moisture through properly timed irrigation events should further improve NUE of corn.

In collaboration with the US Geological Survey (USGS) and the Delaware Department of Natural Resources and Environmental Control (DNREC), we were able to evaluate the effects of irrigation and fertilization practices on WUE and N use efficiency (NUE) at the UD Warrington Irrigation Research Farm in Harbeson, DE under controlled conditions and in the Bucks Branch watershed under grower-managed conditions. Bucks Branch is a small subwatershed of the Nanticoke River in the Chesapeake Bay drainage area of Sussex County, DE. In previous DNREC and USGS studies, 60% of groundwater samples and 42% of surface water samples from the Bucks Branch watershed exceeded the USEPA drinking water standard of 10 mg L^{-1} (Clune and Denver, 2012). In a second phase of this work, the USGS and DNREC further studied nutrient transport processes in this one subwatershed. Using a mass balance approach, the USGS assessed the impacts of irrigation on shallow groundwater quality by comparing water quality under irrigated and dryland corn production.

OBJECTIVES

The overall goal of this proposed project was to quantify differences in WUE and NUE for a variety of advanced soil moisture-based irrigation, subsurface drip irrigation, and fertigation techniques for irrigated corn grown on sandy Coastal Plain soils. This project goal was achieved by completing the objectives:

1) Quantify the effects of advanced soil moisture-based irrigation on WUE and NUE of corn under a center pivot irrigation system at the UD Warrington Irrigation Research Farm, Sussex County, DE.
2) Quantify the effects of selected fertilizer strategies on WUE and NUE of corn irrigated under a center pivot and subsurface drip irrigation at the UD Warrington Irrigation Research Farm, Sussex County, DE.
3) Compare WUE and NUE of corn under irrigated and dryland conditions in Bucks Branch watershed, Sussex County, DE in cooperation with USGS.

METHODOLOGY

Warrington Irrigation Research Farm, Sussex County, DE

Replicated field plots were established annually from 2013 to 2016 at the UD Warrington Irrigation Research Farm in Harbeson, DE to evaluate irrigation and fertilization practices effects on NUE and WUE. Field plots were established on approximately 16 ha (40 ac) of sandy, soils at the UD Warrington Irrigation Research Farm in a 10-ha (24-ac) center pivot (CP) irrigated field and a 6-ha (16-ac) drip-irrigated field (SSD; Fig. 1). Soil series within the CP field were mapped as follows: 8.4 ha of Rosedale loamy sand (loamy, siliceous, semiactive, mesic Arenic Hapludults), 6.9 ha of Pepperbox (loamy, mixed, semiactive, mesic aquic Arenic Paleudults)-Rosedale complex, and 0.8 ha of Hurlock sandy loam (loamy, siliceous, semiactive, mesic Typic Endoaquults). Pepperbox soils are moderately well-drained loamy sands, Rosedale soils are well-drained loamy sands, and Hurlock soils are poorly drained loamy sands.

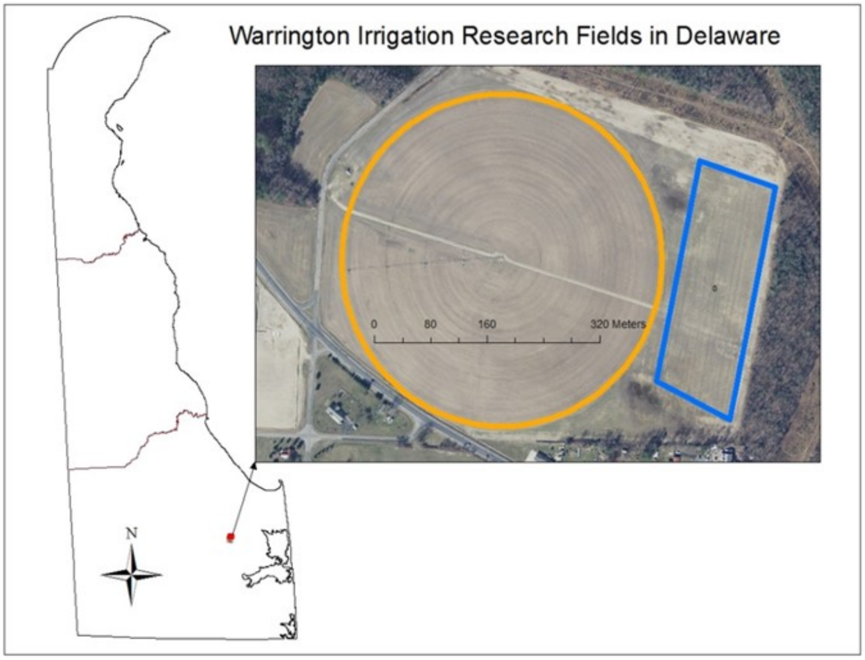

Figure 1. Location of the University of Delaware (UD) Warrington Irrigation Farm research fields near Harbeson, Sussex County, DE. The map inset shows the center pivot (CP) field on left (yellow) and the subsurface-drip (SSD) field on the right (blue).

The 16 ha CP field location was planted in a two year rotation with corn followed by 1) full season soybean [*Glycine max* (L.) Merill] or 2) winter wheat (*Triticum aestivum* L.) followed by double crop soybean. As such, the location of the corn plots in the center pivot field shifted (north and south) each year. In contrast, the 2.4 ha SSD field was planted in continuous corn.

Each fall (following corn harvest), the entire site was soil sampled, limed, and fertilized with phosphorus (P), potassium (K), and micronutrients as needed based on soil test results. Each spring, poultry litter was applied to the entire research site (with the exception of the zero N control plots in 2015 and 2016) at a rate of 6.72 Mg ha^{-1} (3 ton/ac). Poultry litter was incorporated to a depth of 25 cm by chisel plow within 3 d of application. Plant available N in manure was determined based on results of manure analysis as completed by the Delaware Department of Agriculture's Agriculture Compliance Laboratory, where 60% of total organic N (Organic N = TN - NH_4-N) and 60% (2013) or 80% (2014-2016) of NH_4-N was assumed to be plant available during the growing season (Table 1). The research fields were disked to 30 cm prior to planting grain corn in 76 cm rows to achieve a population density of 84,000 plants ha^{-1}. In 2015 and 2016, additional rainfed (non-irrigated) plots were planted to achieve a population of 54,000 plants ha^{-1}.

Table 1. Manure nutrient analysis for poultry litter applied to grain corn research plots at the University of Delaware (UD) Warrington Irrigation Research Farm near Harbeson, DE. A total of 6.72 tons ha^{-1} of manure was applied to all plots except the zero N control (in 2015 and 2016 only).

Parameter	**Growing Season**			
	2013	**2014**	**2015**	**2016**
	g kg^{-1}			
Total N	29.8	27.2	25.4	36.4
Total NH_4-N	5.39	4.74	4.55	4.25
Plant available N	17.9	17.3	16.2	22.7
Total P_2O_5	30.5	17.2	20.5	44.7
Total K_2O	27.6	18.1	22.6	40.5
Moisture	271	371	390	141
Dry matter	728	629	609	859

In addition to poultry litter, nitrogen (N) fertilizer was applied to meet crop N requirements at a realistic yield goal for irrigated corn at this site (~16 Mg ha^{-1}; 280 bu/ac). A small amount of starter N (40.1 kg ha^{-1} in 2013 and 37.1 kg ha^{-1} in 2014-2016) was applied at planting. Herbicides and any other pesticide treatments needed for insect control were based on standard UD guidelines for corn. A detailed field management history including products applied and field operations is available in the Appendix.

Irrigation Management

To quantify the effects of advanced soil moisture-based irrigation on WUE and NUE under a center pivot irrigation system (Objective 1: Irrigation plots), we applied eight irrigation treatments (with five replications) based on sensor measurements of soil matric potential and two evapotranspiration (ET)-based irrigation treatments; a non-irrigated control treatment was also included (Table 2). The irrigation treatments were selected based on results of on-farm studies conducted with irrigated corn in Delaware and represent strategies our past studies suggested would lead to more efficient irrigation management (J. Adkins, unpublished data).

Table 2. Summary of irrigation strategies (Objective 1) assessed under a center pivot irrigation system at the University of Delaware (UD) Warrington Irrigation Research Farm.

Treatment	**Treatment Description**	**Rationale**
20 kPa	Irrigation events triggered when soil moisture at 15 cm reached 20 kPa; water applied from emergence to maturity	Over-irrigation anticipated
30 kPa	Irrigation events triggered when soil moisture at 15 cm reached 30 kPa from emergence to maturity	Current UD recommendation to trigger irrigation based on soil moisture
40 kPa	Irrigation events triggered when soil moisture at 15 cm reached 40 kPa from emergence to maturity	Quantify effects of maintaining drier soil conditions on WUE and yield
50 kPa	Irrigation events triggered when soil moisture at 15 cm reached 50 kPa from emergence to maturity	Quantify effects of maintaining drier soil conditions on WUE and yield
20-40-20 kPa	Irrigation events triggered when soil moisture at 15 cm reached 20 kPa from emergence to V16; 40 kPa from V16 to R3; and 20 kPa from R3 to maturity	Evaluate management of soil matric potential at different thresholds as crop develops on WUE and yield
40-20-40 kPa	Irrigation events triggered when soil moisture at 15 cm reached 40 kPa from emergence to V16; 20 kPa from V16 to R3; and 40 kPa from R3 to maturity	Evaluate management of soil matric potential at different thresholds as crop develops on WUE and yield
30 kPa to R5	Irrigation events triggered when soil moisture at 15 cm reached 30 kPa from emergence to R5; no supplemental irrigation past R5	Evaluate effect of discontinuing irrigation events prior to crop maturity on WUE and yield
30 kPa to milk	Irrigation events triggered when soil moisture at 15 cm reached 30 kPa from emergence to half milk line; no supplemental irrigation past half milk line	Evaluate effect of discontinuing irrigation events prior to crop maturity on WUE and yield
ET - 100%	Irrigate based on standard ET model only using KanSched 2 irrigation software, no soil moisture monitoring; irrigation trigger at 50% of field capacity depletion	ET-based schedule (standard)
ET - 80%	Irrigate based on 80% standard ET model only using KanSched 2 irrigation software, no soil moisture monitoring; irrigation trigger at 50% of field capacity depletion	ET-based schedule to simulate typical grower irrigation system efficiency
No irrigation	No supplemental irrigation will be applied	Simulated non-irrigated (dryland) conditions

Irrigation was applied utilizing a Precision variable rate irrigation (VRI) controller on a 4 span (232 m) center pivot irrigation system. The Precision VRI system is capable of controlling each of the 85 Low Drift Nozzles on the pivot independently to apply various and distinct irrigation rates to areas as small as 9 m × 30 m. Due to the potential for between-plot drift and surface movement of irrigation water, plot sizes for this project were 18 m × 90 m, with a 9 m buffer between plots to eliminate areas where overspray may confound treatment effects.

Soil matric potential in each of the plots was continuously monitored by a Watermark 950T (Irrometer Co., Riverside, CA) wireless soil moisture monitoring transmitter. Each transmitter collected soil matric potential data from three Watermark matric potential sensors placed at 15, 30, and 45 cm below the soil surface; sensors transmitted the data to a central logger approximately 15 times per day. The corresponding soil moisture data was transmitted wirelessly approximately 10 - 20 times daily from the field to a data logging receiver. A detailed history of soil moisture at the research site is available upon request. Soil moisture data was viewed, analyzed, and interpreted daily to determine if any plots required irrigation. For each treatment, irrigation was initiated when soil matric potential at 15 cm reached a specific soil matric potential threshold. The actual volume of irrigation water applied was then based on soil matric potential data obtained from sensors at the 30 and 45 cm depths in each treatment. The irrigation system at the site was managed daily to optimize the application of irrigation to the fullest extent possible.

Irrigation for the CP fertilizer treatment plots used to evaluate various N application rate, timing, and application method strategies (Objective 2: Fertilizer strategies) was applied following the 100% ET treatment (Table 2). Various N application strategies were also evaluated in 2014 and 2015 under SSD irrigation. Subsurface drip irrigation was applied through drip tape that was run on 1.5-m centers (one tape centered between every other row), 7.5 cm deep, with emitters located every 30 cm. Subsurface irrigation was applied at a rate of 0.05 L s^{-1} per 1 m of drip tape at 70 kPa.

In-Season Nitrogen Fertilizer Management

In-season N applications were applied as a sidedress application and/or through the irrigation system (fertigation). During fertigation events for plots receiving CP irrigation, fertilizer was injected using a diaphragm pump that allowed fertilizer to flow through the nozzles on the center pivot line. Fertilizer was applied during a single pass of the center pivot system. The variable rate irrigation system applied fertigation only to the randomized plots. Similarly, fertilizer was injected (with back-flow prevention) into dedicated subsurface drip lines for each treatment under the SSD irrigation system. In-season applications of N for the CP irrigation treatment plots (Objective 1) was 125, 232, 197, and 165 kg/ha in 2013, 2014, 2015, and 2016, respectively. All irrigation treatment plots received in-season N applications via sidedress and fertigation.

Table 3. In-season N fertilizer treatments applied to center pivot irrigated grain corn in 2013 at the University of Delaware (UD) Warrington Irrigation Research Farm near Harbeson, DE.

Treatment	**Planting Population**	**Sidedress N Rate†**	**Fertigation N Rate**			
			V5	**V8**	**V11**	**V13**
	1000 ha^{-1}	——— kg ha-1 ———				
		Irrigated				
Manure + Starter	84	0	0	0	0	0
Sidedress	84	70.6	0	0	0	0
	84	129	0	0	0	0
Fertigation	84	0	17.65	17.65	17.65	17.65
	84	0	32.25	32.25	32.25	32.25
		Rainfed				
Manure +Starter	84	0	0	0	0	0

†All plots received 120 kg ha^{-1} (107 lb/ac) of PAN in manure and 40.8 kg ha^{-1} (36.4 lb/ac) of starter N.

Table 4. In-season N fertilizer treatments applied to center pivot (2014-2016) and subsurface drip (2014-2015) irrigated grain corn at the University of Delaware (UD) Warrington Irrigation Research Farm near Harbeson, DE.

Treatment	**Planting Population**	**Sidedress N Rate†**	**Fertigation N Rate**			
			V5	**V8**	**V11**	**V13**
	1000 ha^{-1}	——— kg ha^{-1} ———				
		Irrigated				
Control‡	84	0	0	0	0	0
Manure + Starter	84	0	0	0	0	0
Sidedress						
Low	84	82.0	0	0	0	0
Medium§	84	140	0	0	0	0
High	84	198	0	0	0	0
Fertigation						
Low	84	0	20.5	20.5	20.5	20.5
Medium§	84	0	35.0	35.0	35.0	35.0
High	84	0	49.5	49.5	49.5	49.5
		Rainfed				
Control‡	54	0	0	0	0	0
Manure +Starter‡	54	0	0	0	0	0
	84	0	0	0	0	0

† PAN applied in manure was 116, 109, and 153 kg ha^{-1} in 2014, 2015, and 2016, respectively; starter N was 40.8 kg ha^{-1}

‡ indicates a treatment that was not included in the experimental design in 2014.

