Field Crops Research 288 (2022) 108663

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Subsurface drainage reduces the amount and interannual variability of optimum nitrogen fertilizer input to maize cropping systems in southeast Iowa, USA

Ellen D.v.L. Maas[a,*], Sotirios V. Archontoulis[a], Matthew J. Helmers[b], Javed Iqbal[a,c], Carl H. Pederson[b], Hanna J. Poffenbarger[a,d], Kristina J. TeBockhorst[b], Michael J. Castellano[a]

[a] *Department of Agronomy, Iowa State University, Agronomy Hall, Ames, IA 50011-1010, USA*
[b] *Department of Agricultural and Biosystems Engineering, Iowa State University, Elings Hall, Ames, IA, USA*
[c] *Department of Agronomy and Horticulture, University of Nebraska-Lincoln, Lincoln, NE 68583, USA*
[d] *Department of Plant and Soil Sciences, University of Kentucky, Lexington, KY, USA*

ARTICLE INFO

Keywords:
Sustainable agriculture
Nitrogen use efficiency
Optimum nitrogen rate
Nitrogen surplus
Maize

ABSTRACT

Subsurface drainage is widely used to improve field trafficability and crop growth on poorly drained soils. Although drainage causes or exacerbates some environmental challenges, drained croplands are among the most productive in the world and there may be opportunities to better manage drainage for positive environmental outcomes including improved nitrogen use efficiency. The objective of this study was to determine the effects of drainage on cropping system N use. We hypothesized that drainage reduces the agronomic optimum N fertilizer rate (AONR) while increasing grain yield thereby increasing agronomic efficiency (kg grain kg^{-1} N at the AONR; AE) and reducing N surplus (i.e., N inputs minus outputs). Using a site in southeast Iowa, USA that included four drainage treatments in both continuous maize and maize-soybean crop rotations with eight N rates (0–392 kg N ha^{-1}), maize grain yield was measured from 2016 to 2020. The four drainage systems included conventional (1.2 m depth x 18 m spacing), shallow (0.76 m x 12.2 m), controlled (1.2 m x 18 m, with a water table control structure), and a no drainage control. In addition, maize N uptake in the no drain and conventional depth systems was measured from 2016 to 2018. No drainage produced the highest grain yields at the AONR (13.3 ± 1.8 Mg ha^{-1}), but also the highest AONR (243 ± 155 kg N ha^{-1}) and lowest AE at the AONR (73 ± 37 kg grain kg^{-1} N); moreover, no drainage was the most variable system from year-to-year over all metrics (mean CV 44% ± 20%). In contrast, controlled drainage had the greatest average AE at the AONR (85 ± 28 kg grain kg^{-1} N) and the least variability over nearly all metrics from year-to-year (mean CV 25% ± 14%). Conventional drainage had consistently higher maize grain N concentrations than no drainage across N rates, particularly in the continuous maize rotation (6.9 ± 2.8%) and a lower AONR in four of five years compared to no drainage. Within each rotation at the economic optimum rate, no drainage had higher N surplus than conventional (45 and 19 kg N ha^{-1} and 137% and 72% higher for the continuous maize and the maize phase of maize-soybean rotations, respectively). This study demonstrates that drainage reduces the amount and interannual variability of N fertilizer requirements while also reducing interannual variability in yields. Better recognition, understanding, and management of these effects can benefit both productivity and the environment.

Abbreviations: AONR, agronomic optimum nitrogen rate; AE, agronomic efficiency; EONR, economic optimum nitrogen rate; GNU, grain nitrogen uptake; MRTN, maximum return to nitrogen; NRTN, net return to nitrogen; RE, recovery efficiency; TNU, total nitrogen uptake.

* Corresponding author.
E-mail addresses: alaskabasin@gmail.com (E.D.v.L. Maas), sarchont@iastate.edu (S.V. Archontoulis), mhelmers@iastate.edu (M.J. Helmers), javed.iqbal@unl.edu (J. Iqbal), carl@iastate.edu (C.H. Pederson), hanna.poffenbarger@uky.edu (H.J. Poffenbarger), ktebock@iastate.edu (K.J. TeBockhorst), castelmj@iastate.edu (M.J. Castellano).

https://doi.org/10.1016/j.fcr.2022.108663
Received 12 January 2022; Received in revised form 13 August 2022; Accepted 17 August 2022
Available online 15 September 2022
0378-4290/

1. Introduction

Agricultural drainage benefits crop growth and field trafficability on approximately 22.7 Mha of United States cropland and > 150 Mha globally (Valipour et al., 2020; Zulauf and Brown, 2019), and it could benefit as much as 450 Mha additional undrained croplands globally (FAO, 2001). Many studies have demonstrated higher grain yields in drained over undrained fields (Cox et al., 1990; Sigunga et al., 2002; Nelson et al., 2009; Helmers et al., 2012; Singh and Nelson, 2021). Removal of excess water early in the growing season improves root growth and increases leaf nitrogen, net photosynthesis, and yield (Ebrahimi-Mollabashi et al., 2019; Herrera, 2013; Ordóñez et al., 2018; Schott et al., 2017a; Kaur et al., 2017). Improved field trafficability allows for earlier planting dates, resulting in an extended growing season and greater flexibility in crop varieties and field management (Kucharik, 2008; Seymour et al., 1992; Baum et al., 2019). However, drainage also increases NO_3^- leaching below the root zone, resulting in nutrient pollution of local and regional waters (David et al., 2010; Gilliam et al., 1979; Skaggs and Gilliam, 1981). Indeed, drainage is a leading cause of nutrient loading to the Gulf of Mexico (Goolsby et al., 1999; David et al., 2010).

Yet not all changes to N dynamics in drained soils are undesirable (Castellano et al., 2019). Drainage can reduce denitrification including N_2O emissions (Kumar et al., 2014; Butterbach-Bahl et al., 2013) and reduce N fertilizer requirements through increased mineralization of soil organic matter (Gill et al., 1995; Davis et al., 2000; Paiao et al., 2021, Fernández et al., 2017). The potential increase in NO_3^- loss due to drainage may be small compared to the sum of decreased denitrification losses and increased N mineralization inputs. Outputs of nitrate through denitrification and leaching each range from 10 to 100 kg N ha^{-1} yr^{-1} (e.g., Davis et al., 2000; Kladivko et al., 2004; Sela et al., 2016). However, soil N mineralization inputs inorganic N can be > 200 kg N ha^{-1} yr^{-1} (and gross N mineralization of much higher; Osterholz et al., 2017), which is not a surprise because drained soils can contain > 10,000 kg N ha^{-1} in soil organic matter (SOM, e.g., Russell et al., 2005; Poffenbarger et al., 2020). In fact, N mineralization from SOM – rather than fertilizer – is the largest direct source of crop N uptake regardless of fertilizer N input (Stevens et al., 2005; Gardner and Drinkwater, 2009; Poffenbarger et al., 2018; Yan et al., 2020). An increase in soil N mineralization could cause a simultaneous increase in NO_3^- leaching and decrease in N fertilizer requirements. A portion of the increased soil N mineralization might be lost as NO_3^-, but another portion might be accessed by the crop thereby reducing crop reliance on N fertilizer.

By increasing grain yield while decreasing N fertilizer requirements, drainage has been hypothesized to increase N fertilizer use efficiency (Castellano et al., 2019). Indeed, Paiao et al. (2021) demonstrated lower optimum N fertilizer rates and higher grain yield in drained vs. undrained maize (*Zea mays L.*) systems in Minnesota, USA. Similarly, across four long-term N fertilizer rate trials (Poffenbarger et al., 2017), this study observed that in the long-term, average agronomic optimum N rate (AONR) was negatively associated with depth to the water table from estimates in USDA SSURGO. Another study with > 15 locations confirmed the negative relationship between water table depth and economic optimum N rate (EONR; Qin et al., 2018). These patterns suggest poorly drained soils require more N fertilizer to optimize profitability. Hence, drainage may also have the potential to reduce the system's N surplus (defined here as the difference between N fertilizer input and harvested grain N content as output), which is desirable because nitrogen applied beyond the rate required for optimum productivity results in exponential increases in NO_3^- leaching and N_2O emissions (Lawlor et al., 2008; Shcherbak et al., 2014).

However, few studies have directly measured the agronomic or economic optimum N fertilizer rate and indicators of N fertilizer use efficiency under drainage (Paiao et al., 2021). As far as we know, no study has done so across multiple drainage system designs. While there have been improvements in N fertilizer use efficiency in the US and globally in recent decades, there are still substantial knowledge gaps to fill and technological improvements to be made (Cassman and Dobermann, 2021). Drainage may offer a new pathway to enhance the nitrogen use efficiency (NUE), but there are many uncertainties. For example, in a continuous maize cropping system, drainage increased yield, aboveground biomass, harvest index, leaf N content, N uptake, and agronomic and recovery efficiencies of N (Sigunga et al., 2002). However, in a maize-soybean (*Glycine max L.*) rotation, Nelson et al. (2009) found that drainage improved yield but had no effect on N uptake. Weather is also known to be a confounding factor introducing substantial year-to-year variability (Balkcom et al., 2003; van Es et al., 2005).

Our objectives were to analyze the effects and implications of drainage and crop rotation in three contexts: cropping system efficiency, maize N use, and sustainability, which is considered here to include both environmental and financial impacts. To address these objectives, experimental data were used from southeast Iowa, USA with four drainage treatments containing continuous maize and maize-soybean rotations with eight different N fertilizer rates to maize. The maize grain yield response to N was measured over five years, and, aiming to better understand causes for variable AONR, this study also measured plant traits over three years. This experimental design allowed a better understanding of the effects of drainage on crop productivity and N use efficiency. Based on a conceptual understanding of the effects of drainage on soil N dynamics and plant growth, together with evidence in the literature, we hypothesized that drainage reduces the agronomic optimum N fertilizer rate while increasing grain yield thereby increasing N recovery efficiency, economic return and reducing N surplus.

2. Materials and methods

2.1. Study site

The study site is located at the Iowa State University Southeast Research Farm (SERF) in Crawfordsville, Iowa, USA (41.193251°, −91.482956°). The field slope is less than 1% and contains two poorly drained soil series: Taintor (silty clay loam, fine smectitic, mesic Vertic Argiaquolls) and Kalona (silty clay loam, fine, smectitic, mesic Vertic Endoaquolls). The climate is temperate continental with 30-year average annual precipitation, minimum temperature, and maximum temperature of 936 mm, 5 °C, and 16 °C, respectively (IEM 2021).

