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Rainfall Intensification Enhances Deep Percolation and Soil Water Content in Tilled and No-Till Cropping Systems of the US Midwest

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Core Ideas

- Rainfall intensification increased deep percolation in tilled and no-till systems.
- Rainfall intensification increased deep soil water content in both cropping systems.
- A bromide tracer was detected at 1.2-m depth sooner in no-till than tilled systems.
- The effect of rainfall intensification on surface soil moisture varied seasonally.

Globally, the proportion of total rainfall occurring as extreme events is increasing, which may have consequences for agriculture. In the US Midwest, we conducted a 234-d manipulative experiment in 16 paired plots where we increased the proportion of rain falling in extreme events on tilled and no-till cropping systems. We compared the effects of larger, less frequent rain events ("intensified" rainfall) vs. smaller, more frequent rain events ("normal" rainfall) on soil water content and deep percolation. The effect of intensified rainfall on the volumetric water content (VWC) of soil at the 10-cm depth during the experiment varied seasonally: in spring, intensified rainfall decreased the average VWC at the 10-cm depth by 0.05 $\pm$ 0.01 $cm^3 cm^{-3}$ compared with normal rainfall, but in summer and fall, it had no effect. In soil at the 100-cm depth, VWC declined during the summer in normal but not intensified plots. A surface-added Br^- tracer was detected and peaked earlier in soil water at 120 cm under intensified rainfall vs. normal rainfall (by 6 $\pm$ 3 and 74 $\pm$ 33 d, respectively) regardless of tillage, although it was detected sooner in no-till than tilled systems (by 9 $\pm$ 3 d). Also, less Br^- was recovered in soil under intensified (8 $\pm$ 8% of total Br^- added) vs. normal rainfall (21 $\pm$ 3%). Our results suggest that rainfall intensification will increase deep percolation and deep soil water content in cropping systems regardless of tillage. Such changes to soil water dynamics may alter plant water and nutrient availability.

Abbreviations: KBS, Kellogg Biological Station; MCSE, Main Cropping System Experiment; VWC, volumetric water content.

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In many areas of the world, precipitation patterns are changing as a result of rising global surface temperatures (Fischer and Knutti, 2015; IPCC, 2013). As temperatures continue to increase in the coming century, climate models predict that in many areas the proportion of total precipitation falling in extreme events will also continue to increase (Li et al., 2018; Pfahl et al., 2017; Berg and Hall, 2015; Easterling et al., 2000); observational studies report that these trends are already occurring (Lehmann et al., 2015). Extreme events are often defined relative to the historical distribution of daily precipitation amounts (e.g., above the 90th or 95th percentile: Marquardt Collow et al., 2016; IPCC, 2012), and their frequency has already begun to increase in many parts of North America. For example, the US Midwest, a major agricultural region, has seen an increase in the amount of precipitation falling in the largest 1% of 24-h precipitation events (calculated for the time period between 1901 and 2012) of nearly 40% since 1958 (Pryor et al., 2013, 2014).

Decades of research have documented the effects of episodic precipitation on soil water availability and partitioning in arid and semiarid ecosystems, where rainfall is characterized by pulsed events (e.g., Liu et al., 2015; Wang et al., 2008; Noy-Meir, 1973). However, comparatively little is known about how the consolidation of precipitation into larger, less frequent events—defined here as *rainfall intensification*—will affect ecosystems in mesic climates, where rainfall events have historically been frequent and more evenly distributed with time. The hydrologic response to rainfall intensification in mesic systems will depend on climatic conditions, the nature of rainfall changes, and how altered rainfall interacts with soil characteristics (e.g., structure and texture). For example, larger, less frequent rainfall events may amplify fluctuations in soil water content and increase water stress in mesic ecosystems due to enhanced soil drying during the longer intervals between rainfall events (Barbeta et al., 2015; Heisler-White et al., 2009; Knapp et al., 2008; Knapp et al., 2002). Jongen et al. (2013) found that while rainfall intensification did amplify fluctuations in soil moisture in a Mediterranean ecosystem, it did not lead to increased plant water stress. Large rainfall events may lead to plant stress due to soil saturation; in a modeling study, Rosenzweig et al. (2002) found that projected future increases in heavy precipitation would lead to increased crop damage in agricultural systems due to soil saturation. Other consequences of rainfall intensification may include increased infiltration and percolation deeper within the vadose zone compared with smaller, more frequent events, thereby decreasing evaporation and transpiration (Ries et al., 2015; Jongen et al., 2013; Knapp et al., 2008), although this effect may depend largely on antecedent soil moisture (Lai et al., 2016). In addition, rainfall intensification could alter infiltration and percolation pathways, as preferential flow pathways appear to be activated at higher soil moisture and when rainfall rates exceed the soil infiltration capacity (Pot et al., 2005; Beven and Germann, 1982).

An increase in overland runoff due to soil saturation occurring during large events is another possible consequence of rainfall intensification. Increases in runoff would be most pronounced in areas with slope (Wienhold et al., 2018; Nearing et al., 2005). Many studies of changes in rainfall in agricultural systems, including those in humid climates, have focused on the effects of rainfall intensity (at the scale of minutes to hours) on overland runoff and soil erosion (e.g., Wei et al., 2014; Kleinman et al., 2006), whereas the effects of rainfall intensification on vadose zone flow have been much less investigated.

Annual cropping systems present another important factor to consider with respect to the consequences of altered precipitation regimes: tillage. Tillage changes the physical structure of the soil by disrupting soil aggregates and macropore connectivity, potentially leading to a reduction in hydraulic conductivity (Strudley et al., 2008). No-till practices may restore aggregation and macropore connectivity, thereby increasing preferential (i.e., rapid, vertical macropore) flow to subsurface soil horizons (Strudley et al., 2008; Ogden et al., 1999). In no-till systems, therefore, larger storms may result in lower losses via evapotranspiration and greater soil water storage at depth. Thus, the response of annual cropping systems to changing precipitation patterns may be strongly influenced by tillage management. Determining the response of agricultural systems to rainfall intensification is particularly important in areas where agriculture is rainfed because changes in soil water availability may have consequences for crop yield (Steiner et al., 2018). In addition, changes in percolation through the vadose zone may affect nutrient and pesticide leaching—major contaminants of downstream aquatic systems (Sinha et al., 2017; Otto et al., 2016; Ye et al., 2016).

Manipulative field experiments that modify rainfall event frequency and intensity, but not total rainfall amount, are not common because they are logistically difficult and resource intensive. As a result, many studies examining rainfall intensification effects have used observational data from ambient rainfall records and did not control for total precipitation amount, which can confound results.

