

## Article

# Adaptation to Early-Season Soil Waterlogging Using Different Nitrogen Fertilizer Practices and Corn Hybrids

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**Abstract:** Excessive rainfall occurring in the early spring season in the Midwestern United States result in waterlogged soils contributing to corn production losses. The objective of our study is to evaluate the impact of soil waterlogging [non-waterlogged or waterlogged for 7 days when corn was at V3 growth stage (corn plant having three fully developed leaves with collar visible)], different pre-plant nitrogen (N) fertilizer sources and post-waterlogging rescue N fertilizer on grain and silage yield of two commercially available corn hybrids with different flood tolerance. Pre-plant N fertilizer was applied at 168 kg N ha<sup>-1</sup>. Nitrogen sources were a non-treated control (CO), polymer coated urea (PCU), urea (NCU), and urea plus Instinct (NCU + NI). A post-waterlogging rescue N fertilizer was applied at V7 as 0 or 83 kg N ha<sup>-1</sup> of urea plus N-(n-butyl) thiophosphoric triamide (NBPT) (NCU + UI). Waterlogging decreased grain and silage yields in different years; however, significant interactions were observed among treatments. Rescue N applications increased grain yields by 6–46% in non-waterlogged treatments, but not in waterlogged treatments. The PCU and NCU + NI increased grain yields compared to the CO. Pre-plant N sources showed no significant differences in grain yield, probably due to existing environmental conditions or incorporation of fertilizer. The N source, application method, and timing for post-waterlogging rescue N application and flood-tolerant corn hybrids needs further investigation in poorly-drained claypan soils prone to waterlogging under a changing climate.

**Keywords:** enhanced efficiency N fertilizer; silage

## 1. Introduction

Climate change has affected crop production globally by increasing extremes in soil water availability comprising of both droughts and flooding/soil waterlogging in agricultural landscapes. In the United States, the rate of occurrence of excessive precipitation events and numerous wet days has increased since the 1920–1930s resulting in greater frequency and magnitude of flooding [1]. In 12 Midwestern States, a 16.79 mm per decade increase in early season precipitation has resulted in wetter soil conditions from April to June, whereas drier growing conditions are occurring from July to September with a 4.73 mm per decade decrease in late season precipitation [2]. In 1993, record-breaking heavy precipitation created saturated soils and increased stream flows that caused a major Mississippi River flood [1] resulting in nutrient (such as nitrate) runoff that contributed to the doubling of the Gulf's "Dead Zone" and damages to crop production (\$6–8 billion) [3,4]. Crop losses caused by flooding were ranked second only to drought during last the 12-years from 2000–2012, and as high as 80% yield reductions have been reported

due to soil waterlogging [5]. The Intergovernmental Panel on Climate Change assessed that frequency of excessive precipitation episodes is expected to increase in the future due to climate change caused by potential increases in greenhouse gas emissions [6].

Other than floods, excessive soil moisture or waterlogged soils resulting from extreme precipitation events also cause major crop production losses [7]. In the 1993 Mississippi river flood, 70% of crop losses occurred due to saturated soil conditions resulting from excessive rainfall in upland areas and increased pathogen outbreaks in low-lying areas [4]. Corn production losses from temporarily flooded or saturated soils are a persistent problem in Missouri and other regions where soil waterlogging occurs. Furthermore, about 3.3 million hectares of land in Missouri and Illinois are under poorly drained claypan soils that may have waterlogging after rainfall events in top soil layers due to poor drainage [8,9].

Oxygen deficiency in soil caused by excessive soil moisture affects the respiration process in plant roots and reduces water and nutrient uptake due to lower root conductance. This condition causes reduced plant N uptake as well as wilting under warm conditions due to high transpiration rate. Excessive soil moisture also leads to higher nutrient losses and delayed planting or harvesting due to the difficulty of operating machinery under wet soil conditions [10,11]. The extent of injury to plants due to flooding depends upon the timing of flooding during the life cycle of the crop, flooding frequency and duration, and soil temperatures during the flooding event. The early growth stages (V2) of corn may be more prone to excessive water damage than later stages [V7 (corn plant having seven fully developed leaves with collar visible), VT (tasseling stage), R1 (silking stage)] because the growing point of the plant is still below soil surface or close to the soil surface during early crop stages [12,13]. A rise in flood water temperature increases flooding damage [14]. Survival of plants is determined by the interaction between flooding duration and temperature. At the V6 growth stage, corn plants can survive for two to four days under flooding at 15 °C, but plants may die at temperatures >25 °C [15].

Many researchers have reported beneficial effects of N fertilizer application for improving crop yields under waterlogged conditions [16–18]. High N fertilizer application rates (392 kg ha<sup>-1</sup>) decreased yield losses due to flooding compared to low N fertilizer applications (56 kg ha<sup>-1</sup>) [12]. Nitrogen (60 kg N ha<sup>-1</sup>) applied after waterlogging increased corn grain yield 65% to 77%, which was flooded for 10–11 days at early vegetative growth stage [19]. Addition of N fertilizer may accelerate plant adaptive mechanisms to waterlogging, such as root re-growth after flooding and adventitious root growth. Flooding can increase N losses via denitrification and leaching resulting in N deficiencies and reduced crop N uptake resulting from low oxygen levels in waterlogged soils [15].

