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Landscape and Watershed Processes

Poorly drained depressions can be hotspots of nutrient leaching from agricultural soils

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Abstract

Much of the US Corn Belt has been drained with subsurface tile to improve crop production, yet poorly drained depressions often still flood intermittently, suppressing crop growth. Impacts of depressions on field-scale nutrient leaching are unclear. Poor drainage might promote denitrification and physicochemical retention of phosphorus (P), but ample availability of water and nutrients might exacerbate nutrient leaching from cropped depressions. We monitored nitrate, ammonium, and reactive P leaching across multiple depression-to-upland transects in north-central Iowa, using resin lysimeters buried and retrieved on an annual basis. Crops included conventional corn/soybean (*Zea mays*/*Glycine max*) rotations measured at fields with and without a winter rye (*Secale cereale*) cover crop, as well as juvenile miscanthus (*Miscanthus* × *giganteus*), a perennial grass. Leaching of nitrogen (N) and P was greater in depressions than in uplands for most transects and years. The median difference in nutrient leaching between paired depressions and uplands was 56 kg N ha^{-1} $year^{-1}$ for nitrate ($p = 0.0008$), 0.6 kg N ha^{-1} $year^{-1}$ for ammonium ($p = 0.03$), and 2.4 kg P ha^{-1} $year^{-1}$ for reactive P ($p = 0.006$). Transects managed with a cover crop or miscanthus tended to have a smaller median difference in nitrate (but not ammonium or P) leaching between depressions and uplands. Cropped depressions may be disproportionate sources of N and P to downstream waters despite their generally poor drainage characteristics, and targeted management with cover crops or perennials might partially mitigate these impacts for N, but not necessarily for P.

1 | INTRODUCTION

A major proportion of the US Corn Belt has been drained with subsurface tile to enable row crop production, and these tile-drained agricultural watersheds are dominant sources of nitrogen (N) and phosphorus (P) to surface water (David et al., 2010; Helmers et al., 2012). Yet, even in landscapes with extensive tile drainage, excess moisture may routinely suppress crop yields in areas within individual fields, leading to large cumulative yield losses at regional scale

(Li et al., 2019; Martinez-Feria & Basso, 2020). These impacts are especially evident in topographic depressions, a common feature of recently glaciated landscapes such as the Prairie Pothole Region (Edmonds et al., 2021; McNunn et al., 2019). For example, closed topographic depressions comprise almost 10% of the area of Iowa's Des Moines Lobe (McDeid et al., 2018). Depressions historically supported wetland vegetation but have now mostly been drained with subsurface tile to enable row crop agriculture (Miller et al., 2009). We refer to these features as "cropped depressions" as they are not always classified as jurisdictional farmed wetlands, and to distinguish them from remnant or restored prairie pothole wetlands. Despite extensive drainage, standing water often ponds in cropped depressions for days or weeks during most growing seasons (Figure S1; Arenas et al., 2018; Martin, Kaleita et al., 2019; Schilling et al., 2018). Cropped depressions often have lower grain yield and profitability than upland soils (Edmonds et al., 2021; McNunn et al., 2019) and they might also disproportionately affect nutrient leaching. Modeling or remote sensing studies often predict greater nitrate leaching from low-yielding field areas, including depressions (Basso et al., 2019; Brandes et al., 2018; McNunn et al., 2019), but we are unaware of field measurements that have explicitly compared nutrient leaching between cropped depressions and their adjacent uplands.

In some cases, we might expect cropped depressional soils to have lower leaching of N and P than upland soils due to variation in biological and physicochemical processes with topographic position. For example, potential denitrification rates were twofold greater in surface soils of depressions than uplands in a north-central Iowa agricultural field (Cambardella et al., 1999). Also, the high calcium carbonate and clay content of depressional soils relative to uplands might provide greater P sorption and precipitation, consistent with observations of lower soil-test P in depressional than upland soils in north-central Iowa agricultural fields (Karlen et al., 2008). Finally, because of the low infiltration rates of depressional soils under saturated conditions, we might expect lower leaching of N and P through soil, and greater losses of water and nutrients through surface drainage inlets in cases where they are present (Martin, Kaleita et al., 2019; Roth & Capel, 2012).

Yet, despite these mechanisms, several other factors could potentially sustain the leaching of N and P from cropped depressional soils. They receive nutrient-rich runoff and shallow groundwater flow from their surrounding catchments (Andino et al., 2020; Martin, Kaleita et al., 2019; Martin, Soupir et al., 2019), resulting in greater inputs of water and nutrients per unit area to depressional than upland soils. Accordingly, content of the more reactive soil P fractions may also be greater in depressional than upland soils (Andino et al., 2020; Plach et al., 2022). Suppressed plant nutrient uptake could also increase nutrient availability in depressional soils. When elevated moisture suppresses or eliminates crop growth (Edmonds et al., 2021; McNunn et al., 2019), plant nutrient uptake and nutrient removal in harvested grain typically decrease (Basso et al., 2019). Finally, cropped depressions often have flashy hydroperiods whereby ponding occurs over periods of hours or days (Arenas et al., 2018; Martin, Kaleita et al., 2019; Schilling et al., 2018), bracketed by extended periods when soils are not saturated. Depressional soils of north-central Iowa are rich in smectite clay, which shrinks and swells upon drying and wetting (Czapar et al., 1992). Visible cracks form during dry periods, providing a conduit for preferential flow at the beginning of large rainfall events before soils become fully saturated (Martin, Kaleita et al., 2019; Smith & Capel, 2018). Preferential flow can allow soluble reactive P to rapidly move from surface soils to tile drains, even in soils with high P sorption capacity (Smith et al., 2015; Stamm et al., 1998). Therefore, significant nutrient leaching might occur during periods when depression soils are not ponded with surface water.

Core Ideas

- Poorly drained depressions had greater nitrogen and phosphorus leaching than uplands within several Iowa corn and soybean fields.
- Depressions with cover crops or perennials had smaller differences in nitrate leaching compared to uplands.
- Targeted management of cropped depressions could disproportionately benefit water quality.