In this study, we report on the first manipulative field experiment to test how changes in rainfall event frequency and size, but not total rainfall amount during the experimental period, affect soil water content and deep percolation in a mesic agricultural system and to examine the interactions of these effects with cropping system management. We compared the hydrologic response of cropping systems typical of the US Midwest to relatively small, frequent rainfall events based on historical precipitation patterns (normal) and to intensified rainfall, with extreme rain events applied less frequently. We explored how this rainfall intensification affected the cropping systems and how tillage influenced the response of these systems. We hypothesized that rainfall intensification would (i) amplify fluctuations in soil water content at the soil surface, and (ii) increase deep percolation below the root zone, particularly under no-till management where macroporosity may be increased.

Methods

Study Site

Our study consisted of a 234-d manipulative rainfall experiment in the Main Cropping System Experiment (MCSE) of the Kellogg Biological Station's Long-Term Ecological Research site. The Kellogg Biological Station (KBS) is located in southwestern Michigan (85°24′ W, 42°24′ N, 288 m elevation). The mean annual temperature is 10.1°C, with annual precipitation averaging 1005 mm (Robertson and Hamilton, 2015). Approximately 17% of the total precipitation falls in winter, with the remaining amount evenly distributed across seasons (Robertson and Hamilton, 2015). The comingled Kalamazoo (fine loamy) and Oshtemo (coarse loamy) soils are well-drained mixed, active, mesic Typic Hapludalfs developed on glacial till and outwash (Crum and Collins, 1995) mixed with silt-rich loess (Luehmann et al., 2016; Table 1). In general, there is very little to no overland flow at the site due to the combination of well-drained soils and shallow slopes (<6%).

Experimental Design

The MCSE was established in 1988, 27 yr before the start of this study, and includes both conventional and no-till cropping systems planted in annual rotations of corn (*Zea mays* L.), soybean [*Glycine max* (L.) Merr.], and winter wheat (*Triticum aestivum* L.). The conventional cropping system is managed with nutrient inputs and tillage (hereafter *tilled*). The no-till cropping system is managed with the same nutrient inputs but has not been tilled since 1988. Each cropping system is assigned to 1-ha plots, replicated within each of six blocks. Further establishment and management details are available in Robertson and Hamilton (2015). From 19 May through 30 Sept. 2015, soybean was grown in all plots, followed by winter wheat that was planted on 2 and 6 October in the no-till and tilled cropping systems, respectively. The tilled cropping system was chisel plowed, and a cultimulcher was used to remove large soil clumps, on 2 and 18 May, respectively (prior to soybean planting), and on 3 and 6 October, respectively (prior to wheat planting).

We conducted a rainfall manipulation experiment from mid-April through early December 2015. On 14 April, paired 5- by 5-m rainout shelters were installed in four tilled and four no-till plots, for a total of 2 tillage treatments × 2 rainfall treatments × 4 replicate blocks = 16 shelters (Fig. 1 and 2). Shelters were located in areas with minimal to no slope (<1%) and at least 5 m from plot edges and neighboring shelters.

The shelters were constructed with polyvinyl chloride pipe and clear, corrugated polycarbonate roof panels that allowed 90 to 95% of photosynthetically active radiation to pass through. Shelters were 150 cm high at their tallest point and 110 cm tall at their lowest, allowing space between roofs and plants; they were anchored with rebar stakes and straps. Gutters at the base of the roof panels channeled rainwater to tanks for storage until application. In each MCSE plot, one rainout shelter covered a normal rainfall plot while the other shelter covered an intensified rainfall plot (hereafter referred to as *normal* and *intensified* plots). From mid-April through mid-June 2015, all plots received 80 mm of applied rainfall per month, approximating the average monthly precipitation at KBS based on weather data recorded since 1989 (http://lter.kbs.msu.edu/datatables/448). In plots exposed to normal conditions, 6.7-mm rain events were applied three times per week, with two dry intervals of 2 d and one of 3 d (Fig. 3). This schedule most closely represented median wet-day precipitation (6 mm) and dry-period length between wet days (3 d) from March to November, based on long-term weather data (from 1988–2015) at the KBS (http://lter.kbs.msu.edu/datatables/7; Supplemental Fig. S1).

We defined wet days as those with ≥1 mm of precipitation. In intensified plots, 40-mm rain events were applied approximately every 14 d, which corresponds to the 97th percentile of both precipitation event size and dry-period length at KBS (Supplemental Fig. S1). The application interval of 14 d could not always be strictly followed due to logistical constraints (e.g., weather, agronomic management activities).

Table 1. Representative soil profile properties at the Kellogg Biological Station's Long-Term Ecological Research site (data from Crum and Collins [1995] except where noted).

Horizon	Depth	Sand	Silt	Clay	Texture classification	Bulk density
	cm	——	%	——		g cm^{-3}
Kalamazoo series						
Ap	0–30	43	38	19	loam	1.6
E	30–41	39	41	20	loam	1.7
Bt1	41–69	48	23	29	sandy clay loam	1.8
2Bt2	69–88	79	4	17	sandy loam	1.6†
2E/Bt	88–152	93	0	7	sand	1.6†
Oshtemo series						
Ap	0–25	59	27	14	sandy loam	1.6
E	25–41	64	22	14	sandy loam	1.7
Bt1	41–57	67	13	20	sandy clay loam	1.8
2Bt2	57–97	83	4	13	sandy loam	1.6†
2E/Bt	97–152	92	0	8	sand	1.6†

† Data from Syswerda et al. (2011).

When ambient rainfall did not provide enough water for applications, a supplemental mix of pumped groundwater and precipitation from a nearby reservoir (low conductivity, low nitrate) was used. Water was applied to plots using overhead sprinklers connected to bilge pumps powered at a rate of 13 mm h^{-1}, a rate that avoided overland flow. At our study site, overland flow rarely occurs at the landscape scale, so we chose not to introduce that as a factor in our experimental design. We instead attempted to mimic the landscape-scale conditions of the site at the plot scale of our study, where micro-topographical variation could result in surface runoff outside the rainout shelter plots at lesser rainfall intensities than would generate surface runoff at the landscape scale. The simulated rainfall intensity (13 mm h^{-1}) has a recurrence interval of <1 yr in this geographic region (NOAA, 2017).

On 13 June 2015, a storm with wind speeds in excess of 96 km h^{-1} destroyed the rainout shelters. They were rebuilt and reinstalled on 6 July, resulting in a 3-wk period during which all plots were exposed to ambient rainfall. Shelters were replaced only in intensified plots, and slits were cut in the roofs to allow airflow and reduce resistance to wind, providing 90% rain exclusion. In intensified plots, excluded rainwater was collected in tanks and applied approximately once every 14 d. During naturally occurring extended dry periods, we simulated 6.7-mm rain events in normal plots using supplemental water to prevent soil drying. The equivalent amount of supplemental water was added to the intensified plots during the next extreme rain event to maintain an equal amount of total precipitation between the two rainfall treatments.

Total precipitation during the months of the experimental period was 891 mm (Fig. 3). Of that, 230 mm was ambient rainfall to which all plots were exposed when shelters were not in place between 13 June and 6 July 2015. During the experimental period, all precipitation fell as rainfall, except for one event on 21 Nov. 2015 that fell as snow, with 11-mm snow water equivalent.