§ the medium in-season rate was not included in field trials under subsurface drip irrigation due to lack of space.

To quantify the effects of selected fertilizer strategies on WUE and NUE of corn irrigated under a center pivot and subsurface drip irrigation (Objective 2), we applied various N fertilizer treatments (Tables 3 and 4) under both irrigated and dryland conditions (all years). Fertilizer treatments were selected based on results of on-farm studies conducted with irrigated corn and feedback from growers in Delaware, which suggested high-yielding irrigated corn could be fertilized at rates that are lower than the current UD recommendations (17.7 kg ha^{-1} of PAN recommended for every 1 Mg ha^{-1} of yield).

Meteorological Data

Multiple meteorological parameters were measured at a Delaware Environmental Observing System (DEOS) weather station located on-site (DEOS, 2017). Precipitation depth was measured using a tipping bucket rain gauge (25.4 mm trigger); temperature was recorded using a thermistor in gilled housing. The weather station reports 5-minute averages to the DEOS server in Newark, DE. Reference ET was recorded daily based on the Penman-Monteith method (Allen et al., 1998).

Irrigation volume applied to the plots was determined by calibrating the center pivot spray nozzles to the ASABE/ICC 802 standard. Individual irrigation applications of a known volume were recorded daily over the growing season and summed at the end of the season to determine total irrigation volume to each plot.

Crop evapotranspiration (ET_c) for each replication of all 11 irrigation treatments was calculated in KanSched2 (http://www.bae.ksu.edu/mobileirrigationlab/kansched2), which was developed by Kansas State University. We applied initial, maximum, and final crop coefficients of 0.25, 1.2, and 0.6 to calculate ET_c. Effective rainfall was calculated by KandSched2 for each plot.

Soil Sample Collection and Analysis

Prior to planting and manure application, each research field area was soil sampled by splitting the field into sections (section size of 1 or 1.3 ha for SSD and CP fields, respectively) to a depth of 20 cm using a soil probe. A total of 12-15 cores were collected from each field section for a total of nine composite soil samples per field. Samples were taken by walking in a “zig zag” transect in each section. To avoid sampling banded starter fertilizer from previous crop years, samples were taken between rows where possible. Prior to analysis, all soil samples were air-dried and ground to pass through a 2 mm sieve.

Soils were analyzed for pH (1:2 ratio of soil to DI water) and organic matter (OM; loss on ignition) following standard methods (Sims and Eckert, 2011). Soils were also analyzed for P, K, Ca, Mg, Na, and S by inductively coupled plasma – optical emission spectroscopy (ICP-OES) following Mehlich 3 extraction (1:10 ratio of soil to extraction solution consisting of 0.2 *N* acetic acid [CH_3COOH], 0.25 *N* ammonium [NH_4NO_3], 0.015 *N* ammonium fluoride [NH_4F], 0.013 *N* nitric acid [HNO_3], and 0.001 *M* ethylenediaminetetraacetic acid [EDTA]; Wolf and Beegle, 2011). In 2015 and 2016, pre-season soils were extracted using a 2 *M* KCl solution (1:10 weight:volume) following methods of Mulvaney (1996) and the extract was analyzed for ammonium-N (NH_4-N) and nitrate-N (NO_3+NO_2-N) colorimetrically using a Bran & Luebbe AutoAnalyzer 3 (Buffalo Grove, IL; Bran+Luebbe, 1998).

A 7-d anaerobic incubation was completed on 2015 pre-season soils to estimate the N mineralization potential of the soil from soil organic matter, past manure applications, and previous legume crops. Following the methods of Wyngaard et al. (2015) and Waring and Bremner (1964), 10 g of soil and 20 mL of water were added to a stoppered tube. Each tube was placed in a water bath at 40 ^{o}C for 7 d without exposure to light. Following the incubation, the resulting soil slurry was poured into distillation flasks. Remaining sediment was washed from the incubation tubes using 15 mL of 4 mol L^{-1} KCl and transferred into the distillation flasks. Steam distillation with MgO and then Devarda's Alloy produced two 35-mL aliquots, which were poured into glass tubes with 10 mL of 4% mixed boric acid with phenolphthalein indicator. The boric acid solution was then titrated with 0.02 N H_2SO_4 until the solution turned bright pink as dictated by Eaton et al. (2016). Calculation of inorganic N (NO_3-N and NH_4-N) in solution was determined followed the methods of Eaton et al. (2016). Total N mineralization potential was determined by subtraction the concentration of inorganic N prior to incubation (as described previously).

Post-harvest soil samples were taken within each research plot by collecting a total of eight soil cores to a depth of 20 cm from the center of each plot. Samples were collected in 2013-2016 for the irrigation treatments (Objective 1) and 2014-2016 for the fertilizer treatments (Objective 2). Soils were dried, sieved, and analyzed for total N, NO_3-N, and NH_4-N and routine soil fertility analysis, as described previously. Analysis of post-harvest soil samples collected in 2016 was not completed due to contamination of soil samples by rats during an infestation of our sample holding facility.

Plant Tissue Sampling, Analysis, and Yield

Three whole plants were harvested from each plot, immediately preceding grain harvest, by cutting the plant with a machete as close to the ground as possible (but above the roots) to collect above ground biomass. After collection, all tissue samples were placed in cotton or canvas bags and dried at 55^{o}C. After drying to a constant mass, grain was separated by hand. The mass of both grain and whole plants was recorded. Harvest index (HI) was calculated by taking the dried weight of grain and dividing it by the whole plant mass (tissue + grain). Grain and whole plant weights were not available for the irrigation treatment plots in 2014 or for any plots in 2016 due to sample infestation by mice/rats during storage. As such, we estimated HI for the irrigation plots in 2014 based on the measured HI as 0.61 from the high in-season N rate treatments the fertilizer study. This HI value was also used for all samples in 2016.

Whole plants were chipped and then ground in a Wiley mill. Grain samples were ground in a Wiley Mill. Ground plant tissue and grain samples were analyzed for TN by combustion using an Elementar VarioMax CN Analyzer (elementar Americas, Mt. Holly, NJ) following the procedure of Campbell (1992).

Grain yield was determined by harvesting the center 90 m^2 from each 400 m^2 field plot using a Kincaid MF-8XP (Kincaid Equipment Manufacturing, Haven, KS) combine using a HarvestMaster GrainGauge data collection system (Juniper Systems, Logan, UT). The combine for calibrated per manufacturer's instructions and the data collected at harvest included plot weight, test weight, and grain moisture. Grain yield values were adjusted for moisture content as determined by the on-combine moisture monitor.

Irrigation and Lysimeter Water Sampling and Analysis

Irrigation water samples were collected quarterly from the irrigation well located on the UD Warrington Irrigation Research Farm. Water was collected following irrigation events to ensure fresh water sample collection. Samples were collected in acid washed, 250-mL high density polyethylene (HDPE) containers, placed into an ice filled cooler, then submitted to the Delaware DNREC water quality lab within 12 h after collection (average hold time <4 h).

Porous cup lysimeters (SSAT 24.C, Irrometer, Riverside CA) were installed into three plots per treatment in each field to a depth of 60 cm after removing a soil core with a 1.75-cm diameter soil probe. A total of 42 lysimeters were installed from the second week of July to harvest in 2014, the first week in June to harvest in 2015, and the last week of July to harvest in 2016. Lysimeters were soaked for 3 d in tap water prior to installation to ensure good contact between the porous cup and the surrounding soil. Lysimeter sampling frequency was influenced by duration and intensity of precipitation events, but occurred approximately bi-weekly. Lysimeters were primed for sampling by applying a vacuum with a hand pump within 12 h of a precipitation event that was predicted to deliver 2 cm or more rainfall within a 24 h period (as estimated by examining Doppler radar) or when the DEOS weather station located at the UD Warrington Irrigation Research Farm showed 1.25 cm or greater precipitation within a 24 h period. Soil water samples were then collected from primed lysimeters using acid washed 60-mL polyphenylene ether (PPE) syringes 24 h after the lysimeters were primed. Water samples exceeding a 25 mL volume were stored in ice filled coolers until delivery to the DNREC water quality testing lab (holding time < 24 h after collection) for analysis.

Water samples from irrigation wells and lysimeters were analyzed for NH_3-N following EPA method 350.1 using a Seal autoanalyzer (AA3, Seal, Mequon WI; USEPA, 1993). Irrigation water samples were also analyzed for NO_3+NO_2-N following EPA 353.2 using an Alpkem auto-analyzer (Alpkem, OI Analytical, College Town, TX; USEPA, 1993). The total amount of inorganic N applied in irrigation water over the season was determined by multiplying the mean concentration of N in irrigation water by the total amount of water applied to each irrigated plot.

The average total N concentration was 5.53 mg L^{-1} based on analysis of multiple samples during the 2015 growing season. There was little variability in the concentration of total N over the sampling periods (data not shown); therefore, this value was assumed to represent the average conditions at the UD Warrington Irrigation Research Farm when determining the amount of N applied in irrigation water for calculation of NUE using the mass balance approach (e_f and UA_N).

Water Use Efficiency

Water use efficiency was determined using the following equation:

$$\mathrm{WUE} = \frac{Y_g}{\mathrm{ET}}$$

where, WUE is water use efficiency (kg m^{-3}), Y_g is the dry matter yield (kg m^{-2}), and ETc is the crop water use (m) (Howell, 2003). We also calculated irrigation water use efficiency (Objective 1 irrigation treatment plots only) using the following equation:

$$\mathrm{IWUE} = \frac{Y_{gi} - Y_{gd}}{\mathrm{IRR}_i}$$

where, IWUE is irrigation water use efficiency (kg m^{-3}), Y_{gi} is the economic yield (kg m^{-2}) for irrigation level i, Y_{gd} is dry-land yield (kg/m^2), and IRR_i is the irrigation water applied (m) for irrigation level i (Howell, 2003).

Nitrogen Use Efficiency

The most basic calculation of NUE is the partial factor productivity (PFP_N), which integrates the economics of production by comparing the grain yield gained to the rate of fertilizer N applied (Dobermann, 2005). The PFP_N (kg yield per kg applied N) was calculated by the following equation:

$$PFP_N = \frac{Yield}{Fertilizer\ N}$$

where, yield and fertilizer N applied were reported in kg ha^{-1}. We also assessed crop N uptake efficiency using a N mass balance approach that allows for determination of the efficiency of fertilizer N recovery (e_f) based on data from our studies and reference values for certain parameters (as needed) as summarized in the following equation (Meisinger et al., 2008):

$$e_f = \frac{(N_{crop})\text{-}(N_{soil})\text{-}(N_{other})}{N_f}$$

where, e_f = the efficiency of fertilizer N recovery (unitless), N_{crop} = Crop removal in grain and in crop residue remaining in the field after harvest (kg ha^{-1}), N_{soil} = Available inorganic N and mineralized organic N from soil (kg ha^{-1}), N_{other} = Atmospheric deposition and irrigation water (kg ha^{-1}), and N_f = rate of plant available N (PAN) applied as fertilizer or manure (kg ha^{-1}). An e_f of 1 (100%) represents complete recovery and no atmospheric (i.e., volatilization and denitrification) or leaching losses of N. When calculating e_f, we estimated seasonal wet atmospheric N deposition (N_{atm}) based on seasonal rainfall and monthly estimated of precipitation total N as determined at the University of Maryland Wye Research and Education Center in Queenstown, MD as part of the National Atmospheric Deposition Program (NADP, 2017); N_{atm} was estimated as 2.51, 2.80, 3.14, and 2.57 kg ha^{-1} in 2013, 2014, 2015, and 2016, respectively. Other parameters were estimated as described previously.

We then estimated the amount of “unaccounted” for fertilizer/manure N (UA_N; kg ha^{-1}) at the end of the growing season. The UA_N represents the total N lost through all pathways (i.e., runoff, leaching, volatilization, and denitrification) and was calculated based on the following equation:

$$UA_N = (1 - e_f) \times N_f$$

Data Analysis and Statistics

Plots were organized in a randomized complete block design with multiple blocks (replicates) to account for soil variability at the research site. Irrigation treatments (Objective 1) were replicated five times (2013-2016); CP fertilizer treatments (Objective 2) were replicated seven times in 2013 and 2014 and six times in 2015 and 2016; SSD fertilizer treatments (Objective 2) were seven times in 2014 and six times in 2015.

A one way, mixed-model ANOVA (PROC MIXED) was used to determine irrigation or fertilizer rate effects on yield, WUE, NUE, and other selected parameters. Irrigation and fertilizer treatments were included in the model as a fixed effect; block was as a random effect. Normality was checked by visually examining a histogram and normality plots of the conditional residuals. For irrigation treatments (Objective 1), all pairwise comparisons were completed using the Tukey's honestly significant difference test or student's t-test with a significance level of $\alpha = 0.05$. For fertilizer treatments (Objective 2), we partitioned the treatment sum-of-squares using single degree of freedom CONTRAST statements. We also used ESTIMATE statements to determine differences between means as outlined in Marini (2003).

Nitrogen rate response curves were generated for fertilizer treatments under center pivot irrigation (Objective 2) by fitting quadratic models (PROC NLIN) of dry grain yield against N rate for both sidedress and fertigation treatments; yields from plots receiving no N (0 N control) and manure + starter N only were used to generate N response curves for both sidedress and fertigation treatments. Maximum achievable yield was determined by solving the second derivative of the quadratic response equation. Yield response curves were not generated for the irrigation plots (Objective 1) because only one N rate was applied in that study. Similarly, yield response curves were not generated on SSD fertilizer plots or for the CP plots in 2013 because there were not enough responses to generate a reliable response curve (i.e., fewer N rates assessed).

RESULTS

Site Characterization - UD Warrington Irrigation Research Farm

Preplant Soil Analysis

Preplant soils collected from the CP field had a soil pH that was close to the target pH (6.0) for grain corn (Shober et al., 2017) in 2013-2015, while soil pH in the CP field in 2016 and the SSD field (2014-2015) was more acidic (Table 5). Soil organic matter content remained fairly constant over the course of the study. Soils collected from both fields typically had Mehlich 3 P concentrations within the agronomic "optimum" (Mehlich 3 P = 50-100 mg kg^{-1}) fertility category for Delaware soils (Shober et al., 2013); Mehlich 3 K concentrations were within the agronomic "medium" (Mehlich 3 K = 45-91 mg kg^{-1}) or "optimum" (Mehlich 3 K = 91-182 mg kg^{-1}) fertility category.