One possible management approach for preventing N losses under waterlogged conditions is the use of enhanced efficiency N fertilizers that have been shown to increase corn yields and N use efficiency (NUE) under wet environments [20–22]. Controlled release N fertilizers can either delay N availability after application of fertilizer or increase N availability over a longer duration of time [23]. Nitrification inhibitors (NI) are chemicals that either delay, slow down, or restrict the nitrification process by hindering the metabolism of *Nitrosomonas* bacteria [23]. The inhibition of nitrification by NIs ranges from 4 to 10 weeks depending upon environmental and soil conditions as well as the type of inhibitor [24,25]. The UI inhibits urease enzyme activity that reduces the rate of urea hydrolysis into ammonium ions [23]. Nitrogen losses can occur after pre-plant N applications under waterlogged conditions resulting in N deficiencies of the crop and reduced crop yields. In-season rescue N applications can help overcome these flood-induced N deficiencies and increase grain yields [21].

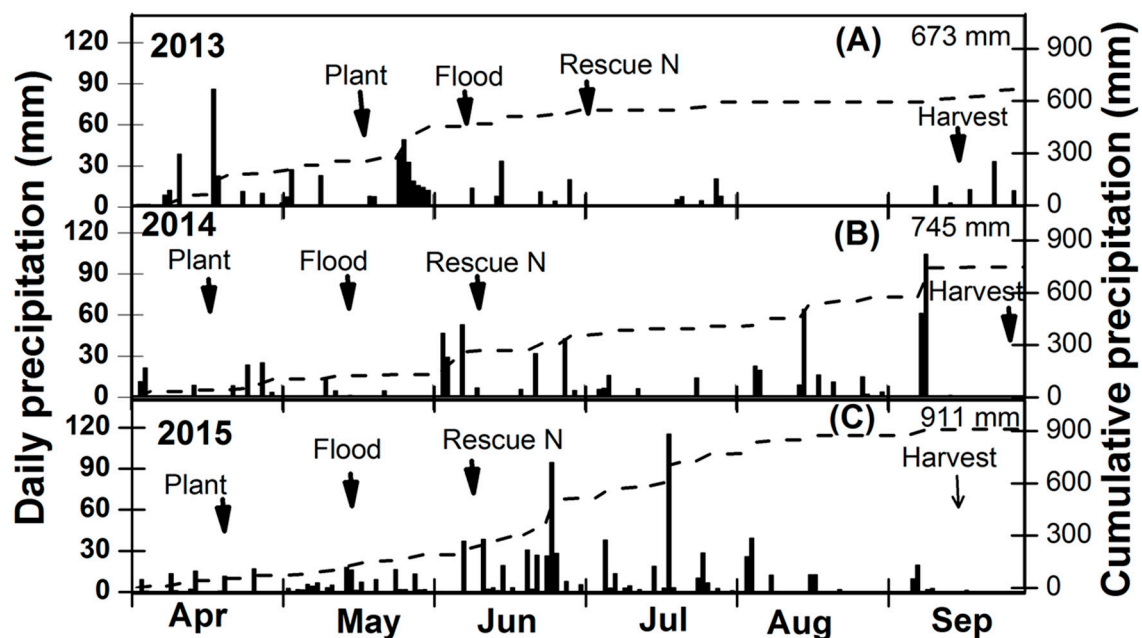
Multiple studies have reported that genetic differences occur in corn hybrids for tolerance to soil waterlogging stress [13,26,27]. Use of flood-tolerant corn hybrids can be a potential management approach for reducing yield losses in agricultural areas prone to periodic soil waterlogging. However, little research has been conducted in poorly-drained soils to evaluate the agronomic effects of short-term early-season soil waterlogging and to develop adaptive practices utilizing pre-plant and post-flood applications of enhanced efficiency N fertilizers in interaction with commercially-available corn hybrids which have differences in flood-tolerance. The objectives of our study were to evaluate the effects of

early-season soil waterlogging, pre-plant N sources and post-waterlogging rescue N on corn grain and silage yield for corn hybrids differing in flood tolerance.