Soil and Soil Water Content Measurements

In May 2014, two soil moisture sensors (EC-5, Decagon Devices) were installed in the center of each plot, one at 10 and the other at 100-cm depth (Fig. 2). For installation, soil was removed to the desired depth (with a trowel for sensors at 10 cm and a hydraulic probe for sensors at 100 cm), and sensors were inserted into undisturbed soil. The sensors logged volumetric water content (VWC) every 15 min from April through December 2015, except when agronomic management operations required temporary removal of the sensors at the 10-cm depth for 9 d in mid-May, 3 d in late July, and 7 d in late September and early October. For removal, the soil that covered the sensors was lifted with a trowel, causing minimal disturbance, and the sensors were gently pulled from the soil where they has been inserted. After agronomic management activities were finished, the 10-cm-depth sensors were reinstalled in nearby, undisturbed soil.

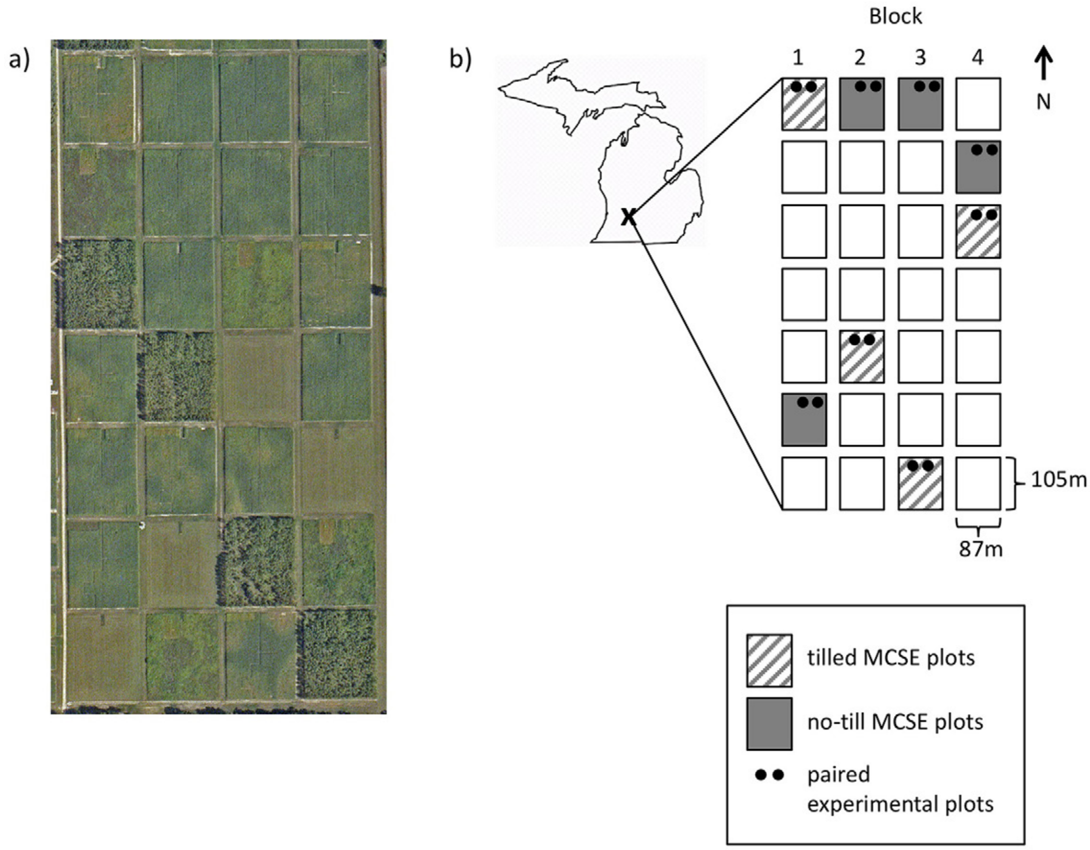

Fig. 1. Study location and rainout shelter design: (a) aerial photo and (b) layout of the Main Cropping System Experiment (MCSE) at the Kellogg Biological Station's Long-Term Ecological Research site. The four MCSE blocks shown run north to south; plots are 87 m wide by 105 m long.

In November 2014, soil horizons and their depths were characterized. Within each plot, one intact soil core (6-cm diameter by 120-cm depth) was collected with a hydraulic sampler, and each core was divided into five horizons based on color, texture, structure, and moisture. We measured bulk density and had the soil particle size analyzed by horizon at Michigan State University's Soil and Plant Nutrient Laboratory (East Lansing, MI).

Within each plot, soil samples representative of horizons to the 120-cm depth were collected and analyzed for gravimetric water content four times: on 30 Apr. to 1 May, 8 to 9 July, 2 to 3 Sept., and 1 to 2 Dec. 2015. For all sampling dates, subsamples were collected from the middle of each horizon, except in December when the hydraulic sampler was used to collect complete soil cores. To collect subsamples, one 10-cm-long soil core was collected from the middle of each soil horizon with a push probe (2.5-cm diameter). Deeper soil depths were reached using a 2.7-cm flighted auger with a carbide tip attached to a gas drill to reach the top of a 10-cm core location. Soil samples were collected at two locations within each plot and composited by depth. Sampling locations were selected such that they were at least 1.5 m inside each plot to minimize edge effects, 1 m from lysimeters and VWC sensors, and 1 m from previous soil samples. Composited soil samples were sieved ($\leq$4 mm), and subsamples were weighed and dried for 48 h at 100°C for determination of gravimetric water content.

Bromide Tracer Experiment

We used KBr as a conservative tracer of water flow through the soil profile to characterize deep percolation. We defined deep percolation as the movement of soil water to the 120-cm soil depth, which is below the root zone of our crops (Merrill et al., 2002; Sprunger, 2015). On 24 Apr. 2015, a 0.037 M solution of KBr in water was applied to the plots with handheld sprayers as a 2-mm rainfall event, adding 5.25 g Br^- m^{-2} soil surface. The soil water was sampled using tension lysimeters (Prenart) installed in May 2014. One lysimeter was installed in the center of each plot at the 120-cm depth. Illuvial clay in this soil layer minimizes preferential flow, and thus we expected water sampled there to be representative of water draining the soil profile (Syswerda et al., 2012). The soil water was sampled approximately weekly from March (for background Br^- concentrations) through December 2015. Before 13 June, sampling was timed to coincide with rainfall applications to both normal and intensified plots. After 6 July, sampling coincided with rainfall applications to intensified plots when those occurred but not during ambient rainfall events. Samples were filtered through 0.45-μm Supor polyethersulfone membrane syringe filters and refrigerated until analysis. Bromide concentrations were measured using a Dionex ICS-1000 ion chromatograph with membrane suppression (AG14A 5- by 50-mm guard column and AS14A 4- by 250-mm analytical column), with a detection limit of 0.02 mg L^{-1}.