Weather data (precipitation and reference evapotranspiration) were downloaded from the Iowa Environmental Mesonet with ISU Soil Moisture Network daily data (IEM 2021) from a weather station within 0.5 miles from the site (41.1933°, −91.4838°). During the study years, 2016 had below-average precipitation at the beginning of the growing season and above-average precipitation later in the summer; 2017 had below-average rainfall for most of the year; 2018 had slightly above-average total rainfall, though most of it fell in the second half of the year; 2019 had substantial rainfall until the growing season but was dry for most of the summer; and 2020 was fairly wet overall, only lacking substantial moisture in August (Supplementary Fig. S1, IEM 2021). Over this five-year period, most rainfall at the site fell in spring and summer, but was exceeded by evapotranspiration, resulting in a water deficit during the summer (Fig. 1). Henceforth, a "dry year" is defined as having a water deficit greater than 30 cm over the summer (June 1 to August 31).

A map of the 17-ha site is provided in Supplementary Fig. S4. It includes eight plots ranging in size from 1.2 to 2.4 ha, divided into two blocks of four randomly-ordered-drainage treatments, installed in 2006, including: 1) Conventional drainage with 1.2 m drain depth and 18 m drain spacing; 2) Controlled drainage with 1.2 m drain depth,18 m drain spacing and a controlled-outlet structure opened fully before planting, then closed to 0.76 m depth after planting; 3) Shallow drainage with 0.76 m drain depth and 12.2 m drain spacing; and 4) No Drainage.

Each plot contains two crop systems, including continuous maize and

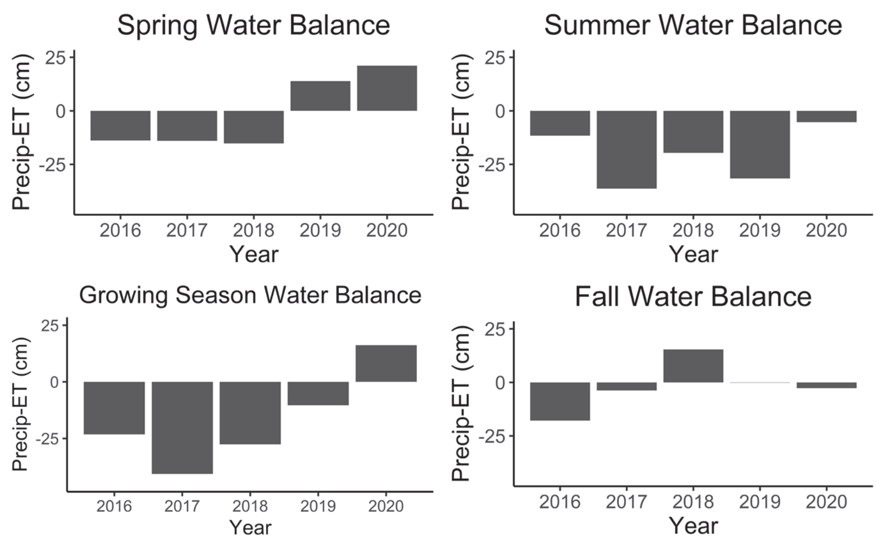

Fig. 1. Spring (March-May), summer (June – August), primary growing season (May-July), and fall (Sept-Nov) water balance, defined as the difference between precipitation and potential evapotranspiration (see Supplementary Fig. S1).

a 2-year maize-soybean rotation, in a split-plot design with both phases of the rotation present every year. Historically, N fertilizer was applied annually the same on all plots at the recommended rate for southeast Iowa for maize crops (NH_3 applied in spring at 169 kg N ha^{-1} and 224 kg N ha^{-1} for maize-soy and continuous maize, respectively; Schott et al., 2017a). In 2016, for this experiment, plots were further divided into a split-split plot design with eight urea-ammonium nitrate fertilizer application rates of 0, 56, 112, 168, 224, 280, 336, and 392 kg N ha^{-1} (N_0, N_{56}, N_{112}, N_{168}, N_{224}, N_{280}, N_{336}, and N_{392}, respectively) applied only to maize with the N treatments in fixed positions each year within the field. While the highest N rates in this study would not realistically be used by farmers, they are used here for research purposes to increase the precision of the AONR calculation.

All maize plots were chisel plowed in fall and all plots were field cultivated in spring. All drainage treatments were planted on the same day each year due to logistical constraints; this is important because a major benefit of artificial sub surface drainage is increased field trafficability that allows earlier planting – a practice well known to increase yield (Kucharik et al., 2008). See Supplementary Table S1 for planting and cultivar data. Maize was harvested with a John Deere 9410 combine with a Harvest Master yield measurement system. Grain harvest moisture was adjusted to 15.5%.

Water table depth, nitrate-nitrogen (NO_3^--N loss, and drainage flow rate were also measured for the whole plot for each drainage treatment. Only 2016 and 2018 were available for water table depth, and all five years (2016 through 2020) were available for most replicates for flow rate and NO_3^--N measurements. It is important to note that each drainage plot had a single measurement for each of these elements, and each plot contains multiple crop rotations and N rates.

Soil fertility and pH were managed according to land grant university recommendations (Mallarino et al., 2013). For additional details of the study site, see Helmers et al. (2012) and Craft et al. (2018).

The study described herein included five years (2016–2020) of yield data and three years (2016–2018) of maize plant trait data. As Poffenbarger et al. (2017) demonstrated, therefore N rate for maize had no impact on subsequent soybean grain yield, maize was the sole focus in this study.

Maize grain yield was measured from 2016–2020 as the whole-plot harvest from combine data from all drainage systems. Additionally, a variety of maize plant physiological traits only in Conventional and No Drainage plots were measured from 2016–2018 to better understand the main determinants of NUE and AONR, and how drainage systems affected yields and plant N use. Plants were sampled destructively in 1 m^2 plots and measured for dry biomass and C and N concentration (Table 1; Archontoulis et al., 2020).

2.2. Calculations

Except where noted, all calculations and graphs were made using R software (version 3.6.1, R Core Team, 2019).

This study used the eight N fertilizer rate treatments in continuous maize and the maize phase of the maize-soybean rotation to calculate the AONR, the agronomic efficiency (equation 1) and net return to N (2) at the AONR, the N recovery efficiency (3), and N surplus (4).

The AONR was calculated by fitting quadratic plateau curves to grain yield data at each N rate by year, rotation, and drainage treatment (Supplementary Figs. S5 and S6) with the *nls()* function of the R *easynls* package (Arnhold, 2017), together with the *purrr* package (Henry and Wickham, 2020) of the *tidyverse* suite (Wickham et al., 2019). The *purrr* package provided efficient iterative data handling with the *map()* function to obtain start values for the quadratic plateau equations using the base *lm()* function, and then with the *nls()* function for up to 1000 attempts towards convergence of the full model.

Agronomic efficiency (AE) scales the grain yield to the N rate and was calculated as the quotient of grain yield at AONR (Y_{AONR}) and the AONR:

Table 1
List of maize plant traits measured or calculated in this study.

Maize plant physiological measurementsMaize plant trait	Abbrev.	Units	Determination
Grain Yield	Y	Mg ha^{-1}	Dry grain weight at 15.5% moisture, measured whole-plot by harvest combine data
Biomass	BIO	g m^2	Weight of dried stem + dried ear
Grain N Concentration	GNC	g 100 g^{-1}	Weight of N per weight of grain
Grain N Uptake	GNU	kg N ha^{-1}	Dry grain weight * GNC
Total N Uptake	TNU	kg N ha^{-1}	N content of stover + GNU
Yield per N Uptake	Y2NU	kg grain kg^{-1} N	Y/TNU
Biomass per N Uptake	B2NU	kg plant kg^{-1} N	BIO/TNU
Harvest Index	HI	unitless	Y/BIO
N Harvest Index	NHI	unitless	GNU/TNU

AE (kg grain kg^{-1} N) = Y_{AONR} / $AONR$

Because AE is linearly correlated with a common NUE calculation ((Y_{AONR}-Y_{N0})/AONR, where Y_{N0} is grain yield at N_0, Supplementary Fig. S7), only AE was included in this study.

Net return to N (NRTN) estimates the additional income from a crop fertilized at a given N rate versus no N applied at all, taking the cost of fertilizer into account. It was calculated as the price of the grain yield increase at Y_{AONR} over Y_{N0} minus an estimated cost of N fertilizer based on a fertilizer:grain price ratio of 0.1 (e.g., $4 per 0.0254 Mg maize which is equal to $4 per bushel of maize).

$NRTN$ ($ ha^{-1}) = ((Y_{AONR} – Y_{N0}) * $4·00/0·0254 Mg maize) – ($AONR$/1000 kg/Mg * $0·40/0·00045 Mg N)

To include an additional economic perspective, the maximum return to N (MRTN) and EONR were also considered in this study. MRTN is the point where NRTN is greatest across the spectrum of N rates. It typically represents NRTN at approximately 97–99% of maximum grain yield (Sawyer et al., 2006). To determine the MRTN, NRTN was calculated in 1 kg N ha^{-1} increments over the grain yield-to-N response curve for each year and drainage treatment, then the *max()* function was applied. The EONR is the N rate at the MRTN.

Recovery efficiency (RE, or N fertilizer efficiency) is the proportion of fertilizer N taken up by the whole plant at a given N application rate (N_X). It was calculated as the difference between the total N uptake (TNU) at each N_X and the N_0 treatment, divided by the N applied at N_X:

RE_X = (TNU at N_X – TNU at N_0) / N_X

RE was also estimated at the AONR for each system by fitting quadratic plateau models to the response curves of RE to N fertilizer rate and extracting the predicted value at the AONR.

Nitrogen surplus (N input – N output) was calculated as an indicator of the environmental sustainability of each N rate. In this study, it was calculated on a grain-only basis as the N application rate (input) minus maize grain N uptake (GNU; output) at each N rate:

$N\ surplus$ (kg ha^{-1}) = N_X – GNU

Because grain N concentration (used to calculate GNU) varied by only 0.05% within each drainage x rotation combination, measured values for 2016–2018 were averaged and substituted in 2019 and 2020 for measurements to provide a full five-year N surplus dataset.

To incorporate an additional indicator of the financial sustainability of each system, the N surplus was also calculated at the EONR by fitting polynomial models to the N surplus at each N rate and extracting the predicted value at the EONR.

To estimate the interannual variability for each metric above, the coefficient of variation (CV) was computed as the standard deviation divided by the mean value.