Our primary objective was to assess whether cropped depressions were consistent hotspots of nutrient leaching within agricultural fields, based on measurements spanning multiple sites over three study years. We monitored nitrate, ammonium, and reactive P leaching across multiple depression-to-upland transects within sites in north-central Iowa using resin lysimeters buried and retrieved on an annual basis (totaling 737 individual lysimeters over 28 "transect-years"). Resin lysimeters have been previously used to assess differences in nutrient leaching among cropping systems in field experiments (e.g., Behnke et al., 2012; Davis et al., 2015; McIsaac et al., 2010; Smith et al., 2013; Studt et al., 2021). In this study, we assessed variability in nutrient leaching over multiple spatial scales, from plot (meters) to topographic position (tens of meters) to hillslope (hundreds of meters; Figure 1). Study sites included agricultural fields with corn (*Zea mays*) and soybean (*Glycine max*) with and without a winter rye (*Secale cereale*) cover crop, as well as corn and soybean fields where depressions were planted with miscanthus (*Miscanthus × giganteus*), a candidate perennial bioenergy crop. Cover crops and perennial vegetation can potentially decrease nutrient leaching relative to traditional grain cropping systems in our region (Daigh et al., 2015; Studt et al., 2021), but these practices have often been evaluated at sites that do not contain prominent depressions. Therefore, our study allowed us to address the overall impacts of cropped depressions on nutrient leaching relative to upland soils, and to further test whether the relative contributions of depressions to nutrient leaching varied under different management scenarios.

2 | MATERIALS AND METHODS

2.1 | Description of research sites

We measured nutrient leaching along topographic transects, each of which included depressional and adjacent upland soils, at several sites within the Des Moines Lobe region of Iowa during 2018, 2019, and 2020 (Table S1, Figure S2). Not all transects could be measured each year due to logistical and site access constraints. All transects had subsurface tile drainage at approximately 1.2-m depth and most did not have surface inlets except for the three depressions listed in Table S1. The precise locations of tiles at each site are unknown as they were mostly installed many decades ago, but there was likely a tile near each depression. Crops included conventional corn and soybean, corn and soybean with a winter rye cover crop, and corn and soybean where depressions were planted to miscanthus (Table S1). Water levels were previously monitored in several of these depressions and all ponded water intermittently during the growing season, even those with surface inlets (Martin, Kaleita et al., 2019). Depression boundaries and morphological characteristics were calculated using a digital elevation model following McDeid et al. (2018). Precipitation data were obtained from the Iowa Environmental Mesonet (https://mesonet.agron.iastate.edu).

In all years, we monitored transects in fields within a 260-ha section located approximately 4 km southwest of Ames, IA (41.96 ˚N, 93.69 ˚W), where surface water ponding and water chemistry were studied previously (Martin, Kaleita et al., 2019; Martin, Soupir et al., 2019). Following the conventions in this previous work, transects were playfully named according to their shapes (Table S1). These fields were planted to corn-soybean rotations for several decades prior to spring 2019, when three transects were planted to miscanthus, with the rest remaining in corn or soybean. The transects planted to miscanthus were surrounded by corn or soybean, and one miscanthus transect (denoted “Moorhen”; Table S1) contained four sampling plots under corn or soybean at the upland end of the transect.

In 2019, we measured seven additional corn-soybean transects spanning two 260-ha sections located 10 km northeast of Ames, IA (42.13 ˚N, 93.50 ˚W), where a winter rye cover crop had also been planted during our sampling period (these transects are designated with the prefix “RS”). In 2018, we measured four additional corn-soybean transects (without cover crop) located 10 km northeast of Emmetsburg, IA (43.21 ˚N, 94.62 ˚W; these transects are designated with the prefix “DD15”). In all transects, corn and soybean were managed within regional norms, with N applied prior to corn planting or as side dress at total rates of 168–252 kg N ha^{-1} (see Table S1 for complete nutrient management details). Cattle manure was applied to the northeast Ames transects and was historically applied to some of the southwest Ames transects, and swine manure was applied to the northeast Emmetsburg transects.

Transects spanned 100–150 m along a hillslope from the local minimum of each depression to an adjacent upland, placed perpendicular to elevation contours as possible to maximize the difference in relative elevation among sampling plots (Figure 1a). Ten plots were established at equidistant intervals along each transect. At each plot, three replicate lysimeters were installed 60 cm apart as described below. Depressional soils were typically mapped as Okoboji (fine, smectitic, mesic Cumulic Vertic Endoaquolls) or Harps (fine-loamy, mixed, superactive, mesic Typic Calciaquolls). Uplands were mapped as Clarion (fine-loamy, mixed, superactive, mesic Typic Hapludolls) or Nicollet (fine-loamy, mixed, superactive, mesic Aquic Hapludolls). Intermediate soils were often mapped as Canisteo (fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls) or Webster (fine-loamy, mixed, superactive, mesic Typic Endoaquolls). Spatial variation in properties of these cropland soil series has been described previously (e.g., Karlen et al., 2008). In this study, we measured time-integrated nutrient leaching rather than extractable or total soil nutrients for two reasons. First, soil mineral N is highly variable over space and time, illustrated by our previous measurements of nitrate and ammonium along the Walnut transect, and mineral N is often unrelated to total N (Lawrence et al., 2021; Yu et al., 2021). Accordingly, one-time N measurements at each of our study plots would not likely predict annual N leaching. Second, although soil-test P is often related to crop P availability, it does not necessarily reflect P leaching through soil, which is jointly controlled by P sorption/desorption dynamics and water infiltration. Characterizing the spatiotemporal dynamics of soil nutrient pools was beyond the scope of this study.

