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Insights on agricultural nitrate leaching from soil block mesocosms

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Abstract
Quantifying nitrate leaching in agricultural fields is often complicated by inability to capture all water draining through a specific area. We designed and tested undisturbed soil monoliths (termed "soil block mesocosms") to achieve complete collection of drainage. Each mesocosm measures 1.5 m × 1.5 m × 1.2 m and is enclosed by steel on the sides and bottom with a single outlet to collect drainage. We compared measurements from replicate mesocosms planted to corn (*Zea mays* L.) with a nearby field experiment with tile-drained plots ("drainage plots"), and with drainage from nearby watersheds from 2020 through 2022 under drought conditions. Annual mesocosm drainage volumes were 6.5–24.6 cm greater than from the drainage plots, likely because the mesocosms were isolated from the subsoil and could not store groundwater below the drain depth, whereas the drainage plots accumulated infiltration as groundwater. Thus, we obtained consistent nitrate leaching measurements from the mesocosms even when some drainage plots yielded no water. Despite drainage volume differences, mean flow-weighted nitrate concentrations were similar between mesocosms and drainage plots in 2 of 3 years. Mesocosm annual drainage volume was 8.7 cm lower to 16.7 cm higher than watershed drainage, likely due to lagged influences of groundwater. Corn yields were lower in mesocosms than drainage plots in 2020, but with irrigation, yields were similar in subsequent years. Mean 2020 surface soil moisture and temperature were similar between the mesocosms and nearby fields. Based on these comparisons, the mesocosms provide a robust method to measure nitrate leaching with lower variability than field plots.

Plain Language Summary
Nitrate leaching is a major cause of water pollution, but it is challenging to measure. We tested a method to measure nitrate leaching by enclosing blocks of soil within a

Abbreviation: CV, coefficient of variation.

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field in steel boxes, each with a single drain for water quality monitoring. Boxes were open at the surface, enabling us to grow corn. These "soil block mesocosms" enabled more precise and timely measurements of nitrate leaching than we could achieve in field plots with subsurface tile drainage pipes. Mesocosm corn plants suffered from drought stress in dry years, but with irrigation, we could achieve corn yields similar to field plots. The mesocosms are a promising method to test water quality benefits of practice changes.

1 | INTRODUCTION

Nitrogen (N) in agricultural fertilizer impacts water quality, climate, and human health through environmental losses. Less than half of applied N is typically recovered in the crop, while the remainder is retained in soil or lost through gaseous emissions or nitrate leaching (Gardner & Drinkwater, 2009; Poffenbarger et al., 2018). Quantifying nitrate leaching is often challenged by the inability to measure the complete volume and nitrate concentration of water that drains through a specific area of soil. Given ongoing agricultural expansion, intensification, and increased reliance on N fertilizer (Cao et al., 2018; Lark et al., 2015), it is important to understand nitrate leaching patterns and relationships with management. Numerous methods have been developed to quantify the volume and chemical composition of water draining from agricultural fields. To measure nitrate in soil water, techniques such as soil cores and tension or zero-tension lysimeters have been utilized. The accuracy of these approaches depends on capturing spatially and temporally variable soil water fluxes and nitrate concentrations representative of the studied area. Estimates of total nitrate losses based on soil water measurements can vary widely, especially as infiltration and fertilizer application increase (Zotarelli et al., 2007). Alternatively, water can be sampled from artificial drainage systems commonly installed to enable crop production in poorly drained soils. For example, measurements from tile lines that drain individual field research plots have long been utilized to study nutrient leaching (Baker et al., 1975). Although tile drainage studies have been crucial in helping to establish relationships between management practices and nutrient losses (Lawlor et al., 2008; Waring et al., 2022), there are several potential limitations.

Drainage from individual tiles may contain water derived from multiple plots, and lateral drainage between plots could complicate efforts to detect specific management effects. Although border tiles between plots have been used to reduce water mixing (Helmers et al., 2012; Lawlor et al., 2008), this prevents capture of the entire water volume draining from a plot, and the volume and chemical composition of drainage lost to the border tiles may not be representative of the total flux. Furthermore, border tiles do not necessarily eliminate lateral mixing between drainage plots, as suggested by highly variable water yields among plots at a single site (Lawlor et al., 2008). Additionally, water collected from drainage tiles may be a mixture of infiltrating soil water and groundwater (Williams & McAfee, 2021), complicating interpretations of management effects. Groundwater could store infiltrating nitrate during dry years and release it to tile drains during wet years, obscuring the short-term response of nitrate leaching to management change. Factors such as transient groundwater storage and differences in drainage volume among experimental plots can result in similar nitrate yields among plots managed under vastly different N rates (Helmers et al., 2012). Consequently, researchers have often focused on flow-weighted nitrate concentrations instead of nitrate yields when evaluating management effects (Helmers et al., 2012; Lagzdins et al., 2016).

Apart from tile drainage plots, other investigators have enclosed large volumes of soil to construct massive monolith mesocosms sometimes referred to as lysimeters. These have typical depths of 1.5–2.4 m and surface areas of 1–8.1 m^2, and drainage is typically measured at a single outlet (Jia et al., 2014; Logsdon et al., 2002; Ostrom et al., 1998; Owens et al., 2000). These studies demonstrated the utility of mesocosms in capturing differences in nitrate leaching across different management scenarios. However, mesocosm designs differ in their soil disturbance. One method entails building large boxes and backfilling with soil (Jia et al., 2006, 2014), enabling straightforward construction of large mesocosms, but with severe soil disturbance. Others devised ways to enclose and/or harvest intact blocks of soil, thus minimizing disturbance (Brown et al., 1974; Harrold & Dreibelbis, 1951; Logsdon et al., 2002; Ostrom et al., 1998; Schneider et al., 1988). Trenches can be dug around a block of soil before placing the mesocosm walls or frame by a combination of cement bags and body weight and inserting a floor beneath the frame (Harrold & Dreibelbis, 1951; Logsdon et al., 2002; Ostrom et al., 1998). Although construction equipment has been used to push a frame over the soil prior to installing the walls and bottom (Schneider et al., 1988), in most studies trenches were laboriously dug with shovels around the soil block to reduce disturbance, before frame walls constructed from welded steel or poured concrete were inserted

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(Brown et al., 1974; Harrold & Dreibelbis, 1951; Schneider et al., 1988). For example, the massive (8.1-m^2 area and 2.4-m deep) "Coshocton" lysimeters constructed in 1937–1940 have long been utilized to measure nitrate leaching, although with limited replication (n = 4; Owens et al., 2000).