2.3. Maize plant physiological measurements

Maize plant trait details and calculations are in Table 1. Values of each trait at the AONR ([plant trait]$_{AONR}$) were determined by first fitting curves for each trait at every N rate for each year, then extracting its value at the AONR for that year and system from the model's fitted values.

2.4. Statistical analysis

Statistical analysis of AONR (the log of) and Y_{AONR} was performed in R and considered significant at $p < 0.1$. Linear mixed effects models were fitted with the *nlme* package (Bates et al., 2022). Drainage, rotation, year, annual mean water table depth, and annual cumulative NO_3-N were fixed effects, while block and block by drainage were random effects. As there were only two years available of usable water table depth data, the full model was limited to 2016 and 2018 years only.

Differences between Conventional and No Drainage treatments for all plant traits were calculated in R as the percent change from the No Drainage value with this generic function:

(($Drained\ value$ – $Undrained\ value$) / $Undrained\ value$) * 100

Paired t-tests using the *t.test()* function in R were performed for crop traits between Conventional and No Drainage for each crop rotation separately as well as combined.

Plant traits were also compared between Conventional and No Drainage treatments using MATLAB R2020a (MATLAB 2020) for the purpose of analyzing trend slope differences. Data for each trait from each drainage treatment were plotted in 1:1 correlation graphs. A regression line was fitted to the plotted data using the *fitlm()* function and then the 95% confidence interval was determined with *coefCI()*. If the confidence interval included 1, then that slope was not significantly different from the 1:1 line. The same data were plotted again identically but separate regressions were run for each crop rotation to determine if there was a significant difference in trend between Conventional and No Drainage treatments by rotation. In this case, after *fitlm()* was run for each rotation, the difference between each rotation's slope was calculated and the slope of the difference values was determined with *fitlm()*. If the slope of the difference values was not significantly different from 0, then the slopes of the separate crop rotations were not significantly different from each other.

3. Results

3.1. Drainage system performance

Annual average water table depths were lowest for Conventional drainge, followed by Controlled, Shallow, and No Drainage (Supplementary Fig. S2), which reflected the overall average flow rates of each drainage treatment of 0.6, 0.25, and 0.18 mm-day for Conventional, Controlled, and Shallow, respectively (see also Supplementary fig. S11) over the five-year study period. This resulted in total cumulative NO_3^--N losses of 98.91, 30.54, and 31.51 kg N ha^{-1} for Conventional, Controlled, and Shallow, respectively (Supplementary Fig. S3).

Given that each drainage plot had a single measurement for each of these elements, and each plot contains multiple crop rotations and N rates, the interaction of N rates, crop rotaions, and drainage could result in differing crop transpiration levels, potentially affection these data.

3.2. Cropping system NUE indicators

On average over all years and crop rotations, Controlled Drainage had the highest AE_{AONR}, which was 18% higher than the lowest, No Drainage (86 vs. 73 kg grain kg^{-1} N). Controlled Drainage also had the lowest AONR, which was 39% lower than the highest, which again was No Drainage (151 vs. 243 kg N ha^{-1}). No Drainage had the highest Y_{AONR} but it was only 7.3% higher than the system with the lowest Y_{AONR} (Controlled Drainage) despite applying 39% more N fertilizer to achieve that yield (13.2 Mg ha^{-1} vs. 12.3 Mg ha^{-1}). Mean annual NRTN was greatest in No Drainage systems and lowest in Conventional drainage ($917 ha^{-1} vs. $782) but was only $12 ha^{-1} greater than Controlled Drainage. The year-to-year variability in NRTN was also greatest in the No Drainage systems. In fact, across both rotations, No Drainage had the highest interannual variability in every metric but one (NRTN; Table 2, Fig. 2), while, on average across all metrics, Controlled Drainage had the lowest.

Specifically comparing Conventional and No Drainage, the AONR in No Drainage was 33% greater than in Conventional Drainage (mean 243 vs 183 kg N ha^{-1} for No Drainage and Conventional, respectively, over all years and rotations), but the greater N input produced only 5% higher

Table 2
The agronomic optimum nitrogen rate (AONR), yield at the AONR (Y_{AONR}) and zero N (Y_{N0}), agronomic efficiency (AE), and net return to nitrogen (NRTN) for each year, drainage system and crop rotation. Bold values indicate the best performing system within each year and crop rotation. "Best" value is relative to each indicator (lowest AONR, highest yield, etc.) and not indicative of any significant difference. Cont = Controlled, Conv = Conventional, Shal = Shallow, No Dr = No Drainage.

		Continuous Maize					Maize-Soybean				
	Year	No Dr	Cont	Conv	Shal	Mean	No Dr	Cont	Conv	Shal	Mean
AONR ($kg\ ha^{-1}$)	2016	79	79	**75**	135	92	**103**	120	125	108	114
	2017	235	129	210	**128**	176	472	136	341	**106**	194
	2018	**154**	191	188	382	229	199	182	**178**	189	187
	2019	556	**179**	217	199	241	186	**162**	167	223	192
	2020	266	**163**	165	225	218	177	166	**157**	200	175
	Mean	258	**148**	171	214	207	227	**153**	194	165	186
	CV	0.70	**0.30**	0.34	0.48	0.50	0.62	**0.16**	0.44	0.33	0.40
Y_{AONR} ($Mg\ ha^{-1}$)	2016	**10.9**	10.5	10.6	10.7	10.7	**13.1**	12.9	**13.1**	12.8	13.0
	2017	**15.1**	13.5	13.9	14.1	14.2	**16.1**	14.2	14.4	14.6	14.8
	2018	**11.2**	10.0	10.1	10.7	10.5	**15**	14.1	14.6	14.8	14.6
	2019	**12.3**	10.9	11.2	11.4	11.9	12	**12.4**	12.3	**12.4**	12.3
	2020	**12.6**	11.5	12.1	10.9	11.8	**14.2**	13.5	13.9	13.9	13.9
	Mean	**12.4**	11.3	11.6	11.6	11.8	**14.1**	13.4	13.7	13.7	13.8
	CV	0.13	**0.12**	0.13	0.13	0.13	0.11	**0.06**	0.07	0.08	0.08
Y_{N0} ($Mg\ ha^{-1}$)	2016	4.1	**5.0**	4.7	4.9	4.7	6.7	6.4	**7.7**	6.4	6.8
	2017	6.9	6.5	6.1	**8.8**	7.1	**11.4**	9.3	10.9	9.3	10.2
	2018	2.9	4.8	4.1	**5.2**	4.3	5.8	6.1	**6.9**	6.6	6.4
	2019	**8.2**	5.4	7.2	6	6.7	6.9	6.8	**7.9**	**7.9**	7.6
	2020	**3.4**	2.5	3.1	3.3	3.5	4.2	5.4	**6.5**	5.2	5.3
	Mean	5.1	4.8	5.0	**5.6**	5.2	7.0	6.8	**8.0**	7.1	7.3
	CV	0.46	**0.30**	0.32	0.36	0.34	0.38	**0.22**	**0.22**	**0.22**	0.26
AE at AONR (kg grain kg^{-1} N)	2016	139	127	**147**	81	123	**126**	108	104	120	115
	2017	64	101	67	**109**	86	34	103	41	**142**	80
	2018	**71**	52	53	29	52	75	77	**84**	79	78
	2019	22	**61**	51	55	43	65	**74**	72	54	66
	2020	49	**74**	73	49	58	79	84	**89**	70	80
	Mean	69	**83**	78	65	72	76	89	78	**93**	84
	CV	0.63	**0.37**	0.51	0.48	0.53	0.44	**0.17**	0.30	0.39	0.33
NRTN at AONR ($ ha^{-1})	2016	**1030**	716	877	824	862	852	994	676	**1005**	870
	2017	1050	829	**1072**	673	957	369	666	171	**849**	490
	2018	**1121**	617	777	606	781	**1239**	1097	1100	1091	1136
	2019	138	**785**	437	610	535	622	**643**	481	432	573
	2020	1337	**1428**	1269	1059	1116	**1415**	1268	962	1238	1189
	Mean	**935**	875	886	754	850	899	**934**	678	923	852
	CV	0.49	0.36	0.35	**0.25**	0.31	0.48	**0.29**	0.55	0.33	0.39

* Calculated AONR value is higher than the maximum N rate.

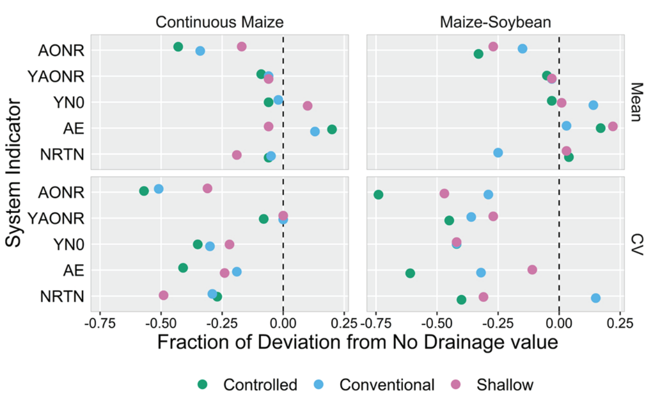

Fig. 2. System performance indicator values as a fraction of the No Drainage value (Eq. 5), averaged over the five years. Vertical dashed lines denote the No Drainage value baseline. Points to the left of the dashed lines indicate smaller values for those drainage systems than No Drainage. Points are "jittered" vertically to improve visibility of overlapped dots. AE=Agronomic Efficiency; AONR=Agronomic Optimum Nitrogen Rate; NRTN=Net Return to N; YAONR=Grain yield at AONR; YN0 =Grain yield at 0 N; CV=coefficient of variation.

mean annual grain yield at the AONR (13.3 vs. 12.7 Mg grain ha^{-1}). As a result of these differences, Conventional Drainage systems had 8% higher AE_{AONR} than No Drainage (78 vs. 73 kg grain kg^{-1} N fertilizer). Additionally, in continuous maize, No Drainage exceeded Conventional Drainage AONR in four of five years by 469 kg N ha^{-1} (mean of 117 kg N ha^{-1} yr^{-1}), whereas No Drainage was less than Conventional in one year (2018) by 34 kg N ha^{-1}, for a net difference of 435 kg N ha^{-1} (mean 109 kg N ha^{-1} yr^{-1}) over five years (Table 2). Likewise in maize-soybean, the No Drainage treatment's AONR was 191 kg N ha^{-1} (48 kg N ha^{-1} yr^{-1}) more over four years and was less in 2016 by 22 kg N ha^{-1}, for a net difference of 169 kg N ha^{-1} (mean 42 kg N ha^{-1} yr^{-1}).

