doi:10.2489/jswc.2024.00146

Infiltration within native prairie vegetative strips embedded in row crop fields across Iowa

E.J. Henning, R.K. Kolka, and M.J. Helmers

Abstract: The integration of native prairie vegetative strips into row crop agriculture is a promising conservation strategy that has gained momentum in adoption rates throughout the US Midwest. Previous studies have shown that prairie strip establishment can lead to several positive soil and water quality outcomes, such as reductions in surface runoff and nutrient and sediment exports. However, the impacts of prairie strips on soil infiltration are not well known. In this study, the Cornell Sprinkle Infiltrometer system was used to measure differences in field-saturated infiltration rate between prairie strip and row crop treatments at six sites across Iowa after five to seven years since prairie strip establishment. Additionally, approximate sorptivity was calculated to compare trends in early infiltration between the two treatments at each site. Measurements were taken over a two-year span during summer and fall testing periods. Further, at two additional prairie strips sites, a separate approach using the tension infiltrometer generated hydraulic conductivity data for prairie strip and row crop treatments at 3, 4, and 14 years since prairie strip establishment. Differences between prairie strip and row crop were mostly undetected across nearly all sites in field-saturated infiltration rate and saturated hydraulic conductivity at 5 to 7 and 14 years after prairie strip establishment, respectively. However, at one site, saturated hydraulic conductivity was significantly greater within prairie strip than row crop, and at another, field-saturated infiltration rate was 3.6 times greater in prairie strip than row crop. Therefore, considering trends from both prairie strip age and infiltration testing method groups, differences in saturated infiltration capacity between prairie strip and row crop appear to be related to site-specific characteristics like soil texture, row crop tillage, and soil organic matter, especially at earlier stages of prairie strip establishment. Comparing trends in sorptivity approximations between the two treatments determined that prairie strips had 26% and 38% greater early infiltration than row crops during fall testing periods, but no treatment difference was found in the summer testing period. Since significant results were mostly limited to the fall, a combination of initial soil moisture and surface roughness disparities between treatments likely explain the observed treatment differences in approximate sorptivity. Within prairie strips, greater early infiltration relative to row crops delays and limits surface runoff generation. Therefore, this study suggests that a row crop field containing prairie strips will generate less surface runoff than a comparable 100% row crop field during a given rainfall event at the end and potentially beginning of the annual corn (*Zea mays* L.) and soybean (*Glycine max* [L.] Merr.) growing season in Iowa. By improving early infiltration and subsequently limiting runoff generation and sediment transport, prairie strips can be a valuable soil and water conservation tool.

Key words: infiltration—reconstructed prairie—row crop—vegetative filters

In Iowa, less than 1% of 12.5 million historical native tallgrass prairie hectares remain, and corn (*Zea mays* L.) and soybean (*Glycine max.* [L.] Merr.) croplands dominate the landscape, accounting for approximately 68% of the state's land cover (Samson and Knopf 1994; USDA NASS 2022). However, interest in efforts to re-establish portions of the native ecosystem has grown in recent decades. In 2007, the Science-based Trials of Row-crops Integrated with Prairie Strips (STRIPS; https://www.nrem.iastate.edu/research/STRIPS/) project was established at the Neal Smith National Wildlife Refuge in Jasper County, Iowa, and STRIPS research has since expanded across the US Midwest. Studies from this project have investigated an array of implications associated with the strategic conversion of 10% to 20% of crop field land area to native prairie vegetation in the form of upslope contour and foot slope strips.

Although multiple findings of soil and water quality improvements in response to prairie strip establishment have been a principal aspect of this research effort (Helmers et al. 2012; Hernandez-Santana et al. 2013; Pérez-Suárez et al. 2014; Zhou et al. 2014), questions remain surrounding the impacts of prairie strip establishment on water infiltration (Lockett 2012; Brittenham 2017). In naturally drained landscapes, increased infiltration has the potential to mitigate multiple soil and water concerns, such as surface runoff quantity, nutrient loss, and sediment transport. In Midwest corn and soybean production areas, periods of limited soil cover at the tail ends of the annual growing season in the spring and fall can create conditions where these negative soil and water outcomes have the greatest potential to occur (O'Neal et al. 2005). Several studies have shown that remnant native prairies possess a significantly greater ability to infiltrate water than tilled cropping systems (Fuentes et al. 2004; Stone and Schlegel 2010). Greater infiltration within prairies is tied to enhanced soil macroporosity, as the abundance and distribution of macropores within the soil profile fundamentally controls saturated hydraulic conductivity (Brady and Weil 2008). Both intrinsic and extrinsic factors influence soil macroporosity, including soil texture, soil organic matter (SOM), disturbance, and biological activity.

