Title: Rainfall intensification increases nitrate leaching from tilled but not no-till cropping systems in the U.S. Midwest

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Abstract

As global surface temperatures rise, the percentage of total precipitation that falls in extreme events is increasing in many areas ("rainfall intensification"), including the U.S. Midwest, a major agricultural region. While it is well known that losses of nitrogen (N) fertilizers applied in excess of crop N demand have consequences for non-agricultural ecosystems, the effects of rainfall intensification on N losses from agricultural fields are uncertain. We conducted a 234-day field experiment in which we evaluated the effects of rainfall intensification on N leaching, soil inorganic N pools, soil N transformations, and crop N content in replicated tilled and no-till row crop systems of the upper Midwest. Under rainfall exclusion shelters we exposed 5 x 5 m plots to a control rainfall treatment with relatively small, frequent rainfall events historically typical of the region, and an intensified rainfall treatment with the same total rainfall added in larger, less frequent events. Although rainfall intensification increased modeled water percolation to 1.2 m in both tilled and no-till systems, as reported previously, it increased nitrate leaching only in tilled systems. Extractable soil nitrate concentrations throughout the experiment were on average 32% higher in surface soils exposed to intensified rainfall compared to control rainfall regardless of tillage management. In-situ net N mineralization and nitrification rates measured during a two-week period in summer showed no significant differences between rainfall or tillage treatments. Inorganic N pools (0 - 1.2 m depth) were 43% greater in no-till soils compared to tilled soils and were unaffected by rainfall intensification; crop N concentrations and total N were likewise unaffected. Our results suggest that rainfall intensification in tilled cropping systems will increase N leaching to groundwater, with consequent economic and environmental harm. No-till management, however, may buffer systems against the effects of intensification on nitrate loss.

Keywords

nitrate leaching, nitrogen, agriculture, tillage, climate change, precipitation

Declarations of interest: none

1. Introduction

Leaching of N, particularly nitrate-N, is one of the most important N loss pathways from cropping systems (Robertson and Vitousek, 2009; Fowler et al., 2013). Leached nitrate can contaminate groundwater, cause eutrophication in estuaries and coastal ecosystems (Howarth and Marino, 2006), and generate increased emissions of nitrous oxide, an important greenhouse gas. Nutrient export from agricultural production in the Mississippi River basin in the U.S., for example, has famously led to the formation of a massive "dead zone" in the Gulf of Mexico (Rabalais et al., 2002). In addition, leached N represents an economic loss to farmers, for whom N fertilizer is often one of the highest direct production costs (Matson et al., 1998).

Anthropogenic emissions of greenhouse gases are changing the climate in ways that could potentially exacerbate N leaching from cropping systems. Increases in atmospheric moisture and changes in circulation patterns resulting from warming global temperatures are leading to rainfall intensification - that is, precipitation patterns with an increased percentage of rainfall occurring in extreme events (IPCC 2013). Heavy precipitation events have already increased over many parts of North America (Melillo et al., 2014): in the U.S. Midwest, the quantity of precipitation occurring in the largest one percent of all daily events has increased by almost 40% over the last 60 years (Pryor et al., 2014). Climate model simulations indicate that in many regions, the percentage of total precipitation that falls in extreme events will continue rising in the future (IPCC 2013).

The effects of pulsed precipitation events on soil N transformations and decomposition rates have been studied for decades (e.g. Birch 1958) and especially in soils of arid and semi-arid ecosystems (e.g. Fierer and Schimel, 2002; Austin et al., 2004). However, comparatively little is known about how pulsed precipitation affects N cycling in situ and especially in mesic climates, where rainfall is more frequent and evenly distributed throughout the growing season. In arid and semi-arid ecosystems, inorganic N accumulates in soil during prolonged dry periods, and rapid rewetting often generates a pulse of decomposition and net N mineralization (Fierer and Schimel, 2002; Austin et al., 2004; Borken and Matzner, 2009). Presumably, similar patterns occur in more mesic ecosystems following periodic droughts, which could, particularly in agricultural ecosystems, lead to elevated N losses by further exaggerating the asynchrony between N supply and demand (Robertson 1997).

Hess et al. (2018) showed that rainfall intensification altered soil moisture patterns and increased deep percolation in an upper Midwest cropping system. Such changes have the potential to alter N cycling and losses in these systems through effects on N transport as well as on plant and microbial dynamics (Lohse et al., 2009; McCulley et al., 2009). For example, increased percolation below the rooting zone may directly increase nitrate losses if hydrologic flow mobilizes soil nitrate. Additionally, changes in soil moisture could affect microbial N dynamics such as mineralization as well as plant N dynamics, such as N uptake and productivity, all of which may affect soil N availability for loss. While these effects are plausible, the extent to which they will actually occur remains largely unknown.

In the annual grain cropping systems that dominate agriculture in the U.S. Midwest, tillage practices affect a range of soil properties that in turn could affect the response of N cycling in these systems to rainfall intensification. No-till management, whereby crop residue is left on the soil surface, typically increases soil organic matter relative to conventional tillage management, especially in surface layers (West and Post, 2002; Syswerda et al., 2011). No-till management may also alter soil structure by creating more stable soil aggregates (Six et al., 2000; Grandy and Robertson, 2007) as well as increasing macropore connectivity and preferential (i.e. rapid, vertical) flow (Strudley et al., 2008).

While several modeling studies have evaluated the effects of rainfall intensification on N leaching (e.g. Gu and Riley, 2010; Congreves et al., 2016), we are unaware of analogous field experiments. Here we report the first documented test of (1) how changes in rainfall event frequency and size, but not total rainfall amount, affect N leaching in a Midwestern cropping system; and (2) how responses are affected by interactions with tillage. We leveraged the Main Cropping System Experiment (MCSE) of the Kellogg Biological Station (KBS) Long-term Ecological Research (LTER) site to conduct this work. There, long term rates of N leaching have been characterized previously, demonstrating greater N leaching from tilled compared to no-till cropping systems (Syswerda et al., 2011); our objective was to understand the response of N leaching from these systems to rainfall intensification. We conducted a 234-day field experiment in which we manipulated rainfall patterns and measured N leaching, soil inorganic N pools, soil N transformations, and crop N in both tilled and no-till cropping systems. We exposed cropping systems to a control rainfall treatment with relatively small, frequent rainfall events historically typical of the region, and an intensified rainfall treatment with the same total amount of rainfall but added in larger, less frequent events. Because rainfall intensification increased percolation at 1.2 m soil depth in these cropping systems (Hess et al., 2018), we hypothesized that it would also increase N leaching.

2. Methods

2.1 Study site

KBS is in southwest Michigan in the northern U.S. corn belt (85° 24′ W, 42° 24′ N). The site is at 288 m elevation and receives 100 cm of mean annual precipitation, with roughly 17% falling in winter and the rest equally divided among spring, summer, and fall (Robertson and Hamilton, 2015). Annual temperature is on average 10.1° C (Robertson and Hamilton, 2015). The soil series at the site are Kalamazoo, which is fine loamy, and Oshtemo, which is coarse loamy (Crum and Collins, 1995; Table 1). These are mixed, active, mesic Typic Hapludalfs which developed on glacial till and outwash. Because the soils are well-drained and the site is relatively flat (<6% slope), there is little to no runoff.

2.2 Experimental design

The Main Cropping System Experiment (MCSE) is made up of plots approximately one hectare in size (81 x 105 m) assigned to different cropping system types in a complete randomized block design (n = 6 replicate blocks) (Figure 1). In this experiment, we utilized the conventional and no-till cropping systems, which were established in 1988 and are planted in annual rotations of soybean (*Glycine max* L.), winter wheat (*Triticum aestivum* L.), and corn (*Zea mays* L.). The conventional plots (hereafter referred to as “tilled”) receive conventional inputs (fertilizer and pesticides) and tillage. The no-till plots also receive conventional inputs, but since 1988 they have been managed without tillage. More information about plot establishment and crop management can be found in Robertson and Hamilton (2015).

The experiment was conducted during the 2015 soybean year, preceded by corn and followed by winter wheat, and followed a rainfall intensification experiment that was in place from July to November 2014. Experimental design and other site details have been previously described in Hess et al (2018). Details of relevant management events can be found in Table 2. From 14 April through early December 2015 (the experimental period), we installed paired 5 m x 5 m rainout shelters in 4 tilled and 4 no-till plots, for a total of 2 tillage treatments x 2 rainfall treatments x 4 replicate blocks = 16 shelters (Figure 1). At least 5 m was left between shelters, and between shelters and MCSE plot edges. Shelters were constructed with PVC pipe to be relatively lightweight to allow temporary removal for agronomic activities (e.g., planting, pesticide application, harvest). Roofs were constructed out of clear, corrugated polycarbonate panels that permitted transmittance of 90-95% photosynthetically active radiation (PAR). Rainwater draining from roof panels was carried by gutters to tanks, where water was held until later application. Shelters were 150 cm tall along the midline and 110 cm tall at the edges, allowing ample room between roofs and soybeans at their tallest height.