There were additional notable differences within and between crop systems (Fig. 2, Table 2). Overall, the maize-soybean rotation had lower AONR and higher yields, and AE with lower variability than continuous maize across drainage systems. Among drainage treatments, Controlled Drainage performed similarly to Conventional Drainage in continuous maize but with 6–27% lower interannual variability in all metrics except NRTN, and 20% higher AE_{AONR} than No Drainage. In the maize-soybean rotation, Controlled Drainage had the lowest interannual variability of any drainage system in the study in all metrics (40–61% less than No Drainage), but its performance was more comparable to Shallow Drainage, both with greater AE_{AONR} (17% and 22% for Controlled and Shallow Drainage, respectively) and similar Y_{AONR} compared to No Drainage (−5% and −3% for Controlled and Shallow Drainage, respectively). While Shallow Drainage had mostly poor overall performance compared to Conventional in continuous maize, Shallow Drainage performed better than Conventional in several metrics in the maize-soybean rotation including AONR, AE_{AONR}, and NRTN (−15%, 19%, and 36%, respectively).

The full-model ANOVA test on the log of AONR showed significant effects of year, NO_3^--N loss, and the interactions of drainage x rotation and rotation x year. Although drainage alone was not significant, it is notable that there is strong evidence ($p < 0.001$) of an effect of drainage type on NO_3^--N loss. The full model ANOVA test on Y_{AONR} found only rotation as significant ($p < 0.05$). It is important to note that with only two replicates, the chances of a Type II error in either ANOVA test are high. The ANOVA results confirm the complexity of the system and the limitations that low replication and high variability have on statistical confirmation of effects.

3.3. Maize plant traits

Plants were only sampled in Conventional and No Drainage systems for three of the five study years (2016–2018). Paired t-tests comparing crop traits across N rates produced a range of evidence of differences between drainage treatments and crop rotations (Table 3). Due to the discussed lack of statistical power in this study and the well-known controversial nature of the *p*-value (Wasserstein and Lazar, 2016), the results here are instead presented as a gradient of evidence, rather than a binary (significant/not significant) result (Muff et al., 2022). The strongest evidence of an effect of drainage over all N rates is seen in yield, biomass, and grain N concentration. There is moderate evidence also seen in yield to N uptake and biomass to N uptake. There appears to be weak to no effect of drainage on the remaining crop traits. Notably, there was almost no evidence that drainage affected crop traits in the maize-soy rotation in general beyond yield and biomass.

Additionally, correlation (1:1) graphs were constructed to compare values of plant traits in Conventional and No Drainage at corresponding N rates, and the paired points were modeled with linear regression to evaluate any significant trend away from the 1:1 line or difference between rotations (Fig. 3). Yield had a significant difference in slope between rotations, with continuous maize trending higher yield in No Drainage than Conventional at most N rates, (see also Supplementary Fig. S9), whereas maize-soybean yield was stronger than continuous maize in Conventional at low N rates. Biomass and grain N uptake also had significant but insubstantial differences between rotations. Four traits had trend lines with significantly different slopes from the 1:1 line: total N uptake, grain N concentration, yield:N uptake and biomass:N uptake. In all cases, the slopes were less than 1, indicating lower values of each trait trended higher in No Drainage, with higher values of the traits trending higher in Conventional. No significant trends were detected in the harvest index or nitrogen harvest index, indicating that drainage and crop rotation had no effect across N rates.

Seven of nine crop traits had higher values in the No Drainage system at the AONR (all but grain N concentration and total N uptake in continuous maize; Fig. 3). Grain N concentration in continuous maize is also the only plant trait with the highest values in Conventional Drainage at nearly all N rates.

Differences in trait values between Conventional and No Drainage were more pronounced in the continuous maize rotation (Supplementary Fig. S8 A-C) than maize-soybean (Supplementary Fig. S8 D-F). Differences across N rates ranged from − 22% to 30% in continuous maize and − 18% to 18 % in maize-soybean, with negative differences indicating higher values in No Drainage. However, the differences between Conventional and No Drainage were small at the AONR of each system, indicating similar performance at the AONR in both drainage treatments (see also Fig. 3).

Plant N RE showed an inverse relationship with N rate, with higher N uptake efficiency at lower N rates and efficiency decreasing with increasing N applied (Fig. 4). In two of the three years, RE at the AONR was higher in continuous maize than the maize-soybean rotation. Although higher RE was demonstrated in Conventional than No Drainage in five of the six rotation x year scenarios, the improvement was small (2–12 % and 3–16 % in continuous maize and maize-soy, respectively).

3.4. Cropping systems sustainability

To include both environmental and financial aspects of sustainability, the N surplus was plotted for Conventional and No Drainage in each rotation and the point of EONR calculated. There were substantial differences in N surplus at the EONR values in each drainage x rotation system (Fig. 5). Within each rotation at the EONR, No Drainage had higher N surplus than Conventional: for the continuous maize and maize-soybean rotations, (45 and 19 kg N ha^{-1}, respectively). In continuous maize, the N surplus in No Drainage was over double that in the Conventional (79 and 34 kg N ha^{-1}, respectively, while the Conventional and No Drainage mean five-year EONR values (Supplementary Table S2) were less than (−70 and −22 kg N ha^{-1}, respectively) the southeast Iowa land grant university-calculated EONR (SEIA_EONR; 225 kg N ha^{-1}; ISU 2021) and resulted in less N surplus (−62 and −18 kg N ha^{-1}, respectively) than if N had been applied at the SEIA_EONR. In maize-soybean, Conventional and No Drainage N surpluses were 25 and 44 kg N ha^{-1}, respectively, while the Conventional Drainage five-year mean EONR was 7 kg N ha^{-1} less than the SEIA_EONR (171 kg N ha^{-1}; ISU 2021) and resulted in 6 kg N ha^{-1} less N surplus. However, No Drainage mean EONR was 20 kg N ha^{-1} more than the SEIA_EONR and would have resulted in 17 kg N ha^{-1} more N surplus.

At each specific N rate, there was very little effect of drainage on the N surplus within each rotation but there were differences between rotations. Nitrogen surplus in the continuous maize rotation was 23 kg N ha^{-1} greater than maize-soybean on average over all N rates. In continuous maize, N_0 and N_{56} resulted in a negative N surplus (−52 to −4 kg N ha^{-1}) in both drainage systems, while N_{112} through N_{392} resulted in near-linear increasing surplus (6–285 kg N ha^{-1}). In the maize-soybean rotations, N_0, N_{56}, and N_{112} resulted in near-zero or negative N surplus (−98

Table 3
Strength of evidence (Muff et al., 2022), based on *p*-values from paired t-tests, that there are significant differences between Conventional and No Drainage treatments among tested crop traits.

Crop Trait	Continuous Maize	Maize-Soy	Combined
Yield	< 0.001	< 0.01	< 0.00001
Biomass	< 0.01	0.09	< 0.001
Total N Uptake	0.6	0.6	0.9
Grain N Uptake	0.8	0.7	0.9
Grain N Concentration	< 0.001	0.3	< 0.01
Yield to N Uptake	0.01	0.4	0.02
Biomass to N Uptake	0.03	0.7	0.07
Harvest Index	0.5	0.3	0.2
N Harvest Index	0.4	0.9	0.5

Evidence	
None	
Little	
Weak	
Moderate	
Strong	
Very Strong	

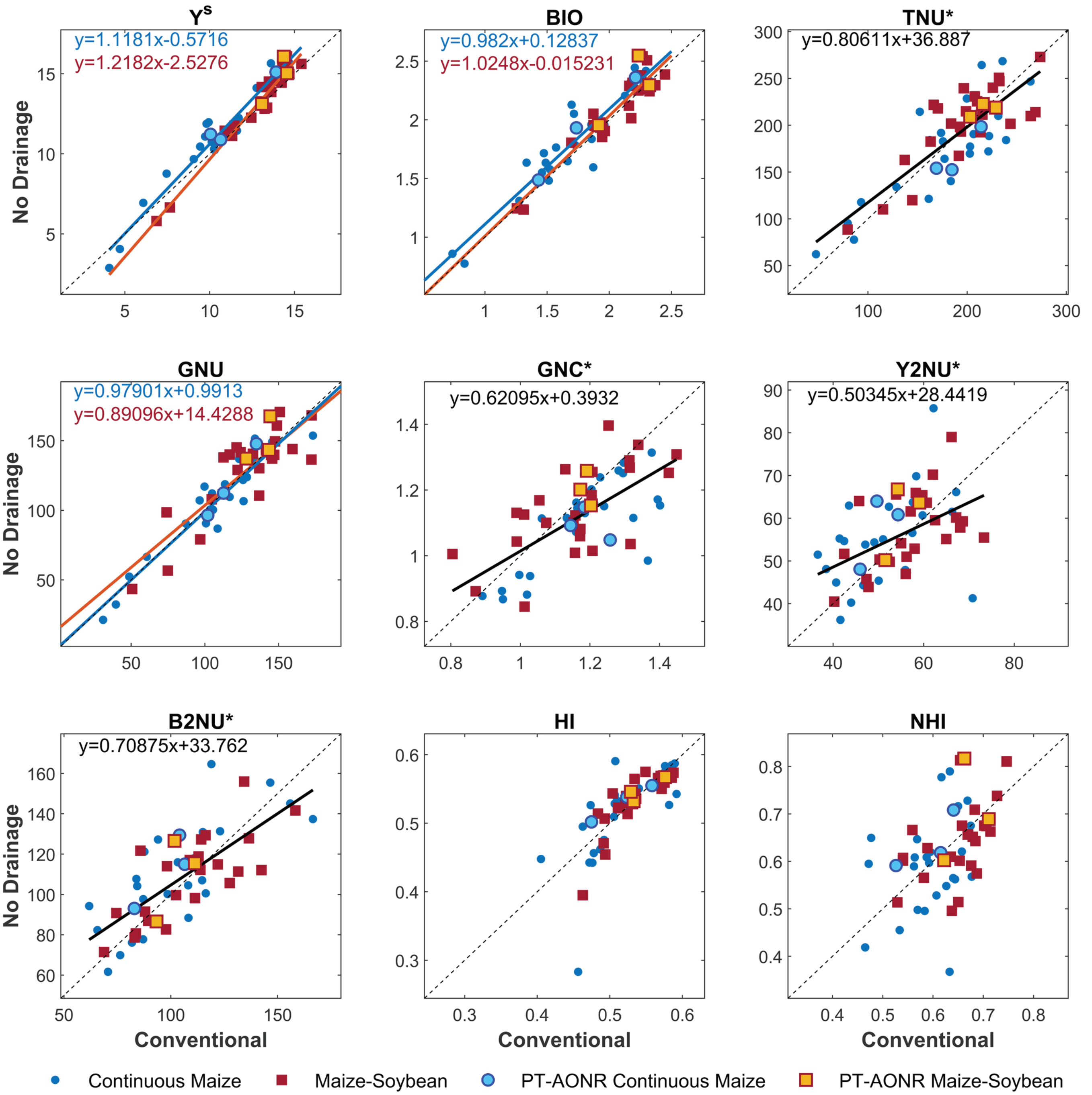

Fig. 3. Three-year (2016–2018) plant trait comparisons between drainage treatments by crop rotation. Calculated values at AONR are added as yellow and green dots. Asterisk after title indicates a significant difference in the mean regression line (solid black) from the 1:1 line (dotted grey). Significant differences found between crop rotations are displayed as separate regression lines. Superscript "s" in Y graph title indicates the maize-soybean regression (only) is also significantly different from the 1:1 line. Though rotations in BIO and GNU are significantly different from each other, neither is significantly different from the 1:1 line. BIO=Biomass; TNU=Total N Uptake; GNU=Grain N Uptake; GNC=Grain N Concentration; Y2NU=Grain yield To N Uptake ratio; B2NU=Biomass To N Uptake ratio; PT-AONR=Plant Trait value at grain yield-based AONR.