Given the challenges of assembling a leak-proof structure around an intact, in situ block of soil, we developed a new method of mesocosm construction to measure nutrient leaching. We inserted a welded four-sided steel lysimeter frame into undisturbed soil through vibration with a pile driver, prior to digging any trenches, to ensure minimal disturbance of the soil profile inside the mesocosm. Then, a trench was dug along one side of the mesocosm to allow installation of a steel plate on the bottom. Each soil block mesocosm ("mesocosm") was fitted with a single pipe at the bottom to enable complete collection of drainage water. In this paper, we asked the following questions: (1) How do mesocosm drainage volumes compare with nearby tile-drained plots ("drainage plots") and watersheds, and how does mesocosm nitrate leaching magnitude compare with drainage plots? (2) How does variability among replicates compare between the mesocosms and drainage plots? (3) How do mesocosm corn (*Zea mays* L.) grain yields compare to drainage plots? and (4) How do moisture and temperature in mesocosm surface soils compare to nearby agricultural fields?

Core Ideas

- We tested a new field study design to measure drainage from undisturbed soil mesocosms planted to corn.
- Annual mesocosm drainage was higher than drainage plots but lower or higher than nearby watersheds during drought.
- Drainage and nitrate differences among mesocosms and drainage plots were likely due to groundwater storage.
- Corn yields from mesocosms and drainage plots were equivalent when irrigation was applied.
- The mesocosm design reduced variability in drainage and nitrate leaching measurements relative to drainage plots.

2 | MATERIALS AND METHODS

2.1 | Soil selection

We used two contrasting soil types (Clarion and Webster) characteristic of north-central Iowa and southern Minnesota. Clarion is a moderately well-drained upland soil (fine-loamy, mixed, superactive, and mesic Typic Hapludolls), whereas Webster is a poorly drained soil (fine-loamy, mixed, superactive, and mesic Typic Endoaquolls). The Webster soil was collected at 42.019 ˚N, 93.772 ˚W, and the Clarion soil at 41.928 ˚N, 93.761 ˚W. Soils were under long-term corn and soybean (*Glycine max* L.) production with conventional management practices. Samples taken from the wall of the trench formed during mesocosm excavation confirmed that the Clarion soil surface (top 15 cm) had a lower bulk density, organic carbon, total N, and pH than the Webster soil, using methods described by Huang et al. (2023) (Figure S1).

2.2 | Mesocosm construction

Each mesocosm consisted of an intact 1.5 × 1.5 × 1.2-m soil monolith enclosed on the sides and bottom in a welded steel box fitted with a single pipe for drainage collection. A depth of 1.2 m was chosen because it is the typical depth of field drainage tile in north-central Iowa. Additionally, most corn roots are in the first meter of soil (Ordóñez et al., 2021). Encasing soils in steel with minimal disturbance was accomplished by sliding the box walls (Figure 1a) into undisturbed soil using a vibratory pile driver mounted on a tracked excavator. The four walls of the box were temporarily bolted to a steel lid attached to the pile driver. The lid was removed after inserting the box into the soil. Box walls are extended 10 cm above the soil surface to prevent loss and mixing of soil. For each soil type, 18 boxes were inserted into the ground along a linear transect, with approximately 1.5 m distance between each box. Then, a trench was excavated along one side of the boxes so that a steel sheet could be inserted flush underneath the box walls using the edge of the excavator bucket. The remaining soil between each individual box along the transect was then excavated so that the bottom could be tack-welded to the box walls. Next, the mesocosms were lifted by crane to a flatbed truck, where the weld connecting the bottom and walls of each box was completed, and transported to the Iowa State University Agricultural Engineering and Agronomy Research Farm near Boone, IA. The mesocosms were then placed into a 1-m deep trench and soil was backfilled around the boxes (Figure 1b). The lip of the steel walls protruded approximately 20 cm above the surrounding soil (Figure 1c). Webster mesocosms were harvested on October 19–20, 2018, and Clarion mesocosms on May 20–21, 2019. We recognize that vibrating the steel boxes into the soil may have resulted in localized soil compaction very close to the mesocosm walls (Bement & Selby, 1997). However, visual examination of the exterior soil during the box installation indicated that effects of vibration were confined within cm of the box wall. Furthermore, the impact of box installation is likely small when compared to the routine vibration and compression of soil by heavy equipment during field operations (Barik et al., 2014).

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FIGURE 1 Soil block mesocosm harvest (a), placement of mesocosms in trenches at the study site (b), and completed mesocosms planted to corn (c).

2.3 | Drainage collection

A slotted stainless steel well point (4.8-cm diameter) was inserted into each box through a hole drilled 8 cm above the box bottom, where a 4-cm diameter schedule 80 PVC pipe was connected and temporarily capped. We observed surface water ponding in all mesocosms following rain, indicating leakproof systems. All mesocosm drainage tubes were run toward a pit in the middle of the site where two corrugated steel grain silos (4.3-m diameter, 4.9-m height, termed "sumps") were installed 3 m below the ground surface and 20 cm of crushed rock was added to the sump bottoms. Holes were cut in the sump walls to accommodate PVC pipes routed from each mesocosm (Figure 2c,d). Below the sumps, a 10-cm diameter tile was installed to remove mesocosm drainage water after measurement as described below. The pipe draining each mesocosm was connected to a 22.7-L bucket (high-density polyethylene, [HDPE]) with vinyl tubing (2.5-cm diameter) inserted through a hole in the bucket lid, with a separate hole in the lid for pressure equilibration.