2.2 | Resin lysimeter construction and deployment

We used ion exchange resin lysimeters (Susfalk & Johnson, 2002) to measure nutrient leaching. Each lysimeter was deployed for one year, with installation in mid-April and retrieval in mid-April of the following year. Lysimeters were

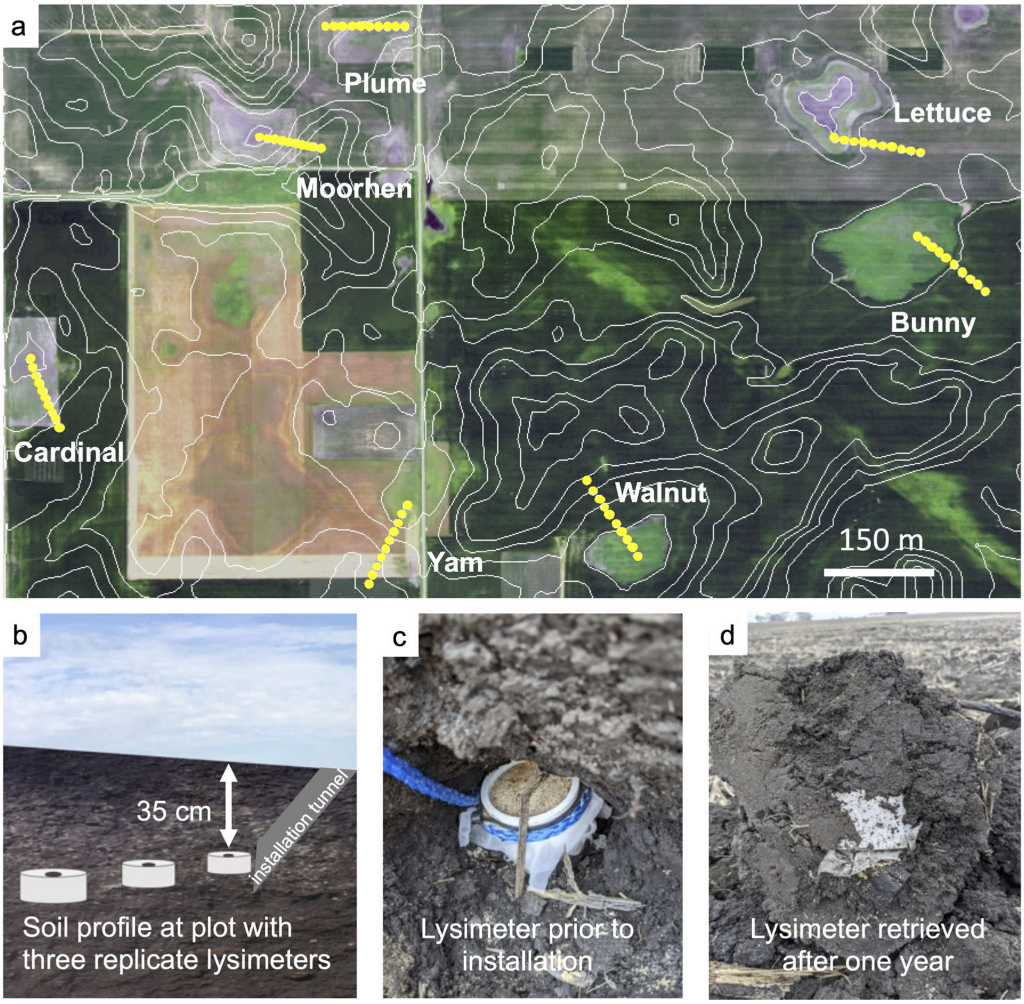

FIGURE 1 A map of the sampling transects at the study site southwest of Ames, IA (a), and details of lysimeter installation and retrieval (b–d). Locations of the other study sites are shown in Figure S2. (a) Yellow circles indicate sampling plots along named transects described in Table S1. (b) At each plot, three replicate lysimeters were installed at 35-cm depth by augering a separate installation tunnel. (c) A new lysimeter at the top of an installation tunnel is shown, and (d) a lysimeter retrieved after 1 year is shown. The map was created in ArcGIS (ESRI, Redlands, CA) with a 2019 orthophoto, using data from the Iowa State University Geographic Information Systems Support and Research Facility.

constructed from 5-cm diameter PVC tubing, unions, and couplers, which contained 25 g of cation/anion exchange resin (IONAC NM-60 H^+/OH^-, J. T. Baker) between nylon mesh screens (153 µm Nitex). The space above and below the mesh was filled with quartz sand and the bottom of the lysimeter was covered with hardware cloth affixed by a cable tie. The horizontal area of each lysimeter was 28.6 cm^2. Assuming resin sorption capacity >0.4 eq L^{-1} specified by the manufacturer, lysimeters could sorb >700 kg N ha^{-1} as nitrate (98% of our measurements were below this, with a maximum observed value of 1038 kg N ha^{-1}).

Lysimeters were installed underneath undisturbed soil by excavating a 50 cm tunnel at a 45˚ angle relative to the soil surface with a 10-cm diameter bucket auger (Figure 1b). At the bottom of each installation tunnel (35-cm depth), a horizontal pocket was excavated with a metal spatula and the lysimeter was pressed into the overlying soil. Nylon rope was tied around each lysimeter and threaded through the excavation tunnel to the surface to assist with location (Figure 1c). Installation tunnels were backfilled with excavated soil and a 10-cm length of rebar was added to each tunnel to enable location by magnetic locator.

The 35 cm lysimeter installation depth balanced multiple considerations. First, it was shallow enough to allow placement of lysimeters by hand in the narrow installation tunnel, minimizing soil disturbance. Second, 35 cm is above typical groundwater levels for these cropped depressions, which most commonly pond from above due to surface and shallow subsurface runoff, rather than from groundwater rise (Schilling et al., 2018). Third, 35 cm is below the dominant zone of corn and soybean root biomass (Nichols et al., 2019) and the dominant zone of denitrification, which is greatest at the surface due to microbial carbon (C) limitation in deeper soils (Cambardella et al., 1999; Yeomans et al., 1992). However, we acknowledge that additional P sorption may have occurred below our lysimeters, and in any case the absolute magnitude of leaching values obtained from resin lysimeters should be interpreted cautiously, as hydraulic properties of lysimeters differ from natural soils (Weihermüller et al., 2007). In this study, we focus on comparisons of nutrient leaching between topographic positions as opposed to their absolute fluxes.