Initial soil concentrations of NH_4-N in the 2015 pre-season soils samples collected from the CP and SSD fields were 5.75 and 6.62 mg kg^{-1}, respectively; initial concentrations of NO_3-N were

3.19 and 4.16 mg kg^{-1}, respectively. Concentrations of inorganic N in 2016 preseason soils (CP only) were comparable, but slightly lower than values reported in 2015 (Table 5). Following anaerobic incubation, concentrations of NH_4-N in the CP and SSD soils was 34.9 and 50.7 mg kg^{-1}, respectively; soil NO_3-N concentrations in these soils were 3.11 and 1.25 mg kg^{-1}, respectively for the CP and SSD field soils. Total N mineralization potential was 31.2 and 41.5 mg kg^{-1}, respectively for the CP and SSD field soils, which is equivalent to total inorganic N concentration of 82.1 and 115 kg ha^{-1}, respectively. These values were used for N_{soil} when calculating nitrogen use efficiency (e_f) because initial soil inorganic N values were not available for the 2013 or 2014 growing seasons. Shapiro et al. (2008) provide guidance for adjusting N recommendations to account for available soil N based on NO_3-N concentrations in soil at a depth of 61 to 122 cm, soil organic matter content and expected yield goal using the following equations:

$$N_{soil} = 8 \times NO_3\text{-N (ppm)}$$

$$N_{min} = 0.14 \times \text{expected yield (lb/ac)} \times \text{OM(\%)}$$

Based on an expected yield goal of ~16 Mg ha^{-1} (280 bu/ac), a 2016 soil NO_3-N concentration of 3.39 mg kg^{-1} at an average depth of 45 cm, and an organic matter content of 0.82%, we estimated that the contribution of N from the soil NO_3-N and mineralization in 2016 was 66.4 kg ha^{-1} (59.3 lb/ac), which was slightly less than was estimated by the anaerobic digestion. However, organic matter concentrations were slightly higher in previous years. As such, we are confident that we have not underestimated soil N contributions when using the values from the anaerobic soil incubation for N_{soil} when calculating e_f.

Meteorological Data

Historical (30 year) seasonal rainfall depths from the Georgetown, DE (airport) station were used to comparison with rainfall at the UD Warrington Irrigation Research Farm. Historical average seasonal rainfall at the Georgetown airport station was 9.02, 11.7, 10.6, 8.97, and 10.5 cm (NCEI, 2016).

In 2013, the corn crop received 70.7 cm of total rainfall between 25 April and 25 September (Fig. 2A). Excessive rainfall during June (+14.7 cm compared to the 30 year historical average), July (+6.8 cm), and August (+7.4 cm) made it an extremely difficult year to conduct irrigation research. The sandy loam soil at the UD Warrington Irrigation Research Farm sits over heavy clay base that is not conducive for timely percolation of large rain events. Under non-irrigated conditions, the effective rainfall (i.e., the volume of rain that is stored in the soil and not lost to deep infiltration or runoff) was only 39.3 cm. As a result, a total of 31.4 cm of rain either ran off the field or infiltrated beyond the root zone, carrying with it at least some of the applied N. The greatest periods of rainfall occurred during the V7 to V11 vegetative growth stages and from tassel emergence to the R1 to R2 stages. The soil moisture sensors indicated saturated soil conditions for most of the plots for up to 3 weeks during June and more than 2 weeks during pollination in early July. As a result, yields were probably limited by plant stress caused by excessive moisture and lack of soil oxygen rather than the irrigation or N fertilizer treatments.

Total seasonal rainfall in 2014 was 53.3 cm between 7 May and 2 October, making 2014 an excellent year for non-irrigated corn production (Fig. 2B). The relatively cool summer created an ideal environment with little heat stress on the crop. Furthermore, rainfall events during the growing season were timely; very few large soil saturating storms were observed during this time period. Rainfall during the 2014 growing season was below the 30 year average in June (-6.5 cm), above average in July (+6.5 cm) and August (+5.7 cm), and average for September (-0.4 cm; NCEI, 2016). Growing season effective rainfall (non-irrigated plots) was 32.2 cm, indicating that 21.1 cm of rainfall was lost in runoff from the field or infiltrated beyond the root zone, carrying with it at least some of the applied N. Overall, ideal rainfall patterns resulted in a marginal to poor year for irrigation research.

Total seasonal rainfall during the 2015 growing season was 40.7 cm between 14 May and to 30 September (Fig. 2C). Overall, 2015 was a good year for corn production statewide. Early season rainfall was timely and able to provide more than adequate water for the crop, with total rainfall in June exceeding the 30 year historical average (+3.7 cm; NCEI, 2016). In contrast, rainfall in July was sparse and inadequate for the crop (-4.3 cm below 30 year average; NCEI, 2016); however, relatively mild temperatures limited yield losses from heat stress. Precipitation during the remainder of the 2015 growing season was -3.3 and +0.2 cm different than the average reported rainfall for August and September, respectively (NCEI, 2016). Growing season effective rainfall (non-irrigated plots) was 26.5 cm, indicating that 14.2 cm of rainfall was lost in runoff from the field or infiltrated beyond the root zone carrying with it at least some of the applied N, which was less than in other years of the study.

Total seasonal rainfall during the 2016 season was 38.3 cm between 20 May and 28 September (Fig. 2D). When compared to 2014 and 2015, 2016 was not a great year for corn production. Planting occurred later than normal (late May), which pushed pollination towards the later-half of July, when nighttime temperatures were higher than in the past 3 years. Early season rainfall through June was lower than the 30 year historical average (-4.1 cm), and July and August also provided less than average rainfall to the crop (-1.7 and -3.6 cm, respectively; NCEI, 2016). Growing season effective rainfall (non-irrigated plots) was 22.7 cm in 2016, indicating that 15.6 cm of rainfall was potentially lost in runoff and leaching events.

Table 5. Mean (standard deviation) pre-season soil properties for the center pivot and subsurface irrigation fields at the UD Warrington Irrigation Research Farm located near Harbeson, DE.

Soil Property	Center Pivot				Subsurface Drip	
	2013	2014	2015	2016	2014	2015
pH	6.29 (0.23)	6.01 (0.18)	6.03 (0.82)	5.17 (0.46)	5.9 (0.1)	5.45 (0.07)
Organic Matter , g kg^{-1}	13.5 (2.42)	15.0 (0.89)	14.5 (0.36)	8.17 (1.17)	12.7 (0.58)	13.5 (0.70)
NH_4-N, mg kg^{-1}	--†	--	5.75 (1.31)	4.58(1.08)	--	6.62 (0.18)
NO_3-N, mg kg^{-1}	--	--	3.68 (0.37)	3.19 (0.67)	--	4.16 (1.17)
Mehlich-3 P, mg kg^{-1}	93.1 (31.4)	104 (44.8)	51.9 (18.7)	94.8 (32.2)	132 (15.7)	75.0 (3.92)
Mehlich-3 K, mg kg^{-1}	119 (43.6)	125 (28.2)	82.4 (16.2)	85. 0 (17.8)	81.7 (2.31)	133 (2.01)
Mehlich-3 Ca, mg kg^{-1}	274 (62.7)	373 (62.7)	311 (41.2)	285 (59.9)	289 (27.3)	254 (11.1)
Mehlich-3 Mg, mg kg^{-1}	64.4 (11.4)	61.5 (14.9)	67.4 (4.25)	39.2 (9.55)	58.3 (4.16)	61.7 (0.50)
Mehlich-3 B, mg kg^{-1}	0.37 (0.04)	0.37 (0.06)	0.21 (0.04)	0.45 (0.19)	0.34 (0.03)	0.22 (0.03)

† -- indicates that pre-season soils were not analyzed for this parameter.

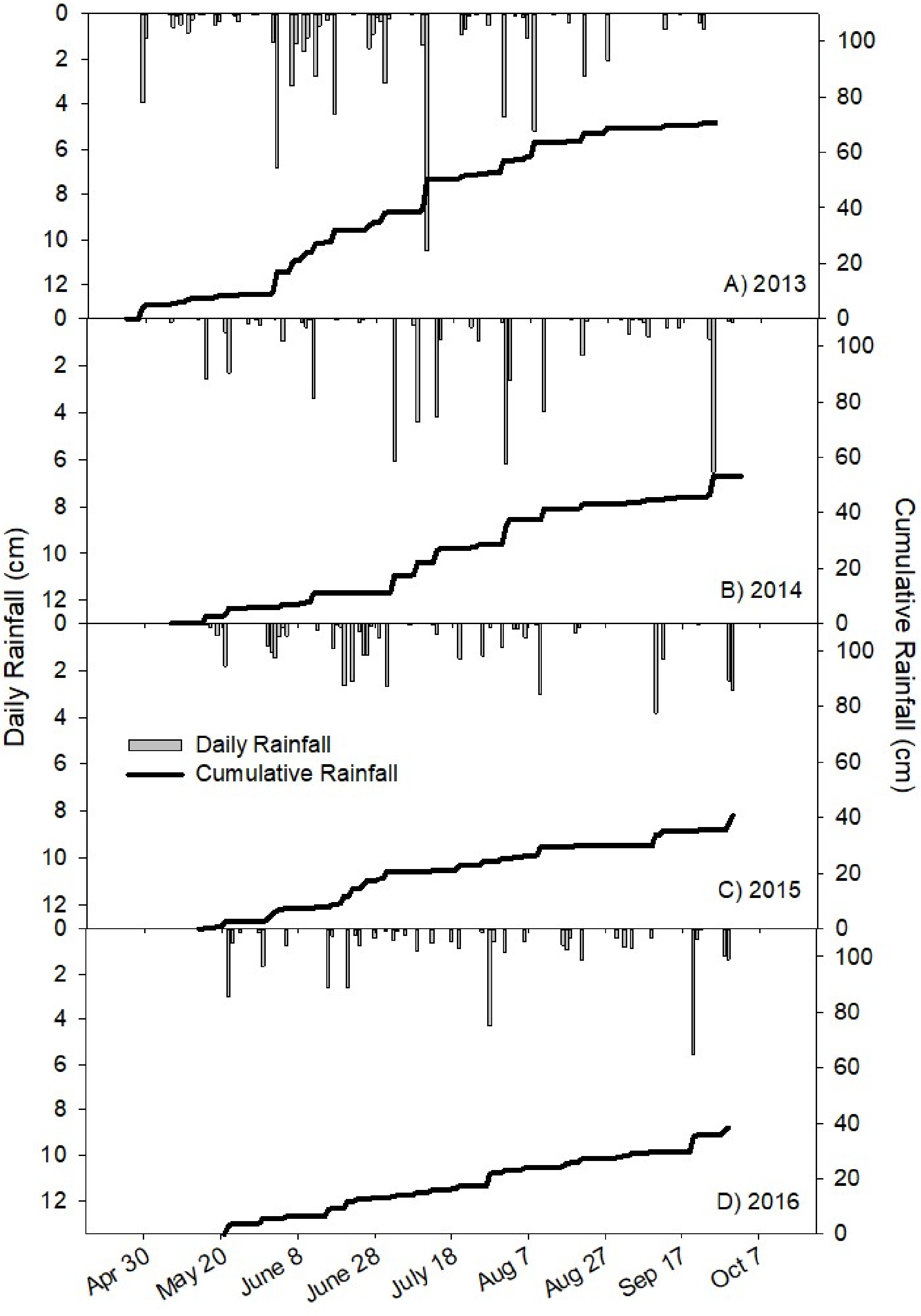

Figure 2. Daily and cumulative seasonal rainfall at the University of Delaware (UD) Warrington Irrigation Research Farm in A) 2013, B) 2014, C) 2015, and D) 2016 growing seasons.

Objective 1. Quantify the effects of advanced soil moisture-based irrigation on WUE and NUE of corn under a center pivot irrigation system at the UD Warrington Irrigation Research Farm, Sussex County, DE.

Irrigation Applied

During the 2013 growing season, irrigation treatments applied 0.83 to 13.6 cm of water on average. All of the soil moisture driven treatments required some small irrigation applications in late May and early June, while the ET-based treatments did not require irrigation until 15 June (data not shown). As such, there was a tendency for the ET model to underestimate the soil evaporation and plant transpiration for sandy loam soils early in the season. Furthermore, the ET-based model recommended significantly more water be applied during the rainy periods in June and July, with irrigation often being applied to saturated soil. As such, the 100% and 80% ET treatments tended to receive the highest volume of irrigation (Fig. 3A). Later in the season the ET-based schedules failed to account for the delayed crop maturity seen in 2013 and thus, called for less water than the comparable soil moisture driven treatments. Overall, the volume of irrigation applied with the 20 kPa and 20-40-20 kPa treatments was not statistically different than the ET-based treatments, with the 20 kPa treatment applying the most water (Fig. 3A). In contrast, the amount of water applied under the 40 and 50 kPa treatments, as well as the 40-20-40 kPa, 30 kPa to R5, and 30 kPa to milk treatments was not statistically different than the no-irrigation control, despite the fact that no water was applied to the control plots (Fig. 3A).

During the 2014 growing season, irrigation applied ranged from 13.6 to 29.3 cm on average (Fig. 3B). The 20-40-20 kPa treatment resulted in application of the most water, and was statistically higher than the amount of water that was applied under all other treatments except the 20 kPa, 80% ET, and 100% ET treatments. The remaining treatments received approximately 15 cm of water, although the timing of the applications varied slightly. The amount of irrigation applied also varied across the 5 in-field replications (or blocks; data not shown). This variance points towards soil type and condition as being a primary driver of irrigation needs. In 2014, all irrigation treatments resulted in the application of statistically more irrigation than the dryland plots, which received 0.87 cm of water, on average.

The average total amount of irrigation applied ranged from 15.5 to 27.1 cm during the 2015 growing season (Fig. 3C). As reported for the 2014 season, the 20 kPa, 20-40-20 kPa, 80% ET, and 100% ET treatments received the most irrigation, but only the 20 kPa treatment resulted in statistically more irrigation applied than the other treatments. These remaining treatments received approximately 15 cm of water throughout the growing season, with timing of application varying slightly among treatments (data not shown). Once again, we saw variability in the amount of irrigation across the 5 replications of any given treatment. In 2015, all irrigation treatments resulted in the application of statistically more irrigation than the dryland plots, which received no irrigation.