Following rain and snowmelt, buckets were examined for drainage. If any bucket had >5 L of water (approximately 0.22 cm of drainage) or if >2 weeks had passed since prior measurement, all volumes were measured, subsamples were collected in 60-mL HDPE bottles, and buckets were emptied. In the lab, water samples were acidified with 0.5 mL of 12 M hydrochloric acid. Starting on November 11, 2021, a pump (Little Giant VCMA-20ULS Franklin Electric) was placed in each bucket in series with a water meter (Dwyer WVT vertical water meter) to automatically measure cumulative drainage volume and collect a flow-proportional subsample through a needle valve in a 1-L HDPE bottle. Drainage volumes were recorded from the water meters weekly or after rain. Drainage subsamples were transferred to 60-mL bottles for acidification and storage as described above. For all drainage sub-samples taken before February 2020, nitrate was quantified using colorimetric microplate analysis (Doane & Horwáth, 2003). Starting in March 2020, nitrate was quantified using second derivative spectrophotometry (Crumpton et al., 1992). A subset of samples was analyzed by both methods, with similar results (R^2 = 0.97; Huang et al., 2023). Flow-weighted nitrate was calculated as cumulative nitrate yield divided by cumulative drainage. Water collection buckets were tipped over on June 6, 2022, so samples on this date were excluded from all calculations.

2.4 | Agronomic management

Mesocosm management was similar to common Midwest corn agricultural practices (Cao et al., 2018; USDA NASS, 2020). Prior to planting, mesocosms were tilled with a rototiller and shovel to approximately 20-cm depth. N fertilizer was applied as granular urea immediately prior to planting and incorporated with a shovel and rake. Mesocosms received different N fertilizer rates; here, we report N leaching data from the 12 mesocosms with the highest N rates (202 kg N ha^{-1} in 2020, and 212 kg N ha^{-1} in 2021 and 2022), which are on average most comparable to the drainage plot experiment described below. Half of the mesocosms at each fertilizer rate also received an amendment of nitrogen-fixing bacteria (Pivot Bio ProveN) applied to corn seeds at planting according to manufacturer instructions. Here, we report the average values of response variables (nitrate leaching and grain yield) for each soil type at the highest synthetic N fertilizer rate as a proof of concept for the mesocosm design. Within the mesocosms, we doubled-planted corn by hand with row spacing of 76.2 cm and thinned excess plants at V4 to 15,352 plants ha^{-1} (Table S1), for approximately 11 plants per row spaced approximately 12.5 cm apart.

Corn was planted in early to mid-May and harvested in late September or early October (see Table S1 for further details, including hybrid type). All ears and aboveground biomass were collected and immediately weighted from each

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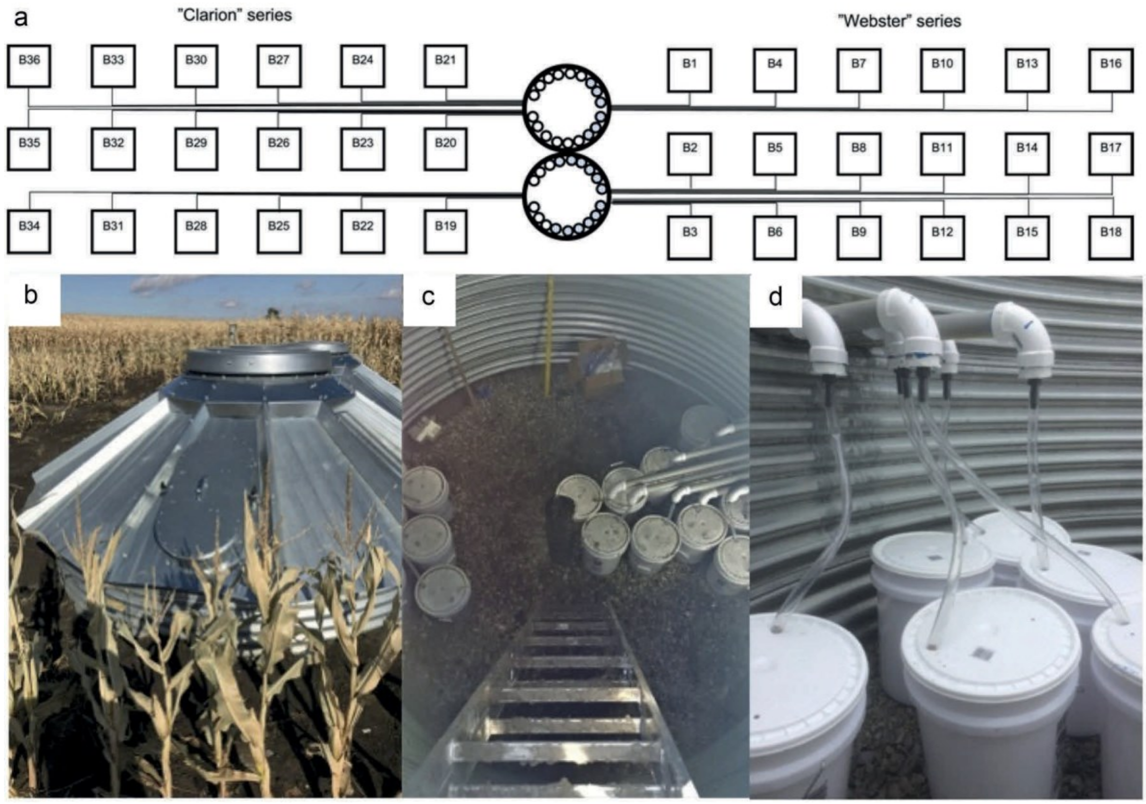

