Plant Soil
https://doi.org/10.1007/s11104-026-08943-4

RESEARCH ARTICLE

Flooding temperature affected corn (*Zea mays* L.) emergence and root growth

N. A. S. Anuththara Neththasinghe · **Christine D. Sprunger** · **Alexander J. Lindsey**

Received: 6 May 2026 / Accepted: 25 July 2026

Abstract
Background and aims Early season weather fluctuations significantly impact corn (*Zea mays* L.) seedling establishment and soil nitrogen availability. This study investigated the effect of flooding duration and temperature after planting on corn emergence, seedling biomass and soil inorganic nitrogen content supplemented by polymer-coated urea fertilizer.
Methods A controlled environment experiment was conducted using a split-plot randomized complete block design. Corn seeds were planted in soil trays and maintained at temperatures of 5, 12.5, 20, 27.5, or 35 °C in five temperature-controlled chambers during the first four days after planting. Within each chamber, trays were flooded for 0, 1, or 3 days. Trays were relocated to a 25 °C greenhouse for 14 days and assessed for emergence and seedling growth. Soil samples were collected post-flooding and at seedling termination for nitrogen analysis.
Results Final emergence remained above 80% when flooded for up to 3 days at temperatures ≤ 12.5 °C. In contrast, flooding reduced final emergence to 35–55% at 20 °C and to 0–8% at temperatures ≥ 27.5 °C. Despite maintaining high emergence rates at cooler temperatures (≤ 12.5 °C), flooding reduced root biomass by 20–60% compared to non-flooded conditions, while shoot growth remained unaffected. At seedling termination, soil NO_3-N had accumulated significantly under flooding at 27.5 °C, while NH4-N concentration and the NO_3-N: NH_4-N ratio remained consistent across all treatments.
Conclusion These findings suggest that early season flooding is more detrimental to corn emergence at warmer temperatures. Although emergence remained high under cooler temperatures, impaired root development indicates the substantial risks of stand establishment and nutrient uptake under excessive soil moisture conditions.

Keywords Corn · Flooding · Soil temperature · Emergence · Germination

Responsible Editor: Al Imran Malik.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11104-026-08943-4.

N. A. S. A. Neththasinghe (✉) · A. J. Lindsey
Department of Horticulture and Crop Science, The Ohio State University, Columbus, OH 43210, USA
e-mail: neththasingheappuhamilage.1@osu.edu

C. D. Sprunger
W.K. Kellogg Biological Station, Michigan State University, 3700 E Gull Lake Drive, Hickory Corners, MI 49060, USA

C. D. Sprunger
Department of Plant, Soil and Microbial Sciences, Michigan State University, 1066 Bogue St, East Lansing, MI 48824, USA

C. D. Sprunger
Plant Resilience Institute, Michigan State University, 1066 Bogue St, East Lansing, MI 48824, USA

Published online: 03 August 2026

Abbreviations

AA	Accelerated aging
AOSA	Association of Official Seed Analysis
ESN	Environmentally smart nitrogen
FC	Field capacity
FD	Flooding duration
PCU	Polymer-coated urea
PWP	Permanent wilting point
SG	Standard seed germination test

Introduction

Over recent decades, the Midwestern United States has experienced more frequent extreme weather events and greater precipitation intensity. The distribution of rainfall has also shifted (Lindsey et al. 2024; Walthall et al. 2013). Many climate models also predict that spring precipitation in the Midwestern US will increase by 6–10% under middle-to-high emission scenarios (Pryor et al. 2013; Urban et al. 2015). Specifically, the increasing frequency and intensity of precipitation in early spring can increase the risk of waterlogging and flooding (Urban et al. 2015). Localized flooding incidents have been documented during the early growing season in certain regions of Ohio, occurring at intervals of approximately once every two to three years (Ortez et al. 2023; Novias et al. 2025). Excessively wet conditions occur more frequently during early growth stages compared to later in the season (Fausey and McDonald 1985; Nielsen 2011). Early season weather patterns can greatly influence corn (*Zea mays* L.) planting, germination, and early emergence (Lindsey et al. 2024). Risks of heavy spring rain can also impact planting decisions and other critical management practices. For example, a reduction in workable field days, due to fields being too wet for planting machinery, can delay corn planting. As a result, farmers may plant into marginal soils ahead of a cold front bringing rain to avoid planting delays from unsuitable field conditions (Urban et al. 2015; Lindsey et al. 2024).

The seedbed conditions after planting are critical for the germination, emergence, and development of seedlings (Wuebker et al. 2001). Water is required to initiate seed germination and hydrate the seed's growing tissues (Khaeim et al. 2022), but excess moisture or flooding conditions during early season create an abiotic stress to the germinating and emerging corn seeds/seedlings (Suo et al. 2022). Flooding is a significant abiotic stress that has detrimental impacts on crop growth and development (Wuebker et al. 2001; Wu et al. 2025). Flooding limits oxygen concentration by filling soil pores with water, which creates an anoxic soil condition. A low oxygen concentration has a detrimental impact on germinating seeds, impairing normal seedling development and reducing final stands (Fausey and McDonald 1985; Borisjuk and Rolletschek 2009; Lindsey et al. 2024). Vashisht et al. (2011) reported that soil can reach severely hypoxic or even anoxic after 24 h of water saturation. Both the duration and timing of flooding are important factors in determining the severity of damage to seeds or seedlings (Suo et al. 2022). Khosravi and Anderson (1990) recorded that corn inbred lines showed a decline in emergence after 48 h of flooding at 20 °C, and these losses increased as the flooding duration was extended to 96 h or more.

Temperature is another important factor that determines the level of flooding injury to corn seeds and seedlings. Fausey and McDonald (1985) observed higher emergence rates for corn hybrids across different flooding durations at a lower temperature (10 °C) compared with a higher temperature (25 °C) under both laboratory and field conditions. Warmer temperatures accelerate seed metabolic activities more than lower temperatures. Consequently, flooding under warmer conditions may result in depletion of soil oxygen concentrations more rapidly than under cooler conditions (Lindsey et al. 2024).