Rainfall plots (covered by paired rainout shelters) in each MCSE plot were designated to one of two rainfall treatments: control or intensified. All rainfall conditions, including event size, dry intervals, and intensity, were generated using historical weather data for KBS since 1988 (http://lter.kbs.msu.edu/datatables). Between 14 April and 12 June 2015, rainfall was applied to all rainfall plots at a rate of 80 mm $month^{-1}$. In control plots, we applied three 6.7 mm rainfall events weekly, on the first, third, and seventh days of the week. This rainfall regime approximated median precipitation on wet days (6 mm) and the length of dry intervals between wet days (3 days) between March and November at KBS, with wet days defined as any day with more than 1 mm precipitation. In plots exposed to the intensified rainfall treatment, we applied one 40 mm rainfall event (97^{th} percentile of precipitation event size) once every approximately 2 weeks (97^{th} percentile of dry period length). Water from a nearby surface reservoir (< 0.03 mg N L^{-1}) was used to make up any shortfalls between ambient and scheduled rainfall amounts, with the same quantity added to both control and intensified plots (following the appropriate rainfall schedule). Water was applied to rainfall plots at a rate of 13 mm $hour^{-1}$ with overhead sprinklers supplied by small bilge pumps. This rate was the maximum at which water could be applied without generating runoff and has a recurrence interval of less than one year (NOAA 2017). At KBS, runoff does not frequently occur at the landscape scale, and as such we removed it from our experimental design. Instead, we tried to reflect the landscape-scale site conditions at the plot scale.

On 13 June 2015, rainout shelters were demolished by a storm with wind speeds > 96 km hr^{-1}. Shelters were reconstructed and re-installed in rainfall plots on 6 July. For the three weeks between 13 June and 6 July, all rainfall plots received ambient precipitation. We only replaced shelters in plots exposed to the intensified rainfall treatment, while control plots were left uncovered and exposed to ambient rainfall. New roofs included slits to allow for air flow and to diminish wind resistance, reducing rain exclusion to approximately 90%. From 6 July through the end of the experiment, rainwater excluded from intensified plots was collected and applied at approximately 14-day intervals. Rain events (6.7 mm) were applied to control plots using reservoir water during naturally-occurring prolonged dry periods to prevent extended periods of reduced soil moisture. The same quantity of supplemental water was applied to the intensified rainfall treatment during the next scheduled rainfall application. Rainfall variability was calculated as the coefficient of variation (CV) of daily rainfall for the periods before 13 June and after 6 July.

Precipitation during the experimental period totaled 891 mm, with 230 mm of that falling as ambient rainfall that all rainfall plots received between 13 June and 6 July when shelters were absent. All precipitation during the experiment was rainfall except for one snowfall on 21 November (11 mm snow water equivalent).

2.3 Estimation of nitrate leaching

2.3.1 Soil water sampling

Soil water at the lower boundary of the rooting zone was sampled during the experimental period using quartz/PTFE tension lysimeters (Prenart, Frederiksberg, Denmark) installed in May 2014 (11 months prior to the experiment start). We installed one lysimeter in the middle of each rainfall plot, leaving at least 2 m between it and any rainout shelter edge (Figure 1). Lysimeters were installed at 1.2 m depth, approximately 0.2 m into the unconsolidated sand of the 2Bt2 and 2E/Bt horizons. Preferential flow in these horizons is minimal due to the high sand content especially below 40 cm (Table 1), so sampled water should be representative of water percolating at this depth. Lysimeters were installed in 2.5 cm diameter diagonal boreholes, encased in silica slurry, and backfilled with soil. From March to December 2015, we sampled soil water approximately weekly by applying 50 kPa of vacuum for 24 hrs, during which soil water was collected in clean Nalgene bottles. During the experimental period before 13 June, soil water was sampled during rainfall applications to both control and intensified plots. After 6 July, soil water was sampled during rainfall applications to intensified plots but not during ambient rainfall events. We filtered samples in the field through 0.45 µm Supor membrane syringe filters (Acrodisc) and refrigerated them until analysis. Combined nitrate + nitrite and ammonium concentrations in soil water were measured using a QuikChem 8500 Series 2 Flow Injection Analysis System (Lachat Instruments, Loveland, Colorado; detection limit < 0.01 mg L^{-1} for all N species). Nitrite generally does not accumulate in soils; as such, we refer to measured nitrate + nitrite as simply nitrate throughout the remainder of this paper. Total N was measured with a Shimadzu TOC-L (Shimadzu, Kyoto, Japan; detection limit 5 µg L^{-1}), and dissolved organic N (DON) was calculated as the difference between total N and inorganic N.

Initial soil water nitrate concentrations varied among treatments, so for each sampling point, percent change in concentration relative to initial values was calculated as:

$$C_{relative} = (C_t - C_0)/C_0 * 100 \quad \text{(Eq. 1)}$$

where $C_{relative}$ is the relative concentration, C_t is the soil water nitrate concentration at any given time point, and C_0 is the initial concentration.

2.3.2 Modeling of water percolation

Nitrogen concentrations in soil water were combined with modeled water percolation at 1.2 m depth to estimate N leaching from the soil profile during the experimental period. Modeling of water percolation is described in detail in Hess et al (2018). Briefly, one-dimensional subsurface flow was simulated using Hydrus-1D. In each rainfall plot, water flow and root uptake were modeled daily using two soil layers: a top layer of 0 to ~0.2 m and a bottom layer of ~0.2 to 1.2 m. Exact layer depths depended on the specific rainfall plot. Inputs consisted of meteorological conditions, root depth, and LAI on a daily timestep, as well as soil hydraulic parameters for each soil layer estimated from pedotransfer functions based on soil texture and bulk density (Schaap et al., 2001). Model performance was evaluated by comparing simulated and measured volumetric soil water content at 0.1 and 1 m. Volumetric water content (VWC) was measured continuously (every 15 minutes) with soil moisture sensors (EC-5, Decagon Devices) installed in the center of each plot during the experimental period (Hess et al., 2018). Soil hydraulic parameters were then further refined through inverse modeling, which involved minimization of an objective function expressing the discrepancy between observed and predicted values. VWC data were split into training and testing sets for a 10-fold cross validation to assess model error; the RMSE for testing datasets was on average 0.038 $m^3 m^{-3}$.

To estimate N leaching, we multiplied soil water N concentrations by modeled percolation at 1.2 m soil depth on a daily timestep. We linearly interpolated nitrogen concentrations between time points when concentrations were measured. To allow rough comparisons to other published studies, we annualized N leaching rates by multiplying the total N leaching amount we estimated during the 234-day experimental period by $^{365}/_{234}$.

2.4 Surface soil N dynamics

In all rainfall plots in 2015, surface soils (0 - 0.2 m) were sampled every two weeks, one day prior to application of extreme rain events. One soil sample was collected with a 2.5 cm diameter push probe in each rainfall plot and passed through a 4 mm sieve. A 10 g subsample was then extracted in 50 mL 2M KCl, shaken for one hour, and filtered through pre-leached Whatman 44 filters. Inorganic N concentrations were measured as described in Section 2.3.1.

Rates of net N mineralization and nitrification were measured in late July/early August 2015 with resin cores (DiStefano and Gholz, 1986). Resin cores consist of an undisturbed soil core enclosed in a plastic tube, capped on both ends with resin bags, and incubated in-situ. The upper resin bag captures inorganic N from deposition, while the lower resin bag captures inorganic N leached from the soil core. One day after a simulated extreme rainfall event, one soil core 0.04 m diameter and 0.1 m deep was collected from each rainfall plot with plastic tubes. Approximately 5 mm soil was removed from the bottom of the core to create space to insert a resin bag. Resin bags were made with nylon stocking material and a polyethylene washer to maintain shape, filled with 6 g Dowex Marathon Mr-3 mixed bed ion-exchange resin, and closed with a plastic zip tie. Soil cores were replaced, a resin bag was placed on the top of the core, and cores were incubated for 14 days to capture one full rainfall cycle during which both rainfall treatments received the same total amount of water. At the end of 14 days, soil in cores and the resin bags were extracted in 2M KCl, and extracts were analyzed for inorganic N concentrations. Net N mineralization was calculated as the change in soil inorganic N concentrations, plus inorganic N in the lower resin bag after field incubation, over the incubation period. Net nitrification was calculated as the change in soil nitrate concentration, plus nitrate in the lower resin bag after field incubation, over the incubation period.