FIGURE 2 Layout of soil block mesocosms (squares) and drainage infrastructure, where lines represent drainage pipes, the large circles in the center represent the large sumps, and the small circles represent sampling containers to collect drainage from each mesocosm (a), the outside of one of the sumps used for drainage collection (b), top-down view inside of a sump showing individual buckets for water collection from each mesocosm (c), and connection of drainage pipes to the buckets used for drainage collection and sampling (d).

mesocosm. To calculate dry mass, five grain ears and a mixed subsample of above-ground biomass were dried at 60˚C. Grain yields in 2020 were low, likely due to drought stress. When low precipitation continued in 2021, the mesocosms were irrigated with well water (with negligible nitrate) approximately weekly from June through August, for a total of 12.1 cm. In 2022, irrigation was applied twice in August, for a total of 3.2 cm. Water was uniformly applied to each mesocosm with a hose. The first time the mesocosms were irrigated (June 4, 2021), 2.54 cm of irrigation was applied, which may have partially contributed to 0.9 cm of drainage measured over June 7–18, 2021. Consequently, starting on June 11, 2021, for all subsequent irrigation events, we used 1.3–1.6 cm of well water. Irrigation was applied from June 4 to August 18, 2021. From June 19 to October 25, 2021, the mesocosms did not drain water, nor did they drain water in August 2022, when irrigation was applied on August 11 and 25. Accordingly, most irrigation was likely lost as evapotranspiration rather than contributing to subsequent drainage.

2.5 | Soil temperature and moisture

Soil moisture and temperature were measured at 0- to 10-cm depth in each mesocosm between 08:00 and 12:00 Central Time approximately weekly from March through November, using a handheld soil moisture sensor (HydraSense; Campbell Scientific) and a digital thermometer. Mesocosm measurements were compared with measurements made in nearby fields planted to corn or soybean in 2020, where soils were mapped as Webster (described above), as well as Canisteo (fine-loamy, mixed, superactive calcareous, mesic Typic Endoaquolls), or Nicollet (fine-loamy, mixed, superactive, mesic Aquic Hapludolls). Comparisons were made between the Webster mesocosms and nearby fields, as there were no Clarion soils in the fields where moisture and temperature were measured.

2.6 | Additional datasets

We compared the mesocosms data with a nearby drainage plot experiment, the Comparison of Biofuel Cropping Systems (COBS) established in 2009 and located 11 km south of the mesocosms, and with nearby streams (denoted as KS and RS) draining agricultural watersheds dominated by corn and soybean fields located within 30 km of the mesocosms. The COBS plots measured 27 m × 61 m, with central individual tile drains installed at 1.1-m depth and border tiles to increase hydrologic separation. We only used data from

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continuous corn plots (n = 4), which were fertilized at 179 kg N ha^{-1} in 2020, 224 kg N ha^{-1} in 2021, and 207 kg N ha^{-1} in 2022. Drainage volume and nitrate concentration were monitored from March through December, and corn yield was measured by randomly sampling six to eight plants from a 3-m length of one row in each quadrant of each plot (Daigh et al., 2015). Drainage from the RS and KS watersheds was measured by either velocimeters or weirs and normalized by their areas (300 and 460 ha, respectively; Cao et al., 2023; Crumpton et al., 2020). Neither COBS nor the mesocosm study site is in the KS or RS watersheds.

A station in the Iowa State University Soil Moisture Monitoring Network located 0.8 km from the mesocosms (42.021 ˚N, 93.774 ˚W) was utilized to determine precipitation, including rain and liquid snow fall equivalent. Data from that station only began in 2013, so data were utilized from an additional station located slightly further away to determine long-term (1989–2019) average precipitation (42.030 ˚N, 93.800 ˚W). Direct measurements of precipitation were not available for COBS and the watershed monitoring locations, so precipitation was estimated using Iowa Environmental Mesonet (https://mesonet.agron.iastate.edu). To examine how well estimated precipitation aligned with measured precipitation, precipitation was also estimated for the soil block mesocosm site in addition to the measurements from the monitoring network.

3 | RESULTS AND DISCUSSION

3.1 | Comparison of mesocosm drainage with field plots and watersheds

Drought conditions occurred every year of the study, during which mesocosm drainage differed markedly from COBS and the watersheds (KS and RS). The magnitude of these differences varied among years and was likely impacted by differences in annual precipitation and by possible delays in the response of drainage to changes in precipitation due to differing roles of groundwater. Annual precipitation at the mesocosm site measured 54, 60, and 70 cm in 2020 through 2022, respectively (Figure 3a–c), which all were lower than the 30-year average of 91 cm. Of this precipitation, 16, 13, and 28 cm occurred before planting in 2020 through 2022, respectively. Estimated annual precipitation varied by 0.5–16.9 cm among the various study sites. However, these site differences were within the range of differences between measured and estimated precipitation (7.8–17.0 cm) for the mesocosm site (Figure 3a–c; Table 1).

Cumulative annual drainage differed among the mesocosms, COBS, and watersheds (Figure 3d–f; Table 1). The largest differences were between the mesocosms and COBS,

TABLE 1 Annual precipitation and drainage at the mesocosms (Clarion and Webster), Biofuel Cropping Systems (COBS), and KS and RS watersheds. Values show the mean ± standard error (n = 18 for Clarion and Webster and n = 4 for COBS for all years).