Flooding negatively affects soil nitrogen (N) availability by increasing losses via leaching and denitrification (Kaur et al. 2020; Novais et al. 2025). As N is a vital nutrient for corn development and yield, it is crucial to adjust the timing, rate, and source of supplemental fertilizer, especially when soils are saturated to ensure availability for plant uptake (Kaur et al. 2020; Dill et al. 2020). Slow-release N fertilizers are one method to optimize the fertilizer use efficiency to improved N management in corn production. The polymer-coated urea (PCU) products (e.g., environmentally smart nitrogen or ESN) can reduce N leaching losses during the early part of the growing season (Bundy and Andraski 2007); dry synthetic N sources resulted in greater yield in flooded and non-flooded field trials in Ohio compared to other N sources evaluated (Novais et al. 2025). However, it is unclear if temperatures during flooding would affect the N release and availability of pre-plant applied stabilized N sources.

Only a few studies have reported on the combined effect of flooding duration and temperature on corn germination and emergence (Fausey and McDonald 1985). Some studies have examined the effect of flooding duration, but at only a single temperature (Khosravi and Anderson 1990; Chahal and Jhala 2016). Furthermore, much of the past work has focused on a flooding temperature range of 10–25 °C. Therefore, it is important to understand how flooding duration influences corn germination and emergence across broader range of temperatures. Therefore, the objective of this study was to investigate (1) the effect of flooding duration and temperature after planting on corn germination, emergence, and seedling biomass and (2) the effect of flooding duration and temperature on inorganic nitrogen content in soil supplemented by PCU fertilizer. We hypothesized that: (1) short-term flooding would significantly reduce corn seed germination, emergence and seedling biomass, with the most severe reductions occurring at warm temperatures compared to cooler temperatures; and (2) warmer temperature would accelerate N availability from applied fertilizer, while short-term flooding would increase the loss of N, resulting in lower inorganic N levels in soils after flooding concluded.

Materials and methods

Seed materials

Seeds of a commercially available maize hybrids [Pioneer® P1164AM (111-day RM)] were obtained before project initiation and kept in 10 °C cold storage until initiation of the experiments. Seeds were treated with pesticides including ethaboxam, inpyrfluxam, metalaxyl, ipconazole fungicides, clothianidin insecticide, *Bacillus amyloliquefaciens* strain PTA-4838 and MBI-600. Prior to conducting the experiments, standard warm germination (AOSA 2018), and two vigor tests of accelerated aging (AA) and cold germination tests (AOSA 1983) were conducted and resulted in germination percentages of 99%, 92% and 96%, respectively.

Soil collection and preparation

The study was conducted at The Ohio State University in Columbus, Ohio, from June to August 2025. Field soil (Crosby silt loam [fine, mixed, active, mesic aeric epiaqualfs]) (NRCS USDA 2026) was collected from the Waterman Agricultural and Natural Resources Center (Columbus, OH). Soil was sieved using 1.5–1.6 cm^2 mesh screens to remove plant debris and large soil aggregates. A subsample of sieved soil was analyzed for soil bulk density, available moisture content boundaries (field capacity [FC], permanent wilting point [PWP]), soil texture, and initial soil chemical properties (Table 1). Soil was stored in closed containers at room temperature (21–23 ℃) until being used. Prior to initiation of the experiment, the soil was adjusted to 20% available water content to facilitate adequate moisture conditions for successful seed germination. This was achieved by adding water (60 mL water per 1000 g of soil) in small batches and thoroughly mixing to ensure uniform distribution of water in the soil. Immediately before filling rectangular trays (35.6 × 13.1 × 6.3 cm), PCU (44–0-0; ESN, Nutrien) was thoroughly mixed into bulk soil for uniform distribution. The amount of fertilizer added to the bulk soil was calculated to simulate an agronomic rate of 224 kg N ha^{-1}, ensuring each tray received approximately 2.4 g of PCU.

Tray preparation

The trays were filled with soil to a depth of 5.5 cm. Each tray contained drainage holes of approximately 0.5 cm diameter to ensure proper water circulation through the soil. Six corn seeds were planted at a depth of 3.75 cm in each tray, and furrows were closed after seed placement was completed.

Experimental procedures

The experiment was conducted using controlled environmental chambers to impose initial treatments, with each tray (experimental unit) being relocated to the greenhouse to complete data collection (Fig. 1). This study used a split plot randomized complete block experimental design. The main factor was the air/soil temperature (Temp). Five temperature-controlled chambers (Darwin chamber and Percival scientific chambers) were used to maintain constant, individual

Table 1 Soil physical properties of bulk density (g cm^{-3}), available water content boundaries on gravimetric basis of field capacity (FC) and permanent wilting point (PWP), soil textural classification, and initial soil chemical properties (Soil quality test kit guide; USDA, 2025)

Soil physical property	Method of quantification	Values and units	
Soil bulk density (BD)	Core method	1.23 g cm^{-3}	
Available Water Content Boundaries	Pressure Chamber	FC (0.03 MPa)	0.23 g g^{-1}
		PWP (1.5 MPa)	0.15 g g^{-1}
Soil texture	Hydrometer Analysis	Soil texture	silt loam
		Clay	14%
		Silt	68%
		Sand	18%
Soil Chemical property			
Soil pH	pH 1:1 (Soil: Water)	6.1	
Cation Exchange Capacity		11.9 $cmol_c$ kg^{-1}	
Nitrate–N	Potassium Chloride extraction	21 mg kg^{-1}	
Organic matter	High temperature oxidation	28 g kg^{-1}	