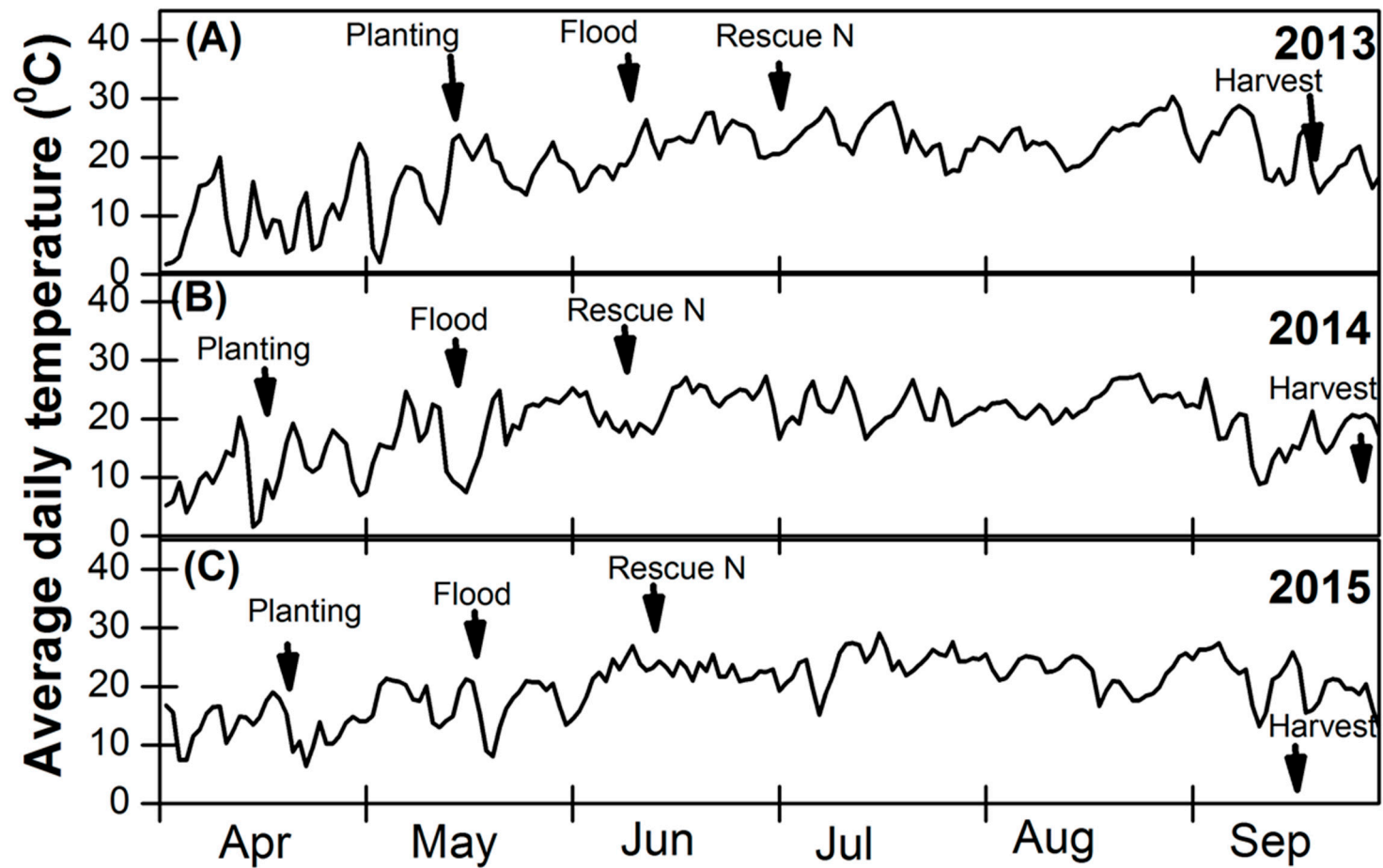
## 2. Materials and Methods

### 2.1. Site Characterization

A field experiment was conducted for three years from 2013 to 2015 at the University of Missouri's Greenley Research Center (40° 1' 17" N, 92° 11' 24.9" W), Novelty, Missouri, USA. Adjacent fields were used for planting corn each year. The soil type was a Putnam silt loam (fine, smectitic, mesic Vertic Albaqualfs), which is a poorly-drained claypan soil. For initial soil characterization of the experimental fields, a stainless steel push probe was used for collection of soil samples in increments of 0–10, 10–20, and 20–30 cm depths before pre-plant fertilizer applications. The collected soil samples were analyzed using the standard soil testing procedures by the University of Missouri Soil and Plant Testing Laboratory [28]. Results for initial soil samples are provided in Kaur, et al. [29]. Daily air temperature and precipitation data were obtained from a nearby automated weather station located at the University of Missouri's Greenley Research Center (Figures 1 and 2).



**Figure 1.** Daily (bars) and cumulative (line) precipitation during the 2013 (A), 2014 (B) and 2015 (C) growing seasons. Arrows represent the timings of major field events. (Source: Kaur, Nelson and Motavalli [29]).



**Figure 2.** Average daily air temperature during the 2013 (A), 2014 (B) and 2015 (C) growing seasons. Arrows represent the timings of major field events. (Source: Kaur, Nelson and Motavalli [29]).

## 2.2. Field Experiment

The experimental study was designed as a randomized complete block with a split-split-split plot arrangement with three replications. Each block had two main plots that included waterlogging treatments of 0 (non-waterlogged) or 7 days. The subplots consisted of different pre-plant N fertilizer sources. The size of main plots and sub-plots was 24 m × 24 m and 6 m × 24 m, respectively. Each sub-plot was randomly planted with two different hybrids creating a sub-sub plot. The size of each sub-sub plot was 3 by 24 m that included four rows of corn. After the flooding treatment, the sub-sub plots were randomly divided into two parts of 12 m length each and one of them was treated with 84 kg N ha<sup>-1</sup> of a rescue post-flood broadcast application of urea plus NBPT (N-(n-butyl) thiophosphoric triamide) urease inhibitor (4.2 L Mg<sup>-1</sup> urea; Agrotain®, Koch Agronomic Services, Wichita, KS, USA) whereas the other sub-sub plot did not receive any rescue N application.