Site	Measured or estimated precipitation + irrigation[a,b]			Cumulative drainage			Cumulative drainage CV			Drainage percent of precipitation + irrigation		
	Study year											
	2020 (cm)	2021 (cm)	2022 (cm)	2020 (cm)	2021 (cm)	2022 (cm)	2020 (%)	2021 (%)	2022 (%)	2020 (%)	2021 (%)	2022 (%)
Clarion	54.2	59.8 + 12.1	69.7 + 3.2	13.1 ± 0.4aB	13.8 ± 0.3aB	34.0 ± 0.9aA	13	10	11	24	19	47
Webster	54.2	59.8 + 12.1	69.7 + 3.2	11.7 ± 0.7aC	14.3 ± 0.4aB	34.5 ± 0.8aA	26	12	10	22	20	47
COBS	66.5	71.7	82.2	5.2 ± 2.3bAB	0.2 ± 0.1bB	9.9 ± 2.3bA	87	131	45	8	0.2	12
KS	78.9	72.9	81.2	21.8	5.5	20.0	–	–	–	28	8	25
RS	73.1	71.9	89.2	22.0	5.2	17.8	–	–	–	30	7	20

Note: Letters indicate significant differences at p = 0.05 with a Tukey test. Values which share a lower-case letter were not significantly different within the column for that respective year. Values which share an upper-case letter were not significantly different within the row for that respective site (i.e., Clarion, Webster, and COBS).

Abbreviation: CV, coefficient of variation.

[a]Precipitation was measured within 1 km of the mesocosms and was estimated using the Iowa Mesonet for the other sites. For the mesocosms, estimated precipitation was 8, 17, and 15 cm greater than measured precipitation in 2020, 2021, and 2022, respectively.

[b]Irrigation applied to the mesocosms in 2021 and 2022 is denoted by the number following the plus sign.

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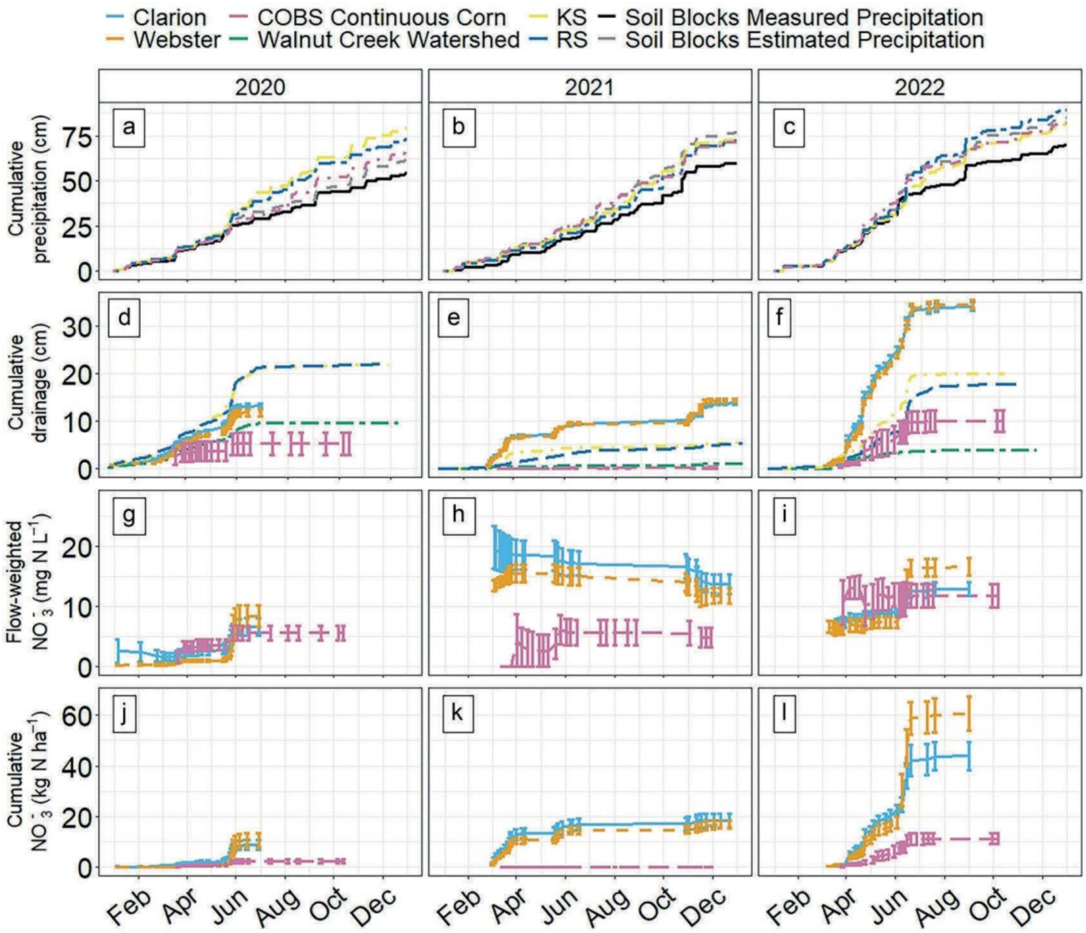

FIGURE 3 Cumulative precipitation (a–c), cumulative drainage (d–f), flow-weighted nitrate concentrations (g–i), and cumulative nitrate yields (j–l) from the soil block mesocosms, Biofuel Cropping Systems (COBS) drainage plots, and watersheds (KS and RS). For panels d–f, $n = 18$ for Clarion and Webster mesocosms and $n = 4$ for the COBS plots. For panels g–l, $n = 6$ for Clarion and Webster mesocosms and $n = 4$ for the COBS plots.

with COBS drainage measuring 6.5–24.6 cm lower than the mesocosms ($p < 0.05$). Differences were especially striking in 2021, when after two successive dry summers, COBS had almost no drainage (mean of 0.2 cm), whereas the mesocosms drained about 14 cm (Figure 3d–f; Table 1). Mesocosm drainage was generally more similar to watershed drainage. In 2020, the KS and RS watersheds had 8.7–10.3 cm greater drainage than the mesocosms, although this pattern was reversed in subsequent years, when the mesocosm drainage was 8.3–16.7 cm greater than in the watersheds. The two mesocosm soil types (Clarion and Webster) had very similar cumulative drainage within each year, differing by only 0.5–1.4 cm (Table 1).