to 1 kg N ha^{-1}) between both drainage systems, while N_{168} through N_{392} resulted in near-linear surpluses (26–256 kg N ha^{-1}).

With N fertilizer at a price of \$0.88 kg^{-1} N, a difference of 49 and 19 kg N ha^{-1} between Conventional and No Drainage treatments at optimum N fertilization rates in continuous maize and maize-soybean rotations equates to \$43 and \$17 ha^{-1}, respectively. The maximum N surplus observed in this study from applying at N_{392} in continuous maize and maize-soybean (285 and 256 kg N ha^{-1}) equates to \$251 and \$225 ha^{-1}, respectively, unused by the crop.

4. Discussion

Our results agree with others who found that weather year was one of the greatest influences on yield and N-related processes (Balkcom et al., 2003; van Es et al., 2005; Puntel et al., 2019; Paiao et al., 2021). High soil moisture is known to increase N losses. van Es et al. (2005) found that seasonal differences affected maize N response more than soil texture and drainage system, requiring higher N rates on finer-textured soils after a wetter-than-normal spring. While this could explain high

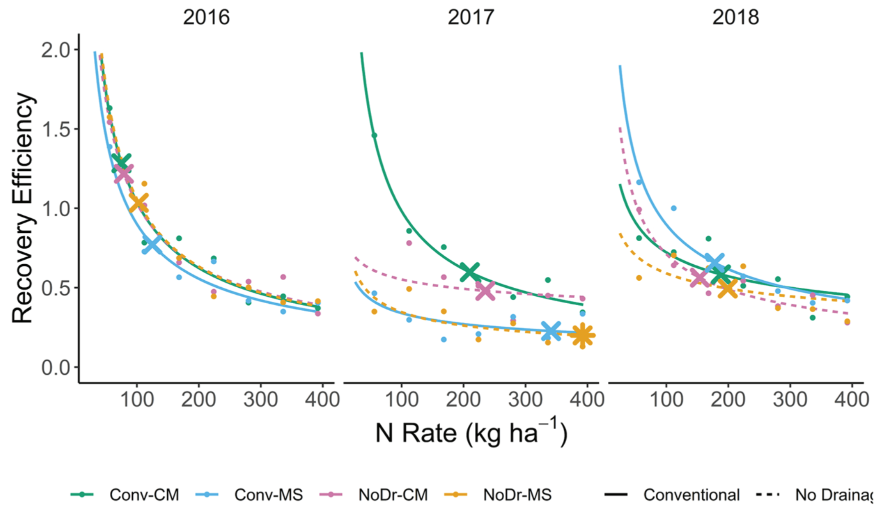

Fig. 4. Maize plant recovery efficiency at each N application rate, by drainage system and crop rotation. Conv = Conventional Drainage; NoDr = No Drainage; CM = Continuous Maize; MS = Maize-Soybean. X = recovery efficiency values at AONR in each system. Note that the 2017 No Drainage value falls above the N rates applied in the study: * = 472 kg N ha^{-1}.

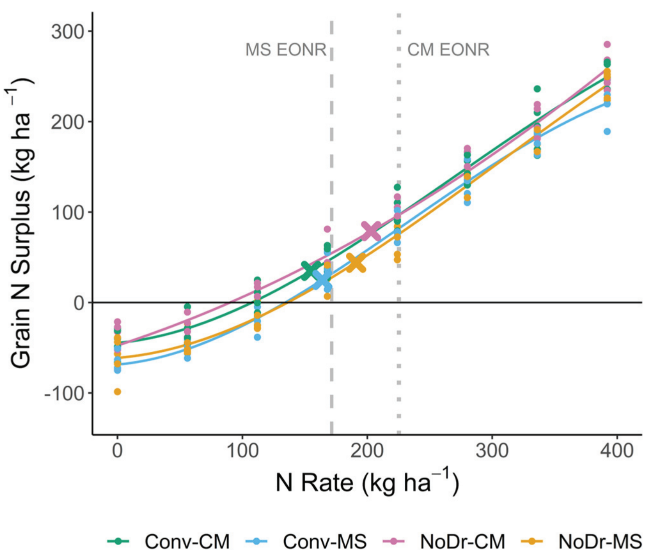

Fig. 5. Five-year mean grain-based N surplus. "X" denotes the mean N surplus at the five-year mean EONR. The vertical lines denote the regional EONR for southeast Iowa for comparison: 171 and 225 kg N ha^{-1} for maize-soybean (dashed line) and continuous maize (dotted line) rotations, respectively (ISU 2021). Conv=Conventional Drainage, NoDr=No Drainage, CM=Continuous Maize, MS=Maize-Soybean.

AONR in continuous maize in 2019 and 2020 (Table 2, see also Supplementary Figs. S5 and S6), AONR in maize-soybean was not particularly high in those years. Paiao et al. (2021) found a positive linear relationship between EONR in drained soils and cumulative precipitation 30 days before fertilization, though undrained soils were insensitive to this factor.

In this study, dry conditions had a substantial impact on N use. It increased not only N surplus and the AONR, for example, but also the variability of multiple metrics. Excluding the 2017 and 2019 dry years from the calculations reduced N surplus by 67% and 64% in Conventional and No Drainage, respectively. Additionally, the total AONR range in Table 2 drops from 481 to 307 and from 369 to 97 kg N ha^{-1} in continuous maize and maize-soybean, respectively, when the two dry years are excluded.

The highest annual mean AONR values over all drainage systems in the maize-soybean rotation were in the two driest summers (2017 and 2019), although the highest mean AONR values in the continuous maize rotation were in 2018 and 2019. Drainage is known to increase soil N mineralization (Davis et al., 2000) and to allow roots to expand deeper into the soil profile and use a greater volume of the soil resource (Davis, 2000; Ordóñez et al., 2018, Nichols et al., 2019). Both factors reduce the need for added N, which may explain Conventional Drainage's lower AONR in most cases. Additionally, low soil moisture limits the movement of N and other nutrients in general throughout the soil matrix due to decreased hydraulic conductivity and highly tortuous or broken flow paths, as well as lower velocity gradients due to water being constrained to smaller pore sizes (Lal and Shukla, 2004). With these constraints on N transport to roots, dry soils can require more N fertilizer for optimum plant growth.

Puntel et al. (2019) found that the number of days with more than 20 mm of rain between planting and silking explained nearly 50% of the variability of EONR. Their lowest EONR rates were in years with a high frequency of low rain events and low frequency of high rain events (> 20 mm) during plant growth. In 2016, the lowest AONR year in this study, there was only one day of rain > 20 mm and 27 days of lower rainfall from planting to silking (Supplementary Fig. S10) for 243 mm total rainfall. In 2019, the highest AONR year overall, there were only two days > 20 mm and 26 days of lower amounts – very similar to 2016 – though with 146 mm total rainfall. These two years highlight the additional importance of the timing of rain events. In 2016, there were three days of rain > 20 mm and 38 days of lower rainfall March through June (271 mm total), supporting a lower N application rate. In July and August, there were 5 rain events > 20 mm and 22 with lower (332 mm total), substantially reducing the moisture deficit during the critical reproductive stage and supporting higher yield. A regularly moist – but not wet – spring and ample rainfall mid-summer resulted in very low AONR. In 2019, there were 7 days of rain > 20 mm and 52 days of lower rainfall March through June (503 mm total), but only one day with > 20 mm rain and 20 days of lower rainfall (95 mm total) over July and August. A very wet spring facilitated N leaching (Supplementary Figs. S3 and S10). Then all plots were replanted mid-June and fertilizer applied late June, just at the start of a dry summer when yields are potentially reduced by 1.2% for each day of water stress during the grain filling stage (Eck, 1984), resulting in very high AONR.

Poffenbarger et al. (2017) calculated the long-term (2000–2015) mean AONR for another drained field at the same site as this study to be 209 kg N ha^{-1} for maize-soybean with a substantially higher rate (>269 kg N ha^{-1}) for continuous maize. Puntel et al. (2019) found EONR to be higher for continuous maize than maize-soybean due to higher net mineralization of soil organic matter in maize-soybean. The higher mineralization therefore explains the lower recovery efficiency in maize-soybean systems compared to continuous maize (Fig. 4). This study's five-year AONR means for Conventional drainage were substantially lower in both rotations but were higher in maize-soybean than continuous maize (194 vs. 171 kg N ha^{-1}). However, the inversion of values between rotations as compared to Poffenbarger et al. (2017) is due to one very dry year (2017), when the AONR was 62% higher in maize-soybean than continuous maize, as the maize-soybean mean would be 157 kg N ha^{-1} without it. The 2017 crop year had the greatest water deficit, and the mulching effect of corn residue may have mitigated the negative effect of this on soil organic matter mineralization (Power et al., 1986).

Drainage caused large reductions in the AONR and year-to-year variability in the AONR and grain yield. Although No Drainage achieved the highest yields at the AONR, it also required substantially more N fertilizer to achieve those yields. Because of this, No Drainage was the least efficient system (lowest AE_{AONR}) in the study except for Shallow Drainage in continuous corn. Moreover, the No Drainage system was consistently the most variable system across all metrics.