2.5 Soil inorganic N pools

In November 2014, soil horizons in each rainfall plot were characterized to 1.2 m depth. Intact cores of 0.06 m diameter were taken to 1.2 m depth with a hydraulic sampler (Geoprobe, Salina, KS). Soils were processed within several hours of collection. First, we separated each core into 5 taxonomic horizons based on color, texture, structure, and moisture. We calculated bulk density for each horizon and corrected for any compaction during sampling; compaction was on average 0.07 m per core. One 10 g subsample from the middle of each horizon, in addition to all the soil from that horizon, were analyzed for inorganic N and total C and N. Results were then compared to determine whether these 10 g subsamples could accurately represent entire horizons. Soils were analyzed for inorganic N concentrations as described in Section 2.4. For total C and N, sieved soils were dried at 65° C for 48 hours, pulverized, packed in tin capsules, and analyzed with a Carlo-Erba NA 1500 Elemental Analyzer (detection limit 0.01%).

Soils (0-1.2 m) were sampled four times in each rainfall plot during the experimental period in 2015 to characterize inorganic N in the entire soil profile: on 30 April – 1 May (after 2 weeks of rainfall manipulation), 8-9 July, 2-3 September, and 1-2 December. Because inorganic N and total C and N were not significantly different between entire horizons and their subsamples in soils collected in November 2014, we relied on subsamples from the middle of each horizon for the 2015 soil sampling (except for the last sampling date, when we used the hydraulic sampler). For these samplings, we used a 2.5 cm diameter push probe to collect a 0.1 m soil core from the middle of each soil horizon. To access deeper sample locations, we used a flighted auger, 2.7 cm in diameter, attached to a gas drill to remove soil down to the top of the sample location, at which point the push probe was inserted to remove the sample. Soils were sampled at two locations in each rainfall plot, leaving at least 1.5 m between a sample and plot borders, 1 m between a sample and the lysimeter, and 1 m between a sample and any previous soil samples. Samples were composited by depth and analyzed for inorganic N as described above. Total inorganic N in each horizon was calculated using inorganic N concentrations and bulk density data from 2014, and horizons were summed to calculate total inorganic N in the soil core (0-1.2 m).

2.6 Nitrogen in crop tissues

Aboveground biomass was collected in two 1 m x 1 m quadrats in each rainfall plot one day prior to soybean harvest. Biomass was dried at 65° C for 48 hours, weighed, and threshed to separate grain and stover. Grain was weighed, and stover weight was calculated as the difference between total weight and grain weight. Grain and stover were ground and analyzed separately for C and N concentrations as for soils. Total N in grain and total N in stover were summed to calculate total N in biomass.

2.7 Statistical analysis

Statistical analyses were performed using R 3.0.2 (R Core Team, 2013). Linear mixed models with a nested design were used to determine the effects of rainfall intensification and tillage on soil water N concentrations, percent change in soil water N concentrations, cumulative N leached, soil inorganic N, net N mineralization and nitrification, and crop tissue N. Fixed effects were rainfall treatment, tillage, and their interaction; random effects were the KBS LTER MCSE blocks and plots, with plot nested within block. Because we were mainly interested in treatment effects and not in changes over time, soil water nitrate, percent change in soil water nitrate, surface soil inorganic N concentrations, and inorganic N in 1.2 m soil cores were averaged across all time points for each rainfall plot before analysis, so as to avoid violations of the independence assumption caused by use of time series data. All data were log or box-cox transformed when necessary to fulfill assumptions of normality and homoscedasticity. Likelihood ratio tests were used to determine factor significance. When interactions between fixed effects were significant, pairwise comparisons were conducted and individual factors were not tested for significance. For all analyses, $\alpha = 0.05$.

3. Results

3.1 Rainfall manipulation

Rainfall variability was higher in the intensified rainfall treatment compared to the control rainfall treatment both for the period of time prior to 13 June ($CV_{control} = 1.24$, $CV_{intensified} = 3.77$) and that after 6 July ($CV_{control} = 2.67$, $CV_{intensified} = 4.33$).

3.2 Soil water N concentrations

Nearly all N in soil water was in the form of nitrate; ammonium was less than 1% and DON was undetectable. Initial soil water nitrate concentrations were significantly different between rainfall treatments (Table 3, Figure S1). Averaged over the entire experimental period, nitrate concentrations were higher in intensified (range: 2.8 mg NO_3^--N L^{-1} min to 11.0 mg NO_3^--N L^{-1} max) versus control (1.5 mg NO_3^--N L^{-1} min to 5.4 mg NO_3^--N L^{-1} max) plots in tilled cropping systems. No-till cropping systems exhibited the opposite pattern: soil water nitrate concentrations were higher in control (6.5 mg NO_3^--N L^{-1} min to 12.7 mg NO_3^--N L^{-1} max) compared with intensified (2.9 mg NO_3^--N L^{-1} min to 8.2 mg NO_3^--N L^{-1} max) plots throughout the experimental period.

Relative soil water nitrate concentrations (percent change in concentration relative to initial values, Eq. 1) increased in tilled plots, while they increased and then decreased in the intensified treatment (Figure 2). In no-till plots, relative soil water nitrate concentrations followed similar patterns in both control and intensified treatments, increasing and then decreasing back down to initial levels. However, there were no statistically significant differences among treatments in relative concentrations averaged over the experimental period (Table 3).

3.3 Nitrate leaching

Rainfall treatment and tillage had interacting effects on nitrate leaching (Figures 3, S2; Table 3). In tilled cropping systems, nitrate leaching was higher in intensified than control plots. In no-till cropping systems, there was no statistical difference between the rainfall treatments, although nitrate leaching was slightly higher in the intensified compared with control plots. These patterns were consistent regardless of whether the period between 13 June and 6 July was included in the analysis (Table 3; Figures 3, S2).

3.4 Surface soil N dynamics

Surface soil nitrate concentrations were higher in the intensified compared with control plots by an average of 32%, and in no-till compared with tilled plots (Figure 4, Table 3). Surface soil ammonium concentrations were low compared to nitrate concentrations and were not significantly affected by either rainfall treatment or tillage.

Rates of net N mineralization and nitrification in surface soils measured with in-situ resin cores were not significantly different between rainfall treatments or tillage treatments (Tables 3 and 4).

3.5 Soil inorganic N pools

Total inorganic N in soil cores sampled to 1.2 m was on average 43% higher in no-till compared to tilled plots (Figure 5, Table 3), with differences apparent early on in the experiment (after two weeks of exposure to rainfall treatments). Total inorganic N was not affected by rainfall treatment. Most soil inorganic N was in the form of nitrate (75%) rather than ammonium, especially in layers below the surface (0 – ~20 cm) layer (79%). While no statistical analysis was performed to determine the effect of time on soil inorganic N to 1.2 m, a generally decreasing trend was observed (from 22 to 9 kg N ha^{-1} averaged across all treatments).

3.6 Nitrogen in crop tissues

Crop N concentrations in grain and stover, and total N in aboveground crop biomass, were not significantly affected by rainfall treatment or tillage (Tables 3 and 4).

4. Discussion

We subjected tilled and no-till cropping systems to two rainfall regimes: one with relatively small, frequent events similar to historical patterns (control), and the other with a higher percentage of precipitation occurring in extreme events (intensified), with no difference in total rainfall amount. In the tilled cropping system, we found that rainfall intensification significantly increased nitrate leaching relative to control rainfall conditions. However, in the no-till system, nitrate leaching was not statistically different between intensified and control treatments. This interaction was not evident for percolation to depth (Hess et al., 2018).

4.1 Effects of rainfall intensification on nitrate leaching in tilled and no-till cropping systems

In the surface soils of both tilled and no-till plots, rainfall intensification increased nitrate concentrations relative to soils under control conditions (Figure 4). There seem to be two likely explanations for greater nitrate accumulation in the intensified rainfall treatment: greater N mineralization and lower plant N uptake. However, lower plant N uptake seems unlikely. Different from patterns in arid and semi-arid systems, soil moisture in our intensified rainfall treatment never decreased below the lower limit of plant-extractable soil water (Hess et al.,

2018) thereby inhibiting plant uptake before inhibiting microbial activity. Moreover, crop N pools were not different between treatments (Tables 3 and 4), nor, in a separate ^{15}N natural abundance study, was biological N fixation (BNF; K. Glanville and G.P. Robertson, personal communication). Lastly, differences in surface soil nitrate concentrations were highest in spring, when crops were either absent or when soybean biomass and thus N demand would have been minimal. Thus, depressed N uptake in the intensified plots is unlikely to explain the greater nitrate pools.

More likely are differences in N mineralization following rainfall exclusion, as has been found for soils from arid and semi-arid systems following rainfall onset (Birch 1958; Fierer and Schimel, 2002; Austin et al., 2004; Borken and Matzner 2009). Although we did not document differences in mineralization between rainfall treatments in our incubation assays, these assays are likely to have been insufficiently sensitive to detect appropriate treatment differences. Indeed, short-term patterns of net N mineralization and nitrification are notoriously difficult to detect in simple incubations, and the data in our relatively small sample size were particularly variable. Furthermore, as noted in the previous paragraph, differences in surface soil nitrate were largest in spring and early fall, when mineralization rates tend to be high due to relatively high soil moisture as well as crop senescence (in fall only).