Annual flow-weighted mean nitrate concentrations in the mesocosms tended to be similar or greater than COBS, though the magnitude of the difference varied among years and mesocosm soil types (Figure 3g–i; Table 2). Mesocosm flow-weighted nitrate ranged from 6.7 ± 1.4 to 16.6 ± 1.5 mg N L^{-1}, within the range of drainage plots in Iowa planted to corn-soybean rotations and continuous corn (5.0–28.7 mg N L^{-1}, Lawlor et al. [2008]; 11.4–30.3 mg N L^{-1}, Bakhsh et al. [2010]). Differences in flow-weighted drainage nitrate concentration between COBS and either mesocosm soil type in 2020 and 2022 were relatively small, between 1.1 and 3.7 mg L^{-1}, and not significant at $p < 0.05$ (Figure 3g–h; Table 2), but in 2021, the Clarion and Webster mesocosms had about twice the flow-weighted nitrate concentration of COBS ($p = 0.004$ and $p = 0.02$ for Clarion and Webster, respectively; Table 2). Differences may have been due to the extremely low COBS drainage volume that year, which was likely insufficient to leach accumulated nitrate. Because of greater drainage volumes, cumulative annual nitrate yields were greater in the mesocosms than in COBS during 2020–2022 though not significantly so in 2020 (Table 2). The difference was greatest in 2022, when nitrate yields were approximately 33 and 49 kg N ha^{-1} greater in the Clarion and Webster mesocosms, respectively, than in COBS. However, nitrate yields in mesocosm drainage were within the range of other studies with similar

TABLE 2 Flow-weighted nitrate concentrations in drainage from the Clarion and Webster mesocosms and Biofuel Cropping Systems (COBS). Values show the mean ± standard errors and coefficient of variations (CVs) with $n = 6$ for Clarion, $n = 6$ for Webster, and COBS $n = 4$.

Site	Flow-weighted NO_3^- concentration			Flow-weighted NO_3^- concentration CV			Cumulative NO_3^- yield			Cumulative NO_3^- yield CV		
	Study year											
	2020 (mg N L^{-1})	2021 (mg N L^{-1})	2022 (mg N L^{-1})	2020 (%)	2021 (%)	2022 (%)	2020 (kg N ha^{-1})	2021 (kg N ha^{-1})	2022 (kg N ha^{-1})	2020 (%)	2021 (%)	2022 (%)
Clarion	6.7 ± 1.4aB	13.7 ± 1.6aA	12.9 ± 1.1aA	53	28	20	8.9 ± 1.9aB	18.4 ± 2.7aB	43.9 ± 5.6aA	52	35	31
Webster	8.4 ± 1.8aB	11.8 ± 1.2aAB	16.6 ± 1.5aA	54	26	22	10.7 ± 2.7aB	16.9 ± 1.6aB	60.6 ± 6.8aA	63	24	27
COBS	5.6 ± 1.2aAB	4.9 ± 1.6bB	11.9 ± 1.9aA	42	67	33	2.4 ± 0.7aB	0.1 ± 0.1bB	11.3 ± 2.3bA	54	132	40

Note: Letters indicate significant difference at $p = 0.05$ with a Tukey test. Values which share a lower-case letter were not significantly different within the column for that respective year. Values which share an upper-case letter were not significantly different within the row for that respective site (i.e., Clarion, Webster, and COBS).

fertilizer N application rates (2–63 kg N ha^{-1} year^{-1}; Lawlor et al., 2008).

Differences in drainage volume among the mesocosms, COBS, and watersheds indicate likely influences of shallow groundwater, in addition to factors such as drainage intensity (Kladivko & Bowling, 2021) (Figure 3d–f). During dry periods, groundwater can decrease below the depth of field tiles due to evapotranspiration and lateral flow (Eidem et al., 1999; James & Fenton, 1993). In tile-drained fields, infiltration following a dry period can accumulate as groundwater, rather than draining through tiles, until groundwater rises to the tile depth. Conversely, shallower water tables can increase nitrate leaching and crop yields (Elli & Archontoulis, 2023). The mesocosms are isolated from groundwater, so groundwater storage and groundwater loss through evapotranspiration do not impact mesocosm measurements of drainage and nitrate leaching. This likely explains why the mesocosms had higher drainage than COBS in all 3 years and higher drainage than KS and RS watersheds in 2021 and 2022, when a larger fraction of precipitation was likely stored as groundwater rather than exported in drainage (Figure 3d–f).

Groundwater storage and mixing with soil water may have delayed the response of drainage and nitrate yields to precipitation changes in COBS and the watersheds. This explanation is consistent with markedly lower drainage from COBS and the watersheds in 2021 than 2020, despite similar precipitation (Figure 3d–e). Conversely, mesocosm drainage volume and nitrate concentration responded to changes in precipitation within and among years (Figure 3d–e). This was especially evident in 2021 and 2022, where drainage and flow-weighted nitrate concentrations in the mesocosms responded rapidly to spring and early summer rainfall, whereas little drainage and little change in flow-weighted nitrate were observed in COBS, likely due to rainfall storage as groundwater (Figure 3f,i). Newly infiltrating soil water may have different nitrate concentrations than shallow groundwater, as a previous study in the area found that groundwater mean nitrate N concentration at 1.5–3.0 m (10.3 mg L^{-1}) was nearly twice that at 0.9–1.5 m (5.7 mg L^{-1}; Cambardella et al., 1999). The mixing of new water and older groundwater may have decreased the temporal variability of flow-weighted nitrate in drainage from COBS. Similarly, the KS and RS watershed drainage volumes responded more slowly than the mesocosms to spring 2022 precipitation, consistent with findings that drainage volume from three different Iowa Rivers was influenced by both the current and the previous year's precipitation (Wolf et al., 2020). Thus, the mesocosm measurements may more closely reflect the volume and composition of recent drainage from the soil profile, whereas tile drainage measurements following dry periods likely reflect the storage and mixing of soil water with groundwater.