Waterlogging was initiated after the V3 growth stage [30] of corn by the formation of earthen berms around the main plots and the use of supplemental water to pond water on the soil surface in the fields to a depth of 4 to 8 cm in order to partially submerge the plants, leaving the upper one or two leaves above the water surface. After the 7th day of waterlogging, the berms were removed to allow ponded water to escape. The pre-plant N fertilizer treatments comprised non-coated urea (NCU), non-coated urea plus a nitrification inhibitor (Instinct®, nitrapyrin, Dow AgroSciences, Indianapolis, IN, USA), polymer coated urea (PCU; ESN®, Agrium, Inc., Calgary, AB, Canada), and a non-treated control (CO). Nitrogen was applied at 168 kg N ha<sup>-1</sup> as pre-plant N fertilizer sources. All pre-plant fertilizer N was uniformly surface broadcasted and then incorporated 15 cm deep immediately after application using a Tilloll (Landoll Corp., Marysville, KS, USA). Two commercially available corn hybrids, Hybrid #1 (P1360HR) and Hybrid #2 (P1498AM) (DuPont Pioneer, Johnston, IA, USA), used in this study were selected based on a greenhouse screening trial on flooding tolerance of commercially available corn hybrids in order to obtain one hybrid that showed tolerance and another that was less tolerant to soil waterlogging [31]. Hybrid #2 appeared to be more tolerant to waterlogging based on waterlogging screening in greenhouse experiment. Row spacing used for corn planting was 76 cm and seeding rate was 81,512 seeds ha<sup>-1</sup>. Rescue N was broadcast applied at V7–V8 growth stage when corn was approximately 51 cm tall. The rate selected for the rescue N application was based on an estimate of an economical optimal N rate for a corn yield response at the V7 growth stage using SPAD 502 chlorophyll meter (CM) readings (Konica Minolta, Hong Kong) taken after a 7-day flooding event in 2013 and recommendation equations from [32]. The dates for field activities is provided in Table 1.

**Table 1.** Dates for field activities from 2013 to 2015.

Field Activities	Dates		
	2013	2014	2015
N application	14 May	18 Apr.	22 Apr.
Planting	15 May	18 Apr.	22 Apr.
Waterlogging	3 June	15 May	13 May
Rescue N Application	1 July	9 June	7 June
Harvested	18 Sep.	29 Sep.	16 Sep.

Corn was harvested using a plot combine (Wintersteiger, Salt Lake City, UT, USA) and grain yields were determined from the two center rows of the sub-sub-sub-plot. The corn grain yields were adjusted to 150 g kg<sup>-1</sup> moisture. Whole aboveground plant tissue samples were collected at physiological maturity from 300 cm of one row length to determine silage yield. The plant samples were ground using a portable chopper and a sub-sample was collected for determining moisture. Silage yield data were expressed on a dry weight basis.



### 2.3. Statistical Analysis

The MIXED procedure available in the SAS v. 9.4 statistical software (SAS Institute, 2013) was used for analysis of all collected data. The UNIVARIATE procedure was used for verifying the normality of all collected data. Data were pooled over other factors when appropriate as indicated by the MIXED procedure results. The p-values from MIXED procedure results represented in this paper are provided in Kaur (2016). Means were separated using Fisher's protected least significant difference (LSD) at the  $p < 0.10$  probability level.

## 3. Results and Discussion

### 3.1. Climatic Conditions During Growing Seasons

The cumulative precipitation from April to September was variable during all three years of this research (Figure 1 A–C). The cumulative seasonal precipitation over the three years was in the order: 2015 (911 mm) > 2014 (745 mm) > 2013 (673 mm). The cumulative precipitation during the growing season in 2013 was 72 mm and 238 mm lower than 2014 and 2015, respectively.

The variable precipitation conditions during all three years resulted in different soil moisture conditions and consequently, different planting times for corn as well as the waterlogging initiation time each year. Corn was planted in April 2014 and 2015 as compared to May 2013. Consequently, flooding was initiated for the waterlogged treatments in the month of June 2013 compared to May 2014 and 2015. About 199 mm of precipitation occurred during the time period between planting and flooding initiation, with a major proportion of it during a few days before the initiation of waterlogging events in 2013. However, precipitation amounts that occurred in the period between planting and flood initiation in 2014 and 2015 were 83 and 48 mm, respectively. More precipitation occurred in a period of 30 days after the flooding treatment in 2014 and 2015 compared to 2013. The 2013 growing season had a highly variable distribution of precipitation, with extreme spring rains resulting in the 15th wettest April–June time period during the past 120 years (NOAA 2013) followed by a prolonged drought period in August and September. Precipitation was evenly distributed during the 2014 and 2015 growing periods (Figure 1C). Heavy rainfall occurred later in the season after flooding treatments were imposed in 2015, which might have resulted in a longer period of excessive moist soil conditions that may have affected plant growth.

Waterlogging was initiated earlier in 2014 and 2015 in May with relatively lower air temperatures compared to higher air temperatures experienced during waterlogging in the month of June during 2013 (Figure 2A–C). When averaged over the 7-day flooding events, air temperatures were 2.5 °C higher in 2013 compared to 2014 and 2015. The air temperature ranged from 15–20 °C in 2013, 7.5–24.8 °C in 2014, and 8–21 °C in 2015. The air temperature during the 7-day flooding events was highly variable in 2014 and 2015 compared to 2013. The air temperature in 2015 was 9.7 and 12.3 °C lower than in 2013 on the 6th and 7th day of waterlogging. However, the air temperatures were 4.4 to 9.8 °C lower for first four days of waterlogging in 2014 compared to 2013. The air temperatures were higher during the remaining days of waterlogging in 2014 than in 2013. Greater air temperatures in 2013 compared to the 2012 growing season caused higher soil temperature at a depth of 10 cm [33].