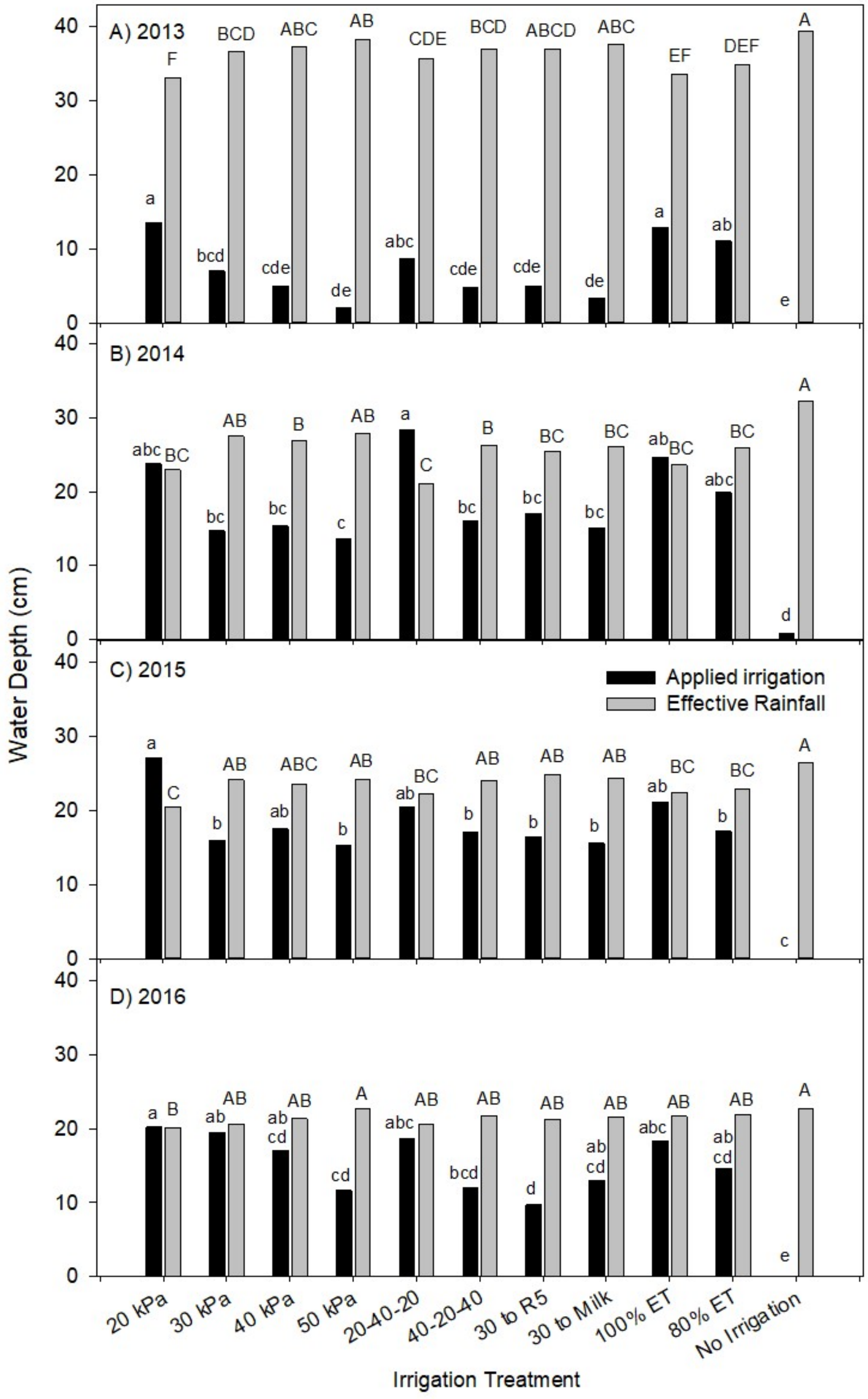

Figure 3. Irrigation water applied (black) and effective rainfall (gray) for irrigation treatment plots at the University of Delaware (UD) Warrington Irrigation Research Farm near Harbeson, DE in A) 2013, B) 2014, C) 2015, and D) 2016. Letters that are the same indicate no significant differences between treatments using Tukey's HSD test at α=0.05 (lowercase = irrigation; uppercase = effective rainfall).

The average total amount of irrigation applied during the 2016 growing season ranged from 9.7 to 20.2 cm (Fig. 3D). There were few statistical differences in the amount of water applied among the various irrigation treatments. In general, the 20 kPa treatment resulted in application of statistically more irrigation water than the 50 kPa, 40-20-40 kPa, and 30 kPa to R5 treatments; these treatments received the least amount of water. The amount of irrigation applied varied by about 4.06 cm across the 5 replications of any given treatment (data not shown). Similar trends during the previous growing season indicate that that soil type and condition are primary drivers of irrigation needs under similar weather patterns.

Irrigation Treatment Influence on Effective Rainfall

When compared with the non-irrigated treatments, application of supplemental irrigation typically resulted in a reduction in effective rainfall (Fig. 3). In general, the trends for effective rainfall followed trends in applied irrigation, where effective rainfall decreased significantly for irrigation treatments that applied more water. As such, the potential for water loss in runoff or leaching events is increased as effective rainfall decreases. Irrigation applications also tended to increase ET_c when compared to the no irrigation control. Detailed information about ET_c is located in the Appendix; these values were used to calculate WUE.

Grain Yield and Plant Tissue Analysis

Irrigated yields in 2013 were 15 to 20% lower than were obtained at the UD Warrington Irrigation Research Farm in previous seasons. Irrigation treatments had no significant effect on grain yields, with average dry yield of 11.0 Mg ha^{-1} (208 bu/ac at 15.5% moisture) across all treatments (Fig. 4A). The lack of treatment differences was likely a direct result of high variability in yields among replicates within each treatment, which resulted due to the occurrence of saturated soil conditions for many of the plots for up to 3 weeks during June and more than 2 weeks during pollination in early July. Overall, we suspect that yields were limited by plant stress due to excessive moisture and lack of soil oxygen and not irrigation treatments. Of significant interest was the fact that dryland yield was 10.7 Mg ha^{-1} (202 bu/ac), which was extremely high when compared with dryland yields at the site during previous seasons that ranged from 3 to 5 Mg ha^{-1} (50-80 bu/ac). It is important to note that dryland yields achieved in the irrigation study are not directly comparable to regional dryland yields because of the increased planted population needed to directly compare dryland yields with yields under the various irrigation treatments.

Grain yields in 2014 were higher than reported for 2013, with an average yield of 14.6 Mg ha^{-1} (275 bu/ac) across all irrigation treatments (Fig. 4B). Again, we reported no significant irrigation treatment effect on grain yields despite differences in water application, effective rainfall, and ET_c. Similarly, dryland yields were exceptional and were much higher than historical average; on average, dry yields for the non-irrigated plots were 14.2 Mg ha^{-1} (268 bu/ac) in 2014. High yields were a result of timely rains and mild temperatures during August, which eliminated any advantage to irrigating (Fig. 2).

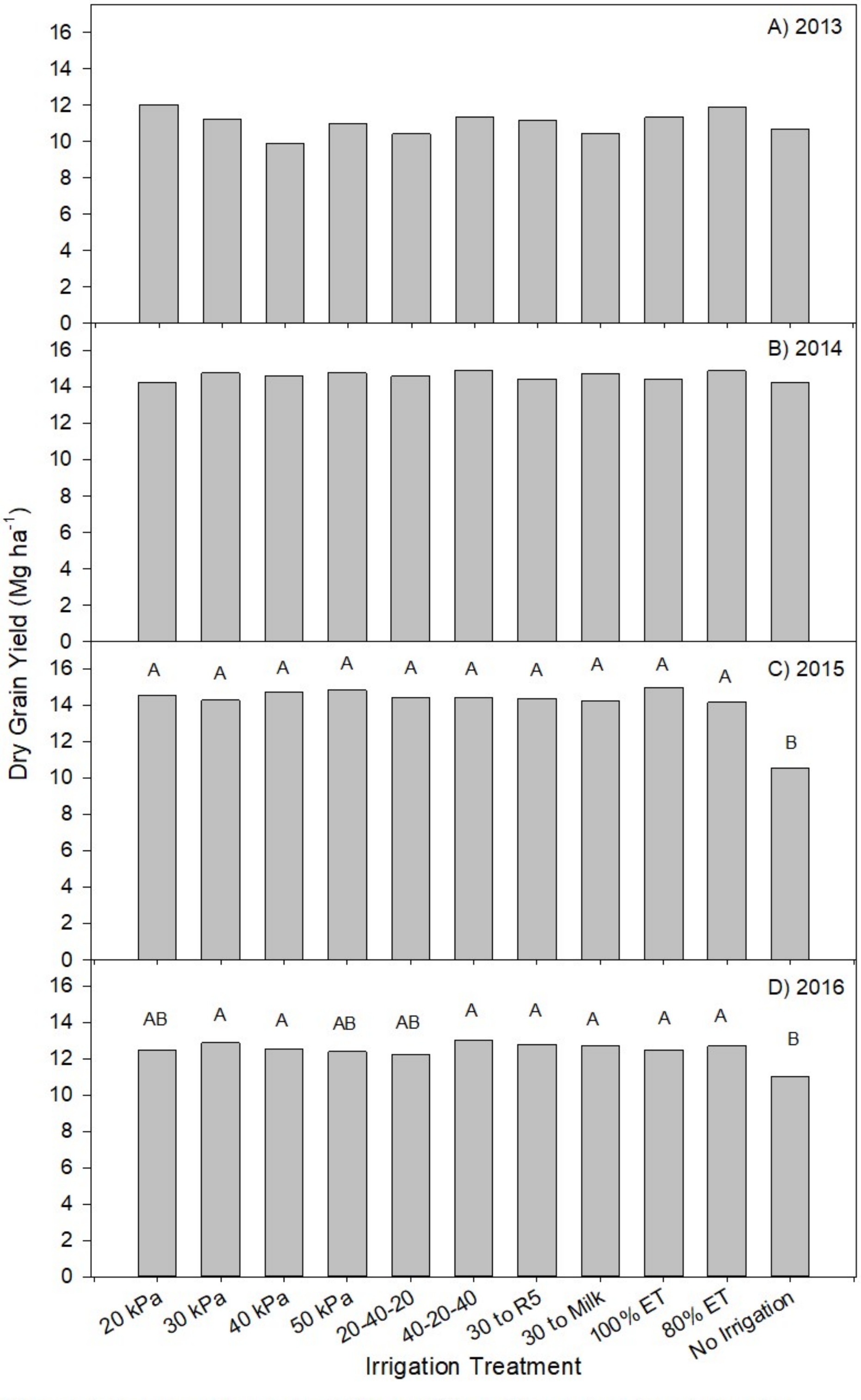

Figure 4. Average dry grain yields as affected by center pivot irrigation treatments at the University of Delaware (UD) Warrington Irrigation Research Farm near Harbeson, DE in A) 2013, B) 2014, C) 2015, and D) 2016. Letters that are the same indicate no significant differences between treatments using Tukey's HSD test at α=0.05.

In 2015, grain yields were significantly lower for the non-irrigated treatment [10.6 Mg ha^{-1} (199 bu/ac)] when compared with all other treatments [average dry yield = 14.5 Mg ha^{-1} (273 bu/ac); Fig. 4C]. Despite significant differences in the amount of water applied, there was no significant effect of specific irrigation treatments on crop yields in 2015.

Corn grain yields in 2016 were approximately 2.5 Mg ha^{-1} (40 bu/ac) lower than yields achieved in 2014 and 2015 (Fig. 4D). All irrigation treatments, with the exception of the 20 kPa, 50 kPa, and 20-40-20 kPa treatments, resulted in significantly higher yields (12.7 Mg ha^{-1}; 240 bu/ac) than the unirrigated control (11.0 Mg ha^{-1}; 208 bu/ac). Based on these results, it appears that irrigation was necessary to increase yields in 2016, but higher amounts of irrigation actually ended up suppressing yields.

Water Use Efficiency Response to Irrigation Treatments

Irrigation treatments had no significant effect on WUE in 2013 or 2015, with average WUE values of 2.23 and 3.47 kg m^{-3}, respectively (Fig. 5A and C). As mentioned previously, 2013 was an extremely wet year and yields were impacted by stress due to excessive soil wetness and potentially denitrification. In contrast, 2015 was an excellent year for corn production. While irrigated yield was significantly higher than the non-irrigated control in 2015, the ET_c was also higher for irrigated treatments. As such, the each unit of ET produced roughly the same amount of yield.

In 2014, the non-irrigated control treatment had significantly higher WUE than all other treatments (Fig. 5B). We saw a similar trend in 2016, where the WUE of the non-irrigated control treatment was significantly higher than many of the irrigated treatments (Fig. 5D). However, WUE of irrigation treatments that applied the least amount of water (i.e., 50 kPa, 40-20-40 kPa and 30 kPa to milk) were not statistically different than the non-irrigated control. The reduction in WUE efficiency with increased irrigation was due to the high yields and lower ET_c that were achieved in the non-irrigated control plots. We suspect that results would have been more favorable for the irrigation treatments had rainfall been deficient during June, July, and August when plants growth and development is most active. Overall, there was a trend for decreasing WUE with increasing irrigation volume applied. In both 2014 and 2016, the 100% ET treatment had the lowest WUE, and it was statistically lower than many of the soil moisture sensor based treatments. As such, we see value in using soil moisture to trigger irrigation events over ET to account for spatial and temporal differences in soil properties that affect water holding capacity.

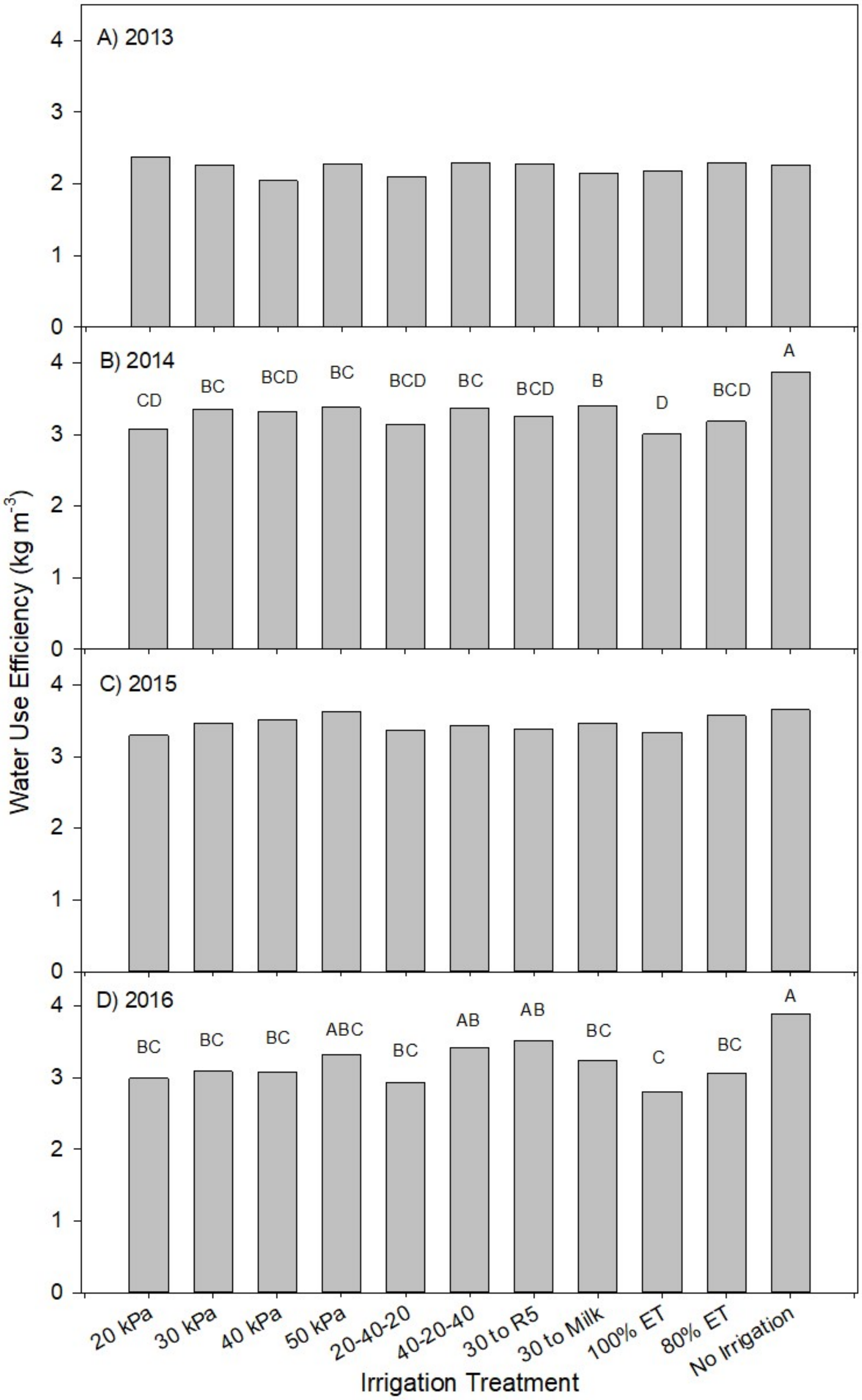

Figure 5. Average water use efficiency as affected by center pivot irrigation treatments at the University of Delaware (UD) Warrington Irrigation Research Farm near Harbeson, DE in A) 2013, B) 2014, C) 2015, and D) 2016. Letters that are the same indicate no significant differences between treatments using Tukey's HSD test at α=0.05.