Several factors suggest that prairie strip establishment should improve infiltration

Received October 26, 2022; Revised September 17, 2023; Accepted October 14, 2023.

Eric J. Henning is a graduate student in the Department of Agricultural and Biosystems Engineering at Iowa State University, Ames, Iowa. **Randall K. Kolka** is a research soil scientist at the USDA Forest Service, Northern Research Station, Grand Rapids, Minnesota. **Matthew J. Helmers** is a professor in the Department of Agricultural and Biosystems Engineering at Iowa State University, Ames, Iowa.

compared to row crop agriculture. First, common agricultural occurrences like tillage and wheel traffic disrupt soil structure and can impede hydraulic conductivity (Ankeny et al. 1990), whereas, in prairie strips, these disturbances do not occur. Additionally, perennial vegetation within prairie strips continuously protects the soil surface from raindrop impacts that can cause surface sealing (Torri and Poesen 2014). Moreover, several chronosequence studies have shown that prairie restorations can replenish SOM to precultivated levels on a decadal timescale (McLauchlan et al. 2006; Matamala et al. 2008), and that increases in soil organic carbon (C), a principal component of SOM, occur most rapidly in the beginning stages of re-establishment (Bugeja and Castellano 2018; Li et al. 2021). Organic matter enhances soil structure and contributes to pore distributions favorable to infiltration (Boyle et al. 1989). Lastly, plant root and fungal hyphae growth increases during prairie restoration and can create water transport channels (Wu et al. 2017). However, it should also be noted that root growth's influence on infiltration is temporally variable as it has the potential to clog channels at different physiological stages (Liu et al. 2019).

While abundant evidence exists to support expected improvements in infiltration as a result of prairie strip establishment, previous research has not provided a consistent explanation of how these changes might occur over time and space. Both Bharati et al. (2002) and Alagele et al. (2019) found that infiltration under switchgrass (*Panicum Virgatum* L.), a native tallgrass prairie species, was significantly greater than under row crop less than 10 years after establishment. Additionally, Udawatta et al. (2008) reported greater saturated hydraulic conductivity and macropores per unit area in a 12-year-old restored prairie compared to a row cropping system in Missouri. However, Anderson et al. (2020) found no differences in water infiltration between at least 10-year-old Conservation Reserve Program (CRP) grassland and row crop fields in Arkansas, and Pey and Dolliver (2020) predicted that retired land in Minnesota seeded to a native grass mix would take 128 years to fully recover its precultivation infiltration rate.

The goal of this study was to characterize infiltration responses to prairie strips embedded in row crops across multiple establishment stages and locations in Iowa. To capture factors affecting infiltration including soil surface conditions and pore structure under initial wetting and saturated conditions, two different systems—the Cornell Sprinkle Infiltrometer and the Tension Infiltrometer—were employed to measure infiltration parameters such as field-saturated infiltration rate, approximate sorptivity, and hydraulic conductivity. Study locations varied by soil type, agricultural management practices, and time since prairie strip establishment. Additionally, testing occurred over multiple years and seasons to account for temporal variation in infiltration and analyze any potential trends occurring over time. We hypothesized that over time, the perennial, undisturbed vegetation of prairie strips would enhance the soil's ability to infiltrate water both upon initial wetting and at saturation, providing support for prairie strips as a soil and water conservation management tool.