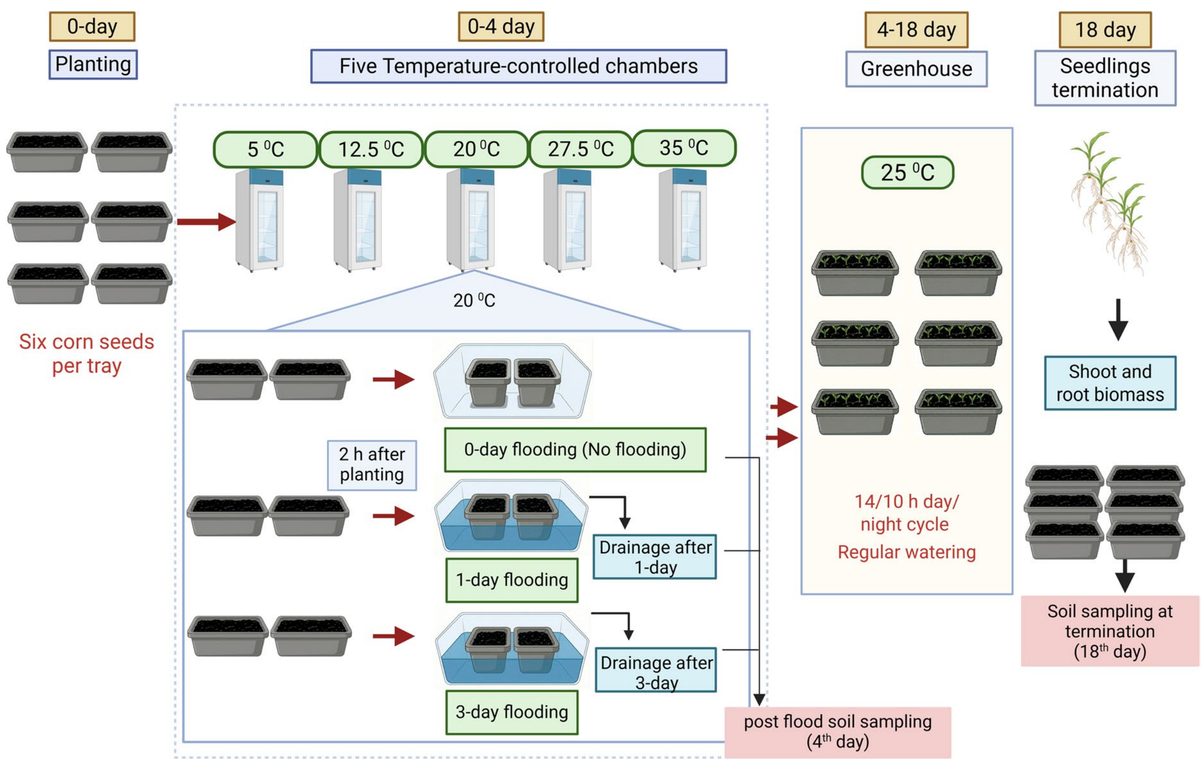

Fig. 1 Outline of the experimental design illustrates the application of five temperature treatments and three flooding durations to corn seed trays over the 18-day study period. The figure represents the six trays undergoing flooding durations within a single temperature chamber

setpoints of 5, 12.5, 20, 27.5, and 35 °C throughout the first four days.

The sub-factor was flooding duration (FD), imposed 2 h after planting, with three levels: 0 (no flooding imposed), 1 and 3 days; two subsample trays of each sub-plot were present for each run. Seed trays were placed inside a larger tray (50×27×6.5 cm) without drainage holes to facilitate the flooding. Two hours after planting, the 1-day and 3-day flooding treatments were initiated by adding 3.25 L of water to each flooding container, ensuring flooding up to soil surface level of the seed trays. After the flooding period was achieved, the seed trays were removed from the flooding containers and allowed to drain within their respective temperature-controlled chambers. On the fourth day after the start of the experiment, all trays were transferred to a temperature-controlled greenhouse maintained at a 25 °C setpoint with a 14/10 h day/night cycle for another 14 days. Trays were watered regularly in the greenhouse beginning on the fifth day after initiation (beginning 24 h after placement in the greenhouse).

Data collection

Emergence was measured for each tray, with emergence defined as the number of seedlings with coleoptile above the soil surface. Fourteen days after transferring to the greenhouse, corn seedlings were uprooted carefully from the soil. If a plant was not present within a row where a seed was planted, the seed was recovered and assessed for condition as abnormal or dead. Uprooted plants were washed gently to remove adhered soil particles from the root system. Final emergence was quantified based on the number of normal seedlings, defined as those exhibiting well-balanced and symmetrical development across all essential structures, including roots, coleoptile and leaves (AOSA 2018). In addition, the numbers of abnormal seedlings emerged, abnormal seedlings germinated but not emerged, and dead seeds were recorded. Seedlings with malformed roots, missing or damaged coleoptile were counted as abnormal seedlings. Normal seedlings from each experimental unit (seed tray) were pooled and measured the fresh weight (g) of the above ground biomass and root biomass separately. The above ground biomass and root biomass in each tray were then divided by number of plants and obtain per plant above ground and root biomass. The percentage of final emergence was calculated based on the number of plant emergences out of six seeds per tray.

For soil N analysis, three soil samples were collected from the bulk soil mixture after fertilizer application but prior to planting (pre-flooding) to establish baseline inorganic values. Nitrate–N (NO_3-N) and ammonium (NH_4-N) were then determined via an automated colorimetric method using Lachat instruments Quick-Chem 8500 (EPA 353.2 and 350.1). Soil samples were also collected from each tray after the first four-day period in the chambers (post-flooding; 4th day after planting) and at experiment termination (18 days after planting). Approximately six cores (2 cm diameter, of 5.5 cm depth) were collected and composited into a single sample for each treatment combination. All soil samples were air-dried before being analyzed for nitrate (NO_3-N) and ammonium (NH_4-N) concentrations.