After 1 year of deployment, lysimeters were excavated by shovel (Figure 1d). In the lab, resin from each lysimeter was immersed in 2 M potassium chloride in a 1:5 ratio of resin mass (g) to solution volume (mL) and shaken for 1 h. The supernatant solution was decanted to plastic bottles and stored at −20˚C. Each sample was extracted twice to increase nutrient recovery (Langlois et al., 2003).

2.3 | Chemical analyses

Nitrate, ammonium, and P in the lysimeter extraction solutions were measured using colorimetric assays on a microplate reader (Biotek Synergy HT) (D'Angelo et al., 2001; Doane & Horwáth, 2003; Weatherburn, 1967). The P in the lysimeter extraction solutions might approximate a "soluble reactive" pool but cannot be strictly defined as such because samples were not filtered prior to analysis. However, sand at the top of the lysimeter prevented direct mixing between resin and soil. Nitrate, ammonium, and P recovered in the second extraction was 20% (8%), 20% (15%), and 17% (18%) of the first extraction, respectively (values in parentheses are standard deviations). Nutrient masses from the first and second extractions were summed and expressed on an area basis by dividing by the area of each lysimeter. Three samples had unusually high ammonium or P and were excluded from subsequent analyses.

For additional context, the 2018 lysimeter extraction solutions were also analyzed for sodium (Na), magnesium (Mg), manganese (Mn), aluminum (Al), and iron (Fe) by inductively coupled plasma optical emission spectroscopy (Perkin Elmer Optima 5300 DV) in radial mode with three technical replicates. Sources of Na at our field sites are likely to be spatially uniform and dominated by atmospheric deposition and any agricultural lime or manure, with small additional fluxes from primary mineral weathering (Kaspari, 2020). Exchangeable Na is a minor component of total cations (<1%) in area soils (Karlen et al., 2002) and Na is not a limiting nutrient for plants or microbes. Therefore, if we assume approximate steady state between Na inputs and outputs at field scale, Na may provide a semi-quantitative index of the relative water flux among lysimeters. This approach is conceptually analogous to the use of chlorine (Cl) as a tracer of water flow (Czapar et al., 1992).

2.4 | Statistical analyses

First, we averaged data from replicate lysimeters at the plot level to account for their spatial correlation. Then, we averaged the plot-level data by topographic position (depression vs. upland) within a transect to calculate a single leaching value for each depression or upland area. This was done to avoid pseudoreplication and complications in interpretation due to differing numbers of depression and upland sampling plots among transects. For example, plots 1–6 along the Bunny transect were located within the depression and plots 7–10 were located in the upland, whereas plots 1–5 for the Walnut transect were located within the depression and 6–10 were located in the upland. Impacts of topographic position on nutrient leaching were tested using a paired Wilcoxon signed-rank test (R function "wilcox.test"), which evaluated the median difference between paired depressions and uplands across the entire dataset.

Next, we tested the effects of cropping system on differences in nutrient leaching between depressions and uplands. We used this approach because the observational nature of our study precluded a direct test of the impact of cropping systems on nutrient leaching (i.e., study sites differed in other factors aside from cropping system type, and cropping systems were not randomly assigned). We first calculated the difference in nutrient leaching between the depression and upland positions for each transect, which we define as the "depression excess value"; this is positive where a depression has greater nutrient leaching than the adjacent upland. Then, we compared the depression excess values between cropping systems using a non-paired Wilcoxon test (i.e., a rank sum test). Specifically, we compared the cover-cropped and non-cover-cropped grain systems in 2019, and the miscanthus versus non-cover-cropped grain systems in 2019 and 2020. All analyses were conducted in R 4.1.2 (R Development Core Team, 2021).

3 | RESULTS

3.1 | Variation in nutrient leaching across spatial scales

Cumulative precipitation at the southwest Ames sites bracketed the 20-year mean (84 cm year^{-1}), measuring 88 cm, 102 cm, and 65 cm during the 2018–2019, 2019–2020, and 2020–2021 lysimeter deployment periods, respectively (values for other sites are shown in Table S2). Of the 840 lysimeters initially deployed, 737 were located after 1 year. Ammonium accounted for a mean of 5% (SD = 7%) of total inorganic N leaching (ammonium N + nitrate N). Nutrient leaching in individual lysimeters varied by more than three orders of magnitude and values were highly right-skewed (Figure 2a, Table S3), with high variability even among the three adjacent replicates within an individual 1.2-m sampling plot. In cases where all three replicates were recovered from a plot, the median standard deviation at the plot level was 41 kg N ha^{-1} for nitrate, 0.7 kg N ha^{-1} for ammonium, and 1 kg ha^{-1} for P, and the plot-level standard deviations were 54%, 48%,