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3.2 | Variation among replicate mesocosms and drainage-plots

The mesocosms had lower variation in cumulative drainage among replicates than COBS in all years (Table 1). The cumulative annual drainage coefficient of variation (CV, defined as the standard deviation divided by the mean) was 9%–13% in the Clarion mesocosms and 9%–26% in the Webster mesocosms (Table 1), compared to 45%–87% in COBS (Table 1). The lower CV of the mesocosms versus the COBS plots was not simply a result of differing sample size. To illustrate this, we subsampled measured drainage values at varying levels of replication and found minor and inconsistent trends between CV and the number of replicates (Figure S2). Differences in the variation in cumulative nitrate yields between the mesocosms and COBS varied over the years. The cumulative nitrate yield CV was 31%–52% in the Clarion mesocosms and 24%–63% in the Webster mesocosms (Table 2). This was generally lower than the corresponding cumulative nitrate yield CV in COBS, which was 54%–132% (Table 2). In 2021, cumulative nitrate yields in COBS were highly variable with a CV of 132%, as one plot had no drainage. Even excluding that plot, the CV of cumulative nitrate yields was still higher than the mesocosms (105%).

Previous studies were often challenged by large differences in drainage among plots due to interactions with groundwater and lateral flow (Bakhsh et al., 2010; Lawlor et al., 2008). By enclosing the mesocosms, we standardized the drainage area and removed groundwater interactions and lateral flow, which likely explains decreased CV of drainage and nitrate concentration relative to COBS. Perhaps due in part to the hydrologic variability of drainage plots, some previous drainage studies did not find consistent differences among treatments such as crop type or N rate (Bakhsh et al., 2010; Lawlor et al., 2008). The mesocosm soil types did not significantly differ in nitrate concentrations or yields, but replicate variability was lower than COBS, and drainage was more responsive to rainfall events.

3.3 | Comparison of corn yields from the mesocosms with field plots

Just as groundwater can influence drainage, groundwater can contribute to stable yields during drought (Elli & Archontoulis, 2023; Rizzo et al., 2018). In 2020, grain yields from the mesocosms were significantly lower than COBS by 2.1–2.5 Mg ha^{-1} ($p < 0.05$), but in 2021 the difference was only 0.8–1.0 Mg ha^{-1} ($p > 0.21$), and in 2022 grain yields were 0.3–1.1 Mg ha^{-1} greater ($p > 0.26$) from the mesocosms than COBS (Figure 4a–c; Table S2). We suspect that the 13.3 cm of

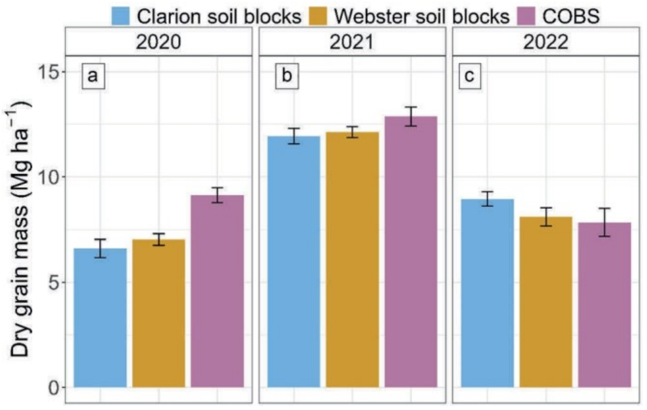

FIGURE 4 Mean dry grain yields from the Clarion and Webster soil block mesocosms and Biofuel Cropping Systems (COBS) drainage plots. Error bars indicate standard errors (n = 6 for Clarion and Webster soil blocks, and n = 4 for COBS).

irrigation applied to the mesocosms in 2021 helped maintain nearly equivalent yields relative to COBS, where groundwater presumably supplemented evapotranspiration. In another study, groundwater improved corn yields by 6% under normal precipitation and as much as 24% during drought (Rizzo et al., 2018). While groundwater can buffer drought stress, groundwater storage can be depleted, especially under warming conditions as evapotranspiration increases (Condon et al., 2020). Depletion of shallow groundwater at the COBS site during the multi-year drought could explain decreased grain yields in 2022 relative to 2021. We sparingly irrigated the mesocosms in 2022 because of greater precipitation early in the growing season, and although yields were likely suppressed by hot and dry weather in early August, they were still greater on average in the mesocosms than in COBS (Figure 4c), likely due to 3.2 cm of August irrigation. Grain yields from the Clarion mesocosms and Webster mesocosms were similar, within 0.8 Mg ha^{-1} year^{-1}, throughout the study ($p > 0.37$ all years, Figure 4a–c).

By isolating the top 1.2 m of soil from shallow groundwater, our mesocosm design enabled rigorous measurements of nitrate leaching, with the drawback of increased plant drought stress during dry years. Previous mesocosm studies either utilized only irrigation and shielded their mesocosms from all precipitation (Jia et al., 2014; Logsdon et al., 2002) or made no mention of irrigation (Brown et al., 1974; Ostrom et al., 1998; Owens et al., 2000). Timely irrigation may be critical to sustain crop productivity in mesocosms that attempt to replicate fields where groundwater can supplement evapotranspiration. Despite challenges in unpredictable precipitation and anticipating crop water needs, we achieved reasonable crop yields in all years, and thus included the key effects of corn growth and harvest on the N balance.