Statistical analysis

Plant biomass components, final emergence percentage, and inorganic soil nitrogen concentrations (NO_3-N, NH_4-N and NO_3:NH_4-N ratio) at post-flooding and at the end of the experiment were analyzed using a split-plot mixed model with the PROC GLIMMIX procedure in SAS 9.4 at $\alpha = 0.1$ (SAS Institute, Cary, NC; version 9.4). Due to space limitation within temperature chambers, the entire experiment was independently repeated twice yielding two temporal runs. Temperature (Temp), flooding duration (FD) and their interaction were treated as fixed effects. Prior to statistical analysis, data from the two subsample trays within each treatment combination and each run were averaged to yield a single value per experimental unit. To evaluate the relationship between soil NO_3-N and NH_4-N concentrations across flooding durations, simple linear regression analysis was conducted separately for each of the five temperatures using SAS 9.4 (SAS Institute, Cary, NC). A significance threshold of $\alpha = 0.1$ was used to minimize type 2 errors giving small sample size and the high natural variability in soil and root data (Kaur et al. 2018; Paiao et al. 2021).

Table 2 Analysis of variance results for final emergence percentage, per plant shoot, and root biomass of corn for temperature, flooding duration (FD), and their interactions in 16 days after initiation

Effect	*p*-value		
	Final emergence percentage (%)	Per plant shoot biomass	Per plant root biomass
Temperature	**0.0002**	**0.0621**	**0.0246**
FD	**< 0.0001**	**0.0206**	**< 0.0001**
Temperature × FD	**< 0.0001**	**0.0262**	**0.0023**

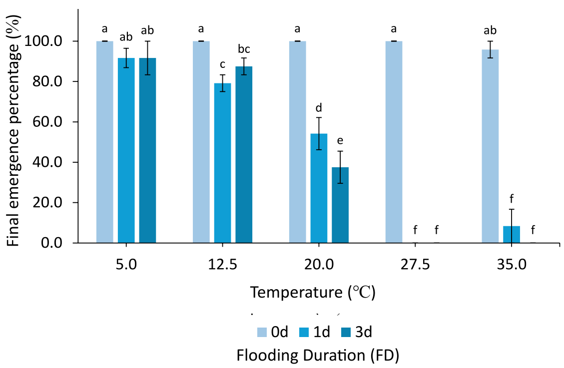

Fig. 2 Final emergence percentage as function of temperature and flooding duration (FD) treatments. Means followed by the same letter are not significantly different ($p < 0.1$). Error bars within each series are depicting the standard error of the means

Results

Final emergence response

The interaction between temperature and FD was statistically significant for final emergence and seedling biomass (Table 2). Under 0-day flooding conditions (no flooding), final emergence percentages were statistically similar across all temperature treatments, maintaining approximately 100% final emergence (Table 2, Fig. 2). No emergence was recorded for the 3-day FD at 27.5 ℃ and 35 ℃, or for the 1-day FD at 27.5℃. One-day flooding duration at 35 ℃ also only recorded 8.3% of final emergence. At 5 ℃, final emergence remained above 90% regardless of flooding duration, with no significant differences observed between treatments. At 12.5 ℃, 1-day and 3-day FD produced significantly lower seedling percentage compared to no-flooding treatment, although emergence remained above 75%. At 20 ℃, the emergence percentage significantly decreased as flooding duration increased. Compared to the no-flooding treatment, 1-day and 3-day flooding reduced emergence by 46% and 62%, respectively.

At 35 ℃, seeds that failed to emerge during 1-day and 3-day flooding, were found to be dead and decaying without no visible signs of germination. At 27.5 ℃ and 20 °C, > 95% of the non-emerged seeds were dead. Of the remaining areas lacking emergence, at 27.5 C less than 5% of the seeds from the total planted seeds showed radicle emergence suggesting germination occurred though plants died prior to emergence; at 20 ℃, the remaining non-emerged areas showed abnormal seedling development with radicles emerged and unfurling of leaves below the soil surface without emerging, indicating some plant development occurred. All seedlings that successfully emerged above the soil surface were classified as 100% normal seedlings across all treatments.

Seedling biomass response

No seedling biomass was recorded under the 3-day FD at 27.5 °C and 35 °C, or under the 1-day FD at 27.5 °C due to no emergence of plants being present at termination (Figs. 2 and 3). At 5 ℃, per-plant shoot biomass was statistically similar across all flooding durations. However, root biomass under 1-day and 3-days FD was reduced by approximately 40% compared to 0-day FD (Fig. 3). At 12.5 ℃, per-plant shoot and root biomass were statistically similar for all flooding conditions, although the 1-day and 3-day FD significantly reduced the final emergence percentage (Figs. 2 and 3). At 20 ℃, while short-term FD reduced emergence by 46–62%, shoot and root biomass remained similar across the three FD. For the 0-day FD, while seedling emergence and shoot biomass were statistically similar across all temperatures, root biomass was significantly reduced at 20 and 27.5 ℃ compared to 5 ℃.

Soil nitrogen availability

During the post-flood period (4 days after planting), soil NO_3-N was significantly impacted only by the main effect of FD (Table 3), with the 1-day FD