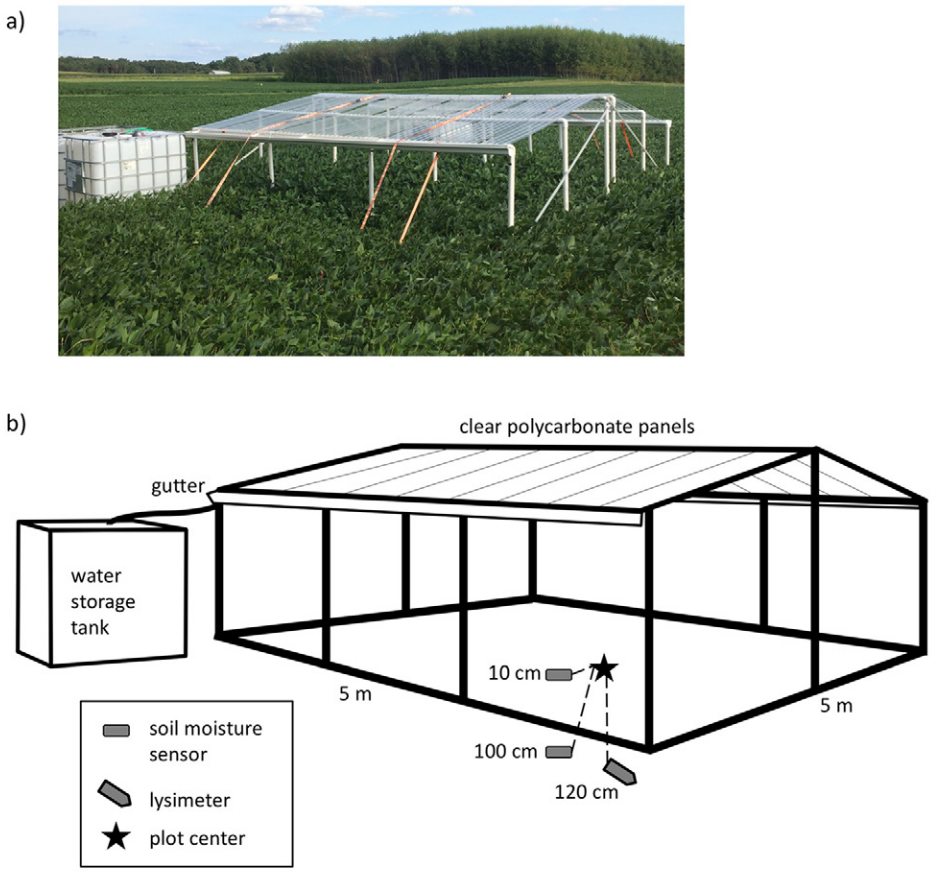

Fig. 2. Rainout shelters: (a) photo of a rainout shelter and (b) diagram of rainout shelter and instrumentation installed in each experimental plot. Labels in drawing refer to depths of installation. Cables attached to soil moisture sensors and tubing attached to tension lysimeters were buried in trenches running directly north to the plot edge.

To estimate the total amount of Br^- lost through percolation, measured Br^- concentrations were multiplied by modeled water fluxes at the 120-cm soil depth (see the Supplemental Material) for daily intervals. These daily losses were then summed to calculate the total mass of Br^- lost from the soil profile by deep percolation during the experiment. Bromide concentrations were estimated through linear interpolation between measurement dates. Soil samples (0–120 cm) collected in December 2015 were used to measure the Br^- remaining in the soil at the end of the experimental period. A 10-g sample from each horizon was extracted in 50 mL of distilled water and shaken for 1 h. Extracts were filtered, stored, and analyzed for Br^- as described above for soil water.

Crop Biomass and Yield

To understand how differences in transpiration may have contributed to differences in soil water dynamics among treatments, we sampled the aboveground crop biomass in two 1-m^2 quadrats in each plot 1 d before soybean was harvested, on 29 Sept. 2015. All biomass was dried at 65°C for 48 h, weighed, and threshed to separate grain and stover. After threshing, the grain

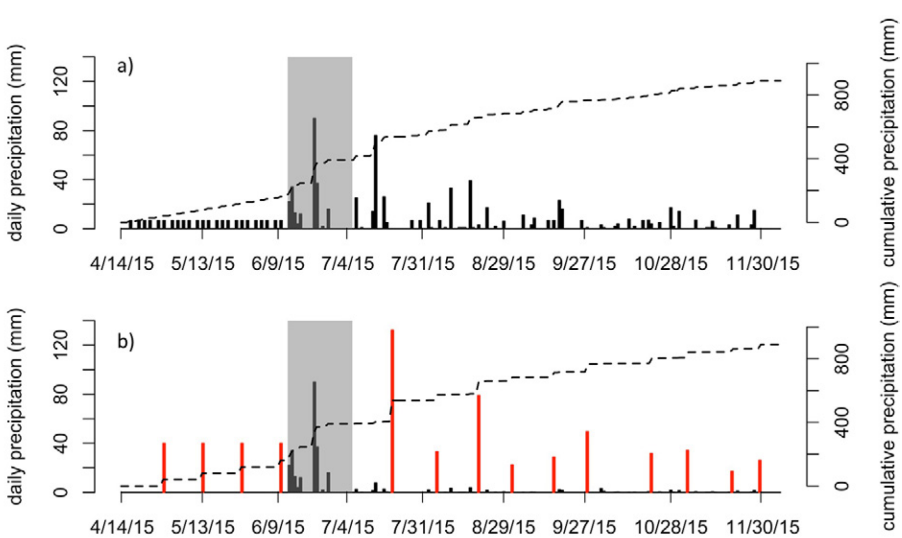

Fig. 3. Daily (bars) and cumulative (lines) precipitation during the experimental period (14 Apr.–6 Dec. 2015) for (a) the normal rainfall plots and (b) intensified rainfall plots. The time period during which all plots were exposed to ambient rainfall when rainout shelters were not in place (13 June–6 July) is shaded in gray. Red bars indicate simulated extreme events.

was collected and weighed, and the stover weight was calculated by difference.

Statistical Analyses

All statistical analyses were conducted using R 3.0.2 (R Core Team, 2013). We used linear mixed models with a nested design to analyze the effects of rainfall and tillage on multiple variables of interest. Rainfall treatment and tillage were included as fixed effects with interactions, while blocks and plots of the MCSE were included as random effects, with plot nested within block. This approach was used to analyze the time until detection of Br^- in the soil water, the time to the peak concentration of Br^- in the soil water, Br^- lost via percolation, Br^- remaining in the soil, total Br^- accounted for, crop biomass, and crop yield ($n = 4$ for each treatment). We also used this approach to analyze gravimetric water content in soil cores, with horizon depth, tillage, sampling date, and their interactions with rainfall included as fixed effects. In addition, we evaluated a horizon depth × tillage × sampling date × rainfall interaction, a horizon depth × sampling date × rainfall interaction, and a horizon depth × sampling date interaction to determine changes in the depth distribution of the gravimetric water content over time.