This variation in air and soil temperatures, along with different rainfall amounts, probably accounted for some of the observed differences in corn yield among years. The extent of injury to plants caused by waterlogging or flooding also depended upon the soil temperature [34]. Nielsen [15] reported that the survival chances of young corn plants, when subjected to waterlogging, increased from a few days to 4 days if the temperatures decreased from  $\geq 24$  °C to  $\leq 15$  °C. Consequently, different results for corn yield were obtained from various treatments during three years of field experiments.

### 3.2. Corn Grain Yields

In 2013, corn grain yields were significantly affected by the main effects of waterlogging, pre-plant N fertilizer sources and corn hybrids as well as by the interaction of waterlogging duration and rescue

N applications. Corn grain yields decreased 16% in 7-day waterlogging treatments compared to the non-waterlogged treatments in 2013, when data were averaged over other treatments. When data were averaged over corn hybrids and pre-plant N fertilizer sources, rescue N applications increased grain yields by 6% compared to treatments not receiving rescue N, only in the non-waterlogged treatments in 2013 (Table 2). No beneficial effects of rescue N applications in increasing grain yields were observed in waterlogged treatments in 2013 (Table 2). Corn grain yields were lower in 7-day waterlogged treatments compared to non-waterlogged treatments, irrespective of rescue N applications (Table 2). Corn grain yield for Hybrid #1 (less flood-tolerant) was 1.33 Mg ha<sup>-1</sup> lower than Hybrid #2 (more flood-tolerant) when data were averaged over other treatments in 2013.

**Table 2.** Effects of waterlogging duration and rescue N application on corn grain yield in 2013 and silage yield in 2015.

Waterlogging Duration	Rescue N Application	Corn Grain Yield	Corn Silage Yield
		2013	2015
days		Mg ha <sup>-1</sup>	
0	NR <sup>†</sup>	8.12 b <sup>‡</sup>	16.42 b
0	NCU + UI	8.63 a	20.24 a
7	NR	7.21 c	10.87 c
7	NCU + UI	6.94 c	11.16 bc

<sup>†</sup> Abbreviations: NR, no rescue N application; NCU + UI, non-coated urea + urease inhibitor. <sup>‡</sup> Means followed by the same letter within a column do not differ significantly ( $p < 0.10$ ) based on Fisher's least significant difference test.

In 2013, all pre-plant N fertilizer sources including PCU (8.06 Mg ha<sup>-1</sup>), NCU (7.97 Mg ha<sup>-1</sup>) and NCU + NI (8.06 Mg ha<sup>-1</sup>) resulted in 1.16 to 1.25 Mg ha<sup>-1</sup> higher grain yields compared to the CO (6.81 Mg ha<sup>-1</sup>). Similarly, Kaur, et al. [35] also found that pre-plant N fertilizer applications of NCU, PCU, and NCU + NI had 19% higher yields compared to CO in one out of two years when waterlogging occurred at V6 growth stage of corn. Ritter and Beer [12] found that corn yield reductions due to 72-hrs of waterlogging were 15% lower in plots applied with high N fertilizer rates compared to plots applied with low N rates. Wu, Li, Wei, Wang, Zhang and Sun [18] reported that supplementary N mitigated adverse effects caused by waterlogging in winter wheat at the post-anthesis stage as foliar N application significantly improved root respiratory activity, photosynthetic rate, stomatal conductance, transpiration rate, leaf greenness, 1000 grain weight and winter wheat yield. No significant differences between PCU, NCU and NCU + NI sources were observed which might be due to similar N losses either through denitrification, leaching or runoff among all three sources during waterlogging since all treatments were incorporated in the soil. Zurweller, et al. [33] reported a sharp reduction in soil NO<sub>3</sub><sup>-</sup>-N and NH<sub>4</sub><sup>+</sup>-N concentrations with each day of waterlogging from different N fertilizer sources. Zurweller, et al. [33] concluded that the denitrification process under waterlogged soil conditions in these poorly-drained claypan soils resulted in major cumulative surface N<sub>2</sub>O emissions, predominantly during and shortly after soil flooding events.

Grain yields were not affected by the waterlogging duration in 2014, which may be due to lower air temperatures at the time of waterlogging events (Figure 2) and comparatively drier soils due to less precipitation before and after waterlogging events in 2014. The air temperature ranged from 7.5–24.8 °C in 2014 during the waterlogging event, whereas it was 4.4 to 9.8 °C lower during first four days of the waterlogging event compared to 2013 (Figure 2). Similarly, the soil temperature measured during the waterlogging event was significantly lower in 7-days waterlogged treatments than in non-waterlogged treatments [36]. In contrast, waterlogged treatments had higher soil temperature than non-waterlogged in 2013 and 2015 [36]. Damage due to flooding is less at lower temperatures and flooding damage increased with a rise in temperature [14]. Luxmoore, et al. [37] reported that soil flooding for 20 to 30 days reduced wheat (*Triticum aestivum*) grain yields by 15% to 23% at soil

temperature of 15–17 °C and by 73% at 25 °C, whereas no significant effect on grain yield was observed at soil temperature of 5 °C. No significant differences in yield were shown by corn hybrids in 2014.