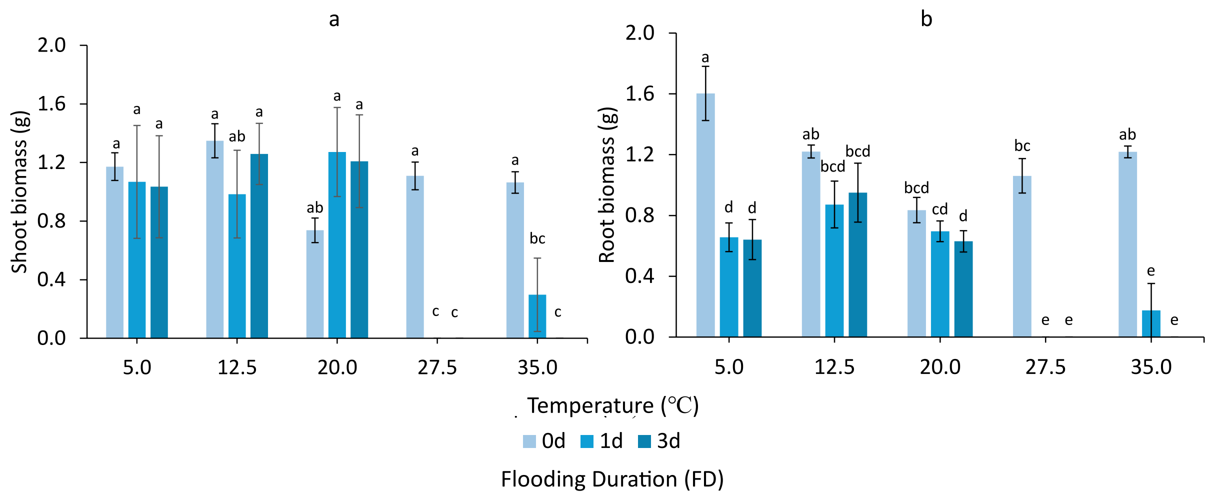

Fig. 3 (**a**) Shoot biomass and (**b**) root biomass per plant as a function of temperature and flooding duration (FD) treatments. Means followed by the same letter are not significantly different ($p<0.1$). Error bars within each series are depicting the standard error of the means

Table 3 Analysis of variance results for soil NH_4-N, NO_3-N concentrations and NO_3-N: NH_4-N ratio during post-flood (4-day after planting) and seedling termination (18-days after planting) for temperature, flooding duration (FD), and their interactions (

Effect	*p*-value					
	NH_4-N concentration		NO_3-N concentration		NO_3-N: NH_4-N ratio	
	post-flood	Termination	post-flood	Termination	Post-flood	Termination
Temperature	0.9085	0.2912	0.5484	0.1068	0.4606	0.5983
FD	0.8796	0.5458	**0.0877**	**0.0458**	0.3437	0.1068
Temperature × FD	0.1895	0.8787	0.1621	**0.0747**	0.7862	0.4177

yielding higher concentrations (130.0 mg kg^{-1}) than the no flooding treatment (87.2 mg kg^{-1}).

Soil NO_3-N levels at study termination (18 days after planting) increased with initial 4-day temperature treatments, up to 27.5 °C where the 1-day FD at 27.5 ℃ recorded the highest overall concentration. However, at 35 °C, NO_3-N concentrations declined across all flooding durations compared to the 27.5 °C (Fig. 4). Soil NO_3-N concentration at seedling termination ranged from 98.0–236.5 mg kg^{-1}. In contrast, soil NH_4-N concentrations were not significantly influenced by temperature, FD, or their interaction at either sampling time (Table 3). Soil NH_4-N values ranged from 57.5 to 276.0 mg kg^{-1} at the post-flood sampling time, and from 22.0 to 144.5 mg kg^{-1} at seedling termination. Similarly, the ratio of NO_3-N to NH_4-N was not significantly affected by the treatments at either sampling time, indicating ratios remained relatively stable despite the significant NO_3-N fluctuation specially during seedling termination.

During the post-flooding period, no significant linear regression trends between NO_3-N and NH_4-N were identified (data not shown). However, one negative relationship between soil NO_3-N and NH_4-N concentrations was identified at study termination for trays held at 35 ℃ for the initial period ($p=0.0553$; Supplementary Fig. 1).

Discussion

Flooding and temperature effects on emergence

The result of this study highlighted the significant interaction between soil temperature and flooding

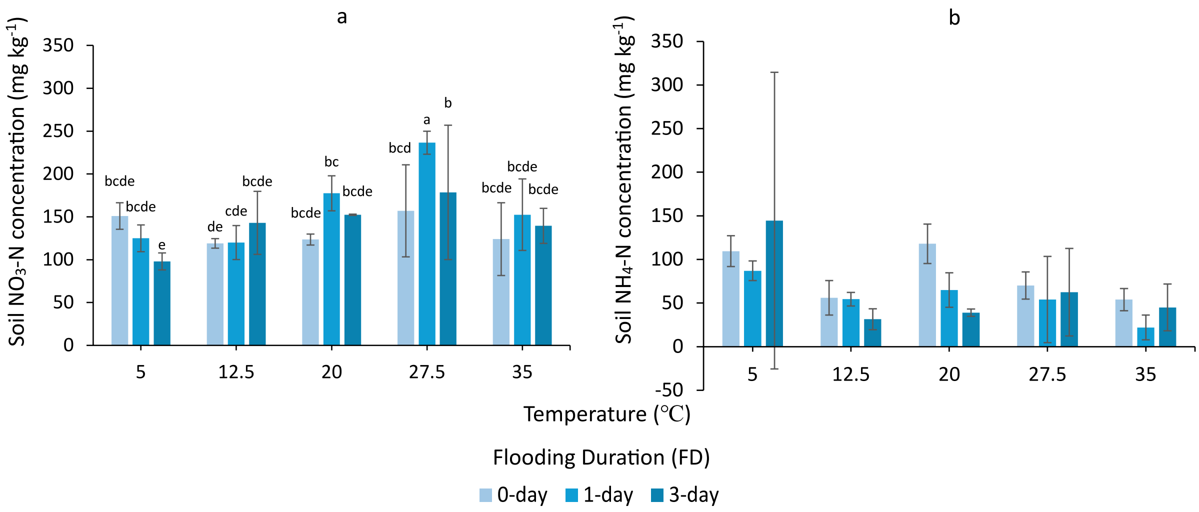

Fig. 4 (**a**) Soil NO_3-N and (**b**) soil NH_4-N concentration (mg kg^{-1}) during seedling termination (18 days after planting) as a function of soil temperature and flooding duration (FD) treatments. Means followed by the same letter are not significantly different ($p < 0.1$). Error bars within each series are depicting the standard error of the means

duration on corn emergence. Flooding at warmer temperatures (27.5 and 35 °C) suppressed or eliminated seedling emergence. Conversely, at cooler temperatures (5 and 12.5 °C), emergence was not inhibited, even under 1- and 3-day flooding durations (Fig. 2). These findings indicate that flooding is significantly more detrimental to corn emergence at higher temperatures than at lower temperatures. Observing the majority of non-emerged seed as dead seeds (> 95%) revealed that flooding at higher temperatures (≥ 27.5 ℃) suppressed the seed germination as well.