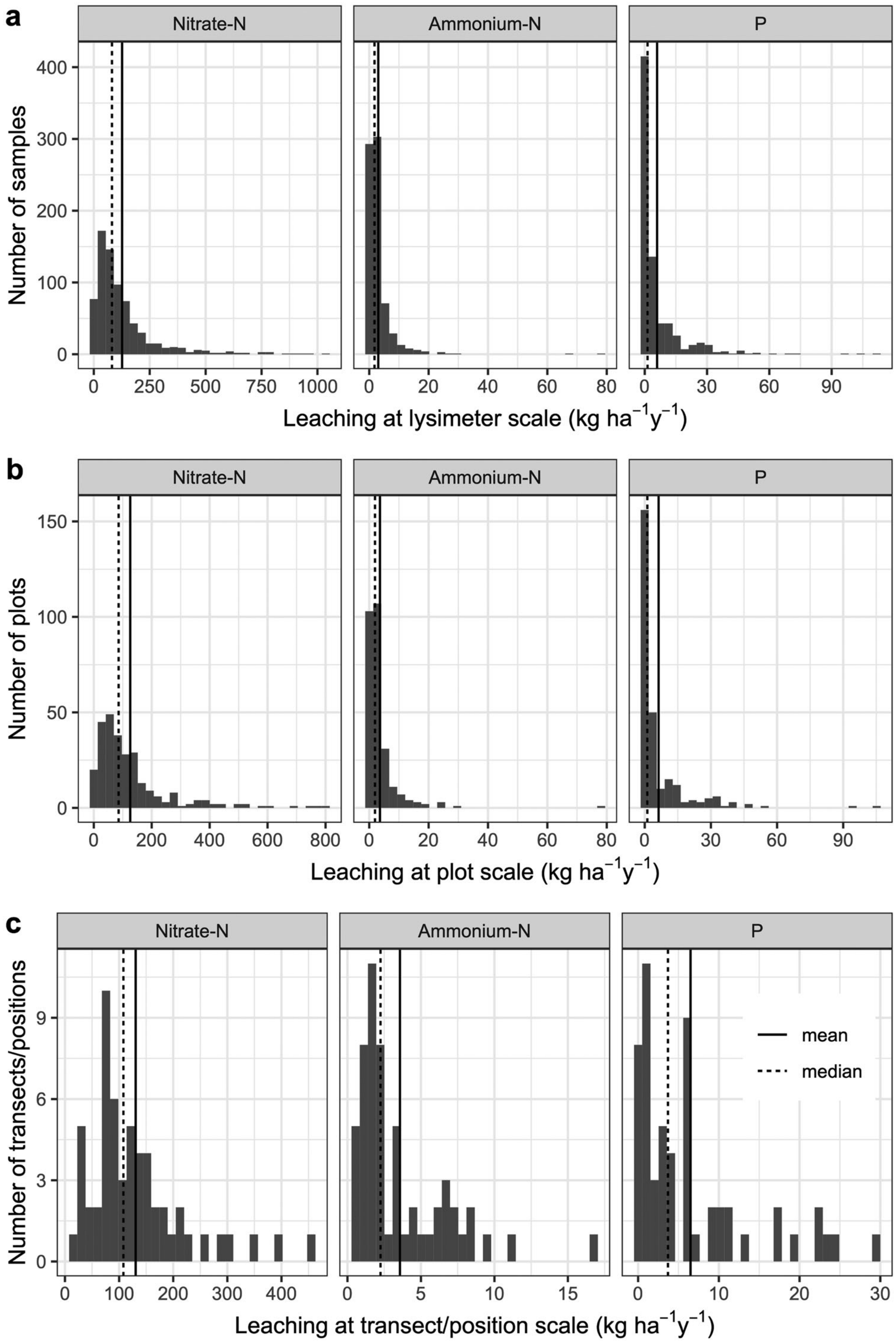

FIGURE 2 Histograms showing the frequency distributions of nitrate, ammonium, and P leaching over 1-year intervals across multiple spatial scales: (a) individual resin lysimeters, (b) lysimeters averaged by plot, and (c) lysimeters averaged by plot and then by topographic position (depression or upland) within each transect. Solid and dashed lines indicate means and medians, respectively, with values reported in Table S3. N, nitrogen; P, phosphorus.

and 68% of the respective plot-level means. After averaging replicate lysimeters within sampling plots (Figure 2b), or within plots and then by depression or upland within a transect (Figure 2c), skewness of the entire dataset decreased markedly (Table S3). Considering the entire plot-scale dataset, nutrient leaching increased exponentially ($p < 0.0001$) along the topographic transects from uplands to depressions, but the predictive relationship between leaching and plot position along the transects was weak ($R^2 < 0.13$; Figure S3). Therefore, for clarity of interpretation we focused our

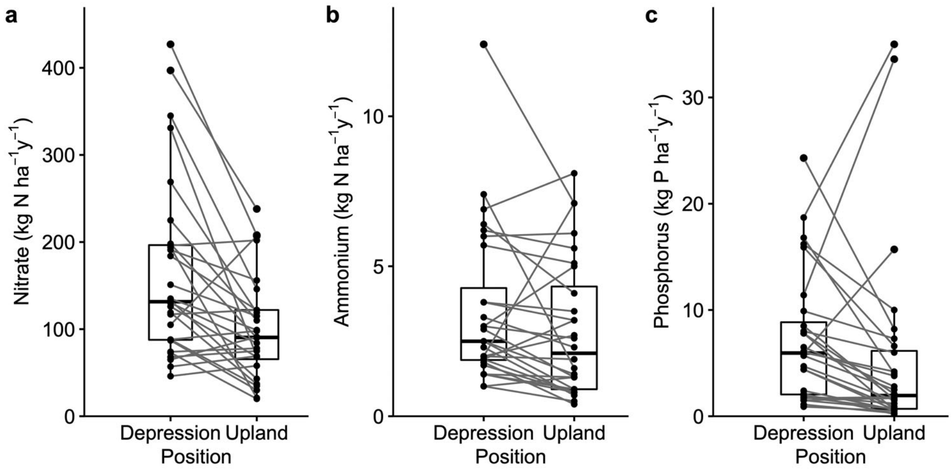

FIGURE 3 Boxplots of (a) nitrate-N, (b) ammonium-N, and (c) reactive P leaching from depression and upland locations along each transect over each study year. Gray lines denote paired measurements for a given transect and study year. The thick horizontal line is the median, the edges of the boxes denote the 25th and 75th quantiles, and whiskers extend up to 1.5× the interquartile range. N, nitrogen; P, phosphorus.

subsequent analyses on nutrient leaching averaged by depression or upland position within each transect.