The increase in surface soil nitrate concentrations driven by rainfall intensification was associated with an increase in N leaching in tilled cropping systems. In tilled plots exposed to the control rainfall treatment, low cumulative nitrate leaching (Figure 4) is consistent with data from a bromide tracer experiment suggesting little deep percolation in the control rainfall treatment (Hess et al., 2018). Within tilled plots subjected to the intensified rainfall treatment, in contrast, higher rates of deep percolation (Hess et al., 2018), higher surface soil nitrate concentrations

(Figure 4), and interaction of water with the soil matrix appear to have led to the mobilization and leaching of much greater amounts of nitrate.

In no-till cropping systems, on the other hand, no difference was observed in nitrate leaching between the intensified and control rainfall treatments in spite of greater deep percolation (Hess et al., 2018) and more surface soil nitrate (Figure 4) in the intensified treatment. Our data suggest that this difference in the response of N leaching between tilled and no-till cropping systems may be attributable to differences in soil structure and flow paths (Figure 6). In soils under no-till management, macropores may develop from decaying roots and soil fauna, and increased macro-aggregation (Grandy and Robertson, 2007) may also facilitate flow in the spaces between aggregates. Previously reported data suggest that in the particular no-till soils in this study, rapid macropore flow may have been a larger component of percolation than matrix flow relative to the tilled soils (Hess et al., 2018). In addition, extensive previous research has shown that macropore connectivity increases under no-till management compared to management with tillage in general, with corresponding increases in macropore flow and hydraulic conductivity (e.g. Ogden et al., 1999; Strudley et al., 2008).

It seems likely, then, that excess percolating water from extreme events “bypassed” inorganic N in the soil matrix in the no-till system. Other researchers have found that the contribution of macropore flow to total flow increases with rainfall event size (Vidon and Cuadra, 2010). Also consistent with rapid macropore flow in no-till cropping systems, patterns in soil water nitrate concentrations over the year were similar between rainfall treatments, and to patterns in surface soil nitrate (Figures 2, 4, S1). This suggests that soil water at depth reflected surface soil processes on relatively short timescales in the no-till system, regardless of rainfall treatment. All that said, it is also possible that nitrate in no-till soils under the intensified rainfall treatment was lost through other pathways besides leaching: denitrification, crop uptake, or some other pathway that we did not directly measure.

Our estimates of nitrate leaching from the control rainfall treatment (9.4 and 22.2 kg N ha^{-1} during the experiment duration for tilled and no-till cropping systems, respectively, or extrapolated to 14.1 and 33.3 kg N ha^{-1} $year^{-1}$) are within the range of rates of nitrate leaching reported by Syswerda et al. (2012) at the KBS LTER. Syswerda et al. (2012) estimated that 62.3 and 41.6 kg N ha^{-1} $year^{-1}$ were leached on average from the tilled and no-till cropping systems from 1995-2006. However, they estimated that only 5.9 and 3.9 kg N ha^{-1} $year^{-1}$ were leached on average from tilled and no-till cropping systems, respectively, during soybean seasons (from soybean planting until planting of the subsequent winter wheat crop), the lowest leaching rate of the three crops in the corn-soybean-winter wheat rotation. Our experiment spanned a full soybean season as well as part of the prior corn off-season (before soybean planting) and following winter wheat season (after winter wheat planting) as defined by Syswerda et al. (2012), which is likely why our estimates fall in between those for soybean seasons and those averaged across all years.

Our estimates also fall within the range of previous estimates of N leaching and losses from cropping systems elsewhere in the Midwest region. Donner et al. (2004) estimated mean annual N leaching rates from fertilized soybeans in the Mississippi River Basin in the early 1990s as 35.6 - 45.8 kg N ha^{-1} $year^{-1}$. However, nutrient imbalances in agriculture within the region have declined over the last several decades, and a slightly more recent estimate (from 1997 – 2006) places total N excess from corn-soybean rotations at approximately 10 kg N ha^{-1} $year^{-1}$ (Vitousek et al 2009). Our estimate of N leaching under control rainfall patterns from the tilled cropping systems – which are more representative of agricultural practices in the region than the no-till systems – falls very close to this number.

Syswerda et al (2012) found lower rates of nitrate leaching in the no-till cropping systems compared to tilled cropping systems, while we found no statistical differences. There are several possible reasons for this discrepancy. First, Syswerda and colleagues estimated nitrate leaching over 11 years, while our experiment lasted less than a year. We also did not measure nitrate leaching during snowmelt (early spring) or immediately after N fertilizer application (which did not occur during our study period), times when nitrate leaching can be substantial. Our annualized estimates are extrapolations and thus are uncertain by definition.

Our finding of increased nitrate leaching under rainfall intensification in tilled cropping systems is consistent with findings of similar rainfall intensification experiments in other ecosystem types. In an arid steppe, Yahdjian and Sala (2010) found that fewer, less frequent rainfall events increased nitrate leaching measured with resin bags at 0.1 m soil depth. In a semi-arid Mediterranean woodland, Jongen et al (2013) also concluded that fewer, less frequent rainfall events increased nitrate leaching, estimated by multiplying soil water nitrate concentrations by water infiltration in the top 35 cm soil 24 hrs after rainfall events. However, it is worth noting that not all infiltrated water in that study may have drained below the rooting zone, given the presence of deep-rooted shrubs and trees.

4.2 Uncertainty in nitrate leaching estimations

There are several sources of uncertainty in our estimates of nitrate leaching. First, there is uncertainty associated with the modeled estimates of deep percolation, as discussed in Hess et al. (2018). Specifically, calibrated parameter estimates in addition to lack of information about macropore flow in our study site soils contribute uncertainty to percolation estimates (Hess et al., 2018). Secondly, the period of time between 13 June and 6 July, during which all rainfall plots received ambient rainfall, introduced error into our experiment and may have caused us to underestimate the effect of rainfall intensification on nitrate leaching. In the control rainfall treatment, more than half of the total deep percolation during the experiment occurred during this period (Hess et al., 2018). This percolation likely leached N that may have otherwise remained in the soil profile given relatively little deep percolation during the rest of the experiment. Our results (Figure 3) thus likely overestimate nitrate leaching in control plots. We also calculated nitrate leaching without the time period between 13 June and 6 July (Figure S2), in an attempt to remove the nitrate leaching contribution from this unplanned event. However, even with this alternative analysis, it is impossible to remove the influence of this time period from our results. For example, in the intensified rainfall treatment, nitrate leached during this time period would likely have been leached later on in the experiment, given relatively high rates of deep percolation (Hess et al., 2018). These alternative results (Figure S2) thus likely underestimate nitrate leaching under intensified rainfall conditions. It is possible that had this event not occurred, we would have measured elevated nitrate leaching in intensified relative to control conditions within no-till plots, similar to tilled plots, although relative differences in the response of tilled and no-till systems to rainfall intensification would likely have been similar to what we observed.

Finally, differences in antecedent soil water nitrate concentrations among treatments (Figure S1) may have affected our comparative estimates of nitrate leaching. Our experiment in 2015 followed a rainfall intensification experiment the previous year, which may have affected the distribution of nitrate in the soil profile. Ultimately, however, we do not know the reason for pre-existing differences, only that they were present.

5. Conclusion

The frequency of extreme daily precipitation is forecast to increase by the end of the century everywhere in the U.S., including the Midwest (Melillo et al., 2014). Our results show that rainfall intensification may exacerbate leaching losses of reactive N from cropping systems, and that no-till management may buffer against these losses.

Variation in soil type and structure, climate, and agronomic practices across larger spatial scales may influence the way that cropping systems respond to rainfall intensification. For example, in places with less well-drained soils than ours, rainfall intensification could reduce infiltration and increase overland flow (Zhang and Nearing, 2005), decreasing deep percolation and thus N leaching. In such places, rainfall intensification may generate other negative consequences for agricultural productivity and water quality, such as increased soil erosion (Zhang and Nearing, 2005) and loss of nutrients in particulate form (e.g. phosphorus). Also, fertilizer application and the large pulses of soil inorganic N that accompany it during the cultivation of crops like corn may make cropping systems even more vulnerable to rainfall intensification, particularly if extreme events occur shortly after fertilizer application.

Evaluating the effects of rainfall intensification on nutrient leaching from cropping systems is in its infancy. Modeling studies have explored this topic and found increased nitrate leaching associated with rainfall intensification (Gu and Riley, 2010; Congreves et al., 2016); experimental field studies, however, are scarce. While much can be learned from modeling studies, models are also limited to the extent that they accurately represent ecosystem processes. Macropore flow, for example, is rarely represented in models (Beven and Germann, 2013), and results from our study suggest that macropore flow may be responsible for the difference in the response of tilled and no-till cropping systems to rainfall intensification. Further research is needed over longer time scales and in more locations to develop a more robust framework for understanding how rainfall intensification may affect nutrient losses from agriculture in general.