Under cooler temperatures (5 and 12.5 °C), flooding resulted in marginally lower emergence, but this reduction was not statistically significant compared to non-flooded conditions. At 20 ℃, 0-day flooding treatment recorded maximum emergence, while flooding at the same temperature resulted in approximately a 50% reduction in germination (Fig. 2). This suggests that during flooding at 5 and 12.5 °C, metabolic activity within the seeds was slow enough to ensure survival, whereas at 20 °C, metabolic processes might accelerate. Furthermore, successful emergence at 5 and 12.5 °C indicates that corn seeds were not affected by imbibitional chilling, despite being exposed to cold, waterlogged conditions for 24 to 72 h. The seeds used in this study were considered high vigor seeds, recording 96% germination under cold test and 92% vigor score for the AA test at the time of the project initiation, also might be the reason not to observe imbibitional chilling damage (Seed laboratory, Iowa State University, n.d.; Sodak Labs, Inc.). Given that seeds showed approximately 96% final emergence at 35 °C under 0-day flooded conditions, the suppression of germination observed in this study was evidently driven by flooding stress rather than high temperature alone.

The study conducted by Fausey and McDonald, (1985) also revealed that germination losses were less when flooding at low temperatures compared to high temperatures. They found that corn hybrid means percent germination at 10 ℃ decreases from 83% at 0 h to 47% at 144 h resulting 43% of germination decline compared to 0 h. However, at 25 ℃, mean germination decreases from 85% at 0 h to 1% at 144 h resulting 98% germination reduction. Similar results were reported under field conditions, that corn germination under flooding was low under warm weather compared to cold weather conditions. Khosravi and Anderson (1990) recorded that loss of corn germination started at 48 h of flooding and losses increased when the duration of flooding increased. However, even at 4-day of flooding at 20 ℃ these researchers recorded more than 60% germination in each tested cultivar. This contrasts to our results that a 1-day flood was sufficient to reduce emergence to below 60%. This discrepancy may be attributed to the difference in soil media between the studies. Previous research used bulk soil-sand mixture (1:1), while this study was conducted using field soil. Greater drainage and microporosity in the sand amended soil may have reduced the flooding stress and supported higher emergence.

Mechanisms of emergence failure

Although this study did not investigate the specific physiological mechanisms behind flooding conditions, has documented these processes. Flooding induces anoxic conditions by filling soil pores with water, thereby limiting the oxygen concentration (Fausey and McDonald 1985; Pan et al. 2021; Lindsey et al. 2024). Vashisht et al. (2011) recorded that soil oxygen levels reach zero after 24 h of flooding, and oxygen availability is further restricted due to the lower diffusion rate of oxygen in water compared to air (Pan et al. 2021). Furthermore, warmer temperatures accelerate seed metabolic activity and respiration (Fausey and McDonald 1985; Wiebold 2013; Lindsey et al. 2024). Under these warmer conditions, the limited oxygen supply in flooded soil cannot meet the seed's higher respiratory demand, resulting in rapid oxygen depletion. This forces anaerobic metabolism and the subsequent production of toxic byproducts, such as ethanol and acetaldehyde, which can cause seed death before germination (Martin et al. 1991; Borisjuk and Rolletschek 2009). These might be the reasons to produce lower germination and emergence under flooding at higher temperatures. Rate of water uptake by seed depends on the water potential gradient between the seed and soil. Under saturated soil conditions seeds absorb water rapidly during imbibition phase may cause detrimental impact to the seed tissues and membrane permeability. Under warmer temperature conditions this process is faster, and the impact was much faster and severe (Cheng et al. 2010; Suo et al. 2022). This could also be a reason to result in no emergence under flooding conditions at warmer temperatures.

Root growth responses

Even though flooding at 5 and 12.5 °C temperatures produced similar emergence rates, root biomass was significantly reduced by flooding stress, whereas shoot biomass remained similar compared to unflooded conditions (Fig. 3). This reduction in root biomass was also observed at 20 °C. Flooding suppresses root growth and volume by limiting oxygen availability, thereby impairing respiration and nutrient uptake. Prolonged hypoxia can lead to cellular necrosis and ultimately root death (Wenkert et al. 1981; Colmer and Voesenek 2009; Wiebold 2013). While considerable research has examined the effects of flooding on the root and shoot growth of already emerged corn seedlings (Lizaso et al. 2001; Nagel et al. 2009; McDaniel et al. 2016; Kaur et al. 2018), this study showed that flooding suppresses root development even when it occurs immediately after planting and prior to emergence. Anaerobic soil conditions can disrupt the imbibition phase and radicle emergence during germination, which can suppress primary root development in emerging corn seedlings (Wenkert et al. 1981; Lizaso et al. 2001).