Continuously measured VWC at the 10- and 100-cm depths were analyzed across seasonal periods. Natural breaks occurred between spring and summer due to the storm on 13 June, and between summer and fall due to management activities between 30 September and 6 October. The period of time when all plots were exposed to ambient rainfall, from 13 June to 6 July, was excluded. In the normal rainfall treatment, VWC data at the 100-cm depth were excluded for tilled Replicate 4 and no-till Replicate 2 due to large amounts (i.e., >50%) of missing data. Volumetric water content was averaged for each season and analyzed with a rainfall

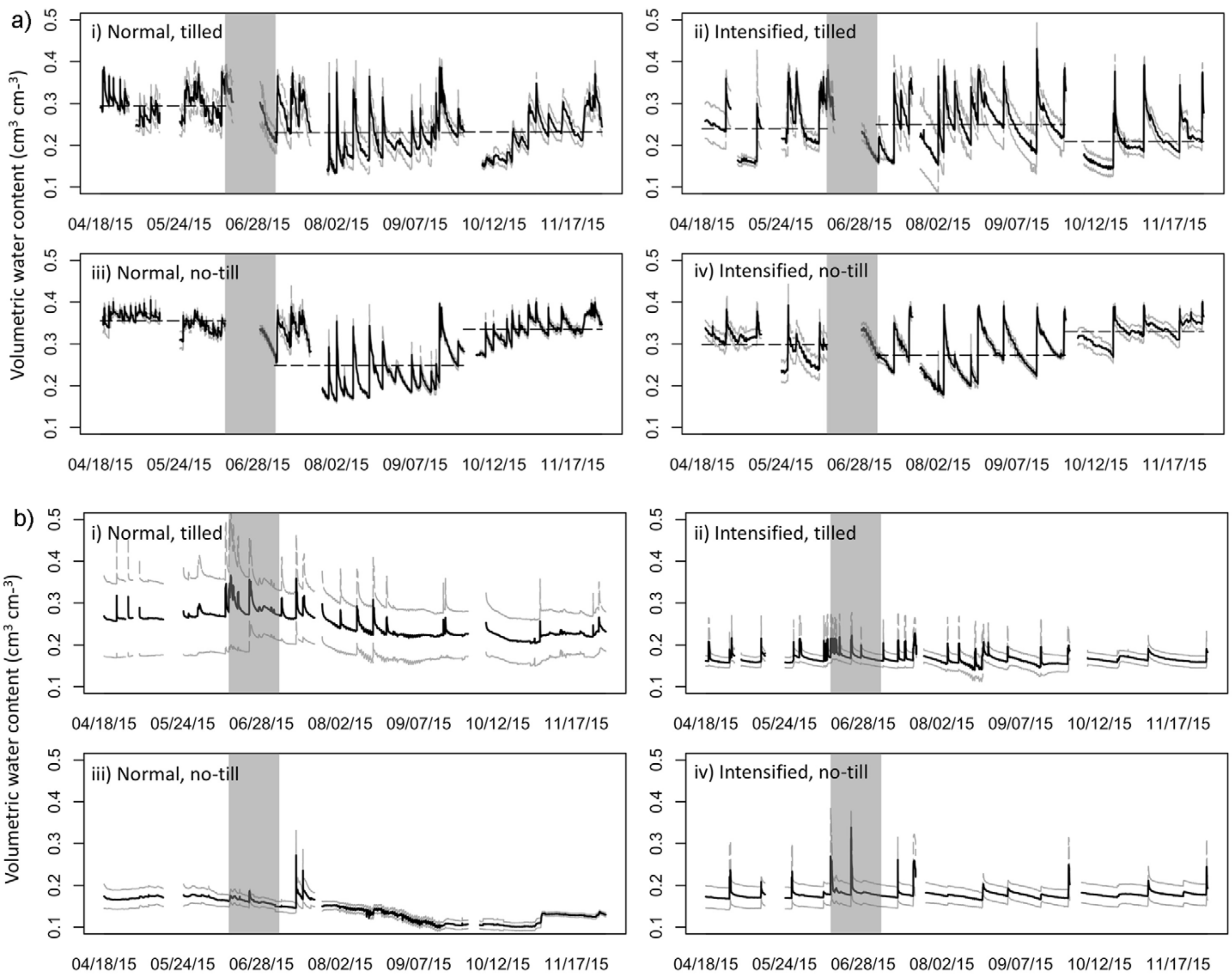

Fig. 4. Volumetric water content (VWC) at (a) the 10-cm depth and (b) the 100-cm depth during the experimental period by rainfall and tillage treatment. Solid black lines represent average VWC, and gray lines represent the average ±1 standard error ($n = 4$ replicate plots). The time period during which all plots were exposed to ambient rainfall (13 June–6 July) is shaded in gray. Dashed lines in (a) indicate average VWC by season. Breaks in the lines in (a) reflect time periods when sensors at the 10-cm depth were removed due to agronomic activities (sensors at the 100-cm depth were only unplugged from dataloggers during these breaks). In the normal rainfall treatment, tilled Replicate 4 and no-till Replicate 2 were excluded due to large amounts of missing data.

treatment × tillage × season model. The CV was also calculated for VWC at the 10-cm depth as a measure of variability and analyzed with a rainfall treatment × tillage linear mixed model.

For VWC at the 100-cm depth, we were also interested in characterizing trends over time from 7 July through 29 October, when evapotranspiration was highest. This analysis was motivated in part because of large apparent differences in the absolute value of VWC at this depth in the tilled plots, probably due to fine spatial-scale variation in soil texture, which may have obscured treatment differences in the previous analysis (see Fig. 4). We used a linear mixed model to understand the effects of time on the VWC at the 100-cm depth for this period. Rainfall treatment and time (in days) were included as fixed effects with interactions, and blocks and plots of the MCSE were include as random effects, with plot nested within block. The VWC data were averaged on daily intervals. This indicated a significant interaction, so we then used a linear mixed model with time as the only fixed effect for the normal and intensified rainfall treatments separately. We used a nonparametric bootstrap to calculate confidence intervals for the effect of time on the VWC at the 100-cm depth. As in the prior analysis, in the normal rainfall treatment, data were excluded for tilled Replicate 4 and no-till Replicate 2 due to missing data.

Factor significance for linear mixed models was determined using likelihood ratio tests, and pairwise comparisons were conducted for significant interactions between fixed effects. In the case that interactions were significant, individual factors were not tested for significance. Data were logarithmically or Box-Cox transformed when necessary to meet conditions of homoscedasticity and normality. For all analyses, $\alpha = 0.05$.

Results

Soil Water Content

Volumetric water content at 10 cm varied significantly, with interactions of rainfall × season and tillage × season (Fig. 4; Table 2).