When considering only the 2018 data, when all measured transects were under corn or soybean management (no cover crop or miscanthus), annual leaching of nitrate, ammonium, and P varied ninefold, eightfold, and 39-fold, respectively, among all combinations of transects and topographic positions (Table S4). After averaging depression and upland values within a transect, the 2018 transects differed threefold, threefold, and ninefold in nitrate, ammonium, and P leaching, respectively. Variation in leaching among different transects within a study year was generally similar or larger than variation among the same corn and soybean transects measured over multiple years (Bunny, Lettuce, and Walnut), which varied fourfold, twofold, and twofold, for nitrate, ammonium, and P, respectively (Table S4). There was no clear relationship between mean nutrient leaching values (Table S4) and depression morphological characteristics or presence of a surface inlet (Table S1).

3.2 | Variation in nutrient leaching between depressions and uplands

There was a strong overall relationship between topographic position and leaching of nitrate, ammonium, and P, and values in depressions were almost always greater than uplands (Figure 3). The median difference in nitrate leaching between depressions and uplands across all cropping systems was 56 kg N ha^{-1} year^{-1} (25–97 kg N ha^{-1} year^{-1} with 95% confidence, p = 0.0008). The median difference in ammonium leaching between depressions and uplands was 0.6 kg N ha^{-1} year^{-1} (0.1–1.05, p = 0.03), and for P it was 2.4 kg ha^{-1} year^{-1} (1.1–4.2, p = 0.006). To test whether this conclusion was affected by sampling intensity at the plot scale, we randomly subsampled the dataset to select a single lysimeter for each plot year, and then recalculated the differences in leaching between depressions and uplands. Results from the subsampled data were similar in direction and magnitude to the full dataset, with higher p-values (Figure S4).

Several other elements were measured in the 2018 samples to provide additional context (Table S5, Figure S5). Leaching of Na was highly variable at the scale of topographic position within transect (3–48 kg Na ha^{-1} year^{-1}) and tended to be higher in transects with recent manure application (14–48 kg Na ha^{-1} year^{-1}) than in non-manured transects (3–8 kg Na ha^{-1} year^{-1}). Despite the variation among transects, leaching of Na was similar between depressions and uplands (median difference of −1.5 kg Na ha^{-1} year^{-1}, −10 to 3, p = 0.60). Leaching of Mg was less variable among transects and topographic positions (32–91 kg Mg ha^{-1} year^{-1}) and was consistently greater in depressions than uplands (median difference of 21 kg Mg ha^{-1} year^{-1}, 7–36, p = 0.01). Leaching of Mn, Al, and Fe did not vary consistently between depressions and uplands and fluxes were low (<1 kg ha^{-1}).

3.3 | Differences in nutrient leaching between depressions and uplands among cropping systems

Next, we assessed whether the magnitude of excess nutrient leaching from depressions differed among cropping systems. We focused our cropping system comparison on the topographic difference in nutrient leaching because pre-existing site differences confounded direct comparisons of leaching values between cropping systems (for completeness, absolute values are shown in Figure S6). Using the 2019 data,

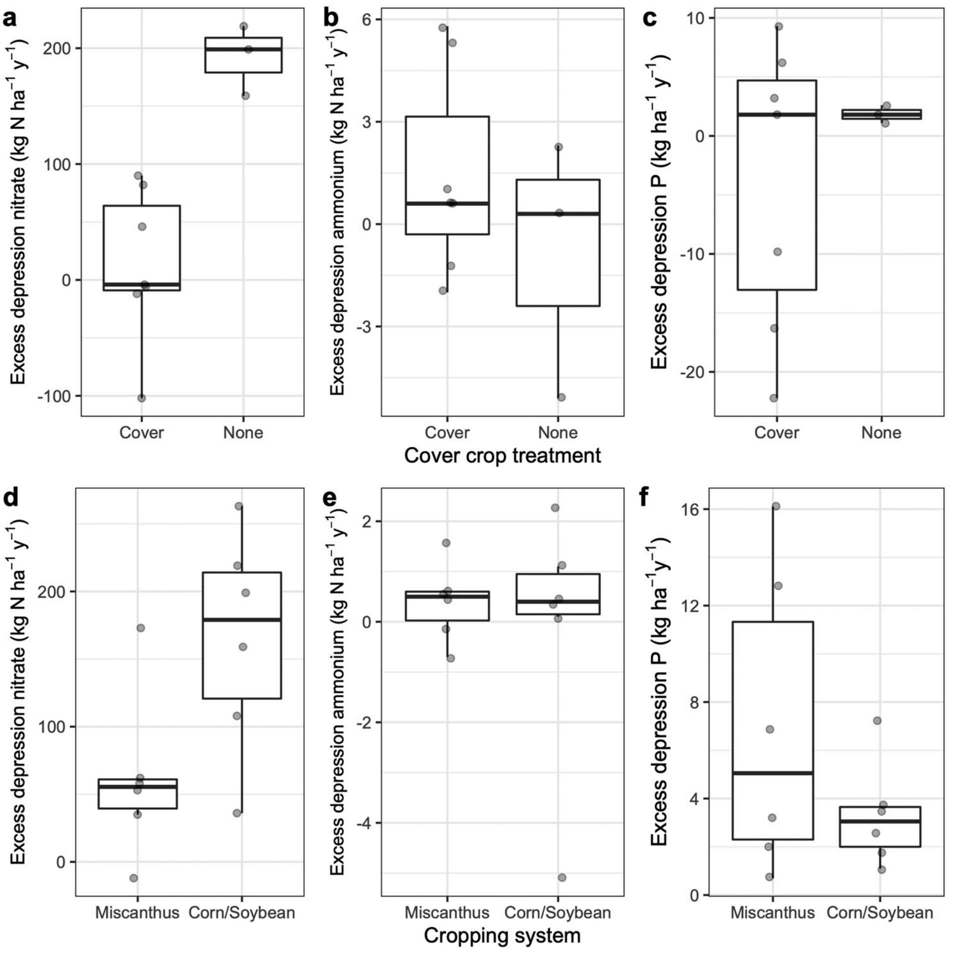

FIGURE 4 Boxplots of the difference in nutrient leaching between depression and upland locations in a transect, where a positive value indicates excess nutrient leaching in the depression versus the upland. Categories on the *x*-axis indicate crop management; panels (a–c) compare corn and soybean systems with a winter rye cover crop ("Cover") or without a cover crop ("None") in 2019. Panels (d–f) compare transects planted with miscanthus with transects planted to corn or soybean in 2019 or 2020. N, nitrogen; P, phosphorus.