Nitrogen dynamics

The elevated soil NO_3-N concentrations observed under 1 and 3-day flooding at 27.5 ℃ at seedling termination can be partially explained by the corresponding seedling biomass and emergence results. The severe reduction in seedling emergence and growth under these conditions likely suppressed plant N uptake, causing NO_3-N to accumulate in the soil. While the 1 and 3-day FD at 35 ℃ resulted in similarly poor seedling biomass, soil NO_3-N did not accumulate as observed at 27.5 ℃ but instead resulted statistically similar values as seen with 0-day flooding at 35 °C and at lower temperatures (Fig. 4). Furthermore, the absence of significant treatment effects immediately post-flooding might suggest that the brief 1 to 3-day exposure period was too short to significantly alter the nitrogen release pattern from the applied PCU fertilizer. Flooding can lower plant-available soil N by promoting nitrate leaching and increasing bacterial denitrification caused by anaerobic conditions (Robertson and Vitousek 2009; Naasko et al. 2026). The polymer-coated urea products can reduce N leaching losses during the early part of the growing season (Bundy and Andraski 2007). However, the study conducted by Golden et al. (2011), suggested that excessive rainfall shortly after PCU application would not greatly influence N release rate and would tend to minimize runoff and leaching losses of N compared to immediately available form of N fertilizer. Although significant variation was observed in the NO_3-N pool at termination, the NO_3-N: NH_4-N ratio and the linear regressions between NO_3-N and NH_4-N remained non-significant. The lack of significant trends may be attributed to the short eighteen-day duration of the experiment, which was likely an insufficient timeframe to observe the full nitrogen release pattern from the controlled-release PCU fertilizer and soil microbial activities on soil nitrogen cycle.

Agronomic implications

This study supports the hypothesis that soil temperature during early season flooding cause sever reduction of corn germination and emergence with most detrimental effects at higher temperatures (≥ 27.5 ℃). However, extended flooding durations even at moderate temperatures (e.g., 3 days at 20 °C) resulted in a 50% reduction in emergence. These results also suggest that imbibitional chilling from cooler temperatures during flooding was not as great as flooding at low temperatures reducing root biomass. Damage to root systems, even if under low temperatures, might be problematic for future crop growth and yield by limiting the nutrient and water uptake. These findings highlight the risk of early season corn stand establishment, aligning with climate models that predict an increased frequency of heavy precipitation events and altered rainfall distributions during the Midwestern planting window. Poor stand establishment directly impacts the replanting decisions of farmers to compensate for the potential yield losses. Therefore, it is important to consider rainfall forecast along with soil temperature before and after planting. While this study focused on early season growth of corn, future field research must evaluate how the compounding effects of early season flooding and varied temperatures impact the reproductive stages and final grain yield.

Acknowledgements We thank Pioneer® for donating the seeds used in this study. This work was funded through the USDA-NIFA AFRI Foundational program, Award 2021-67013-33615. This work was also supported, in part, by Hatch funds from the USDA National Institute of Food and Agriculture.

Author contributions Material preparation, data collection and analysis were performed by N.A.S. Anuththara Neththasinghe and Alexander J. Lindsey. The first draft of the manuscript was written by N.A.S. Anuththara Neththasinghe and Alexander J. Lindsey and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding This work was funded through the USDA-NIFA AFRI Foundational program, Award 2021–67013-33615. This work was also supported, in part, by Hatch funds from the USDA National Institute of Food and Agriculture.

Data availability The datasets generated during and/or analyses during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

References

Association of Official Seed Analysis (AOSA) (1983) Seed Vigor Testing Handbook, Contribution No. 32 to the handbook on Seed Testing.

Association of Official Seed Analysts (AOSA) (2018) Rules for testing seeds. Association of Official Seed Analysts

Bundy LG, Andraski TW (2007) Polymer-coated urea (ESN) for corn. In Proc. 2007 Wisconsin Fertilizer, Aglime, and Pest Management Conf 46:54–59

Borisjuk L, Rolletschek H (2009) The oxygen status of the developing seed. New Phytol 182(1):17–30. https://doi.org/10.1111/j.1469-8137.2008.02752.x

Chahal PS, Jhala AJ (2016) Factors affecting germination and emergence of glyphosate-resistant hybrid corn (*Zea mays* L.) and its progeny. Can J Plant Sci 96(4):613–620. https://doi.org/10.1139/cjps-2015-0346

Cheng L, Gao X, Li S, Shi M, Javeed H, Jing X, Yang G, He G (2010) Proteomic analysis of soybean [*Glycine max* (L.) Meer.] seeds during imbibition at chilling temperature.