In spring, VWC at the 10-cm depth was 0.05 ± 0.01 cm^3 cm^{-3} higher in normal plots than in intensified plots. In summer and fall, however, there was no significant difference in VWC at the 10-cm depth between the rainfall treatments. In tilled plots, VWC at the 10-cm depth was higher in spring than in fall, and in no-till plots, VWC was higher in spring and fall than in summer. The CV for VWC at the 10-cm depth did not vary between intensified and normal plots but was lower in no-till than tilled soils (Table 2). At the 100-cm depth, in tilled cropping systems only, VWC was also approximately 0.06 cm^3 cm^{-3} higher in all seasons exposed to normal rainfall compared with plots exposed to intensified rainfall. The VWC at the 100-cm depth declined significantly in plots exposed to the normal rainfall treatment, with 95% confidence intervals for the effect of time not including zero ($\beta = -6.0 \times 10^{-4}$, lower CI = -6.4×10^{-4}, upper CI = -5.5×10^{-4}, where β is the estimate of the effect of time and CIs are the confidence intervals). During the same time period,

Table 2. Results of linear mixed models as determined through likelihood ratio tests. Significant factors and *p* values are in italics.

Measurement	Factor	*p* value
Volumetric water content (VWC) (10 cm)	tillage × rainfall†	0.63
	rainfall × season	*<0.001*
	tillage × season	*<0.001*
	tillage × rainfall × season	0.91
Coefficient of variation of VWC (10 cm)	*tillage*	*0.007*
	rainfall	0.26
	tillage × rainfall	0.12
VWC (100 cm)	season	0.55
	tillage × rainfall	*<0.001*
	rainfall × season	0.28
	tillage × season	0.98
	tillage × rainfall × season	0.99
Gravimetric water content	*horizon*	*<0.001*
	tillage × rainfall	*<0.001*
	time × rainfall	*<0.001*
	horizon × rainfall	0.68
	horizon × time	0.12
	horizon × rainfall × time	0.11
	horizon × rainfall × tillage × time	0.91
Time to Br^- detection in soil water	*tillage*	*0.005*
	rainfall	*0.04*
	tillage × rainfall	0.52
Time to peak Br^- concentration in soil water	tillage	0.40
	rainfall	*0.03*
	tillage × rainfall	0.47
Br^- lost via percolation	tillage	0.71
	rainfall	*0.002*
	tillage × rainfall	0.41
Br^- retained in soil	tillage	0.11
	rainfall	*0.004*
	tillage × rainfall	0.73
Total Br^- accounted for	tillage	0.15
	rainfall	*0.01*
	tillage × rainfall	0.19
Crop biomass	*tillage*	*0.05*
	rainfall	0.42
	tillage × rainfall	0.27
Crop yield	tillage	0.57
	rainfall	0.40
	tillage × rainfall	0.36

† Rainfall refers to normal vs. intensified rainfall patterns.

Table 3. Mean gravimetric water content averaged from the soil surface to the 120-cm depth over time.

Tillage	Rainfall	Gravimetric water content by sampling date			
		April 2015	July 2015	Sept. 2015	Dec. 2015
		——— $g\ H_2O\ g^{-1}$ dry soil ———			
Tilled	normal	0.127 ± 0.007ab†	0.123 ± 0.013ab***	0.089 ± 0.014ab	0.138 ± 0.009ab
Tilled	intensified	0.128 ± 0.008ab	0.101 ± 0.012ab	0.111 ± 0.014ab***	0.134 ± 0.012ab
No-till	normal	0.140 ± 0.005a	0.133 ± 0.008a***	0.097 ± 0.009a	0.146 ± 0.006a
No-till	intensified	0.154 ± 0.010b	0.128 ± 0.011b	0.145 ± 0.013b***	0.158 ± 0.009b

*** Significant difference ($p < 0.001$) between intensified and normal conditions for a given date resulting from a rainfall × time interaction resulting in higher gravimetric water content.
† Mean ±1 standard error ($n = 4$ replicate plots). Means followed by different letters indicate significant differences resulting from a rainfall × tillage interaction for all dates.

VWC at the 100-cm depth in the intensified rainfall treatment showed no trend, as the CIs included 0 ($\beta = -3.0 \times 10^{-5}$, lower CI = -6.3×10^{-5}, upper CI = 2.5×10^{-6}).

Gravimetric water content varied significantly by depth and interactions of rainfall treatment × tillage and rainfall treatment × sampling date (Tables 2 and 3). The depth distribution of gravimetric water content did not vary over time.

Gravimetric water content decreased with depth, from an average of 0.16 g H_2O g^{-1} dry soil in surface horizons to 0.09 g H_2O g^{-1} dry soil in the deepest horizons. For the rainfall treatment × tillage interaction, intensified plots had higher water content (by 0.02 g H_2O g^{-1} dry soil on average) than normal plots, but only in no-till cropping systems. For the rainfall × sampling date interaction, normal plots had higher water content than intensified plots by 0.01 g H_2O g^{-1} dry soil in July, and intensified plots had higher water content than normal plots by 0.04 g H_2O g^{-1} dry soil in September.

Bromide Tracer Study

Bromide concentrations in the soil water collected from tension lysimeters are shown in Fig. 5.

Prior to KBr application, Br^- concentrations were undetectable (<0.02 mg L^{-1}). Bromide was measured in the soil water in all plots within several weeks after application, although the time