which included seven corn and soybean transects with a winter rye cover crop and six without a cover crop, we found that transects with cover crops had a smaller excess nitrate leaching from depressions, but there was no difference for ammonium or P (Figure 4; Table S4). Specifically, transects planted with a cover crop had a median difference in nitrate between depressions and uplands that was 171 kg N ha^{-1} year^{-1} lower (77–301, values indicate the minimum and maximum difference between depressions and uplands, $p = 0.02$) than in transects without a cover crop. In contrast, the median difference in ammonium between depressions and uplands was similar in transects with and without cover crops (3 kg N ha^{-1} year^{-1}, −3.5 to 10.4, $p = 0.49$), as was the median difference in P (0 kg P ha^{-1} year^{-1}, −24 to 7.5, $p = 1$).

Similar to the comparison between cover-cropped and non-cover-cropped systems, differences in nitrate leaching between depressions and uplands were smaller in transects with miscanthus than with corn or soybean (Figure 4, Figure S5). Transects with miscanthus had a median difference in nitrate between depressions and uplands that was 113 kg N ha^{-1} year^{-1} lower than in transects with corn or soybean (−14 to 204, $p = 0.065$). However, the median difference in ammonium between depressions and uplands was similar between transects with miscanthus and corn or soybean (0.0 kg N ha^{-1} year^{-1}, −1.7 to 4.4, $p = 1$), as was the median difference in P (1.75 kg P ha^{-1} year^{-1}, −1.9 to 11.7, $p = 0.59$).

4 | DISCUSSION

Because of their poor drainage characteristics, topographic depressions in tile-drained agricultural fields may pond water for hours to weeks at a time (Martin, Kaleita et al., 2019; Schilling et al., 2018), yet our data indicate that depressions can still contribute disproportionately to nutrient leaching. Across three sampling years and multiple sites in north-central Iowa, cropped depressions had higher overall leaching of N and P than their adjacent uplands, with few exceptions

(Figure 3). The difference in leaching between paired depressions and uplands was largest for nitrate and P and was also detectable for ammonium, which comprised a small fraction of inorganic N leaching. The median difference in leaching between depressions and uplands was 56 kg N ha^{-1} year^{-1} for nitrate and 2.4 kg ha^{-1} year^{-1} for P. These values represented about half of the overall median leaching fluxes of 112 kg N ha^{-1} year^{-1} and 4.1 kg P ha^{-1} year^{-1} measured across both depressions and uplands. Legacy nutrients as well as recent fertilizer and manure contributed to measured leaching, given that several transects received no N or P fertilizer during periods of lysimeter deployment.

We quantified variation in nutrient leaching at multiple spatial scales (Figure 2). Previous studies employing resin lysimeters often reported very high variability among replicates within a plot (Behnke et al., 2012; McIsaac et al., 2010). Indeed, in our study nitrate leaching varied by more than three orders of magnitude among lysimeters and the median standard deviation of nitrate leaching for replicates within a 1.2-m plot was almost as large as the median difference between depressions and uplands (Figure 3). Nevertheless, we calculated a similar median difference in nutrient leaching between depressions and uplands when we subsampled the data to include only a single replicate per plot (Figure S4). Therefore, our conclusion regarding the influence of depressions on nutrient leaching was robust to plot-scale variation, and aggregating data from replicate lysimeters enhanced our capacity to detect topographic differences.

The N and P leaching values reported here are larger than typically measured in tile drainage plot studies in our region (e.g., Daigh et al., 2015), and we emphasize that the absolute values should be interpreted cautiously. Greater hydraulic conductivity of the sand/resin matrix than the surrounding soil might promote preferential flow through lysimeters, leading to overestimates of nutrient leaching (Weihermüller et al., 2007). Yet, the opposite has also been reported, whereby increased water flow around the lysimeter leads to underestimation of solute fluxes (Singh et al., 2018). Acknowledging these potential biases, our nitrate leaching values were within the range of previous resin lysimeter measurements from other agricultural soils near Ames, IA (Studt et al., 2021) and were generally higher than values reported from elsewhere in the US Corn Belt (Davis et al., 2015); those studies did not report P leaching data.

4.1 | Potential mechanisms underlying topographic differences in nutrient leaching

Increased nutrient leaching in depressions relative to uplands may have been caused by multiple physical and biological factors, including increased water infiltration and/or greater nutrient availability in depressional soils. Because precipitation inputs to depressional soils are augmented by runoff and shallow groundwater flow from the surrounding catchment (Arenas et al., 2018; Martin, Kaleita et al., 2019; Schilling et al., 2018), we might expect that total infiltration would still be substantial even in depressions with poor drainage characteristics. Consistent with this expectation, we found that Na fluxes were similar between depressions and uplands (Figure S5), which would indicate similar water infiltration among depressions and uplands if we assume that Na acts as a semi-conservative tracer of water flow, in a manner analogous to the use of Cl in other studies (Czapar et al., 1992). In contrast to Na, Mg leaching was greater from depressions than upland soils, consistent with long-term Mg accumulation during soil development under natural hydrologic conditions prior to installation of subsurface drainage (Richardson et al., 1994).