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Tables

Table 1. Soil profile characteristics at the KBS LTER (from Crum and Collins, 1995, unless otherwise indicated). All information except soil carbon and nitrogen is reproduced from Hess et al (2018).

Horizon	Depth	Sand	Silt	Clay	Texture classification	Soil carbon	Soil nitrogen	Bulk density
	cm		- % -			g C kg soil^{-1}	g N kg soil^{-1}	g cm^{-3}
<u>Kalamazoo series</u>								
Ap	0-30	43	38	19	loam	12.85	1.31	1.6
E	30-41	39	41	20	loam	3.25	0.53	1.7
Bt1	41-69	48	23	29	sandy clay loam	2.25	0.42	1.8
2Bt2	69-88	79	4	17	sandy loam	0.67	0.42	1.6*
2E/Bt	88-152	93	0	7	sand	0.2	0.18	1.6*
<u>Oshtemo series</u>								
Ap	0-25	59	27	14	sandy loam	9.67	1.04	1.6
E	25-41	64	22	14	sandy loam	2.52	0.43	1.7
Bt1	41-57	67	13	20	sandy clay loam	1.99	0.4	1.8
2Bt2	57-97	83	4	13	sandy loam	1.28	0.53	1.6*
2E/Bt	97-152	92	0	8	sand	0.25	0.18	1.6*

* data from Syswerda et al (2011)

Table 2. Details of relevant management events (planting, harvest, tillage, and N fertilizer application) before and during the rainfall manipulation experiment.

crop	date	management event
corn	5/20/14	33 kg N/ha applied
corn	6/19/14	133 kg N/ha applied
	5/2/15	Tillage with chisel plow
	5/18/15	Tillage with cultimulcher to remove large soil clumps
soybeans	5/19 – 5/20/15	Soybeans planted
soybeans	9/30/15	Soybeans harvested
	10/3/15	Tillage with chisel plow
	10/6/15	Tillage with cultimulcher to remove large soil clumps
wheat	10/2/15	Wheat planted in no-till plots
wheat	10/6/15	Wheat planted in tilled plots

Table 3. Significance of factors in linear mixed models as estimated through likelihood ratio tests. When interactions between fixed effects were significant, individual factors were not tested. Significant p values are in bold.

	Tillage	**Rainfall**	**Tillage x rainfall**
Soil water NO_3^--N concentrations	-	-	**< 0.001**
Percent change in soil water NO_3^--N concentrations	0.12	0.19	0.32
Cumulative NO_3^--N leached (13 June – 6 July included)	-	-	**0.001**
Cumulative NO_3^--N leached (13 June – 6 July excluded)	-	-	**0.006**
Inorganic N in deep soil cores	**0.02**	0.10	0.12
Surface soil NO_3^--N concentrations	**0.01**	**<0.001**	0.34
Surface soil NH_4^+-N concentrations	0.18	0.88	0.72
Net N mineralization	0.87	0.49	0.20
Net nitrification	0.54	0.82	0.39
%N in grain	0.80	0.27	0.22
%N in stover	0.27	1.00	0.33
Total N in aboveground biomass	0.38	0.78	0.20

Table 4. Net N mineralization, net nitrification, crop N concentrations, and total crop N. Values shown are averaged by rainfall and tillage treatments, ± 1 SE (n = 4 replicate plots).

	Tilled, control	**Tilled, intensified**	**No-till, control**	**No-till, intensified**
Net N mineralization ($\mu g\ NH_4^+$-N+ NO_3^--N g $soil^{-1}$ day^{-1})	0.28 ± 0.12	0.20 ± 0.12	0.17 ± 0.04	0.32 ± 0.04
Net nitrification ($\mu g\ NO_3^-$-N g $soil^{-1} day^{-1}$)	0.28 ± 0.12	0.22 ± 0.03	0.19 ± 0.05	0.31 ± 0.10
N in grain (%)	5.57 ± 0.08	5.66 ± 0.06	5.63 ± 0.07	5.63 ± 0.07
N in stover (%)	0.69 ± 0.03	0.71 ± 0.05	0.66 ± 0.04	0.63 ± 0.05
Total N in aboveground biomass (kg N ha^{-1})	218 ± 24	226 ± 18	244 ± 5	226 ± 6

Figure captions

Figure 1. Study location and rainout shelter design. a) Diagram of the Main Cropping System Experiment (MCSE) at the Kellogg Biological Station (KBS) Long Term Ecological Research (LTER) site; b) Rainout shelters and other instrumentation installed in each rainfall plot. Tension lysimeters were installed in the middle of each rainfall plot at 1.2 m soil depth. Tubing connected to lysimeters was buried in trenches running north from the rainfall plot to the MCSE plot border. Reproduced from Hess et al. (2018).

Figure 2. Percent change in soil water nitrate concentrations relative to initial values at 1.2 m depth in tilled (a) and no-till (b) plots. The period of time between 13 June and 6 July 2015, when all rainfall plots received ambient rainfall, is indicated by gray shading. Black arrows indicate the date when rainout shelters were installed in plots. There were no significant differences among treatments for values averaged over the entire experimental period. Error bars represent standard error (n = 4 replicate plots).

Figure 3. Cumulative estimated nitrate leached during the experiment, by rainfall and tillage treatments. Blue lines show mean cumulative nitrate leached, with shaded envelopes representing ± 1 SE (n = 4 replicate plots). The period of time between 13 June and 6 July 2015, when all rainfall plots received ambient rainfall, is indicated by gray shading. Letters indicate significant differences in total nitrate leached between rainfall treatments in tilled cropping systems only ($p = 0.002$).

Figure 4. Exchangeable inorganic N concentrations in surface soils (0 – 0.2 m) in tilled (a and c) and no-till (b and d) cropping systems in 2015, measured one day prior to applied extreme rainfall events in the intensified plots. a) Nitrate concentrations in tilled cropping systems; b)

nitrate concentrations in no-till cropping systems; c) ammonium concentrations in tilled cropping systems; d) ammonium concentrations in no-till cropping systems. Averages represent averages over the entire experimental period, and error bars represent ± 1 SE (n = 4 replicate plots). Average nitrate concentrations over the experimental period were higher in soils exposed to the intensified rainfall treatment compared to the control rainfall treatment ($p < 0.001$), and in no-till soils compared to tilled soils ($p = 0.01$). Ammonium concentrations were not significantly different between rainfall or tillage treatments. In panels c and d, average points for the control plots are behind average points for the intensified plots.

Figure 5. Total inorganic N in soils (0-1.2 m) during the experimental period. Points shown are averages for each tillage treatment, with error bars representing ± 1 SE (n = 8 replicate plots).

Figure 6. Conceptual diagram of the effects of rainfall intensification on nitrate leaching in tilled and no-till cropping systems in mesic climates. In tilled soils (top panels), soil water flux is dominated by matrix flow. In the control rainfall treatment (top left panel), very low deep percolation and surface soil nitrate concentrations result in very low nitrate leaching. In the intensified rainfall treatment (top right panel), increased deep percolation mobilizes elevated soil nitrate, resulting in high nitrate leaching. In no-till soils (bottom panels), more percolation is through macropores than in tilled soils. In the control rainfall treatment (bottom left panel), low deep percolation and moderate surface soil nitrate concentrations results in moderate nitrate leaching. In the intensified rainfall treatment, high percolation and surface soil nitrate concentrations also result in only moderate nitrate leaching, as percolating water bypasses inorganic soil N to a greater extent than in tilled soils. Evapotranspiration is abbreviated as ETA.