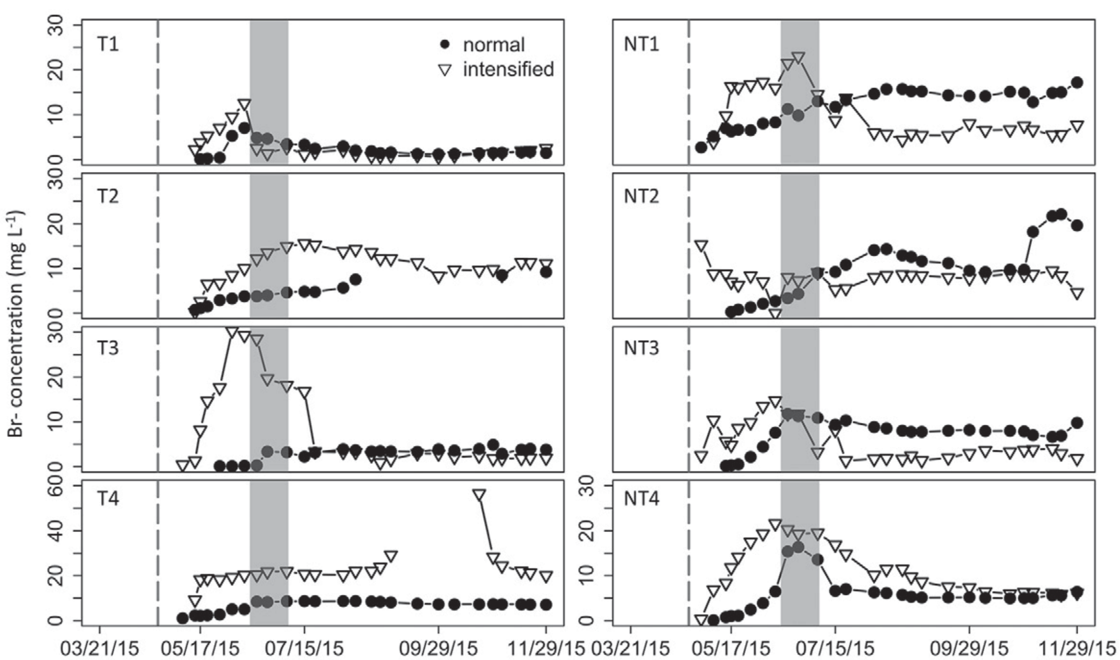

Fig. 5. Bromide concentrations in soil water sampled from tension lysimeters at the 120-cm depth. Each panel represents one plot, with tilled cropping systems on the left side (T) and no-till cropping systems on the right side (NT); numbers refer to Main Cropping System Experiment (MCSE) blocks. The dashed gray line marks the date of KBr application on 24 April. The time period during which all plots were exposed to ambient rainfall (13 June–6 July) is shaded in gray. Soil water was sampled beginning in March 2015, but only samples with Br^- concentrations above the instrument detection limit are shown. Note the different *y* axis scale for Panel T4.

lag between application and detection–an indicator of the percolation rate–varied significantly by both tillage and rainfall treatment. Bromide was detectable in the soil water sooner after application in intensified plots (18 ± 2 d in tilled and 8 ± 2 d in no-till) than in normal plots (23 ± 4 d in tilled and 16 ± 4 d in no-till). Bromide concentrations in the soil water also peaked in intensified plots (89 ± 32 d after application in tilled and 41 ± 12 d after application in no-till) before normal plots (141 ± 39 d after application in tilled and 137 ± 46 d after application in no-till) (Table 2).

The amount of Br^- lost from the soil profile via percolation by the end of measurements in December was greater in intensified (70 and 77% of added Br^- in tilled and no-till cropping systems, respectively) than normal plots (23 and 45% of added Br^- in tilled and no-till cropping systems, respectively; Tables 2 and 4).

Bromide retained in the soil at the end of the experimental period is consistent with the observed lower Br^- loss by percolation in normal vs. intensified plots; more Br^- was recovered in soil cores from the normal (16 and 25% of added Br^- in tilled and no-till cropping systems, respectively) than the intensified plots (5 and 11% of added Br^- in tilled and no-till cropping systems, respectively). The total Br^- accounted for by percolation plus soil retention was higher in intensified (75 and 87% in tilled and no-till cropping systems, respectively) than normal plots (39 and 70% in tilled and no-till cropping systems, respectively).

Crop Biomass

Aboveground crop biomass was greater in no-till than tilled cropping systems and did not differ between rainfall treatments (Table 5). Crop yield was not significantly affected by rainfall treatment or tillage.

Discussion

We exposed cropping systems under long-term tilled and no-till management to two different rainfall treatments: one with relatively small, frequent events ("normal") and the other with a greater proportion of rain falling in extreme events ("intensified"). Although both normal and intensified rainfall plots received identical total rainfall amounts during the experimental period, soil water dynamics differed between the treatments. We found no support for our first hypothesis that rainfall intensification amplifies fluctuations in surface soil water content, but evidence supports our second hypothesis that rainfall intensification increases deep percolation. Soil water content at the 100-cm depth declined during the summer in the normal rainfall treatment, while it stayed relatively constant in the intensified rainfall treatment. Our Br^- tracer experiment demonstrates that increasing the proportion of rainfall added in extreme events increases percolation to deep soil layers, regardless of tillage. Also consistent with our second hypothesis, Br^- percolated more rapidly through the soil profile to the 120-cm depth in no-till than tilled soils, probably via macropore flow.

Table 4. Added Br^- lost via percolation and remaining in the soil profile.

Tillage	Rainfall	Br^- lost via percolation	Br^- remaining in soil	Total Br^- accounted for
		%		
Tilled	Normal	23 ± 6a†	16 ± 5b	39 ± 11a
Tilled	Intensified	70 ± 26b	5 ± 2a	75 ± 25b
No-till	Normal	45 ± 26a	25 ± 4b	70 ± 7a
No-till	Intensified	77 ± 13b	11 ± 5a	87 ± 8b

† Value ± 1 standard error (n = 4 replicate plots). Values followed by different letters are significantly different ($p \leq 0.01$) between intensified and normal conditions within a column.

Effects of Rainfall Intensification on Soil Water Content

In contrast to the patterns predicted by the Knapp et al. (2008) conceptual model, we found that rainfall intensification did not increase the variability of the surface water content (VWC at the 10-cm soil depth): CVs did not significantly differ between normal and intensified rainfall treatments (Table 2). We did, however, find that rainfall intensification reduced surface soil VWC in spring, although not in summer and fall (Table 2; Fig. 4). In spring, water from the large rainfall events in the intensified plots appears to have infiltrated more quickly and percolated farther downward than did the water from relatively small rainfall events in the normal plots. We did not find any differences in crop biomass between the rainfall treatments (Table 5), which suggests that transpiration did not vary substantially between them. In normal plots, more of the water may have evaporated from the surface soils, whereas in intensified plots, deeper percolation may have stored soil water and protected it from higher rates of evaporation at the surface. That said, due to the change in our experimental design following the June storm, we unfortunately cannot rule out the possibility that the rainout shelters in the intensified rainfall treatment also reduced the wind speed and thus evapotranspiration.

The contrast between our results and those of non-agricultural rainfall intensification studies may be due to differences in experimental design as well as environmental conditions. While the data

Table 5. Crop biomass and yield.

Parameter	Tilled, normal	Tilled, intensified	No-till, normal	No-till, intensified
Yield, kg ha^{-1}	3574 ± 386†	3583 ± 321	3905 ± 150	3575 ± 128
Aboveground biomass, kg ha^{-1}	6213 ± 674a‡	6865 ± 503a	7556 ± 171b	7470 ± 250b

† Values are averages by rainfall treatment and tillage ±1 standard error (n = 4 replicate plots).
‡ Letters indicate significant differences in biomass between tilled and no-till plots.

presented by Knapp et al. (2008) are from an experiment with similar rainfall characteristics (3-d dry interval vs. 15-d dry interval, 1000 mm mean annual precipitation), the data are from soil mesocosms planted with native grass species, which may generate different hydrologic dynamics than a field experiment with annual crops. Their data also begin in early June, while ours begin in mid-April, when conditions are cooler and potential evapotranspiration lower.