Crop N Uptake Response to Irrigation Treatments

Irrigation treatments had no effect on grain N removal in 2013 or 2014 (data not shown) because there were no differences in yield (Fig. 4A and B). In 2015, plots receiving irrigation removed and average of 183 kg ha^{-1} of N in grain compared with 140 kg ha^{-1} from the dryland plots. We saw no significant effect of the different irrigation treatments on N removal in grain beyond the increase when compared to the non-irrigated control. Fewer irrigation treatments resulted in an increase in grain N removal when compared to the non-irrigated control in 2016. Only the 30 kPa and the 40-20-40 kPa treatments resulted in N removal (175.9 kg ha^{-1} average) that was higher than the unirrigated control 152 kg ha^{-1}. There were no other significant treatment differences.

Nitrogen Use Efficiency Response to Irrigation Treatments

Irrigation treatments had no effect on PFP_N in 2013 or 2014 (data not shown). On average, PFP_N ranged from 36.2 to 41.5 kg of grain produced per kg of N applied; in 2014 average PFP_N ranged from 36.9 to 38.7 kg kg^{-1}. In 2015, PFP_N was significantly lower for dryland corn (30.8 kg kg^{-1}) than for all treatments receiving supplemental irrigation (average = 42.3 kg kg^{-1}). As such, it was apparent that application of irrigation at any level increased N use efficiency, which was primarily due to the increase in crop N uptake from the yield bump attained by applying water in-season. Overall, most irrigation treatments resulted in improved PFP_N when compared with non-irrigated plots (31.0 kg kg^{-1}). The PFP_N was highest for irrigated plots (average of responsive treatments = 35.8 kg kg^{-1}) when compared, with the exception of the 20 kPa, 50 kPa, and 20-40-20 kPa. The later did not improve PFP_N compared to the control (average = 34.8 kg kg^{-1}).

When NUE was evaluated on a mass balance basis (i.e., e_f and UA_N) that accounts for N inputs beyond fertilizer and manure (i.e., atmospheric N deposition, soil N mineralization, irrigation water N), irrigation treatments had irrigation effect on e_f or UA_N in 2014 or 2016; e_f ranged from 0.24 to 0.32 in 2014 and from 0.24 to 0.29 in 2016, while UA_N ranged from 262 to 291 kg ha^{-1} in 2014 and 252 to 271 kg ha^{-1} in 2016.

In contrast, e_f and UA_N were significantly affected by irrigation treatment in 2013. The 30 kPa to milk treatment had a significantly lower e_f and higher UA_N (0.13 and 250 kg kg^{-1}, respectively) than corn irrigated with the 20 kPa treatment (0.37 and 180 kg ha^{-1}). This was the only statistically significant irrigation treatment effect in 2013; e_f ranged from 0.15 to 0.27 and UA_N ranged from 209 to 250 kg ha^{-1} across all other irrigation treatments in 2013.

Irrigation treatment affected e_f and UA_N again in 2015, where corn receiving the 50 kPa, 30 kPa to R5, and 80% ET irrigation treatments had significantly higher e_f and lower UA_N (average = 0.39 and 209 kg ha^{-1}, respectively) than the non-irrigated control (0.21 and 272 kg ha^{-1}). The overall range among other irrigated treatments was 0.29 to 0.36 for e_f and 220 to 243 kg ha^{-1} for UA_N.

An e_f of 1 (100%) represents complete recovery and no atmospheric (i.e., volatilization and denitrification), leaching, or runoff losses of N. Again, non-irrigated yields tended to be much higher than historical averages for this field site. Also, PAN application rates for the irrigation treatment were quite high 286 to 385 kg ha^{-1}, which ranged from 102 to 138% of UD recommendations for a 16 Mg ha^{-1} yield goal. However, it is still clear that management of the irrigation treatment plots led to somewhat lower e_f values, especially when compared with PFP_N. Certainly, irrigation treatments had some effect on improving e_f and reducing UA_N in two out of four years. Had treatments been applied in a year with significant drought, we would likely see increased NUE with irrigation when compared to non-irrigated conditions. More detailed discussion of NUE is included with results for the fertilizer treatment plots (Objective 3).

Post-harvest Soil Analysis

Irrigation treatment had no effect on post-harvest soil properties; therefore, mean concentrations are reported (Table 6). Post-harvest soils exhibited moderately acid soil pH, with mean soil pH declining by 2015 to approximately 4.44. Soil organic matter concentrations following harvest remained quite low, regardless of irrigation treatment. Mehlich 3 P concentrations, on average, remained within the agronomic optimum ranges of 50 to 100 mg kg^{-1} (Shober et al., 2013). Post-harvest soil concentrations of NH_4-N were typically higher than soil NO_3-N concentrations, except in 2016 when soil NO_3-N concentrations were higher. Yet, we reported no significant irrigation treatment effects on soil N in any year of the study. We regret that we were unable to complete the analysis of 2016 post-harvest soil samples due to a rat infestation in our storage area that caused significant contamination of the soil samples.

Table 6. Selected chemical properties of post-harvest soils collected from 20 cm from the irrigation treatment research plots at the University of Delaware (UD) Warrington Irrigation Research Farm. Chemical properties were averaged across treatments because there was no significant irrigation treatment effect on soil properties.

Mean Property	**Irrigation**		
	2013	**2014**	**2015**
pH	5.61 (0.15)	5.12 (0.29)	4.44 (0.48)
Organic Matter, g kg^{-1}	8.15 (1.98)	9.44 (3.18)	11.0 (2.53)
NH_4-N, mg kg^{-1}	6.77 (1.52)	4.95 (1.40)	5.98 (0.79)
NO_3-N, mg kg^{-1}	0.62 (1.02)	6.27 (2.20)	8.17 (3.17)
Total N, g kg^{-1}	0.61 (0.09)	0.65 (0.13)	0.68 (0.11)
Mehlich-3 P, mg kg^{-1}	55.6 (27.0)	87.0 (24.3)	58.4 (18.5)
Mehlich-3 K, mg kg^{-1}	119 (21.7)	60.0 (17.2)	79.6 (19.8)
Mehlich-3 Ca, mg kg^{-1}	378 (56.3)	271 (39.8)	348 (71.2)
Mehlich-3 Mg, mg kg^{-1}	68.3 (14.70	44.5 (7.01)	49.4 (13.7)
Mehlich-3 B, mg kg^{-1}	0.24 (0.18)	0.17 (0.05)	0.19 (0.06)

Objective 2. Quantify the effects of selected fertilizer strategies on WUE and NUE of corn irrigated under a center pivot and subsurface drip irrigation at the UD Warrington Irrigation Research Farm, Sussex County, DE.

Irrigation water Applied

Irrigation water was applied to the fertilizer plots (CP and SSD) based on ET demand (upon depletion of 50% of the field capacity), with most of the irrigation applied later in the growing season (August and September). The total amount of supplemental water applied to the irrigated CP fertilizer trial plots was 15.2, 29.0, 25.4, and 21.6 cm during the 2013, 2014, 2015, and 2016 growing seasons, respectively. The irrigated SSD plots received a total of 14.8 and 22.7 cm of water during the 2014 and 2015 growing seasons, respectively. Both the CP and SSDI fertilizer trials included a non-irrigated control, which received no irrigation.

Grain Yield Response to Nitrogen Fertilizer Rate, Timing, and Application Methods

A significant quadratic response of grain yield to N rate was noted for corn receiving both sidedress and fertigation applications under CP irrigation in 2014, 2015, and 2016 (Fig. 6). Nitrogen rates to achieve maximum (modeled) yields were predicted at 117 to 154% of UD recommended N rates (Table 7). It is important to note that the “maximum achievable yield” will be higher than the economic optimum yield. Nitrogen use efficiency will also be lower when fertilizing to achieve maximum yield because it often takes more N to increase yields between economic optimum and maximum achievable yield.

Method of in-season fertilizer application often had no effect on grain dry yields when evaluated over all N rates regardless of irrigation type (Tables 8-10). The exception was in 2015, when CP fertigated plots yielded more dry grain than the sidedress plots across all N rates (Table 9). In 2014, the plots receiving sidedress N at the lowest in-season N rate (82 kg ha^{-1}) yielded significantly more dry grain than the fertigated plots for both CP and SSD irrigation. Overall, it seemed that method of in-season application made little difference in dry grain production. In addition, in-season N rate had no effect on dry grain production in any year, regardless of irrigation method.

Application of in-season N always increased dry grain yield when compared to yields produced on plots receiving only manure + starter, regardless of in-season N application method or type of irrigation applied (Tables 8-10). Typically, yield gains were achieved with all in-season N rates. It was only in 2016 (CP irrigation), when dry grain yields from plots receiving the medium rate of in-season N did not have statistically higher dry grain yields than plots receiving manure + starter only.

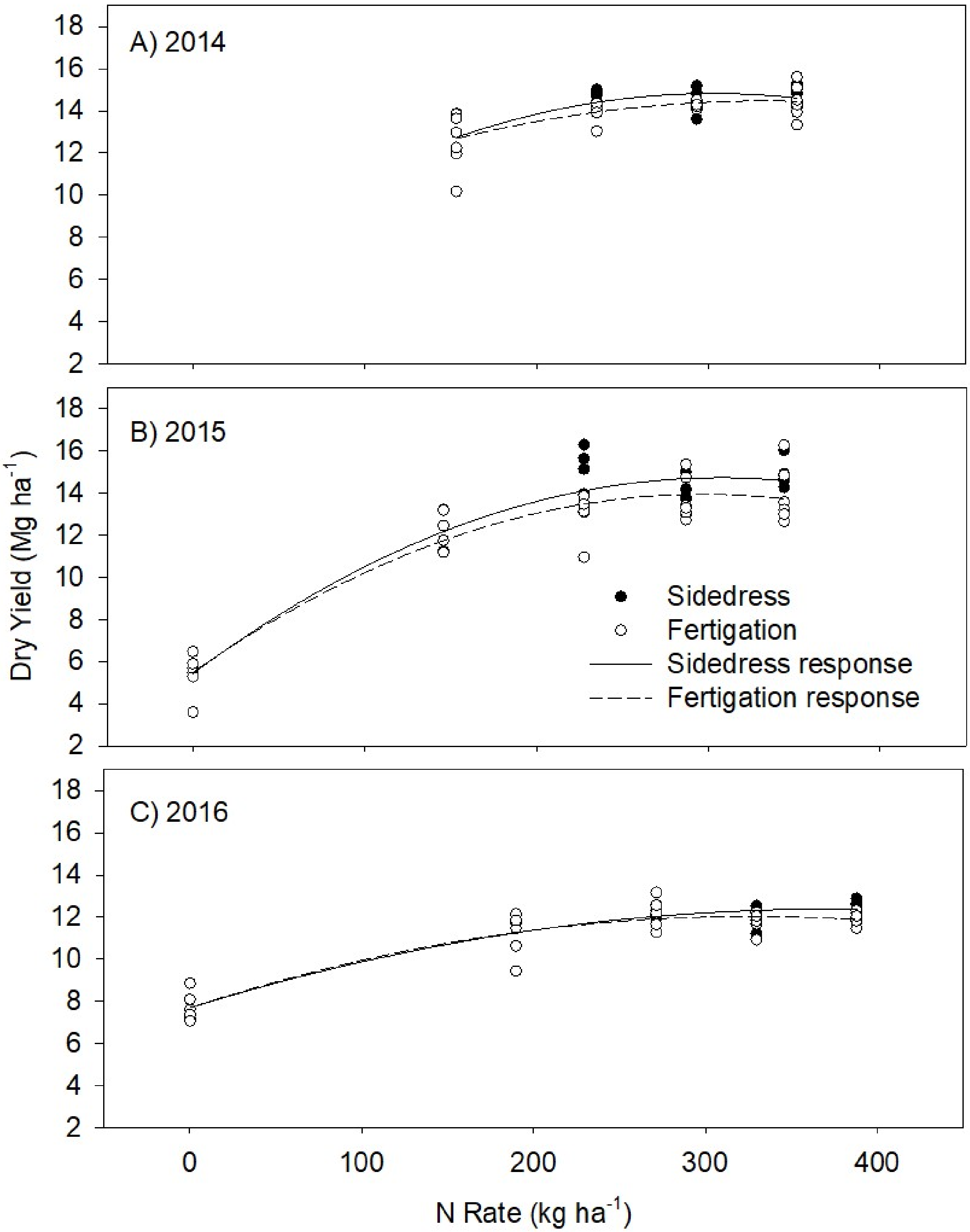

Figure 6. Quadratic model fit to grain yield against fertilizer N applied for sidedress and fertigation application methods in A) 2014, B) 2015, and C) 2016 for corn irrigated by center pivot at the University of Delaware (UD) Warrington Irrigation Research Farm near Harbeson, Delaware.

Table 7. Predicted maximum achievable yields and the corresponding N rate as identified by quadratic relationship of yield to N rate in 2014, 2015, and 2016 for corn grown under center pivot (CP) irrigation at the University of Delaware (UD) Warrington Irrigation Research Farm near Harbeson, DE.