Figure 1

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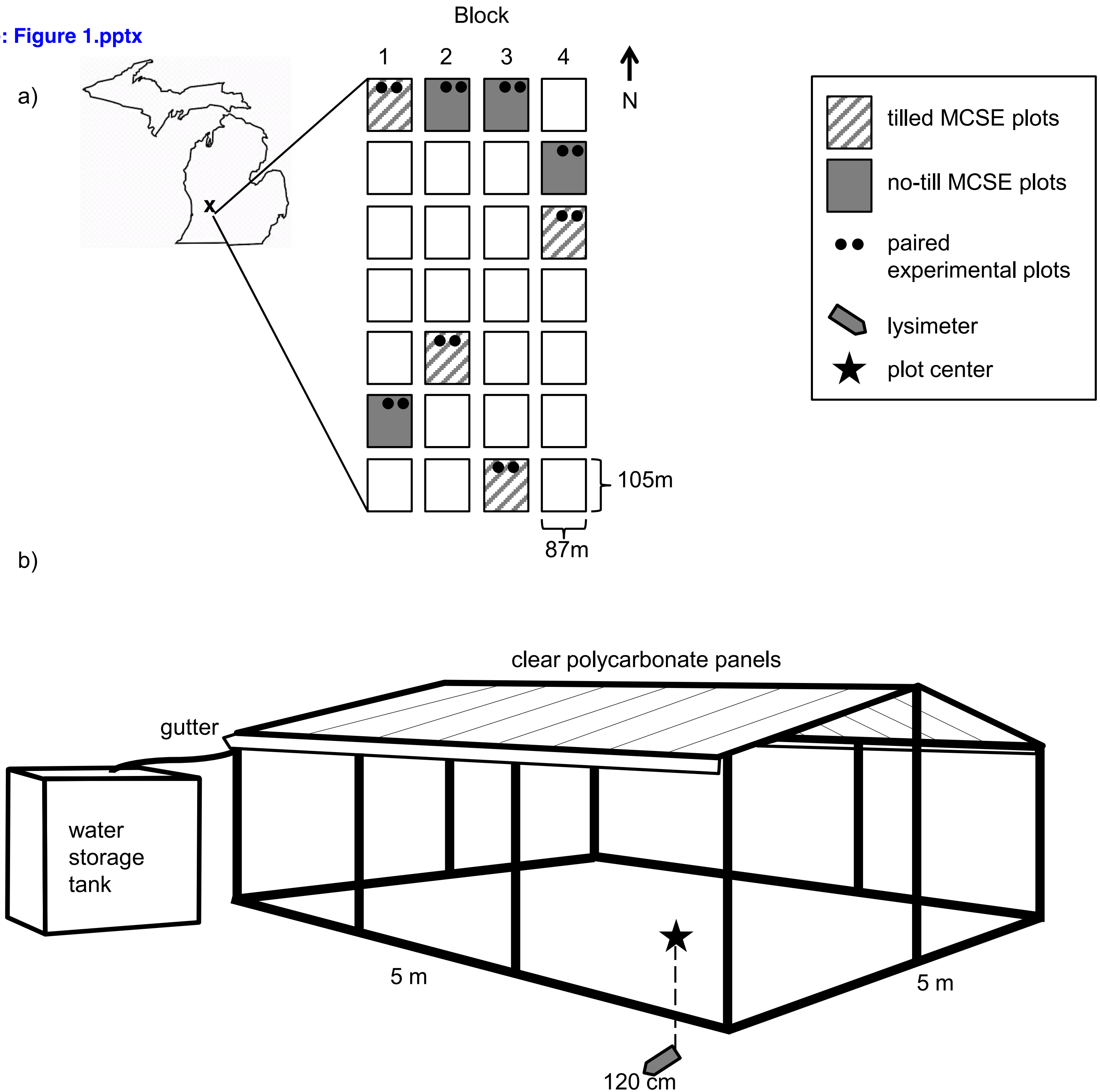

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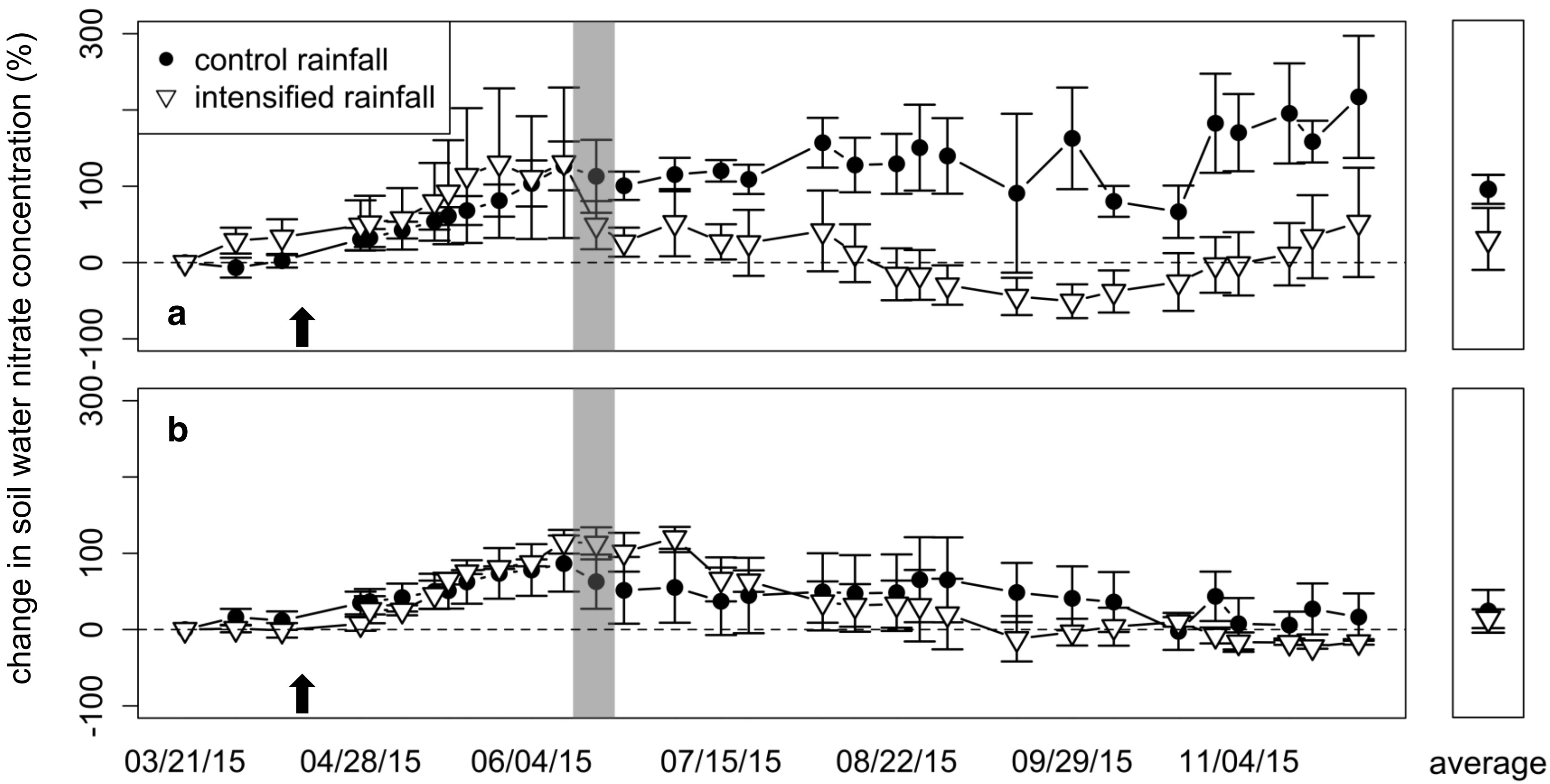

Figure 3

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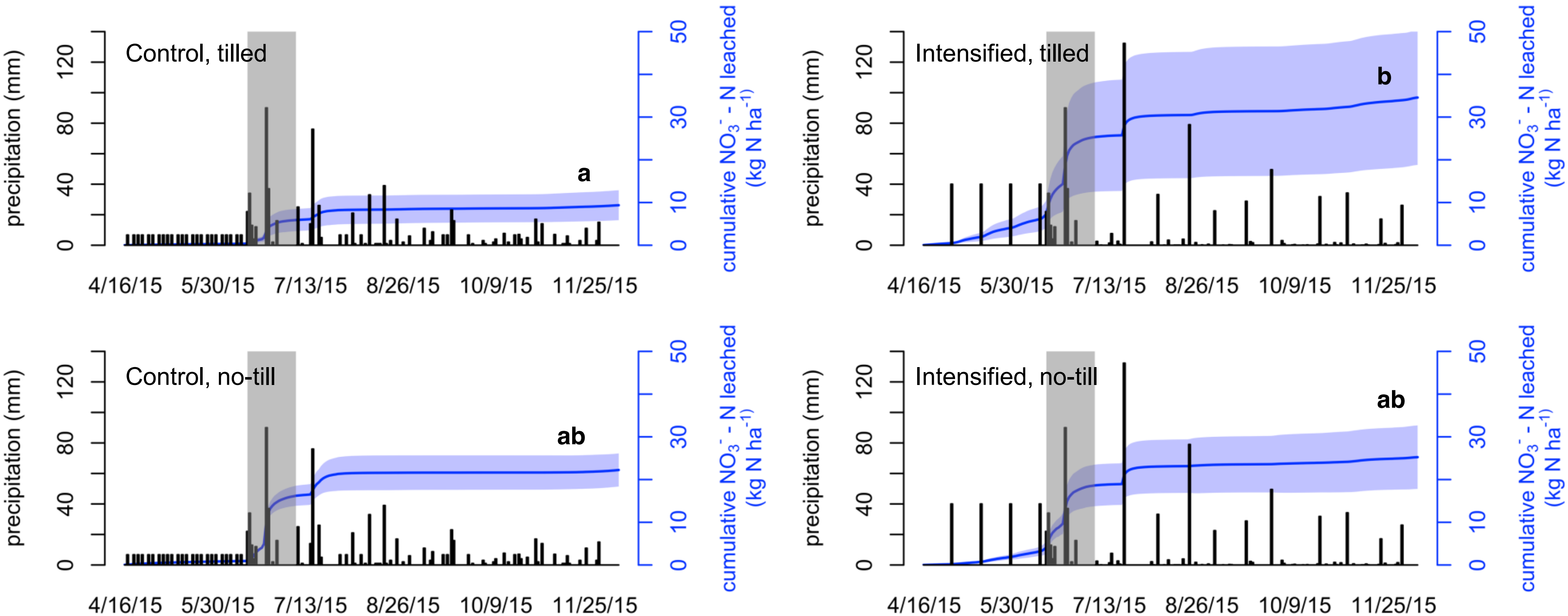