Mol Breed 26(1):1–17. https://doi.org/10.1007/s11032-009-9371-y
Colmer TD, Voesenek LACJ (2009) Flooding tolerance: suites of plant traits in variable environments. Funct Plant Biol 36(8):665–681. https://doi.org/10.1071/FP09144
Dill TE, Harrison SK, Culman SW, Lindsey AJ (2020) Grain yield response of corn (*Zea mays* L.) to nitrogen management practices and flooding. Plants (Basel) 9(3):348. https://doi.org/10.3390/plants9030348
Fausey NR, McDonald MB Jr (1985) Emergence of inbred and hybrid corn following flooding 1. Agron J 77(1):51–56. https://doi.org/10.2134/agronj1985.00021962007700010013x
Golden B, Slaton N, Norman R, Gbur E, Wilson C (2011) Nitrogen release from environmentally smart nitrogen fertilizer as influenced by soil series, temperature, moisture, and incubation method. Commun Soil Sci Plant Anal 42(15):1809–1824. https://doi.org/10.1080/00103624.2011.587568
Kaur G, Nelson KA, Motavalli PP (2018) Early-season soil waterlogging and N fertilizer sources impacts on corn N uptake and apparent N recovery efficiency. Agronomy 8(7):102. https://doi.org/10.3390/agronomy8070102
Kaur G, Singh G, Motavalli PP, Nelson KA, Orlowski JM, Golden BR (2020) Impacts and management strategies for crop production in waterlogged or flooded soils: a review. Agron J 112(3):1475–1501. https://doi.org/10.1002/agj2.20093
Khaeim H, Kende Z, Balla I, Gyuricza C, Eser A, Tarnawa Á (2022) The effect of temperature and water stresses on seed germination and seedling growth of wheat (Triticum aestivum L.). Sustainability 14(7):3887. https://doi.org/10.3390/su14073887
Khosravi GR, Anderson IC (1990) Pre-emergence flooding and nitrogen atmosphere effects on germinating corn inbreds. Agron J 82(3):495–499. https://doi.org/10.2134/agronj1990.00021962008200030010x
Lindsey AJ, Ortez OA, Thomison PR, Carter PR, Coulter JA, Roth GW, Carrijo DR, Quinn DJ, Licht MA (2024) Severe storm damage and short-term weather stresses on corn: A review. Crop Sci 64(3):1129–1166. https://doi.org/10.1002/csc2.21212
Lizaso JI, Melendez LM, Ramirez R (2001) Early flooding of two cultivars of tropical maize. I. Shoot and root growth. J Plant Nutr 24(7):979–995. https://doi.org/10.1081/PLN-100103798
Martin BA, Cerwick SF, Reding LD (1991) Physiological basis for inhibition of maize seed germination by flooding. Crop Sci 31(4):1052–1057. https://doi.org/10.2135/cropsci1991.0011183X003100040042x
McDaniel V, Skaggs RW, Negm LM (2016) Injury and recovery of maize roots affected by flooding. Appl Eng Agric 32(5):627–638
Naasko K, Martin T, Zakolski E, Mann M, Malacrinò A, Novais W, Lindsey A, Sprunger C (2026) The impact of short-term flooding on soil microbial communities, soil nitrogen and maize productivity in clay loam soils of Ohio, United States. Ann Appl Biol. https://doi.org/10.1111/aab.70107
Nagel KA, Kastenholz B, Jahnke S, Van Dusschoten D, Aach T, Mühlich M, Truhn D, Scharr H, Terjung S, Walter A, Schurr U (2009) Temperature responses of roots: impact on growth, root system architecture and implications for phenotyping. Funct Plant Biol 36(11):947–959. https://doi.org/10.1071/FP09184
Natural Resources Conservation Service, United States Department of Agriculture (NRCS USDA) (2026). https://soilseries.sc.egov.usda.gov/osdname.aspx
Nielsen, R. L. (2011). Field drydown of mature corn grain. West Lafayette: Purdue University, Extension Entomology; Pest & crop newsletter. https://extension.entm.purdue.edu/newsletters/pestandcrop/article/field-drydown-of-mature-corn-grain/
Novais W, Sprunger CD, Mann M, Lindsey LE, Ortez OA, Lindsey AJ (2025) Assessing pre-plant nitrogen sources and waterlogging on corn growth and yield. Crop, Forage & Turfgrass Management 11(2):e70071. https://doi.org/10.1002/cft2.70071
Ortez OA, Lindsey AJ, Thomison PR, Coulter JA, Singh MP, Carrijo DR, Quinn DJ, Licht MA, Bastos L (2023) Corn response to long-term seasonal weather stressors: A review. Crop Sci 63(6):3210–3235. https://doi.org/10.1002/csc2.21101
Paiao GD, Fernández FG, Naeve SL (2021) Drainage conditions influence corn-nitrogen management in the US Upper Midwest. Agronomy 11(12):2491. https://doi.org/10.3390/agronomy11122491
Pan J, Sharif R, Xu X, Chen X (2021) Mechanisms of waterlogging tolerance in plants: Research progress and prospects. Front Plant Sci 11:627331. https://doi.org/10.3389/fpls.2020.627331
Pryor SC, Barthelmie RJ, Schoof JT (2013) High-resolution projections of climate-related risks for the Midwestern USA. Clim Res 56:61–79. https://doi.org/10.3354/cr01143
Robertson GP, Vitousek PM (2009) Nitrogen in agriculture: balancing the cost of an essential resource. Annu Rev Environ Resour 34:97–125. https://doi.org/10.1146/annurev.environ.032108.105046
Soil Quality Test Kit Guide, United States Department of Agriculture (2025). https://efotg.sc.egov.usda.gov/references/public/WI/Soil_Quality_Test_Kit_Guide.pdf
Suo R, Sandhu K, Wang M, You F, Conner R, Cober E, Hou A (2022) Soybean (*Glycine max* L.) seed germination in response to waterlogging and cold climate: a review on the genetics and molecular mechanisms of resistance to the abiotic stress. Can J Plant Sci 103(1):13–28. https://doi.org/10.1139/cjps-2022-0111
Urban DW, Sheffield J, Lobell DB (2015) The impacts of future climate and carbon dioxide changes on the average and variability of US maize yields under two emission

scenarios. Environ Res Lett 10(4):045003. https://doi.org/10.1088/1748-9326/10/4/045003

Vashisht D, Hesselink A, Pierik R, Ammerlaan JMH, Bailey-Serres J, Visser EJW, Pedersen O, Van Zanten M, Vreugdenhil D, Jamar DCL, Voesenek LACJ (2011) Natural variation of submergence tolerance among *Arabidopsis thaliana* accessions. New Phytol 190(2):299–310

Walthall CL, Hatfield J, Backlund P, Lengnick L, Marshall E, Walsh M, Adkins S, Aillery M, Ainsworth EA, Ammann C, Anderson CJ, Bartomeus I, Baumgard LH, Booker F, Bradley B, Blumenthal DM, Bunce J, Burkey K, Dabney SM . . . Ziska LH (2013) Climate change and agriculture in the United States: Effects and adaptation (USDA Technical Bulletin 1935). United States Department of Agriculture

Wenkert W, Fausey NR, Watters HD (1981) Flooding responses in *Zea mays* L. Plant Soil 62(3):351–366. https://doi.org/10.1007/BF02374133

Wiebold B (2013) Heavy rain excludes oxygen needed for seedling health from soils. Integrated Pest and Crop Management University of Missouri

Wuebker EF, Mullen RE, Koehler K (2001) Flooding and temperature effects on soybean germination. Crop Sci 41(6):1857–1861. https://doi.org/10.2135/cropsci2001.1857

Wu C, Florez-Palacios L, Acuna A, Harrison D, Rogers D, Carlin J, Mozzoni L, Nguyen HT, Shannon G, Vieira CC (2025) Impact of flooding at the early reproductive growth stage on soybean yield and seed composition. Crop Sci 65(1):e21397. https://doi.org/10.1002/csc2.21397