In-season N method	**N Rate**			**Max Yield**		
	2014	**2015**	**2016**	**2014**	**2015**	**2016**
	kg ha^{-1}			Mg ha^{-1}		
Sidedress	303	306	371	14.8	14.7	12.4
Fertigation	332	297	326	14.5	13.9	12.0

Table 8. Effects of N fertilizer rate, timing and method and irrigation on crop yield response, crop N uptake and NUE in 2013 for corn grown under center pivot irrigation at the University of Delaware (UD) Warrington Irrigation Research Farm near Harbeson, DE.

Treatment	**PAN Rate**	**Dry Yield**	**Grain N**	**Stover N**	$\textbf{PFP}_\textbf{N}$	$\textbf{e}_\textbf{f}$	$\textbf{UA}_\textbf{N}$
	kg ha^{-1}	Mg ha^{-1}	kg ha^{-1}		kg kg^{-1}		kg ha^{-1}
			Irrigated				
Manure + Starter	161	6.66	77.4	31.0	41.6	0.13	142
Sidedress	232	8.66	89.7	40.1	37.3	0.17	191
	289	10.8	127	51.0	37.1	0.30	201
Fertigation	232	9.08	99.0	39.2	39.0	0.21	183
	289	9.26	100	40.9	31.8	0.18	238
			Rainfed				
Manure +Starter†	161	4.57	59.0	26.3	34.0	0.02	165

Contrasts				*P*-value		
Dryland vs. Irrigated (starter + manure)	0.300	0.199	0.431	0.258	0.290	0.395
Sidedress vs. Fertigated	0.496	0.392	0.197	0.706	0.516	0.265
Sidedress vs. Fertigated High N	0.179	0.064	0.090	0.423	0.201	0.044
Sidedress vs. Fertigated Low N	0.716	0.519	0.875	0.804	0.732	0.656
In-season High N vs. Low N	0.154	0.060	0.139	0.431	0.471	0.015
Starter N vs. In-season N	0.006	0.030	0.023	0.339	0.274	0.000
Starter vs. In-season High N	0.003	0.008	0.009	0.236	0.199	<.0001
Starter vs. In-season Low N	0.039	0.192	0.114	0.565	0.465	0.010

Table 9. Effects of N fertilizer rate, timing, and method, irrigation, and planting population on crop yield response and N uptake in 2014, 2015, and 2016 for corn grown under center pivot irrigation at the University of Delaware (UD) Warrington Irrigation Research Farm near Harbeson, DE.

Treatment	**In season N Rate†**	**Planting Population**	**Yield**			**Grain N**			**Stover N**		
			2014	**2015**	**2016**	**2014**	**2015**	**2016**	**2014**	**2015**	**2016**
		1000 ha^{-1}	—— Mg ha^{-1} ——			—————— kg ha^{-1} ——————					
					Irrigated						
Control‡	0	84	--‡	5.4	7.71	--	43.5	69.8	--	14.2	23.1
Manure + Starter	0	84	12.7	12.2	11.2	135	126	135	42.5	31.9	40.9
Sidedress	82	84	14.7	14.5	12.2	169	129	161	59.3	47.5	50.3
	140	84	14.4	14	12.1	169	163	169	57	47.2	64.1
	198	84	14.8	14.9	12.4	180	179	174	71.1	70.9	75.1
Fertigation	82	84	14.5	13.1	12.2	162	150	152	52.5	48.6	50.1
	140	84	13.4	13.8	11.8	171	157	152	56.6	57.2	48.8
	198	84	14	13.9	12	168	157	164	58.5	49.1	52.3
					Rainfed						
Control‡	0	54	--	6.81	7.97	--	56.5	75.8	--	18.7	24.1
Manure +Starter†	0	54	--	10.7	10.6	--	103	140	--	29.8	40.9
					Rainfed Population						
Manure +Starter‡	0	54	--	6.81	10.6	--	103	140	--	18.7	24.1
	0	84	12.6	12.8	11.1	134	137	137	44.2	41.9	44.1

† PAN applied in manure was 116, 109, and 153 kg ha^{-1} in 2014, 2015, and 2016, respectively; starter N was 40.8 kg ha^{-1} to all plots except control

‡ indicates a treatment that was not included in the experimental design in 2014.

Table 9 (cont). Effects of N fertilizer rate, timing, and method, irrigation, and planting population on crop yield response and N uptake in 2014, 2015, and 2016 for corn grown under center pivot irrigation at the University of Delaware (UD) Warrington Irrigation Research Farm near Harbeson, DE.

	Yield			**Grain N**			**Stover N**		
Contrasts	**2014**	**2015**	**2016**	**2014**	**2015**	**2016**	**2014**	**2015**	**2016**
					P-value				
Dryland vs. Irrigated (Starter + Manure)	0.9376	0.3196	0.8743	0.8394	0.2629	0.8113	0.83	0.3012	0.4445
Sidedress vs. Fertigated	0.1556	0.0229	0.2547	0.1856	0.0316	0.0197	0.169	0.5330	<.0001
Sidedress vs. Fertigated Low N	0.0742	0.0303	0.9130	0.3367	0.3245	0.3126	0.407	0.9126	0.9650
Sidedress vs. Fertigated Medium N	0.9776	0.7501	0.3982	0.7685	0.5510	0.0548	0.961	0.3028	0.0005
Sidedress vs. Fertigated High N	0.505	0.1356	0.3062	0.0996	0.0300	0.2515	0.126	0.0361	<.0001
In-season Medium N vs. Low N	0.9342	0.9558	0.4379	0.4062	0.4203	0.4894	0.876	0.5467	0.0372
In-season High N vs. Medium N	0.3809	0.2391	0.4164	0.4215	0.2646	0.1902	0.167	0.2715	0.0177
In-season High N vs. Low N	0.4267	0.2182	0.9702	0.1066	0.0577	0.0428	0.126	0.0944	<.0001
Starter N vs. In-season N	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Starter vs. In-season Low N	<.0001	0.0037	0.0129	<.0001	0.0012	0.0038	0.057	0.0593	0.0132
Starter vs. In-season Medium N	<.0001	0.0033	0.0581	<.0001	0.0001	0.0008	0.043	0.0188	<.0001
Starter vs. In-season High N	<.0001	0.0002	0.012	<.0001	<.0001	<.0001	0.002	0.0017	<.0001
Control vs. Starter (irrigated)	--	<.0001	<.0001	--	<.0001	<.0001	--	0.0735	<.0001
Control vs. In-season Low N	--	<.0001	<.0001	--	<.0001	<.0001	--	0.0002	<.0001
Control vs. In-season Medium N	--	<.0001	<.0001	--	<.0001	<.0001	--	<.0001	<.0001
Control vs. In-season High N	--	<.0001	<.0001	--	<.0001	<.0001	--	<.0001	<.0001
Control vs. Starter (Dryland; Low Population)	--	<.0001	<.0001	--	<.0001	<.0001	--	0.2769	0.0002
Population High vs. Low (Starter; Dryland)	--	0.0034	0.2104	--	0.0016	0.6908	--	0.2382	0.4351

Table 10. Effects of N fertilizer rate, timing, and method, irrigation, and planting population on crop yield response and N uptake in 2014, 2015, and 2016 for corn grown under subsurface drip irrigation at the University of Delaware (UD) Warrington Irrigation Research Farm near Harbeson, DE.

Treatment	**In season N Rate†**	**Yield**		**Grain N**		**Stover N**	
		2014	**2015**	**2014**	**2015**	**2014**	**2015**
		— Mg ha^{-1} —		—— kg ha^{-1} ——			
				Irrigated			
Control‡	0	--	5.07	--	37.3	--	13.8
Manure + Starter	0	11.9	11.3	98.7	84.0	62.0	60.1
Sidedress	82	13.7	14.1	122	142	62.2	82.2
	198	15.0	14.5	148	149	82.3	84.4
Fertigation	82	13.4	13.8	121	124	75.3	72.7
	198	14.2	14.0	139	133	72.1	76.9
				Rainfed			
Manure +Starter	0	11.7	8.3	98.6	72.3	60.1	46.6
Contrasts				*P*-value			
Dryland vs. Irrigated (starter + manure)		0.857	<.0001	0.987	0.157	0.871	0.238
Sidedress vs. Fertigated		0.292	0.328	0.277	0.006	0.864	0.295
Sidedress vs. Fertigated High N		0.298	0.413	0.171	0.057	0.401	0.512
Sidedress vs. Fertigated Low N		0.652	0.569	0.869	0.038	0.272	0.406
In-season High N vs. Low N		0.074	0.487	<.0001	0.213	0.318	0.692
Starter N vs. In-season N		0.001	<.0001	<.0001	<.0001	0.245	0.042
Starter vs. In-season High N		0.000	<.0001	<.0001	<.0001	0.144	0.044
Starter vs. In-season Low N		0.020	<.0001	0.000	<.0001	0.512	0.086
Control vs. Starter		--	<.0001	--	<.0001	--	0.067
Control vs. In-season High N		--	<.0001	--	<.0001	--	0.001
Control vs. In-season Low N		--	<.0001	--	<.0001	--	0.001
Fertilizer vs. Control		--	<.0001	--	<.0001	--	0.001

† PAN applied in manure was 116, 109, and 153 kg ha^{-1} in 2014, 2015, and 2016, respectively; starter N was 40.8 kg ha^{-1} to all plots except control

‡ indicates a treatment that was not included in the experimental design in 2014

In 2015, we added a zero N treatment to facilitate generation of yield response curves and to confirm that the field plots were responsive to N applications. Application of N (manure + starter with and without in-season N) always led to a statistically significant increase in dry grain yields when compared to the zero N control (Table 9 and 10), regardless of irrigation type. We also reported a significant yield increase for dryland plots receiving manure + starter over the zero N control when grown under CP irrigation in both years. A dryland zero N treatment was not included in the SSD plot trials due to lack of space. Regardless, it was clear that the site was responsive to N fertilizer.

Confirming the results of the irrigation treatment trials, we saw no effect of center pivot irrigation on dry grain yield for plots receiving manure + starter N only (no in-season N, planted at the high population) in all years (Tables 8 and 9). Results were similar in 2014 for plots receiving SSD irrigation; however, SSD irrigated plots produced more dry grain than the dryland plots in 2015 (Table 10). We also planted corn under dryland conditions at a lower planting population in 2015 and 2016. Planting population significantly affected dry grain yield only in 2015; no population effect was noted in 2016. Planting population was not assessed in 2013 or 2014.

Crop N Uptake Response to Fertilizer Rate, Timing, and Application Methods

In-season N application method (sidedress vs. fertigation) had no effect on grain N uptake in 2013 or 2014, regardless of irrigation type (Tables 8-10). However, starting in 2015, N uptake in grain was affected by in-season N application method for corn grown under CP and SSD irrigation. When evaluated across all N rates, sidedress N applications resulted in significantly higher grain N uptake than the fertigated plots. Application method effects on grain N uptake were most pronounced (and typically significant) for plots receiving the high in-season N rate. These trends persisted into 2016. When evaluated across both in-season methods, we reported a significant in-season N rate effect on grain N uptake in 2016, where grain N removal at the highest N rates under CP irrigation led to higher grain N removal (Table 9). Similarly, the high in-season N rate increased grain N uptake under SSD irrigation in 2014 (Table 10).

Grain N uptake by corn grown with starter + manure only was significantly lower than grain N uptake for plots receiving in-season N in all seasons under both CP and SSD irrigation (Tables 8-10). However, per unit of N applied, grain harvest from the manure + starter plots removed a greater proportion of applied N (approximately 85-90%) than the plots receiving in-season N (approximately 50-70%). Similarly, grain N uptake always increased when plots received N (manure + starter, with and without in-season applications) when compared to the zero N control (Tables 9 and 10). \

We saw no effect of applying irrigation on grain N uptake at any point in the study for plots that received manure + starter N, regardless of irrigation type (CP or SSD) applied (Tables 8-10). In 2015, dryland plots planted at the low population (manure + starter only) had significantly lower grain N uptake than plots planted at the high population (to match irrigation populations) under both CP and SSD irrigation. No planting population effects on grain N uptake were noted in 2016.

Corn stover is typically left in the field to allow for recycling of nutrients and organic matter. Stover N uptake was estimated in order to calculate NUE using the mass balance approach. We report various treatment effects on stover N uptake (Table 8-10). Briefly, stover N uptake generally increased with increasing N rate, with significant increases when the crop received N (manure + starter, with and without in-season N). Fertilizer application rate did not typically affect stover N uptake (except in 2016). Irrigation did not increase stover N uptake.

Nitrogen Use Efficiency Response to Nitrogen Fertilizer Rate, Timing, and Application Methods

In-season N application method (sidedress vs. fertigation) had no effect on PFP_N in any year of the study (Tables 8, 11, and 12). Even when we factored in the potential for additional N applications from irrigation water, precipitation, and soil mineralization, in-season application method did not significantly affect e_f or UA_N in 2013, 2014, or 2015. In 2016, e_f was significantly higher (average = 0.43) and UA_N was significantly lower (average = 188 kg ha^{-1}) across all in-season N rates when the corn was sidedressed when compared with the fertigated plots (average across all in-season N rates = 0.36 and 213 kg ha^{-1}, respectively).

In-season N rate had mixed effects on NUE estimates throughout the study period. Crop PFP_N was not significantly affected by in-season N rate in 2013 (CP irrigation) or 2015 (SSD irrigation); in-season N rate affected PFP_N in all other cases (Tables 8, 11, and 12). In general, we saw a significant trend for reductions in PFP_N as in-season N rate increased. In-season N application rate (e.g., high vs. low) had no effect on e_f for CP or SSD irrigated plots in most study years. The only exception was in 2014, when CP irrigated plots receiving the medium and high in-season N rates had significantly lower e_f values than plots receiving the low in-season N rate when averaged across both application methods (Table 11). Yet, in-season N rate always had a significant effect on the amount of UA_N, where high in-season N rate > medium in-season N rate > low in-season N rate.

The application of in-season N resulted in a significant reduction of PFP_N and e_f when compared to plots receiving manure + starter N only (Tables 8, 11, and 12). The only exception was in 2013, where PFP_N for CP irrigated plots receiving in-season N were not significantly different than for plots receiving manure + starter N only (Table 8). However, UA_N was significantly higher for the plots receiving in-season N when compared to the manure + starter plots in all years under both types of irrigation. Irrigation improved PFP_N over dryland production for SSD irrigated plots in 2015 only (Table 12). Otherwise, there was no effect of irrigation on PFP_N, e_f, or UA_N during the study.

However, it is important to note that dry grain yields were comparable for dryland and irrigated plots in all years except for 2015 (SSD only). Similarly, the yields for non-irrigated plots were only significantly lower than the irrigation treatments in 2015 and 2016; however, the irrigation treatments received N at a rate that was not limiting to yield. During the fertilizer trials, the comparisons between dryland and irrigated for yield and NUE were based on plots that received manure + starter N; there was a significant yield response to application of in-season N. As such, we are not able to make definitive statements on the value of irrigation in improving NUE.

Evaluation of planting population in 2015 and 2016 compared plots receiving zero N or manure + starter only. In 2015, the lower planting population, which is more in-line with grower standards for dryland production, significantly reduced PFP_N and e_f and increased the amount of UA_N (Table 10). Planting population had no effect on NUE measures in 2016.