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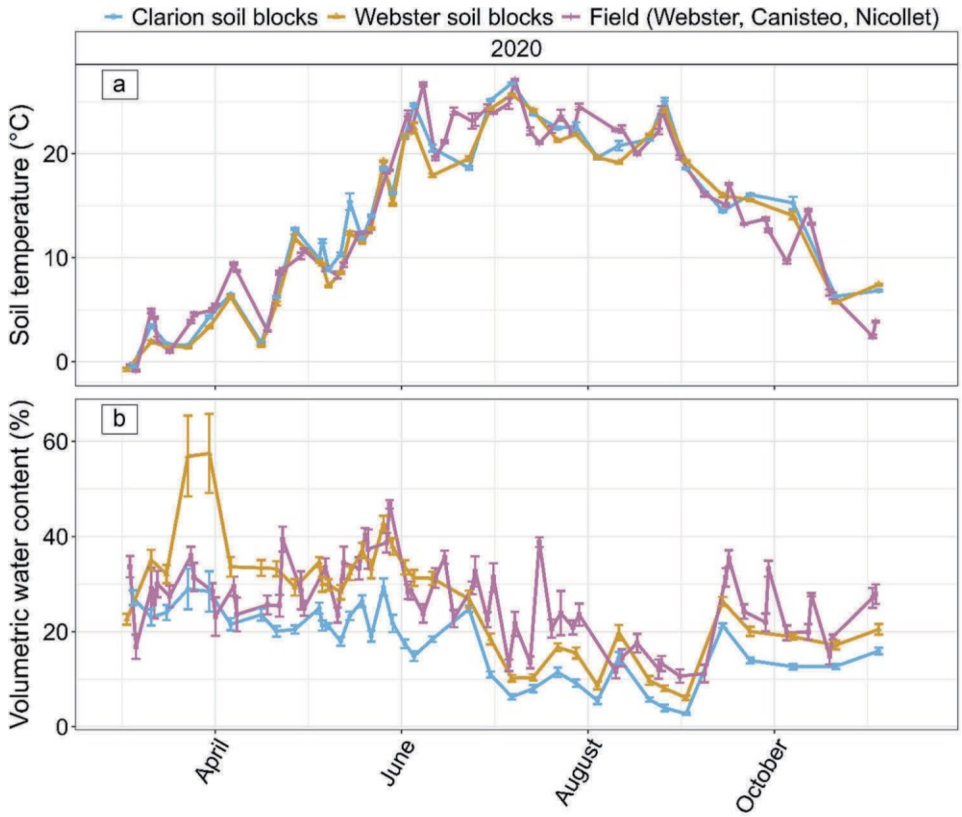

FIGURE 5 Surface soil moisture and temperature (0–10 cm) of the mesocosms and nearby fields for 2020. Points are the means of measurements and lines represent the standard error for that day, with $n = 18$ for Clarion and Webster soil blocks, and $n = 10$ or 5 for the field plots, depending on the day.

3.4 | Comparison of surface soil moisture and temperature between the mesocosms and nearby fields

Without groundwater access, the mesocosms might be expected to have higher surface soil temperature and lower surface soil moisture than fields, potentially impacting N-cycling processes such as mineralization or nitrification, which tend to be greatest in surface soil (Cambardella et al., 1999). However, surface moisture and temperature in the Webster mesocosms were generally comparable to nearby field soils in 2020, with only brief periods of higher or lower moisture (Figure 5a,b). Mean volumetric water content (soil moisture) and mean temperature of the upper 10 cm of soil in the nearby agricultural fields (25.2% and 14.5˚C) was only slightly different ($p = 0.11$ and $p = 0.12$ for soil moisture and temperature) than the Webster mesocosms (26.7% and 13.5˚C). Differences in soil moisture were largest in March (57.5% vs. 28.5% in the Webster mesocosms and fields, respectively, Figure 5b), when the Webster mesocosms were briefly ponded (had standing water at the soil surface) following several large precipitation events. Each mesocosm functions as a discrete "watershed" with vertical drainage, and the mesocosm walls prevent lateral surface and subsurface flow that might further remove excess water, thereby increasing the frequency of ponding relative to field soils during periods of high precipitation. However, ponding following heavy or persistent rainfall is relatively common in low-lying soils such as the Webster series, even with tile drainage (Martin et al., 2019). Thus, ponding can be considered a realistic disturbance in the mesocosms, even if it might occur at greater frequency. Unsurprisingly, the sandier mesocosm soil (Clarion) had lower mean surface moisture (17.6% vs. 26.7%; $p < 0.0001$) and was less prone to ponding than the Webster soil (Figure 5b). Mean surface soil temperature did not significantly differ (14.2˚C vs. 13.5˚C for Clarion and Webster, respectfully, $p = 0.25$) between the two mesocosm soil types (Figure 5a). However, we emphasize that deeper soil moisture and temperature did likely differ between mesocosms and field plots due to varying groundwater interactions.

4 | CONCLUSION

The soil block mesocosms provide a unique opportunity to measure nutrient losses in agricultural drainage. We found that cumulative annual mesocosm drainage during a 3-year period of below-average precipitation was larger than drainage from nearby tile-drained field plots (COBS) and was smaller or larger than drainage from nearby watersheds, depending on the year. Water losses to groundwater recharge likely decreased the drainage from COBS and the watersheds as drought progressed, whereas the mesocosms were isolated from groundwater, thereby enabling drainage measurements even during dry years. Additionally, during wet periods, the mesocosms facilitated detection of potentially rapid nutrient losses without temporal buffering or mixing with groundwater, with lower variability among replicates than in COBS. Mean surface soil moisture and temperature within the mesocosms were similar to nearby fields, despite differences in hydrology. Mesocosm corn yield was lower than COBS during the first year of the study, but when irrigation was applied, mesocosm corn yield was similar to the field plots. Thus, the mesocosms present an opportunity to quantify responses of nutrient losses to management changes in future work.

AUTHOR CONTRIBUTIONS

Holly Loper: Data curation; formal analysis; investigation; writing—original draft; writing—review and editing. **Carlos Tenesaca**: Data curation; investigation; methodology; writing—review and editing. **Carl Pederson**: Investigation; methodology. **Matthew J. Helmers**: Conceptualization; funding acquisition; methodology; writing—review and editing. **William G. Crumpton**: Conceptualization; funding acquisition; methodology; writing—review and editing. **Dean Lemke**: Conceptualization; funding acquisition; methodology. **Steven J. Hall**: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; supervision; writing—original draft; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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