Fig. 3 and Supplementary Fig. S9 illustrate the surprising finding that yield at most N rates was greater in No Drainage than Conventional given equal amounts of fertilizer and same-day planting. Only when no fertilizer was applied was yield higher in Conventional. Although 2017 and 2019 were considered dry years, they were the two most productive in terms of yield. With demonstrated higher water tables in Shallow and No Drainage (Supplementary Fig. S2, Schott et al., 2017b), the crops were likely more N-limited than water-limited, resulting in nearly the highest yield at AONR in both 2017 and 2019 in both crop rotations as well as the highest AONR.

Higher AE_{AONR} in the drained systems indicated a greater effect of each kg of N applied on kg of grain harvested. Nevertheless, the greater efficiency did not translate into higher profits (i.e., NRTN). In almost all years and treatments, No Drainage had the greatest NRTN. However, the extreme cost of N fertilizer inputs required to achieve that NRTN and the extreme year-to-year variability in No Drainage almost certainly makes the application of such high N fertilizer inputs too risky. Indeed, farmer surveys rarely identify such high N fertilizer inputs (INRS 2022). Although this study's results were consistent with past findings that undrained fields have higher interannual variability than drained fields (Schwab et al., 1975, 1985), the higher NRTN in No Drainage was a surprise and it is important to note that the ability of drainage to allow for an earlier planting date, which is one of the greatest effects on crop yield (Kucharik, 2008), was not accounted for in this experimental design. Hence, if planting date was accounted for, the difference in NRTN between the drainage systems may have differed.

There was higher total crop N uptake at high yields (and therefore high N rates) in Conventional Drainage with more N uptake in No Drainage at lower N rates (Fig. 3 and Supplementary Figs. S8A,D and S9). This effect on total N uptake does not come from overall biomass production, which responded similarly to yield, but rather the N concentration in the plant tissue. Grain N was 62% of the total N in the plants in this study. Despite a somewhat inverse relationship between grain yield and drainage (Fig. 3 and Supplementary Fig. S8A,D), the N concentration increased with drainage, possibly due to better aeration in drained soil, allowing roots to take up more N. It is also possible N concentration could be lower in No Drainage due to the "dilution" of N when the yield is higher (Uribelarrea et al., 2004; Ciampitti et al., 2021, but see Tenorio et al., 2019). Furthermore, these patterns of drainage effect on N use by maize plants are the same in both crop rotations, except that grain N uptake was higher in No Drainage in maize-soybean at very low yield and N rates. Feed protein content is of interest to the beef cattle and dairy industries (Lardy, 2002; Olmos Colmenero and Broderick, 2006). Additionally, in many regions of the world, maize is a primary protein source for humans, and much research is devoted to the improvement of the protein content and nutritional value (Ai and Jane, 2016).

In most cases, plant traits at the AONR were similar between drainage treatments or higher in No Drainage (Fig. 3). Exceptions to this are total N uptake and grain N concentration in continuous maize, where almost all values at the AONR are near or well below the 1:1 line, indicating better performance in Conventional Drainage at optimum N application. Nevertheless, the small differences between drainage treatments in plant traits at the AONR indicate that the effect of drainage on field trafficability may be the most important effect of drainage for crop production.

Yield:N uptake and biomass:N uptake both had highest values at the lowest N rates and lowest values at the highest N rates, which echoes the trend of Recovery Efficiency (Fig. 4). This study's data (Fig. 5) agree with Halvorson and Bartolo (2014) who found N surpluses starting at N_{112} or N_{168} rates in irrigated maize fields, with the amount of surplus dependent on N fertilizer type. These trends indicate that cropping systems are more efficient at lower N rates, and rates lower than the current AONR for southeast Iowa (269 kg N ha^{-1}; ISU 2021) benefit the environment with substantially less surplus. Drainage extends these benefits even further with demonstrated reductions in AONR, resulting in less N surplus and potentially very high cost-savings.

Two potential management-based influences on this study's results include a N fertilizer legacy effect and same-day planting for all drained and undrained plots. Although all N rates were applied to the same split-split plot location each year, prior to the experiment all plots were fertilized with the same (optimum) N rate. Wyngaard et al. (2016) showed that changes in N rates can affect soil C and N dynamics for up to eight years. Poffenbarger et al. (2018) linked differences in crop N recovery efficiencies to differences in organic matter pools when changing from an historic N-gradient study to a constant N rate. However, since this study followed the opposite progression (from a constant N rate to a N-gradient), it was expected that the only differences in SOC pools at the beginning of this study were due to natural variability with insignificant differences between plots. The most likely legacy effect might be reflected in elevated yields at lower N rates. Indeed, there is a modest reduction trend of yield at N_0 over time (-0.28 Mg ha^{-1} yr^{-1} average over all treatments; data not shown), but this is also expected where there is no N fertilizer addition to replenish what is removed each year. It was expected overall that the direction of a legacy effect is likely variable from year-to-year depending on weather conditions.

Because it was required to wait until the No Drainage treatments were suitable for planting to plant the drained treatments also, this experiment does not account for the effect of field trafficability and hence necessarily underestimates the benefits of drainage on crop production. No Drainage plots at this site were previously determined to have a 2-week delayed optimum planting date relative to the drained treatments, due to shallow water tables (Schott et al., 2017). Planting date has been shown to explain 70% of the variability in Iowa maize grain yield, with a 0.75% grain yield loss each day silking is delayed beyond July 23 (Baum et al., 2019). By removing the field operation factor, the differences in drainage systems must be wholly attributed to soil and N processes. However, while it is known that earlier planting dates increase yield (Kucharik, 2008), we are not aware of any published studies on a relationship between planting date and AE or AONR. Here we speculate on the likely effect of planting the Conventional Drainage systems earlier than No Drainage. It is well-known that maize planting can begin when soil temperatures reach a minimum of 10 °C (early- to mid-April in Iowa) and when fields are workable. Nitrogen mineralization occurs as soon as soil thaws, though, and mostly at temperatures over 10 °C (MacDonald et al., 1995), so the sooner plant roots can capture the available soil nitrate, the less N fertilizer will be required, particularly in rainy springs when N leaching is high. Crops in 2019 required re-planting late after a rainy spring with high leaching (Supplementary Figs. S3, S10), yields were reduced, and it resulted in the lowest mean AE across drainage systems and nearly the highest AONR.

Soil type affects the timing of planting in drained soils; in southeast Iowa, drained fields can be planted about 5 days earlier than undrained fields (Reeve and Fausey, 1974; Chipanshi et al., 2018). The yield benefit of earlier planting is relative to the planting date. Baum et al. (2019) demonstrated that when the planting date is within the optimum range (about a 10-day window) for the hybrid, there is no or little advantage to planting early, but if planting in No Drainage were to be delayed due to moist field conditions, yields could be reduced as much as 7%. This would improve the AE and AONR in drainage systems relative to No Drainage. Furthermore, climate change is forecast to bring earlier optimum planting dates and wetter springtime weather, further supporting the utility of drainage in this region (Baum et al., 2020).

Although results demonstrate that extra N fertilizer inputs can overcome the negative effects of No Drainage on crop yield, the amount of N fertilizer required to do so was very large. Moreover, considering the high interannual variability in the No Drainage system, it is unlikely that farmers would accept the risk of such costly N fertilizer inputs because in years when the N fertilizer input was not required, economic losses would be extremely high and, in all years, the environmental costs of such applications are extremely high. Our *ex-post* analysis has the benefit of hindsight: it would be very difficult to accurately forecast the optimum N rate in No Drainage systems, especially given the interannual variability in AONR which ranged from < 100 to > 392 kg N ha^{-1} and was much more variable than the AONR in drained systems (Fig. 2). In this region, the AONR is notoriously difficult to predict because the amounts of soil nitrogen mineralization and environmental N losses are highly variable from year-to-year (Puntel et al., 2016, 2018).

Work must continue to determine the drivers of uncertainty and variability in agricultural systems. The comprehensive tools needed to provide estimates to producers for a coming growing season must incorporate reliable weather forecasts and historical land management, as well as local field and soil parameters and knowledge of crop varieties. As an alternative, regional long-term AONR means could be developed based on fertilizer type, yield, and drainage status from surveys or census data, although the connection between these data in the USDA Census of Agriculture is currently lacking. Yet even in the absence of a forecast model, tile installation in poorly drained soils has been demonstrated to reduce the annual unpredictability of crop production as well as the necessary N rate to achieve acceptable yields, resulting in increased confidence in management decisions while benefitting the environment with substantially less N surplus through less N applied.

5. Conclusion

Drainage consistently increased agronomic efficiency, reduced interannual variability in grain yield, and reduced interannual variability in agronomic optimum N fertilizer rate. The high relative efficiency and low interannual variability of Controlled Drainage indicate that this system – operated properly – can provide a solution to attenuate both the effects of insufficient and excessive soil moisture, both being causes of high AONR and low efficiency. Shallow drainage, which provides a similar, static solution to optimizing soil moisture, performed relatively poorly to the other systems in this study and location particularly in continuous maize, but its strengths were best seen in dry conditions, and it was more efficient and profitable in the maize-soybean rotation than continuous maize. Indeed, the maize-soybean rotation was clearly shown overall to be a more stable, efficient cropping system with lower AONR, higher yields, greater system resilience to varying water table depths, and less N waste.

If drainage improves the economics on real farms (and it clearly does), then perhaps the primary justifications for drainage are less in soil processes during crop growth and more in improved field trafficability to plant earlier in spring (and thereby attain higher yield versus No Drainage) and higher grain quality (protein content).

Author Contributions

Ellen Maas: Conceptualization, Formal analysis, Methodology, Software, Visualization, Writing – original draft. **Sotirios Archontoulis**: Writing - review & editing, Project administration. **Matthew Helmers**: Data curation, Project administration. **Javed Iqbal**: Data curation. **Hanna Poffenbarger:** Conceptualization, Writing – review & editing. **Kristina TeBockhorst**: Data curation. **Carl Pederson**: Data curation. **Michael Castellano**: Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Data Availability

Data will be made available on request.

Acknowledgements

This work was supported by the USDA National Institute of Food and Agriculture [2019-67019-29404].

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version atdoi:10.1016/j.fcr.2022.108663.