Corn grain yields in 2014 were only affected by the main effects of pre-plant N fertilizer sources and rescue N applications as well as an interaction of pre-plant N fertilizer sources and post-waterlogging rescue N applications (Table 3). Based on interaction of pre-plant N fertilizer sources and post-waterlogging rescue N application, rescue N application did not provide any yield increase compared to the treatment that received no rescue N, when compared within each pre-plant N fertilizer source treatment. However, a rescue N application increased grain yields by 7% than treatments that received no rescue N in 2014, when data were averaged over pre-plant N sources, corn hybrids, and waterlogging duration. The NCU + NI treatment resulted in 38% higher grain yields compared to the CO in 2014, in treatments that received no rescue N (Table 3). However, grain yield from NCU + NI was similar to other pre-plant N fertilizer sources whether they received rescue N application or not.

**Table 3.** Impact of pre-plant N fertilizer sources and post-waterlogging rescue N application on corn grain yield in 2014.

Pre-Plant N Fertilizer Sources	Rescue N Application	
	NR	NCU + UI
Corn Grain yield (Mg ha <sup>-1</sup> )		
CO <sup>†</sup>	10.38 b <sup>‡</sup>	12.87 ab
PCU	13.18 ab	15.47 a
NCU	13.38 ab	13.25 ab
NCU + NI	14.34 a	13.28 ab

<sup>†</sup> Abbreviations: CO, non-fertilized control; PCU, polymer coated urea; NCU, non-coated urea; NCU + NI, non-coated urea + nitrification inhibitor; NR, no rescue N application; NCU + UI, non-coated urea + urease inhibitor.

<sup>‡</sup> Means followed by the same letter within a column or row do not differ significantly ( $p < 0.10$ ) based on Fisher's least significant difference test.

In 2015, corn grain yields were significantly affected by the main effects of waterlogging, pre-plant N fertilizers, rescue N applications and significant interactions were observed including waterlogging duration x rescue N applications, hybrids x rescue N, waterlogging duration x pre-plant N fertilizer sources x rescue N application, and pre-plant N fertilizer sources x rescue N x hybrids. A three-way interaction between waterlogging duration, pre-plant N fertilizer sources and rescue N application showed that grain yields due to rescue N applications were increased in the CO, PCU and NCU, only in non-waterlogged plots (Table 4). When data were averaged over corn hybrids and pre-plant N fertilizer sources, rescue N applications resulted in 46% higher grain yields than the treatments not receiving rescue N in non-waterlogged treatments in 2015 (Table 4). When data were averaged over corn hybrids, rescue N did not result in any increase in grain yields in 7-day waterlogged treatments for all of the pre-plant N sources



**Table 4.** Waterlogging duration, pre-plant N fertilizer sources and rescue N application effects on corn grain yield in 2015 and silage yield in 2013.

Pre-Plant N Fertilizer Sources	Rescue N Application	Waterlogging Duration (In Days)			
		0	7	0	7
		Corn Grain Yield (2015)		Corn Silage Yield (2013)	
Mg ha <sup>-1</sup>					
CO <sup>†</sup>	NR <sup>†</sup>	4.84 c <sup>‡</sup>	3.96 c	15.15 ab	14.47 ab
CO	NCU + UI	8.07 b	4.30 c	17.43 ab	13.37 ab
PCU	NR	11.39 b	6.38 bc	17.47 ab	15.44 ab
PCU	NCU + UI	14.02 a	8.18 b	19.04 a	18.12 ab
NCU	NR	7.40 bc	4.32 c	18.62 a	14.35 ab
NCU	NCU + UI	14.08 a	6.28 bc	16.95 ab	16.63 ab
NCU + NI	NR	9.22 b	7.55 bc	18.95 a	16.84 ab
NCU + NI	NCU + UI	11.73 ab	8.75 b	17.59 ab	12.81 b

<sup>†</sup> Abbreviations: CO, non-fertilized control; PCU, polymer coated urea; NCU, non-coated urea; NCU + NI, non-coated urea + nitrification inhibitor; NR, no rescue N application; NCU + UI, non-coated urea + urease inhibitor. <sup>‡</sup> Means followed by the same letter within a column or row do not differ significantly ( $p < 0.10$ ) based on Fisher's least significant difference test. Data is compared separately for 2015 and 2013.

In non-waterlogged treatments that received no rescue N applications, PCU and NCU + NI treatments had 135% and 90.5% higher yields than the CO in 2015 (Table 4). No differences in corn grain yields were found between NCU and CO in non-waterlogged treatments that received no rescue N applications. In treatments receiving rescue N, the PCU and NCU in non-waterlogged plots resulted in greater corn grain yields than the CO in 2015 (Table 4). In 7-day waterlogged plots in 2015, pre-plant N fertilizer sources did not increase corn yield as compared to the CO in treatments that received no rescue N. When treatments receiving rescue N were compared in 7-day waterlogged plots, the PCU and NCU + NI resulted in higher grain yields than the CO by 3.88–4.45 Mg ha<sup>-1</sup> in 2015 (Table 4). No differences were found for grain yield between PCU, NCU and NCU + NI in all years under both waterlogged and non-waterlogged treatments (Table 4). When data were averaged over other factors, a 38% decrease in corn grain yields due to 7-day waterlogging in our study might have resulted from excessive wet soil conditions for longer duration of time due to large amount of rainfall that occurred later in the season after waterlogging events in 2015. Grain yields from the NCU treatment was similar to the CO in 2014 and 2015.