Increased N and P availability in depressions also likely contributed to topographic differences in leaching. Corn and soybean production vary greatly among depressions and crop years, but suppressed yields are common. For example, Edmonds et al. (2021) found that the bottom of one of our study depressions (Lettuce) produced no corn or soybean grain over a 10-year period, although the spatial extent of yield suppression within the depression varied markedly among years. During our study period, ponding following spring precipitation caused partial mortality of grain crops and miscanthus in many depressions, especially during 2018 and 2019 (Lawrence et al., 2021; Steiner, 2021). Decreased plant nutrient uptake in depressions may have temporarily increased the availability of soluble forms of N and P. Along the Walnut transect, we previously found no consistent differences in soil inorganic N over time between the depression and upland (Yu et al., 2021), although depressional soils did tend to have greater mineral N than uplands during peak periods of inorganic N availability in spring and early summer of 2018 and 2019 (Lawrence et al., 2021). Transport of N and P from uplands to depressions in surface runoff and shallow groundwater may also have contributed to greater nutrient availability and leaching from depressions.

Our previous measurements also provided evidence of anoxic conditions in depressional soils during periods of high moisture in 2018, when we observed increased ferrous, a product of anaerobic microbial metabolism (Yu et al., 2021). This finding suggests that significant denitrification had occurred, because Fe reduction is less thermodynamically favorable and tends to occur during or after denitrification (Hall et al., 2016). Denitrification may remove large amounts of N (tens of kg N ha^{-1} year^{-1}, with a variable yield of N_2O) from poorly drained agricultural soils (Hofstra & Bouwman, 2005; Lawrence et al., 2021), and this may explain several observations in our dataset where nitrate leaching was lower in depressions than in uplands, contradicting our overall findings (Figure 3). For example, in 2018 some of the southwest Ames depressions were ponded for several weeks (Lawrence et al., 2021), and nitrate leaching from these depressions tended to be lower than during the other study years (Table S4), consistent with greater denitrification. However, when soils are not saturated and oxygen availability is high, denitrification occurs at much lower rates (Krichels et al., 2019). Transport of water and nutrients by preferential flow prior to ponding events may have sustained nitrate leaching from these depressional soils despite their potential for denitrification.

Conversely, the sporadic occurrence of anoxic conditions in flooded depression soils might have sustained the availability of P in forms vulnerable to leaching. Depressional soils in our region often have circumneutral to alkaline pH and are enriched in reactive Fe minerals and calcium carbonate relative to upland soils (Huang et al., 2020; Huang & Hall, 2017; Yu et al., 2021), and these factors can promote P sorption or precipitation (Penn & Camberato, 2019). However, during anoxic periods, pH may decrease and carbonate may dissolve due to accumulation of organic acids and carbon dioxide, and Fe minerals may dissolve following dissimilatory reduction (Huang et al., 2020; Huang & Hall, 2017; Yu et al., 2021). These processes may increase the solubility of P bound with calcium or Fe, as demonstrated for ponded agricultural soils (Amarawansha et al., 2015). Consistent with this reasoning, P concentrations in depressional surface water tended to increase during prolonged ponding events at some of our study sites (Martin, Soupir et al., 2019), and at least some of this P may have leached through the soil during or following ponding events. Overall, the combination of high P transport by preferential flow under non-saturated conditions (Smith et al., 2015; Stamm et al., 1998) and increased P release under saturated conditions (Amarawansha et al., 2015) provide a plausible explanation for greater P leaching in depressions than uplands (Figure 3c).

Comparisons between different cropping systems indicated that extending plant growth beyond the grain crop season may decrease the excess nutrient leaching from depressional soils. The difference in nitrate leaching between depressions and uplands was smaller for corn and soybean transects managed with a winter rye cover crop, or where depressions were planted with miscanthus, compared with soils under traditional corn and soybean management (Figure 4). This result is consistent with an overall reduction in nitrate leaching typically associated with these practices (Blanco-Canqui, 2018; Davis et al., 2015; Studt et al., 2021), but it is intriguing given that growth of miscanthus (and possibly also the cover crop) was suppressed by excess moisture in the depressional soils, especially during 2019 (Steiner, 2021). Sensitivity of cover crop establishment and growth to intermittently ponded conditions merits further study.

5 | CONCLUSION

We observed high spatial variation in nutrient leaching at subfield scales within and among years, even when comparing corn and soybean systems with similar management and soil characteristics. Nevertheless, tile-drained topographic depressions were predictable hotspots of soil nitrate and P leaching despite their poor drainage characteristics compared with the adjacent upland soils. Consequently, targeted management of depressions could disproportionately affect field- and catchment-scale nutrient losses. Given high potential for nutrient loss, refining precision nutrient management (rate, timing, etc.) for depressional soils may disproportionately benefit water quality without necessarily impacting crop production, although legacy P accumulation may challenge these efforts. Perennials and cover crops are generally understood to benefit water quality, and they were associated with smaller excess leaching of nitrate (but not P) from depressions in our study. Where feasible, depressions could be retired from agricultural production and managed for conservation or wetland restoration, acknowledging their frequently poor economic returns (Edmonds et al., 2021; McNunn et al., 2019) and their disproportionate environmental impacts under current management.

AUTHOR CONTRIBUTIONS

Steven J. Hall: Conceptualization; data curation; formal analysis; writing–original draft; Writing–review and editing; funding acquisition. **Carlos G. Tenesaca**: Investigation; methodology; data curation; writing–review and editing. **Nathaniel C. Lawrence**: Investigation; writing–review and editing; visualization. **David I.S. Green**: Formal analysis; writing–review and editing; visualization. **Matthew J. Helmers**: Conceptualization; funding acquisition; resources; writing–review and editing. **William G. Crumpton**: Conceptualization; funding acquisition; resources; writing–review and editing. **Emily A. Heaton**: Conceptualization; funding acquisition; resources; writing–review and editing. **Andy VanLoocke**: Conceptualization; funding acquisition; resources; writing–review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data reported in this study are publicly available in the Environmental Data Initiative repository: https://doi.org/10.6073/pasta/269c447800b797869e89fdd18d30824a

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