References

Ai, Y., Jane, J., 2016. Macronutrients in corn and human nutrition. Compr. Rev. Food Sci. Food Saf. 15 (3), 581–598. https://doi.org/10.1111/1541-4337.12192.
Archontoulis, S.V., Castellano, M.J., Licht, M.A., Nichols, V., Baum, M., Huber, I., Martinez-Feria, R., et al., 2020. Predicting crop yields and soil-plant nitrogen dynamics in the US corn belt. Crop Sci. 60 (2), 721–738. https://doi.org/10.1002/csc2.20039.
Arnhold, E., 2017. easynls: easy nonlinear model. R. Package Version 5, 0. ⟨https://CRAN.R-project.org/package=easynls⟩.
Balkcom, K.S., Blackmer, A.M., Hansen, D.J., Morris, T.F., Mallarino, A.P., 2003. Testing soils and cornstalks to evaluate nitrogen management on the watershed scale. J. Environ. Qual. 32 (3), 1015–1024. https://doi.org/10.2134/jeq2003.1015.
Bates, D.; Maechler, M.; Bolker, B.;Walker, S. Lme4: Linear Mixed-Effects Models Using Eigen and S4. R Package Version 3.1.140. Available online: https://cran.r-project.org/web/packages/lme4/index.html (accessed on 1 March 2022).
Baum, M.E., Archontoulis, S.V., Licht, M.A., 2019. Planting date, hybrid maturity, and weather effects on maize yield and crop stage. Agron. J. 111 (1), 303–313. https://doi.org/10.2134/agronj2018.04.0297.
Baum, Mitch E., Mark, A.Licht, Isaiah, Huber, Sotirios, V.Archontoulis, 2020. Impacts of climate change on the optimum planting date of different maize cultivars in the central US Corn Belt. Eur. J. Agron. 119 (September), 126101 https://doi.org/10.1016/j.eja.2020.126101.
Butterbach-Bahl, K., Baggs, E.M., Dannenmann, M., Kiese, R., Zechmeister-Boltenstern, S., 2013. Nitrous oxide emissions from soils: how well do we understand the processes and their controls? Philos. Trans. R. Soc. B: Biol. Sci. 368 (1621), 20130122. https://doi.org/10.1098/rstb.2013.0122.
Cassman, K.G., Dobermann, A., 2021. Nitrogen and the future of agriculture: 20 years (March). Ambio. https://doi.org/10.1007/s13280-021-01526-w.
Castellano, M.J., Archontoulis, S.V., Helmers, M.J., Poffenbarger, H.J., Six, J., 2019. Sustainable intensification of agricultural drainage. Nat. Sustain. 2 (10), 914–921. https://doi.org/10.1038/s41893-019-0393-0.
Chipanshi, A., Fitzmaurice, J., De Jong, R., Bogdan, D., Lewis, M., Kroetsch, D., Lee, D., 2018. Assessment of soil trafficability across the agricultural region of the Canadian prairies with the gridded climate data set. Soil Tillage Res. 184 (December), 128–141. https://doi.org/10.1016/j.still.2018.07.003.
Ciampitti, I.A., Fernandez, J., Tamagno, S., Zhao, B., Lemaire, G., Makowski, D., 2021. Does the critical N dilution curve for maize crop vary across genotype x environment x management scenarios? - A Bayesian analysis. Eur. J. Agron. 123 (February), 126202 https://doi.org/10.1016/j.eja.2020.126202.
R Core Team, 2019. R: A language and environment for statistical computing. R. Found. Stat. Comput. (URL) ⟨https://www.R-project.org/⟩.
Cox, W.J., Zobel, R.W., van Es, H.M., Otis, D.J., 1990. Growth development and yield of maize under three tillage systems in the Northeastern U.S.A. *Soil Tillage Res.* 18 (2), 295–310. https://doi.org/10.1016/0167-1987(90)90067-N.

Craft, K.J., Helmers, M.J., Malone, R.W., Pederson, C.H., Schott, L.R., 2018. Effects of subsurface drainage systems on water and nitrogen footprints simulated with RZWQM2. *Biol. Syst. Eng.* 550. ⟨https://digitalcommons.unl.edu/biosysengfacpub/550⟩.

David, M.B., Drinkwater, L.E., McIsaac, G.F., 2010. Sources of nitrate yields in the Mississippi River Basin. J. Environ. Qual. 39 (5), 1657–1667.

Davis, D.M., Gowda, P.H., Mulla, D.J., Randall, G.W., 2000. Modeling nitrate nitrogen leaching in response to nitrogen fertilizer rate and tile drain depth or spacing for Southern Minnesota, USA. J. Environ. Qual. 29 (5), 1568–1581. https://doi.org/10.2134/jeq2000.00472425002900050026x.

Ebrahimi-Mollabashi, E., Huth, N.I., Holzwoth, D.P., Ordóñez, R.A., Hatfield, J.L., Huber, I., Castellano, M.J., Archontoulis, S.V., 2019. Enhancing APSIM to simulate excessive moisture effects on root growth. Field Crop. Res. 236 (April), 58–67. https://doi.org/10.1016/j.fcr.2019.03.014.

Eck, H.V., 1984. Irrigated corn yield response to nitrogen and water. Agron. J. 76 (3), 421–428. https://doi.org/10.2134/agronj1984.00021962007600030014x.

van Es, H.M., Yang, C.L., Geohring, L.D., 2005. Maize nitrogen response as affected by soil type and drainage variability. Precis. Agric. 6 (3), 281–295. https://doi.org/10.1007/s11119-005-1387-7.

FAO, 2001. International programme for technology and research in irrigation and drainage. Drainage and Sustainability. Food and Agriculture Organization of the United Nations.

Fernández, F.G., Fabrizzi, K.P., Naeve, S.L., 2017. Corn and soybean's season-long in-situ nitrogen mineralization in drained and undrained soils. Nutr. Cycl. Agroecosyst. 107 (1), 33–47. https://doi.org/10.1007/s10705-016-9810-1.

Gardner, J.B., Drinkwater, L.E., 2009. The fate of nitrogen in grain cropping systems: a meta- analysis of 15N field experiments. Ecol. Appl. 19 (8), 2167–2184.

Gill, K., Jarvis, S.C., Hatch, D.J., 1995. Mineralization of nitrogen in long-term pasture soils: effects of management. Plant Soil 172 (1), 153–162. https://doi.org/10.1007/BF00020869.

Gilliam, J.W., Skaggs, R.W., Weed, S.B., 1979. Drainage control to diminish nitrate loss from agricultural fields. J. Environ. Qual. 8 (1), 137–142. https://doi.org/10.2134/jeq1979.00472425000800010030x.

Goolsby, D.A., W.A. Battaglin, G.B. Lawrence, R.S. Artz, B.T. Aulenbach, R.P. Hooper,. and G.J. Stensland. 1999. "Flux and sources of nutrients in the Mississippi-Atchafalaya River basin." Washington, DC: White House Office of Science and Technology, Policy Committee on Environmental and Natural Resources Hypoxia Work Group.

Halvorson, A.D., Bartolo, M.E., 2014. Nitrogen source and rate effects on irrigated corn yields and nitrogen-use efficiency. *Agron. J.* 2, 681–693. https://doi.org/10.2134/agronj2013.0001.

Helmers, M., Christianson, R., Brenneman, G., Lockett, D., Pederson, C., 2012. Water table, drainage, and yield response to drainage water management in Southeast Iowa. J. Soil Water Conserv. 67 (6), 495–501. https://doi.org/10.2489/jswc.67.6.495.

Henry, L. and H. Wickham. 2020. purrr: Functional Programming Tools. R package version 0.3.4. ⟨https://CRAN.R-project.org/package=purrr⟩.

Herrera, A., 2013. Responses to flooding of plant water relations and leaf gas exchange in tropical tolerant trees of a black-water wetland. Front. Plant Sci. 4, 106.

Iowa Environmental Mesonet (IEM), 2021. Iowa Ag Climate Network. Iowa State University, Ames, IA. ⟨https://mesonet.agron.iastate.edu/agclimate/⟩.

Iowa Nutrient Reduction Strategy (INRS). 2022. "Land Use and In-Field Practices v1.0." Accessed May 6, 2022. ⟨https://www.arcgis.com/apps/dashboards/04f03ece0691466dbe9e33551fdbe0f3⟩.

Iowa State University (ISU). 2021. "Nitrogen Rate Calculator." Accessed August 26, 2021. ⟨http://cnrc.agron.iastate.edu/⟩.

Kaur, G., Zurweller, B.A., Nelson, K.A., Motavalli, P.P., Dudenhoeffer, C.J., 2017. Soil waterlogging and nitrogen fertilizer management effects on corn and soybean yields. Agron. J. 109 (1), 97–106. https://doi.org/10.2134/agronj2016.07.0411.

Kladivko, E.J., Frankenberger, J.R., Jaynes, D.B., Meek, D.W., Jenkinson, B.J., Fausey, N. R., 2004. Nitrate leaching to subsurface drains as affected by drain spacing and changes in crop production system. J. Environ. Qual. 33 (5), 1803–1813.

Kucharik, C.J., 2008. Contribution of planting date trends to increased maize yields in the central United States. Agron. J. 100, 328–336.

Kumar, S., Nakajima, T., Kadono, A., Lal, R., Fausey, N., 2014. Long-term tillage and drainage influences on greenhouse gas fluxes from a poorly drained soil of Central Ohio. J. Soil Water Conserv. 69 (6), 553–563. https://doi.org/10.2489/jswc.69.6.553.

Lal, R., Shukla, M., 2004. Principles of Soil Physics. Marcel Dekker, Inc, New York, NY.

Lardy, G. 2002. Feeding Corn to Beef Cattle. AS-1238. North Dakota State University Extension Service. ⟨https://library.ndsu.edu/ir/bitstream/handle/10365/5349/as1238.pdf?sequence=1⟩.

Lawlor, P.A., Helmers, M.J., Baker, J.L., Melvin, S.W., Lemke, D.W., 2008. Nitrogen application rate effect on nitrate-nitrogen concentration and loss in subsurface drainage for a corn-soybean rotation. Trans. ASABE 51 (1), 83–94. https://doi.org/10.13031/2013.24229).

MacDonald, N.W., Zak, D.R., Pregitzer, K.S., 1995. Temperature effects on kinetics of microbial respiration and net nitrogen and sulfur mineralization\. Soil Sci. Soc. Am. J. 59 (1), 233–240. https://doi.org/10.2136/sssaj1995.03615995005900010036x.

Mallarino, A.P., J.E. Sawyer, S.K. Barnhart. 2013. A general guide for crop nutrient and limestone recommendations in Iowa. PM 1688. Iowa State Univ. Extension and Outreach, Ames, IA. MATLAB.2020. Version 9.8.0.1417392 (R2020a) Update 4. Natick, Massachusetts: The MathWorks Inc.