Corn hybrids responded differently to rescue N applications in 2015. Corn grain yields increased by 70.2% for less flood-tolerant Hybrid #1 and 77.4% for more flood-tolerant Hybrid #2 due to rescue N in the NCU treatment when data were averaged over waterlogging duration in 2015 (Table 5). In NCU + NI treatments in 2015, less flood-tolerant Hybrid #1 showed 45.7% higher yields due to rescue N applications than the treatments receiving no rescue N. No difference in grain yield was found between corn hybrids when yield was compared for each pre-plant N sources and post-waterlogging rescue N application treatment separately (Table 4).

**Table 5.** Effects of pre-plant N fertilizer sources, hybrids and rescue N applications on corn grain yield in 2015.

Pre-Plant N Fertilizer Sources	Rescue N Applications	Corn Grain Yield	
		Hybrid #1	Hybrid #2
		Mg ha <sup>-1</sup>	
CO †	NR	4.62 d ‡	4.19 d
CO	NCU + UI	6.92 bcd	5.45 cd
PCU	NR	9.17 abcd	8.60 abcd
PCU	NCU + UI	11.47 a	10.74 ab
NCU	NR	6.11 cd	5.61 cd
NCU	NCU + UI	10.40 ab	9.95 ab
NCU + NI	NR	7.84 bcd	8.93 abcd
NCU + NI	NCU + UI	11.43 a	9.05 abcd

† Abbreviations: CO, non-fertilized control; PCU, polymer coated urea; NCU, non-coated urea; NCU + NI, non-coated urea + nitrification inhibitor; NR, no rescue N application; NCU + UI, non-coated urea + urease inhibitor.

‡ Means followed by the same letter within a column or row do not differ significantly ( $p < 0.10$ ) based on Fisher's least significant difference test.

Soil waterlogging for 7 days in our study reduced corn yields 16% and 38% in 2013 and 2015, respectively. Reduced leaf chlorophyll content due to waterlogging stress [36] might have reduced photosynthesis causing decreased grain yield. Yield reductions of 20% to 35% due to 24 to 42 h of waterlogging at the V3 growth stage was reported by several studies [12,38–41]. Kaur, et al. [35] reported that corn grain yields were decreased by 29% to 36% due to 7-days of waterlogging at V6 growth stage on a claypan soils of northeast Missouri. Ren, et al. [41] found that waterlogging corn for six days at the V3 growth stage decreased grain yields by 32–35% for two corn hybrids [41]. Ren, et al. [41] reported that the yield reduction in this study was caused by a reduction in the number of kernels per ear and 1000-grain weight, ear height, leaf area index, dry matter accumulation and grain filling rate due to waterlogging. Waterlogging at V3 growth stage delayed growth processes and decreased dry matter accumulation which contributes to the deficiency of source material supplies when the grain sinks formed [41].

The yield response to N applications compared to untreated control can be affected by genetic differences in hybrids, climatic conditions, crop management practices, soil landscape factors, and their dynamic interactions [42,43]. Crop response to N varied even within a field due to variations in crop N needs, soil N supply, N losses and availability of water [43]. Grain yield responses to applications of enhanced-efficiency fertilizer sources are variable and depend on many factors, such as amount, frequency and timing of rainfall after fertilizer application, fertilizer incorporation, soil texture, moisture content and soil temperature [22,44]. Excessive soil moisture and higher soil temperature may increase the rate of hydrolysis and diffusion of NI, which reduced its effectiveness [45] and consequently, it did not show any yield improvement over NCU. In a three-year study conducted by Gagnon et al. [22], PCU increased yields compared to urea only when frequent rainfall events occurred during the growing season, while no differences were found for grain yields between both N sources during drier conditions. Kaur et al. [35] found that pre-plant N fertilizers sources (NCU, NCU + NI, PCU) increased corn grain yields compared to the CO under waterlogged conditions in Northeast Missouri only in one out of two years and concluded that corn responses to soil waterlogging and fertilizer sources depended upon environmental conditions during growing season. All the pre-plant N fertilizers sources applied were incorporated into the soil after application to avoid N losses through volatilization as well as to prevent movement of fertilizer granules across treatments during waterlogging events in this study. This management practice might be another reason for differences among the N fertilizer sources.

Beneficial effects of rescue N for increasing corn yields were only found in non-waterlogged treatments. Rescue N application showed a 46% increase in crop yields during the relatively wet year of 2015, whereas only 6% to 7% increases in corn grain yields were found during other two years. This indicates corn response to mid-season N applications was higher during wet years and rescue N application can be feasible option for increasing grain yields during wet years. Post-waterlogging rescue N application did not increase corn yields in the 7-day waterlogged treatments. Continuous waterlogging for up to 7 days with a ponded water depth of 4 to 8 cm on the soil surface might have caused long-lasting damage to corn plants that limited N uptake and reduced grain yield. Rescue N application timing might be another possible reason for no yield response to waterlogging response. It is also possible that corn plants had not recovered from waterlogging stress when rescue N was applied and plants were unable to use this extra available N supplied by rescue N fertilizer. The urease inhibitor NBPT was used with urea for rescue N application, which might have reduced the ammonium and nitrate availability for a short period for plant uptake that might have caused poor plant recovery and growth. The NBPT can inhibit activity of the urease enzyme up to 14 days [46,47].