Table 11. Effects of N fertilizer rate, timing, and method, irrigation, and planting population on crop NUE in 2014, 2015, and 2016 for corn grown under center pivot irrigation for corn grown under center pivot irrigation at the University of Delaware (UD) Warrington Irrigation Research Farm near Harbeson, DE.

Treatment	**In season N Rate†**	**Planting Population**	**PFP_N**			**e_f**			**UA_N**		
			2014	**2015**	**2016**	**2014**	**2015**	**2016**	**2014**	**2015**	**2016**
		1000 ha^{-1}	——— kg kg^{-1} ———						——— kg ha^{-1} ———		
				Irrigated							
Manure + Starter	0	84	82.7	83.5	59.1	0.57	0.46	0.46	65.6	78.1	103
Sidedress	82	84	62.7	63.9	45	0.59	0.52	0.45	96.5	110	150
	140	84	48.8	48.7	36.8	0.46	0.42	0.44	158	167	186
	198	84	41.8	43.2	32	0.46	0.46	0.41	190	184	229
Fertgation	82	84	59.5	57.7	44.8	0.53	0.48	0.42	111	119	159
	140	84	48.9	47.9	35.6	0.47	0.43	0.34	156	162	219
	198	84	41.1	40.4	30.8	0.39	0.35	0.33	215	224	261
				Population Rainfed							
Manure + Starter	0	54‡	--	73.8	55.7	--	0.61	0.48	--	102	97.9
	0	84	82.5	87.8	58.7	0.58	0.3	0.48	64.2	56	98.1

† PAN applied in manure was 116, 109, and 153 kg ha^{-1} in 2014, 2015, and 2016, respectively; starter N was 40.8 kg ha^{-1} to all plots except control

‡ indicates a treatment that was not included in the experimental design in 2014

Table 11. (cont.) Effects of N fertilizer rate, timing, and method, irrigation, and planting population on crop NUE in 2014, 2015, and 2016 for corn grown under center pivot irrigation for corn grown under center pivot irrigation at the University of Delaware (UD) Warrington Irrigation Research Farm near Harbeson, DE.

	PFP_N			**e_f**			**UA_N**		
Contrasts	**2014**	**2015**	**2016**	**2014**	**2015**	**2016**	**2014**	**2015**	**2016**
					P-value				
Dryland vs. Irrigated (Starter + Manure)	0.9385	0.2018	0.8495	0.8523	0.0932	0.5900	0.9165	0.2500	0.6309
Sidedress vs. Fertigated	0.3804	0.1040	0.4696	0.2425	0.3828	0.0180	0.1055	0.1924	0.0006
Sidedress vs. Fertigated Low N	0.2055	0.0729	0.9305	0.3264	0.6699	0.5011	0.2849	0.6551	0.4400
Sidedress vs. Fertigated Medium N	0.9872	0.8354	0.5670	0.9017	0.8674	0.0594	0.9126	0.8284	0.0077
Sidedress vs. Fertigated High N	0.7797	0.4117	0.5523	0.2340	0.2249	0.1112	0.0609	0.0516	0.0062
In-season Medium N vs. Low N	<.0001	<.0001	<.0001	0.0299	0.2739	0.2170	<.0001	0.0006	<.0001
In-season High N vs. Medium N	0.0002	0.0096	0.0013	0.3295	0.7568	0.5735	<.0001	0.006	<.0001
In-season High N vs. Low N	<.0001	<.0001	<.0001	0.0024	0.1707	0.0686	<.0001	<.0001	<.0001
Starter N vs. In-season N	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Starter vs. In-season Low N	<.0001	<.0001	<.0001	0.7955	0.6455	0.6131	0.0014	0.0309	<.0001
Starter vs. In-season Medium N	<.0001	<.0001	<.0001	0.0381	0.6609	0.133	<.0001	<.0001	<.0001
Starter vs. In-season High N	<.0001	<.0001	<.0001	0.005	0.4933	0.0483	<.0001	<.0001	<.0001
Population High vs. Low (Starter + Manure; Dryland)	--	0.0003	0.1382	--	0.0017	0.9731	--	0.0257	0.9849

Table 12. Effects of N fertilizer rate, timing, and method, irrigation, and planting population on crop NUE in 2014 and 2015 for corn grown under subsurface drip irrigation at the University of Delaware (UD) Warrington Irrigation Research Farm near Harbeson, DE.

Treatment	**In season N Rate†**	**PFPN**		**ef**		**NUA**	
		2014	**2015**	**2014**	**2015**	**2014**	**2015**
		—— kg ha^{-1} —				— kg ha^{-1} —	
				Irrigated			
Control‡	0	--	--	--	--	--	--
Manure + Starter	0	77.7	68.9	0.20	0.04	132	157
Sidedress	82	60.6	57.5	0.23	0.36	175	159
	198	52.8	47.6	0.33	0.32	191	209
Fertigation	82	59.0	56.2	0.29	0.24	163	186
	198	49.7	40.1	0.28	0.24	207	232
				Rainfed			
Manure +Starter‡	0	78.6	50.5	0.21	-0.04	121	170

Contrasts		*P*-value			
Dryland vs. Irrigated (starter + manure)	0.8723	<.0001	0.8594	0.227	0.5577
Sidedress vs. Fertigated	0.5383	0.4036	0.9921	0.0479	0.8812
Sidedress vs. Fertigated High N	0.5709	0.5228	0.5133	0.2366	0.4111
Sidedress vs. Fertigated Low N	0.761	0.5849	0.4959	0.0962	0.5312
In-season High N vs. Low N	0.0266	<.0001	0.4270	0.6139	0.0334
Starter N vs. In-season N	<.0001	<.0001	0.1803	<.0001	0.0010
Starter vs. In-season High N	<.0001	<.0001	0.1240	0.0001	0.0001
Starter vs. In-season Low N	0.0002	<.0001	0.3667	0.0003	0.0269

† PAN applied in manure was 116, 109, and 153 kg ha^{-1} in 2014, 2015, and 2016, respectively; starter N was 40.8 kg ha^{-1} to all plots except control

‡ indicates a treatment that was not included in the experimental design in 2014.

Water Use Efficiency to Response to Nitrogen Fertilizer Rate, Timing, and Application Methods

In-season fertilizer method had no significant effect on WUE in any year, regardless of irrigation type (data not shown). In addition, in-season N rate had no effect on WUE in any year, regardless of irrigation method. Yet, in-season N applications increased WUE when compared to plots receiving manure + starter N only in all years. Center pivot irrigated plots receiving in-season N had an average WUE of 1.82, 3.02, 3.11, and 3.05 kg m^{-3} compared with 1.28, 2.64, 2.64, and 1.73 kg m^{-3} in 2013, 2014, 2015, and 2016, respectively for plots receiving only the manure + starter treatment. Similarly, in-season applications boosted WUE compared with the zero N control, with average WUE of 1.20 and 1.73 kg m^{-3} in 2015 and 2016, respectively. We report similar trends for SSD irrigated plots receiving manure + starter N, which had an average WUE of 3.59 and 3.28 kg m^{-3}, in 2014 and 2015, respectively; WUE was significantly higher than plots receiving manure + starter N only (3.04 and 2.62 kg m^{-3} in 2014 and 2015, respectively). In 2015, SSD irrigated plots receiving any amount of N fertilizer had higher WUE (3.15 kg m^{-3}) than zero N control plots (1.18 kg m^{-3}).

Irrigation of plots receiving manure + starter N had no significant effect on WUE in 2013, with an average WUE of 1.22 kg m^{-3} (data not shown). As discussed for the irrigation treatments (Objective 1), WUE in 2013 was very poor due to extreme moisture that ultimately suppressed yields. In subsequent years, we noted that irrigation of the manure + starter plots typically decreased the WUE (data not shown). This decrease in WUE with irrigation occurred regardless of the type of irrigation we applied (i.e., CP or SSD). The results from our fertilizer plots (Objective 2) were generally in agreement with the results of the irrigation treatments, except that the fertilizer plots showed an irrigation effect on WUE in 2015; the results of the irrigation treatment study suggested no irrigation effect on WUE in 2015. Irrigation for the fertilizer trials followed the 100% ET treatment, which typically applied the highest volume of water. It is possible that variance among blocks masked irrigation treatment effects on WUE in 2015. On average, WUE was 3.43, 4.43, and 3.93 kg m^{-3} for dryland plots in 2014, 2015, and 2016, respectively, compared to WUE of 2.64, 2.70, and 1.73 kg m^{-3} for the same years when irrigated by CP. Similarly, WUE was 3.67 and 3.03 kg m^{-3} for dryland plots field in 2014 and 2015, respectively, compared to WUE of 3.04 and 2.62 kg m^{-3} for the same years when irrigated by SSD. The WUE of the low population dryland planting was not significantly different than the high population planting. On average, WUE was 3.73 and 3.83 kg m^{-3} in 2014 and 2015, respectively for dryland plots receiving manure + starter.

Post-harvest Soil Analysis

Nitrogen fertilizer treatment had no effect on post-harvest soil properties (Table 13), with the exception of soil NO_3-N. Post-harvest soil collected from the field had a soil pH of 5.20 and 5.30 in 2014 and 2015, respectively; soil organic matter concentration following harvest was 11.7 and 15.7 in 2014 and 2015, respectively. Mehlich 3 P concentration was 153 (excessive) and 66.6 (optimum) mg kg^{-1} (Shober et al., 2013) following harvest in 2014 and 2015, respectively. Mehlich 3 K concentration in post-harvest soil samples collected in 2014 and 2015 fell within the medium soil fertility category at 68.9 and 77.4 mg kg^{-1}, respectively (Shober et al., 2013). Post-harvest soil concentration of NH_4-N was 2.40 and 1.13 mg kg^{-1} in 2014 and 2015 respectively; post-harvest soil concentration of NO_3-N was 5.27 and 7.9 in 2014 and 2015 respectively. In 2015, sidedress N plots receiving 318 and 260 kg N ha^{-1} had significantly higher concentrations of post-harvest NO_3-N (14.5 and 11.8 mg kg^{-1}, respectively) than all other plots; mean concentrations of NO_3-N for all other treatments was 6.23 mg kg^{-1}. We were unable to complete the analysis of 2016 post-harvest soil samples due to a rat infestation in our storage area that caused significant contamination to the 2016 soil samples.

Irrigation and Lysimeter Water Sampling and Analysis

No statistically significant N application method/timing effect was found on NO_3-N concentrations in water samples collected from lysimeters in 2014, 2015 or, 2016 (data not shown). In 2014, sidedress and fertigation plots had a mean seasonal concentration in lysimeter water samples of 7.5 and 5.2 mg L^{-1}, respectively. Plots receiving only manure + starter had significantly lower concentrations of NO_3-N in lysimeters water samples of 1.5 mg L^{-1}, on average. In 2015, mean concentration of NO_3-N in water collected from lysimeters in plots receiving sidedress (27 mg L^{-1}) or fertigation (17.1 mg L^{-1}) N were significantly higher than NO_3-N concentrations in lysimeter water samples collected from control and manure + starter plots (9.8 and 8.2 mg L^{-1}, respectively). There was no difference identified among water samples for differing N rates. A bivariate analysis of NO_3-N concentrations in lysimeter water samples over time identified a significant negative linear relationship as the season progressed (*P* <0.0001) in the 2014 crop season, but no significant linear trend was apparent with time in 2015.

Table 13. Selected chemical properties of post-harvest soils collected from 20 cm from the center pivot (CP) and subsurface drip (SSD) irrigated research plots at the University of Delaware (UD) Warrington Irrigation Research Farm. Chemical properties were averaged across treatments because there was no significant N treatment effect on soil properties.

Mean Property	**SSD**		**CP**	
	2014	**2015**	**2014**	**2015**
pH	5.39 (0.39)	5.02 (0.2)	5.2 (0.38)	5.3 (0.22)
Organic Matter, g kg^{-1}	10.8 (0.28)	14.4 (0.48)	11.7 (0.39)	15.7 (0.76)
NH_4-N, mg kg^{-1}	5.89 (1.92)	6.14 (1.66)	2.4 (0.82)	1.13 (0.83)
NO_3-N, mg kg^{-1}	5.48 (1.86)	5.27 (1.42)	5.27 (1.72)	7.9 (4.23)
Mehlich-3 P, mg kg^{-1}	73.6 (25.2)	88.9 (19.5)	153 (79.8)	66.6 (23.1)
Mehlich-3 K, mg kg^{-1}	104 (16.8)	118 (20.1)	68.9 (25.1)	77.4 (17.3)
Mehlich-3 Ca, mg kg^{-1}	275 (64)	306 (75.4)	370 (135)	369 (63)
Mehlich-3 Mg, mg kg^{-1}	58.4 (13.7)	56.5 (10.8)	57.6 (22.8)	55.5 (9.91)
Mehlich-3 B, mg kg^{-1}	0.26 (0.08)	0.22 (0.11)	0.45 (0.14)	0.27 (0.13)

In 2016, an insufficient number of lysimeter samples were collected to determine the effect of sampling date or N application methods on soil nitrate concentrations. However, in 2016, sidedress and fertigation plots had mean seasonal NO_3-N concentrations of 8.3 and 11.9 mg L^{-1}, which were higher but not significantly different from the control and manure + starter plots (0.23 and 0.02 mg L^{-1}, respectively). When 2016 lysimeter NO_3-N concentrations were compared across all N application methods, the mean concentration under plots receiving the highest N rate (29 mg L^{-1}) was significantly higher than lysimeter NO_3-N concentrations for all other N rates (range = 0.02 to 4.7 mg L^{-1}).

Overall Observations from the UD Warrington Irrigation Research Farm Irrigation and Fertilizer Field Trials, 2013-2016

We reported somewhat different trends regarding the best method to schedule pivot irrigation across the four study years. In 2013, wetter treatments performed best; in 2014 there was no need to irrigate as the dryland yields were not significantly lower than irrigated; in 2015 the yields were good as long as some irrigation was provided; and in 2016 irrigated treatments were similar and only slightly higher than the dryland treatment.

Overall, the 2013, 2014, and 2015 seasons were ideal corn production years with little natural moisture stress. In our area, 2016 was less conducive to high-yield corn production, but still did not represent drought conditions. As such, the dryland treatment yield in 2016 was higher than expected despite the less than adequate rainfall received in July and August.

When NUE was calculated as PFP_N, we generally saw good efficiencies. But when NUE was evaluated using a mass balance approach, e_f values were typically lower than 0.6 for irrigated plots receiving in-season N applications across all rates, suggesting that 40% or more of the N available to growing crops was at risk for loss to the environment. This was not entirely surprising, as high rates of in-season N resulted in approximately 300 to 350 kg ha^{-1} of PAN applied, with annual variations due to differences in manure PAN; total N applications are higher because only 60% of manure total N was considered plant available during the growing season. These results highlight the need to adjust in-season rates based on manure analysis, potential for soil N mineralization, and irrigation water N concentrations. The ability to accurately estimate these N inputs will be key to increase NUE within the region. In addition, estimated of NUE are needed in years where rainfall is scarce to more accurately assess the potential for irrigation to influence NUE.