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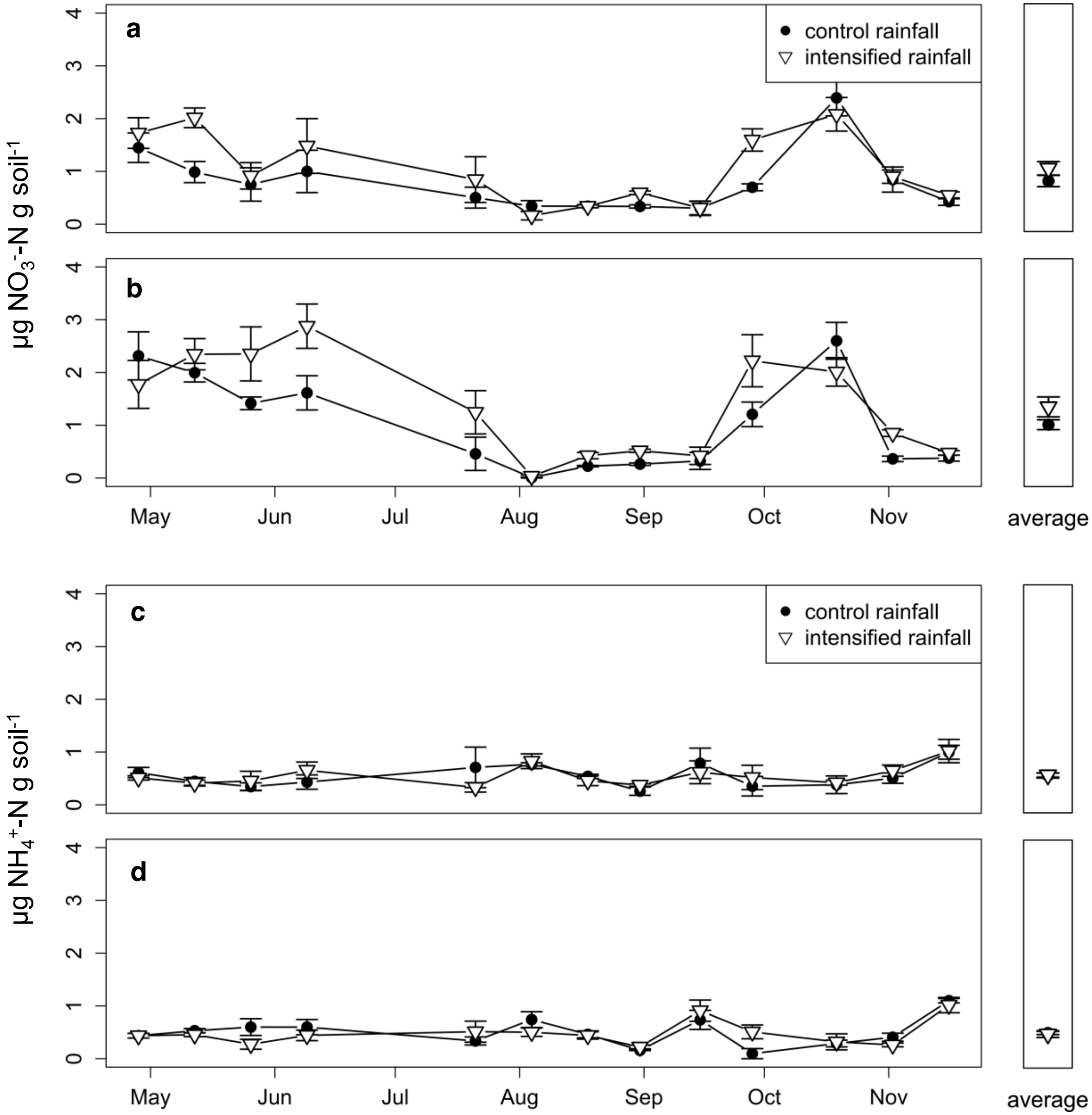

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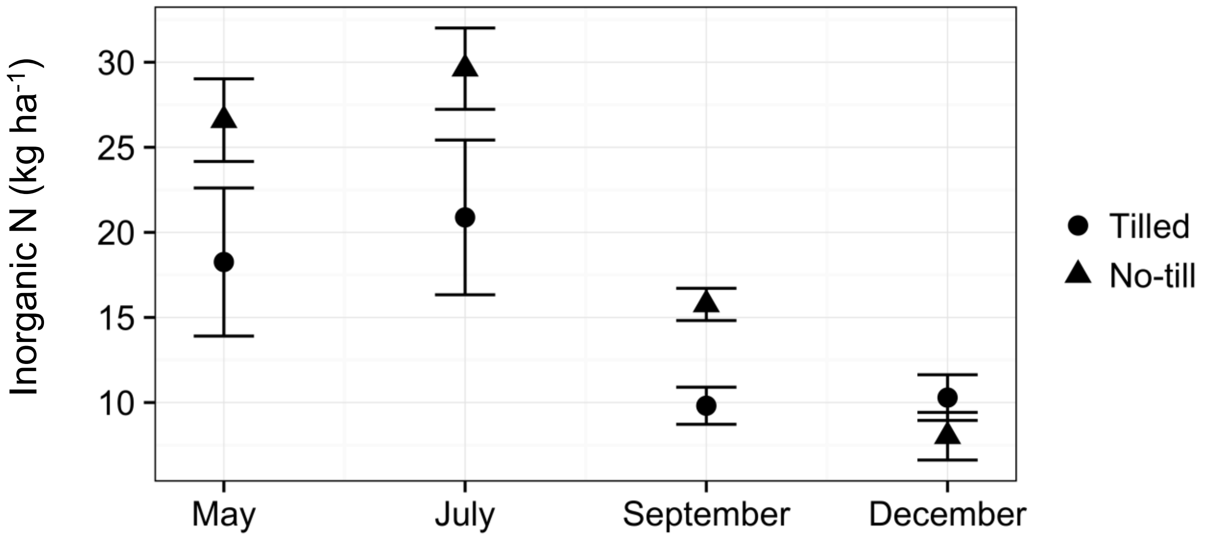