Hybrid #1 was determined to be less flood-tolerant compared to Hybrid #2 based on greenhouse screening at V2 growth stage. Testing of these hybrids in the field did not provide any consistent response during three years of our study. Furthermore, corn hybrids showed no significant interactions with waterlogging duration in order to quantify their tolerance or susceptibility to waterlogging stress in field. The greenhouse screening of commercially available corn hybrids was done using plastic pots that allow restricted spatial root growth. Furthermore, plants were only allowed to recover for one week after the excess water ponded on soil surface was drained after the proposed waterlogging event in the greenhouse screening experiment. The short-term greenhouse experiment performed under controlled environmental conditions might not be representative for the waterlogging environment experienced by corn plants under field conditions with variable environmental conditions during the waterlogging event. Inconsistent responses of both corn hybrids to soil waterlogging and N fertilizer applications indicate that the commercially available hybrids used in our study may not have had large differences in flood tolerance as they had shown during greenhouse screening. Further testing of a larger number of corn hybrids for waterlogging tolerance is needed to identify hybrids that are highly tolerant to waterlogging and whether flood tolerance traits may be enhanced through N fertilizer management.

### 3.3. Corn Silage Yield

The 7-day waterlogging treatment reduced silage yields by 14% in 2013 and 40% in 2015 compared to non-waterlogged treatments, when data were averaged over all other factors. Corn hybrids showed an inconsistent response to silage yield production during all three years. Similar to grain yields, Hybrid #2 (17.28 Mg ha<sup>-1</sup>) had 10.6% higher silage yield than Hybrid #1 (15.62 Mg ha<sup>-1</sup>) in 2013. Hybrid #1 (15.44 Mg ha<sup>-1</sup>) had 10.9% more silage yield than the Hybrid #2 (13.91 Mg ha<sup>-1</sup>) in 2015. Both hybrids showed no significant differences in silage yield production in 2014. Multiple studies have reported that genetic differences occurred in the corn plant response to soil waterlogging stress that results in differences in grain and silage yields [13,26,27,48].

The PCU (18.51 Mg ha<sup>-1</sup>) and NCU + NI (17.49 Mg ha<sup>-1</sup>) treatments resulted in 80.4% and 70.5% more silage yields compared to the CO (10.26 Mg ha<sup>-1</sup>) in 2015. However, no significant differences were obtained between pre-plant N fertilizer sources including PCU, NCU + NI and NCU (12.43 Mg ha<sup>-1</sup>). Nelson, et al. [49] also found no differences in silage yields from PCU and NCU, when applied at similar application rates. The silage yields from NCU (12.43 Mg ha<sup>-1</sup>) treatments were not significantly different from the CO. Comparatively, higher N uptake in pre-plant N sources such as PCU or NCU compared to CO might have resulted in more biomass production resulting in increased silage yields.

In 2015, rescue N applications increased silage yields 23% only in non-waterlogged treatments, but not in the 7-day waterlogged treatments (Table 2). The silage yield from non-waterlogged treatments that were supplied with rescue N was approximately 81 to 86% higher than the silage yields obtained from 7-day waterlogged treatments either with rescue N or without rescue N application (Table 2). In 2013, a three-way interaction was observed between waterlogging duration, pre-plant N fertilizer sources and rescue N applications (Table 4). In 2013, the silage yields from non-waterlogged treatments having PCU with rescue N applied and NCU and NCU + NI without rescue N application resulted in 5.81 to 6.23 Mg ha<sup>-1</sup> higher silage yield compared to NCU + NI with rescue N treatments (12.81 Mg ha<sup>-1</sup>) under waterlogged conditions.

## 4. Conclusions

The corn response to soil waterlogging and different N fertilizers sources varied due to in-season climatic conditions differences. Soil waterlogging reduced corn grain and silage yields. However, under extreme and continuous wet soil conditions resulting from 7-day waterlogging in addition to in-season rainfall events, pre-plant application of enhanced efficiency N fertilizers sources including PCU and NI with urea showed no yield improvement over the NCU when treatments were incorporated. In addition, the use of rescue N application did not help in increasing yield for waterlogged treatments. Lack of response to rescue N application might have occurred from reduced N uptake by plants that have not yet recovered from waterlogging stress at the time of rescue N application. Rescue N application timing, N source and method (foliar vs. soil) needs further investigation in the poorly drained claypan soils of Northeast Missouri for improving crop production under excessive soil moisture conditions. The two hybrids selected from the greenhouse screening experiment showed inconsistent responses in the field experiment among different years. Limited availability of commercial corn hybrids showing little or no flood tolerance suggests the need for breeding and development of flood-tolerant hybrids for agricultural areas susceptible to yield losses by excessive soil moisture under changing climate. It may be necessary to identify specific flood-tolerance traits as they are expressed in the field by including more diverse genetic lines having significant differences in flood-tolerance traits.

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