Smith et al. (2016) observed higher surface VWC with rainfall intensification during the summer in a restored prairie in a region near our study site with similar seasonal precipitation amounts, but only 50% of the rainfall was excluded during "dry" periods in that study. Consistent with the predictions of Knapp et al. (2008), Heisler-White et al. (2009) found an overall reduction in surface VWC during the growing season with intensified rainfall in a mesic grassland. While the seasonal precipitation amounts in the Heisler-White et al. (2009) study were comparable to those in our study, the dry intervals compared in that study were 10 and 30 d with 100% rainfall exclusion, which are longer and drier than the intervals in our study and those in Smith et al. (2016). Differences in evapotranspiration and soil properties among sites may have also contributed to differences in observed results. For example, theoretical ecohydrological studies have shown that high interannual precipitation variability can lead to different soil moisture regimes—either dry or wet—but the probability of these regimes occurring depends in part on rates of evapotranspiration as well as soil properties (D'Odorico et al., 2000; D'Odorico and Porporato, 2006).

Under normal conditions, declines in VWC at the 100-cm depth during the growing season (Fig. 4) are probably driven by evaporation and crop water uptake without recharge from precipitation. Minimum observed values of VWC in the normal treatment (at both 10- and 100-cm soil depths) are consistent with values of the lower limit of plant-extractable soil water, as observed by Hamilton et al. (2015) in a neighboring study location. Under intensified rainfall, however, not only did VWC not decline, it spiked during most applied rainfall events. This is consistent with more water being partitioned to deep percolation relative to evapotranspiration in intensified plots, maintaining higher soil water content at depth. Gravimetric water content in the entire soil profile generally corroborates patterns in VWC at 10 and 100 cm: VWC in the entire soil profile was greater in intensified than normal plots, especially in late summer (Table 3).

Overall, the response of VWC to rainfall intensification was consistent between tilled and no-till cropping systems. However, the variability of surface VWC was higher in tilled than no-till soils in both intensified and normal plots. Increased water-holding capacity (Robertson et al., 2014) and higher infiltration rates (Strudley et al., 2008) in no-till compared with tilled soils may have buffered these soils to drying and saturation, respectively.

Effects of Rainfall Intensification on Water Movement through the Vadose Zone

Earlier arrival of the Br^- tracer in the soil water at the 120-cm depth and earlier peaks in its concentration indicate higher rates of deep percolation in intensified than in normal plots, consistent with soil moisture patterns at the 100-cm depth (Fig. 5). This is also suggested by lower residual soil Br^- at the end of the experiment and higher estimated Br^- export through percolation in plots exposed to intensified rainfall (Table 4). In intensified plots, breakthrough curves were relatively narrow and peaked (Fig. 5), suggesting rapid advection and vertical flow during large events (i.e., "supply-driven" rapid vertical flow; see Hinckley et al., 2014). In some intensified plots, Br^- was detectable at the 120-cm depth within 24 h after the first rainfall event following tracer application; in one plot (NT2), concentrations had peaked by that time. In the normal plots, breakthrough curves were delayed and more attenuated (Fig. 5), indicating dispersion and mixing, and more Br^- was retained in the soil at the end of the experimental period compared with intensified conditions (11% more in tilled and 14% more in no-till cropping systems; Table 4). Rain falling in heavier events may have increased the importance of macropore flow, resulting in greater percolation to deeper soils (Vidon and Cuadra, 2010; Pot et al., 2005). On the last sampling date, 219 d after KBr application, Br^- concentrations appeared to have peaked in all plots exposed to intensified conditions, while concentrations in normal plots appeared to still be rising, indicating a shorter water residence time in soils exposed to intensified rainfall.

The both Br^- and VWC data at the 100-cm depth indicate that there was greater deep percolation under intensified rainfall conditions than normal conditions. Our results are consistent with those from semiarid ecosystems, where large rainfall events have been shown to result in higher rates of infiltration and deep percolation (e.g., Liu et al., 2015). Jongen et al. (2013) also found increased percolation to deep soil layers (70–100 cm) in a Mediterranean woodland when water was added in larger, less frequent events (48 mm once every 3 wk vs. 16 mm once per week).

The amount of residual Br^- in the soil plus that accounted for in percolation losses was greater in plots exposed to intensified compared with normal rainfall patterns; total Br^- accounted for was particularly low in tilled soils of normal plots (Table 4). It is possible that under normal conditions, Br^- moved laterally outside the sampling area as shallow subsurface stormflow, especially in or above the relatively impermeable Bt soil layer. This would be consistent with more matrix flow occurring in the normal than the intensified plots. It is also possible that overland or shallow subsurface stormflow was enhanced in tilled cropping systems during the naturally occurring extreme events in late June due to little macroporosity and macropore connectivity in the Ap soil layer. In addition to lateral flow, it is possible that pulses of Br^- exported in percolating waters were not captured by the temporal frequency of lysimeter sampling.

Earlier detection of Br^- in no-till cropping systems than tilled cropping systems suggests more rapid vertical flow in no-till cropping systems, probably reflecting more macropore or preferential flow paths than in tilled soils (Fig. 5, Table 2; Beven and Germann, 2013; Jarvis, 2007). Similar to our study, Meisinger et al. (2015) found significantly higher drainage in no-till vs. tilled soils in winter wheat systems in the US northern Atlantic Coastal Plain region. Although land at the KBS Long-Term Ecological Research site has been farmed with tillage since the 1850s (Tomecek and Robertson, 1996), no-till cropping systems in the MCSE have existed for nearly 30 yr, allowing biopores to develop. Increased macroaggregation in no-till compared with tilled soils (Grandy and Robertson, 2007) may also increase macropore flow along aggregate faces.

Some of the variation among replicates (i.e., plots with the same tillage and rainfall treatment) may also be due to differences in soil properties. For example, the third tilled replicate plot (T3 in Fig. 5) has relatively sandy soil, and the breakthrough curve in the intensified rainfall treatment rose and peaked relatively rapidly. In contrast, the first tilled replicate plot (T1) has finer texture soil, and low Br^- recovery there may be due to enhanced lateral flow.

Study Implications

By the end of the century, climate models for the United States predict a nearly 30% increase in the number of days with precipitation in the 95th percentile of daily precipitation amounts relative to 1976 to 2005 (Easterling et al., 2017). In our study, we simulated a 117% increase in the number of days with precipitation in the 95th percentile (based on weather station data from 1988–2015) compared with ambient conditions in the year of our study, an increase approximately four times that of the projected increase. We thus caution that our results should be interpreted through this lens. Based on our results, we expect that more frequent extreme events will indeed increase deep percolation and soil water storage; however, increases will probably be of less magnitude than we observed.

The major finding of our research—an increase in deep percolation with rainfall intensification—has important implications for the management of water and nutrients in cropping systems. In particular, increased percolation below the rooting zone has the potential to exacerbate nutrient and pesticide leaching via physical transport to depth (Sinha et al., 2017; Otto et al., 2016; Ye et al., 2016). Furthermore, changes in the vertical distribution of water storage as a result of rainfall intensification may influence microbial activity, affecting the availability of N, P, and other key elements as well as the production of greenhouse gases (Austin et al., 2004; Bergsma et al., 2002; Borken and Matzner, 2009). Ultimately, the results of our study, combined with the cascade of potential effects, highlight the potential vulnerability of agricultural systems to the "new normal" of more frequent extreme precipitation events.

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