We are also concerned that that individual plot yields were affected by an overall cooling affect in the field from adjacent plots receiving irrigation. Future research should utilize larger plot size to minimize any cooling effect from adjacent plots and include intensive sampling of electrical conductivity, soil organic matter, and field elevation to better establish replications.

Objective 3: Compare NUE of corn under irrigation and dryland conditions in Bucks Branch watershed, Sussex County, DE.

Bucks Branch, Sussex County Delaware Site Characterization and Field Operations

In an effort to further extend the information collected at the UD Warrington Irrigation Research Farm, we also quantified WUE and NUE under irrigated and dryland conditions as managed by a grower in the Bucks Branch subwatershed. This work was completed in cooperation with USGS as a compliment to the USGS study "Monitoring Water-Quality Response of Conservation Practices in the Bucks Branch Watershed, Sussex County, Delaware". The selected dryland and irrigated corn fields were managed by a cooperating grower. A detailed description of the field site is available in the USGS report to DNREC.

Field Operations

Detailed information about field operations was provided by the cooperating grower in 2015 only. Attempts were made to obtain additional details for the 2014 and 2016 growing season, but the grower did not share this information with the project team. As such, this discussion is limited to a description of WUE and NUE for a set of paired fields, dryland (approximately 3.84 ha; 9.5 ac) and CP irrigated (approximately 15.4 ha; 38 ac) in 2015. Both fields were planted in continuous corn from 2013-2016. Cover crops were planted in both fields during the non-growing season.

Pre-season soil fertility analysis was completed by a private crop consultant in early spring of each year. The cooperator did not share the results with the project team. On 20 March 2015, the cover crops were terminated by herbicide. A pre-emergence herbicide was applied on 8 May 2015 and a post-emergence herbicide was applied on 1 June 2015 to control weeds. Cover crops were interseeded into standing corn on 17 August 2015. Corn was harvested in mid- to late-September.

Nitrogen Application

Each field received 2.24 kg ha^{-1} (2 ton/ac) of poultry litter on 24 April 2015. Specific information about poultry litter nutrient content and date of incorporation were not shared with the project team, however, the grower indicated that the rate of poultry litter was designed to apply 67.3 kg ha^{-1} (60 lb/ac) of PAN to the corn crop during the 2015 growing season. Corn was planted in each field between 7 and 15 May 2015 and starter N was applied to the irrigated corn crop at a rate of approximately 22.4 kg ha^{-1} (20 lb/ac). The majority of N was applied to corn in-season, between 7 and 15 June 2015. The irrigated field received 185 kg ha^{-1} (165 lb/ac) to achieve a yield goal of 13 Mg ha^{-1} (245 bu/ac); the dryland field received N at a rate of 112 kg ha^{-1} (100 lb/ac) to achieve a yield goal of 8.5 Mg ha^{-1} (160 bu/ac).

Meteorological Data

Meteorological data was obtained from the Bridgeville, DE weather station (DEOS, 2017), which was located near the field sites. Total rainfall received at the Bridgeville, DE station during the 2015 growing season was 0.32 m (12.5 in). Daily ET and precipitation data from the weather station and detailed daily irrigation data (provided by the grower) was input into KanSched2 to determine effective rainfall and ET_c for each field. Effective rainfall was 0.25 and 0.28 m (9.67 and 10.9 in) for the dryland and irrigated fields, respectively. Approximately 0.7 and 0.6 m of rainfall was lost in runoff or was leached below the root zone for the dryland and irrigated fields, respectively. Crop ET was estimated at 0.42 and 0.31 m (16.4 and 12.4 in) for the dryland and irrigated fields, respectively.

Irrigation Applied

Project personnel completed an evaluation of the irrigation system uniformity and calibrated the irrigation pivot on the irrigated field. Detailed information on system uniformity is available upon request. Soil moisture at the site was continuously monitored in both the irrigated and dryland fields using a Watermark 950T (Irrometer Co., Riverside, CA) wireless soil moisture monitoring transmitter. Each transmitter collected soil matric potential data from three Watermark matric potential sensors placed at 15, 30, and 45 cm below the soil surface and transmit the data to a central logger approximately 15 times per day. Detailed soil moisture data for the field sites is available upon request. Total irrigation application was 15.7 cm (6.18 in) over the course of the 2015 growing season.

Water Use Efficiency

Water use efficiency was slightly higher (3.04 kg m^{-3}) for the irrigated field than the field (2.77 kg m^{-3}). While statistical analysis is not possible to determine the effects of irrigation on WUE for these fields, we can compare the results with those from the UD Warrington Irrigation Research Farm. In 2015, we reported no significant treatment effect of irrigation on WUE and values ranged from 3.30 kg m^{-3} for plots receiving the highest volume of water, to 3.65 kg m^{-3} for the non-irrigated control. The WUE at Bucks Branch was lower in both the irrigated and dryland fields when compared to the UD Warrington Irrigation Research Farm, but was close. Lower dryland WUE may indicate that the overall lower WUE at Bucks Branch was due to factors in addition to the grower irrigation practices (i.e., differences in soil properties, lower soil moisture holding capacity and seasonal rainfall patterns between the two sites).

Other Sources of Nitrogen to Crop

We estimated that a total inorganic N concentration of 1.88 mg L^{-1} in rainfall, based on rainfall samples that were collected in 2015 from the University of Maryland Wye Research and Education Center in Queenstown, MD as part of the National Atmospheric Deposition Program (NADP, 2017). As such, seasonal wet deposition (N_{atm}) at the site was estimated at 2.15 kg ha^{-1} (1.91 lb/ac). Water samples collected from the irrigation well at the Bucks Branch site in 2015 had 14.3 mg L^{-1} total N; total N applied with irrigation water (N_{soil}) was estimated at 19.4 kg ha^{-1} (17.3 lb/ac).

Soil N mineralization (N_{soil}) information was estimated based on the recommendations of Shapiro et al. (2008) using post-harvest soil test data (organic matter and soil inorganic N concentrations; pre-season information was not available) from the Bucks Branch field as 73.0 and 52.1 kg ha^{-1} (65.1 and 46.5 lb/ac) for the dryland and irrigated fields, respectively.

Crop Yield and N Uptake

The irrigated field yield was 12.6 Mg ha^{-1} (237.8 bu/ac); the dryland field was 8.7 Mg ha^{-1} (164 bu/ac). Grain N content was 1.38 and 1.45% for the dryland and irrigated fields, respectively, resulting in grain N uptake of 174 and 126 kg ha^{-1} (155 and 112 lb/ac), respectively. Stover N content was lower at 0.86 and 1.0% for the dryland and irrigated fields, respectively, resulting in stover N uptake of 80.6 and 64.1 kg ha^{-1} (71.9 and 57.2 lb/ac), respectively (assuming a harvest index of 0.6).

Nitrogen Use Efficiency

Overall, PFP_N for the two Bucks Branch fields were quite similar, with estimated values of 46.0 and 48.5 kg kg^{-1} (0.97 and 1.03 lb N/bu) for the irrigated and dryland fields, respectively. The Bucks Branch PFP_N values for the irrigated fields were similar in magnitude to the PFP_N for the irrigated plots receiving in-season N at the UD Warrington Irrigation Research Farm (Table 10). Direct comparisons cannot be made between Buck Branch and Irrigation Research Farm dryland PFP_N because of differences in total PAN application and/or planting population. When additional sources of N were considered, the irrigated field at Bucks Branch had reduced e_f (0.61) and increased UA_N (107 kg ha^{-1}) when compared to the dryland field (0.79 and 37.8 kg ha^{-1} for the e_f and UA_N, respectively), which was due to lower N application rates to the dryland field, as well as significant applications of N_{irr} and differences in estimated N_{soil} between the two fields. Higher crop N uptake in the irrigated field when compared to the dryland field (254 vs. 190 kg ha^{-1}) was not enough to overcome the large N_{irr} inputs. As with the UD Warrington Irrigation Research Farm fertilizer trials, these differences highlight the importance of accurate accounting for ancillary sources of N when determining the appropriate fertilizer rate. Regardless, the e_f achieved at Bucks Branch was better than for irrigated plots receiving in-season fertilizer applications at the UD Warrington Irrigation Research Farm. It is important to note that detailed manure nutrient content and starter N data was not provided by the grower, therefore, we estimated the amount of N applied to be at the UD recommendation of 17.1 kg of N per Mg of expected yield. If the grower applied N fertilizer above this recommendation, estimated of NUE would be reduced.

CONCLUSIONS AND IMPLICATIONS

The fact that we received adequate to excessive rainfall over the course of this study makes it difficult to make definitive claims about the benefits of irrigation on WUE and NUE. It is also important to recognize that this study was conducted 1) on one farm with many small plots or 2) on a cooperating farm with no replication. Overall, we feel that a paired field approach of comparing NUE in dryland fields to irrigated fields would be useful to compare grower standard practices and determine the impact of irrigation on yields, WUE, and NUE. As such, we recommend expanding WUE and NUE trials to additional farms, with differing soils and larger scale production. Data should be collected from paired fields (dryland and irrigated) at each site over multiple years to further evaluate yield, WUE, and NUE responses to irrigation during periods with intensive rainfall and extended dry periods, as improvements in NUE with irrigation are expected to be best in drought years.

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APPENDIX

Table A1. Field operations, nutrient, and pesticide applications at the University of Delaware (UD) Warrington Irrigation Research Farm near Harbeson, DE during the 2013-2014 growing season.

Date	Operation	Material	Rate
3-Apr	Potash (0-0-60)		160 lbs/A
8-Apr	Poultry Manure		3 tons/A
11-Apr	Chisel Plow		
17-Apr	Disk		
23-Apr	Disk		
25-Apr	Planted		
	Hybrid	Dekalb 62-98 with Poncho 500/Votivo	
	Seeding Rate		34,000 sd/A
	Starter	20-12-0	16.5 gal/A
6-May	Bicep II Magnum		1.3 qts/A
	Aatrex		0.5 qts/A
	Roundup Powermax		20 oz/A
6-Jun	Sidedress	NSul33	21 gal/A
25-Jun	Fertigate	NSul33	16.6 gal/A
17-July	Quadris Xcel		12.3 oz/A
	Warrior II		1.92 oz/A
25-Sept	Harvest		

Table A2. Field operations, nutrient, and pesticide applications at the University of Delaware (UD) Warrington Irrigation Research Farm near Harbeson, DE during the 2014-2015 growing season.

Date	**Corn**	**Material**	**Rate**
14-Apr	Poultry Manure		3 tons/A
15-Apr	Chisel Plow		
2-May	Disk		
7-May	Planted		
	Hybrid	Dekalb 62-08 with Poncho 500/Votivo	
	Seeding Rate		34,000 sd/A
	Starter	20-12-0-2S	15 gal/A
6-May	Bicep II Magnum		1.4 qts/A
	Generic Glyphosate		32 oz/A
27-May	Generic Glyphosate		32 oz/A
	Callisto		3 oz/A
	Atrex		1 pt/A
5-Jun	Sidedress	NSul33	27 gal/A
17-Jun	Fertigate	NSul33	14.1 gal/A
24-Jun	Fertigate	NSul33	14.1 gal/A
1-Jul	Fertigate	NSul33	14.1 gal/A
17-Jul	Headline Amp		12 oz/A
	Warrior II		1.92 oz/A
2-Oct	Harvest		

Table A3. Field operations, nutrient, and pesticide applications at the University of Delaware (UD) Warrington Irrigation Research Farm near Harbeson, DE during the 2015-2016 growing season.

Date	**Corn**	**Material**	**Rate**
22-Apr	Poultry Manure		3 tons/A
24-Apr	Chisel Plow		
4 & 12 May	Field Cultivate		
14-May	Planted		
	Hybrid	Dekalb 62-08 with Poncho 500/Votivo	
	Seeding Rate		34,000 sd/A
	Starter	20-12-0-2S	15 gal/A
21-May	Bicep II Magnum		1.4 qts/A
	Generic Glyphosate		32 oz/A
17-June	Generic Glyphosate		32 oz/A
	Callisto		3 oz/A
	Aatrex		1 pt/A
11-Jun	Sidedress	26-0-0-4S	23 gal/A
10-Jun	Fertigate	26-0-0-4S	14.1 gal/A
30-Jun	Fertigate	26-0-0-4S	14.1 gal/A
13-Jul	Fertigate	26-0-0-4S	14.1 gal/A
15-Jul	Headline Amp		12.3 oz/A
	Warrior		3.84 oz/A
30-Sept	Harvest		

Table A4. Field operations, nutrient, and pesticide applications at the University of Delaware (UD) Warrington Irrigation Research Farm near Harbeson, DE during the 2016-2017 growing season.

Date	Corn	Material	Rate
18-Apr	Poultry Manure		3 tons/A
19-Apr	Chisel Plow		
25-Apr	Field Cultivate		
16-May	Potash	0-0-60	200 lbs/A
18-May	Field Cultivate		
20-May	Planted		
	Hybrid	Axis 64K24 and Axis 65H25	
	Seeding Rate		34,000 sd/A
	Starter	20-12-0-2S	15 gal/A
20-May	Bicep II Magnum		1.75 qts/A
19-June	Generic Glyphosate		32 oz/A
	Callisto		3 oz/A
	Aatrex		1 pt/A
11-Jun	Sidedress	26-0-0-3S	52.7 gal/A
30-Jul	Headline Amp		12.3 oz/A
13-Oct	Harvest		

Table A5. Crop evapotranspiration (ET_c) as affected by various irrigation treatments applied to corn at the University of Delaware (UD) Warrington Irrigation Research Farm in 2013-2016.

Irrigation Treatment	**ET_c**			
	2013	**2014**	**2015**	**2016**
	——— m ———			
20 kPa	0.506 ab†	0.460 abcd	0.440 ab	0.422 ab
30 kPa	0.498 bc	0.440 de	0.414 ab	0.420 ab
40 kPa	0.484 cd	0.438 de	0.420 ab	0.408 abc
50 kPa	0.478 bc	0.438 de	0.410 ab	0.374 bc
20-40-20 kPa	0.494 bc	0.466 abc	0.428 ab	0.416 ab
40-20-40 kPa	0.494 bc	0.446 bcde	0.422 ab	0.388 bc
30 kPa to R5	0.490 bcd	0.442 cde	0.426 ab	0.366 c
30 kPa to milk	0.484 cd	0.432 e	0.410 ab	0.392 bc
80% ET	0.520 a	0.480 a	0.448 a	0.440 a
100% ET	0.520 a	0.470 ab	0.398 b	0.410 abc
No irrigation	0.470 d	0.370 f	0.290 c	0.280 d

† Letters that are the same indicate no statistical difference using Tukey’s HSD test at $\alpha = 0.05$.