Figure 6

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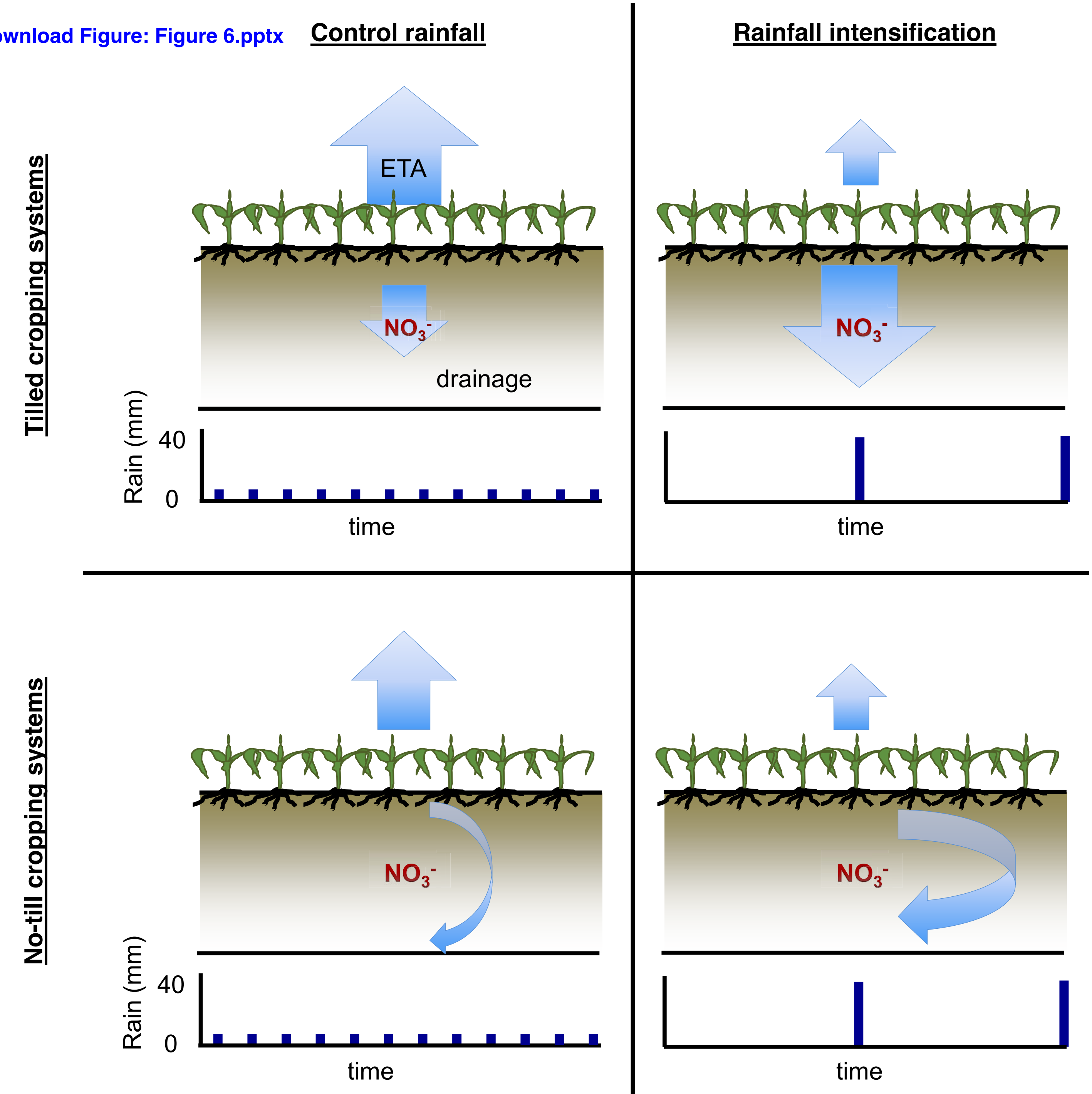

Supplementary Material

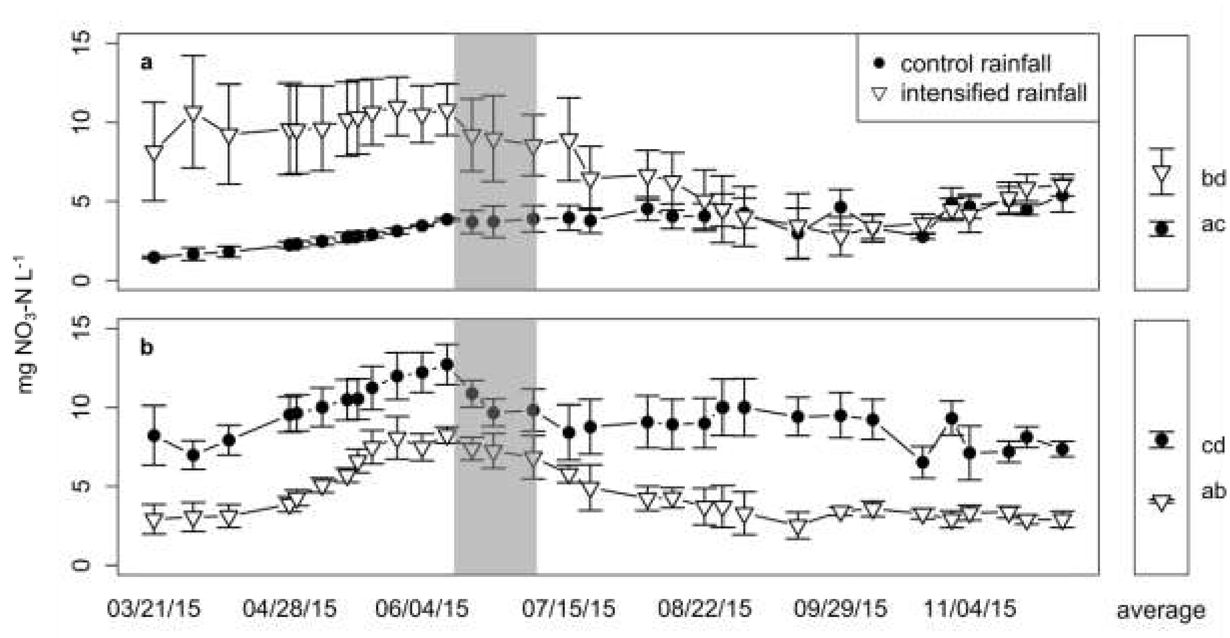

Figure S1. Soil water nitrate concentrations at 1.2 m depth in tilled (a) and no-till (b) plots. The period of time between 13 June and 6 July 2015, when all rainfall plots received ambient rainfall, is indicated by gray shading. Letters indicate significant differences ($p < 0.001$) for values averaged over the entire year. Error bars represent standard error ($n = 4$ replicate plots). Initial values differed between rainfall treatments in both tilled and no-till plots, possibly reflecting prior site use. Changes in soil water nitrate concentrations relative to initial values appear in Figure 2 in the main text.

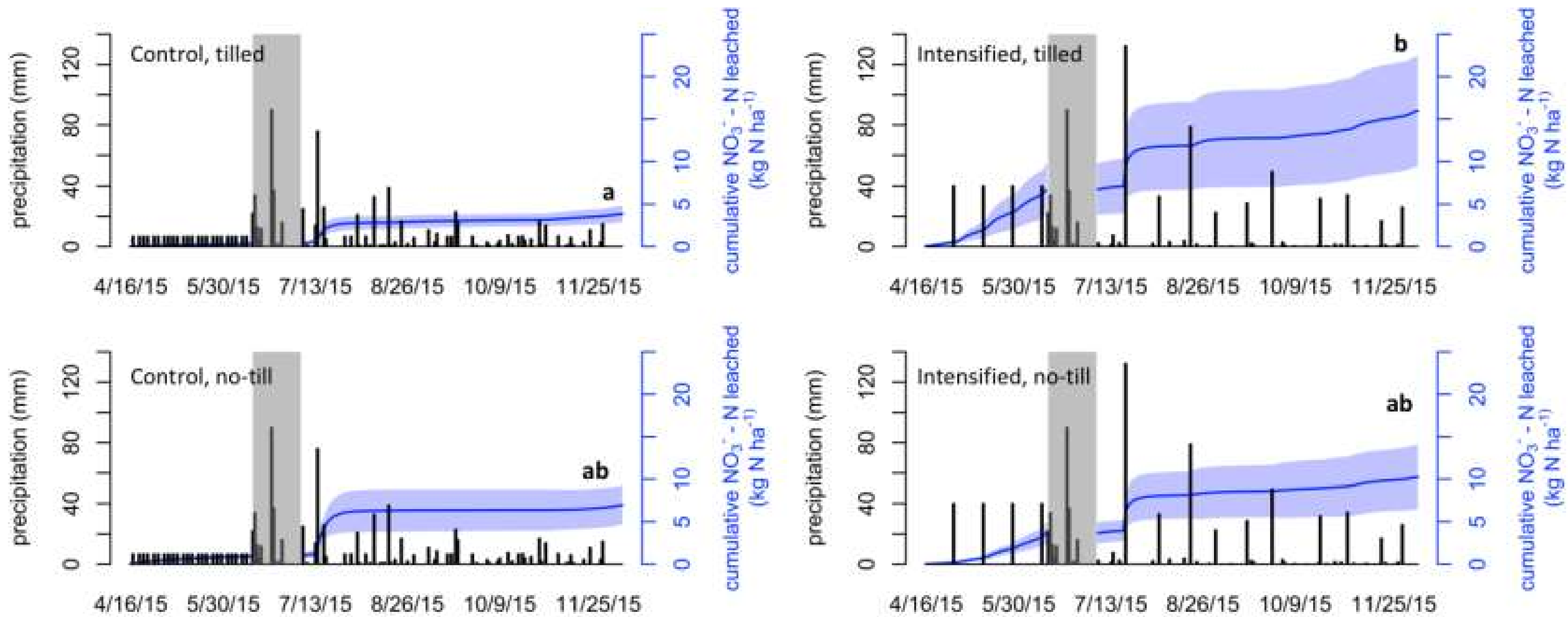

Figure S2. Cumulative estimated nitrate leached during the experimental period, by rainfall and tillage treatment. Blue lines (right hand axis) show mean cumulative nitrate leached, with shaded envelopes representing ± 1 SE (n = 4 replicate plots). The period of time between 13 June and 6 July 2015, when all rainfall plots received ambient rainfall, is indicated by gray shading and *excluded* from the calculation of cumulative nitrate leached. Letters indicate significant differences ($p = 0.01$).