Muff, S., Nilsen, E.B., O'Hara, R.B., Nater, C.R., 2022. Rewriting results sections in the language of evidence. Trends Ecol. Evol. 37 (3), 203–210. https://doi.org/10.1016/j.tree.2021.10.009.

Nelson, K.A., Paniagua, S.M., Motavalli, P.P., 2009. Effect of polymer coated urea, irrigation, and drainage on nitrogen utilization and yield of corn in a claypan soil. Agron. J. 101 (3), 681–687. https://doi.org/10.2134/agronj2008.0201.

Nichols, V.A., Ordóñez, R.A., Wright, E.E., Castellano, M.J., Liebman, M., Hatfield, J.L., Helmers, M., Archontoulis, S.V., 2019. Maize root distributions strongly associated with water tables in Iowa, USA. Plant Soil 444 (1), 225–238. https://doi.org/10.1007/s11104-019-04269-6.

Olmos Colmenero, J.J., Broderick, G.A., 2006. Effect of dietary crude protein concentration on milk production and nitrogen utilization in lactating dairy cows. J. Dairy Sci. 89 (5), 1704–1712. https://doi.org/10.3168/jds.S0022-0302(06)72238-X.

Ordóñez, R.A., Castellano, M.J., Hatfield, J.L., Helmers, M.J., Licht, M.A., Liebman, M., Dietzel, R., et al., 2018. Maize and soybean root front velocity and maximum depth in Iowa, USA. Field Crop. Res. 215 (January), 122–131. https://doi.org/10.1016/j.fcr.2017.09.003.

Osterholz, W.R., Rinot, O., Shaviv, A., Linker, R., Liebman, M., Sanford, G., Castellano, M.J., 2017. Predicting gross nitrogen mineralization and potentially mineralizable nitrogen using soil organic matter properties. Soil Sci. Soc. Am. J. 81 (5), 1115–1126.

Paiao, G.D., Fernández, F.G., Naeve, S.L., 2021. Drainage conditions influence corn-nitrogen management in the US upper midwest. Agronomy 11, 2491. https://doi.org/10.3390/agronomy11122491.

Poffenbarger, H.J., Sawyer, J.E., Barker, D.W., Olk, D.C., Six, J., Castellano, M.J., 2018. Legacy effects of long-term nitrogen fertilizer application on the fate of nitrogen fertilizer inputs in continuous maize. Agric. Ecosyst. Environ. 265, 544–555.

Poffenbarger, H.J., Barker, D.W., Helmers, M.J., Miguez, F.E., Olk, D.C., Sawyer, J.E., Six, J., Castellano, M.J., 2017. Maximum soil organic carbon storage in midwest U.S cropping systems when crops are optimally nitrogen-fertilized. PLoS One 12 (3), e0172293. https://doi.org/10.1371/journal.pone.0172293.

Poffenbarger, H.J., Olk, D.C., Cambardella, C., Kersey, J., Liebman, M., Mallarino, A., Six, J., Castellano, M.J., 2020. Whole-profile soil organic matter content, composition, and stability under cropping systems that differ in belowground inputs. Agric. Ecosyst. Environ. 291 (April), 106810 https://doi.org/10.1016/j.agee.2019.106810.

Power, J.F., Wilhelm, W.W., Doran, J.W., 1986. Crop residue effects on soil environment and dryland maize and soya bean production. Soil Tillage Res. 8 (November), 101–111. https://doi.org/10.1016/0167-1987(86)90326-0.

Puntel, L.A., Pagani, A., Archontoulis, S.V., 2019. Development of a nitrogen recommendation tool for corn considering static and dynamic variables. Eur. J. Agron. 105 (April), 189–199. https://doi.org/10.1016/j.eja.2019.01.003.

Puntel, L.A., Sawyer, J.E., Barker, D.W., Dietzel, R., Poffenbarger, H., Castellano, M.J., Moore, K.J., Thorburn, P., Archontoulis, S.V., 2016. Modeling long-term corn yield response to nitrogen rate and crop rotation. Front. Plant Sci. November, 7. https://doi.org/10.3389/fpls.2016.01630.

Puntel, L.A., Sawyer, J.E., Barker, D.W., Thorburn, P.J., Castellano, M.J., Moore, K.J., VanLoocke, A., Heaton, E.A., Archontoulis, S.V., 2018. A systems modeling approach to forecast corn economic optimum nitrogen rate. Front. Plant Sci. 9. https://doi.org/10.3389/fpls.2018.00436.

Qin, Z., Myers, D.B., Ransom, C.J., Kitchen, N.R., Liang, S.Z., Camberato, J.J., Carter, P. R., et al., 2018. Application of machine learning methodologies for predicting corn economic optimal nitrogen rate. Agron. J. 6, 1.

Reeve, R.C., Fausey, N.R., 1974. Drainage and timeliness of farming operations. Drainage for Agriculture. John Wiley & Sons Ltd,, pp. 55–66. https://doi.org/10.2134/agronmonogr17.c4.

Russell, A.E., Laird, D.A., Parkin, T.B., Mallarino, A.P., 2005. Impact of nitrogen fertilization and cropping system on carbon sequestration in Midwestern Mollisols. Soil Sci. Soc. Am. J. 69 (2), 413–422.

Sawyer, J., Nafziger, E., Randall, G., Bundy, L., Rehm, G., Joern, B., 2006. Concepts and rationale for regional nitrogen rate guidelines for corn, April 2006. University Extension PM 2015. Iowa State University, Ames, Iowa. ⟨http://publications.iowa.gov/3847/⟩.

Schott, L., Lagzdins, A., Daigh, A.L.M., Pederson, C., Brenneman, G., Helmers, M.J., 2017a. Drainage water management effect on corn planting date in Southeast Iowa. J. Soil Water Conserv. 72 (6), 564–574. https://doi.org/10.2489/jswc.72.6.564.

Schott, L., Lagzdins, A., Daigh, A.L.M., Craft, K., Pederson, C., Brenneman, G., Helmers, M.J., 2017b. Drainage water management effects over five years on water tables, drainage, and yields in Southeast Iowa. J. Soil Water Conserv. 72 (3), 251–259. https://doi.org/10.2489/jswc.72.3.251.

Schwab, G.O., Fausey, N.R., Weaver, C.R., 1975. Tile and surface drainage of clay soils (1962-72). Research Bulletin 1081. The Ohio State University, Wooster, Ohio.

Schwab, G.O., Fausey, N.R., Desmond, E.D., Holman, J.R., 1985. Tile and surface drainage of clay soils (1973-80). Research Bulletin 1166. The Ohio State University, Wooster, Ohio.

Sela, S., Van Es, H.M., Moebius-Clune, B.N., Marjerison, R., Melkonian, J., Moebius-Clune, D., Gomes, S., 2016. Adapt-N outperforms grower-selected nitrogen rates in Northeast and Midwestern United States strip trials. Agron. J. 108 (4), 1726–1734.

Seymour, R.M., Skaggs, R.W., Evans, R.O., 1992. Predicting corn yield response to planting date delay. Trans. ASAE 35 (3), 865–869.

Shcherbak, I., Millar, N., Robertson, G.P., 2014. Global metaanalysis of the nonlinear response of soil nitrous oxide (N2O) emissions to fertilizer nitrogen. Proc. Natl. Acad. Sci. U.S.A. 111 (25), 9199–9204. https://doi.org/10.1073/pnas.1322434111.

Sigunga, D.O., Janssen, B.H., Oenema, O., 2002. Effects of improved drainage and nitrogen source on yields, nutrient uptake and utilization efficiencies by maize (Zea mays L.) on vertisols in sub-humid environments. Nutr. Cycl. Agroecosyst. 62 (3), 263–275. https://doi.org/10.1023/A:1021242918555.

Singh, G., Nelson, K.A., 2021. Long-term drainage, subirrigation, and tile spacing effects on maize production. Field Crop. Res. 262 (March), 108032 https://doi.org/10.1016/j.fcr.2020.108032.

Skaggs, R.W., Gilliam, J.W., 1981. Effect of drainage system design and operation on nitrate transport. Trans. ASAE 24 (4), 929–940. https://doi.org/10.13031/2013.34366.

Stevens, W.B., Hoeft, R.G., Mulvaney, R.L., 2005. Fate of nitrogen-15 in a longterm nitrogen rate study. Agron. J. 97 (4), 1046–1053.

Tenorio, F.A.M., Eagle, A.J., McLellan, E.L., Cassman, K.G., Howard, B., Below, F.E., Clay, D.E., et al., 2019. Assessing variation in maize grain nitrogen concentration and its implications for estimating nitrogen balance in the US North Central Region. Field Crop. Res. 240 (July), 185–193. https://doi.org/10.1016/j.fcr.2018.10.017.

Uribelarrea, M., Below, F.E., Moose, S.P., 2004. Grain composition and productivity of maize hybrids derived from the illinois protein strains in response to variable nitrogen supply. Crop Sci. 44 (5), 1593–1600. https://doi.org/10.2135/cropsci2004.1593.

Valipour, M., Krasilnikof, J., Yannopoulos, S., Kumar, R., Deng, J., Roccaro, P., Mays, L., Grismer, M.E., Angelakis, A.N., 2020. The evolution of agricultural drainage from the earliest times to the present. Sustainability 12 (1), 416. https://doi.org/10.3390/su12010416.

Wasserstein, R.L., Lazar, N.A., 2016. The ASA statement on P-values: context, process, and purpose. Am. Stat. 70 (2), 129–133. https://doi.org/10.1080/00031305.2016.1154108.

Wickham, H., et al., 2019. Welcome to the tidyverse. J. Open Source Softw. 4 (43), 1686. https://doi.org/10.21105/joss.01686.

Wyngaard, N., Dorcas, H.F., Habteselassie, M.Y., Mundepi, A., Miguel, L.C., 2016. Legacy effect of fertilization and tillage systems on nitrogen mineralization and microbial communities. Soil Sci. Soc. Am. J. 80 (5), 1262–1271. https://doi.org/10.2136/sssaj2016.03.0070.

Yan, M., Pan, G., Jocelyn, M.L., Richard, T.C., 2020. Rethinking sources of nitrogen to cereal crops. Glob. Change Biol. 26 (1), 191–199. https://doi.org/10.1111/gcb.14908.

Zulauf, C. and B. Brown. 2019. "Use of Tile, 2017 US Census of Agriculture." farmdoc daily (9):141. Department of Agricultural and Consumer Economics, University of Illinois at Urbana-Champaign.