Materials and Methods

Site Descriptions. Infiltration experiments were carried out at eight sites located across the state of Iowa (table 1). Six sites—ARM, HOE, MCN, RHO, WHI, and WOR—were 100% row crop (RC) fields until prairie strip (PS) establishment between 2014 and 2015. These sites are referred to as STRIPS2 sites. The remaining two sites—IN1 and WE2—are located within the Neal Smith National Wildlife Refuge in Jasper County, Iowa, and are considered STRIPS1 sites. STRIPS1 sites were under bromegrass (*Bromus madritensis*) for at least 10 years prior to 2007, when they were converted to RC fields containing PS. All eight sites are located within either the Des Moines Lobe or Southern Iowa Drift Plain landform region (figure 1). The Des Moines Lobe is characterized by a nearly level to gently rolling landscape with deep, loamy soils and highly productive cropland. Dominant soil orders are Mollisols and, to a lesser extent, Alfisols and Inceptisols (USDA NRCS 2006). The Southern Iowa Drift Plain is a mostly rolling to hilly region covering a large swath of Iowa's southern half. Mollisols and Alfisols, along with some Entisols, make up the dominant soil orders of the region (USDA NRCS 2006). While each site has been in corn and soybean production in recent years, notable contrasts in management exist. ARM, WHI, IN1, and WE2 are

Table 1

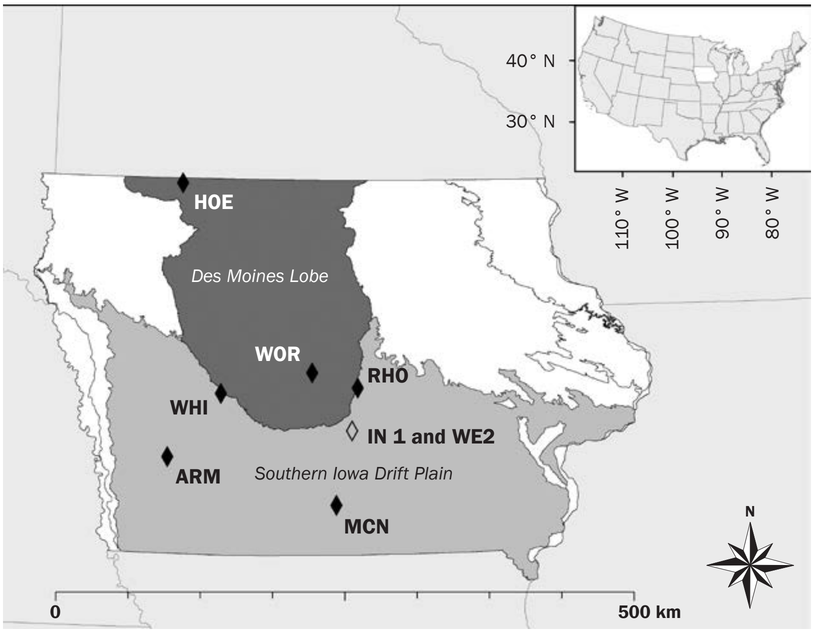
Selected site characteristics. Average soil texture values reflect a 0 to 15 cm depth and were acquired from Lockett (2012) for STRIPS1 sites and Web Soil Survey for STRIPS2 sites.

Site	Prairie strip establishment	Dominant soil order	Sand (%)	Clay (%)	Silt (%)	Tillage	2020 crop	2021 crop
*IN1	Spring 2007	Mollisol	21	32	47	NT	Corn	Soybean
*WE2	Spring 2007	Mollisol	11	33	56	NT	Corn	Soybean
†ARM	Fall 2014	Mollisol	5	30	66	NT	Soybean	Corn
†HOE	Spring 2015	Mollisol	35	28	37	CT	Corn	Soybean
†MCN	Spring 2014	Mollisol	8	32	60	CT	Soybean	Corn
†RHO	Spring 2015	Alfisol	3	23	74	CT	Corn	Corn
†WHI	Fall 2015	Mollisol	11	32	57	NT	Corn	Soybean
†WOR	Spring 2015	Mollisol	42	22	36	CT	Soybean	Corn

Notes: NT = no-tillage. CT = conventional tillage.
*STRIPS1.
†STRIPS2.

Figure 1

Locations of STRIPS1 (open diamond) and STRIPS2 (filled diamonds) sites in relation to Iowa landform regions.



all managed using no-till farming practices, while HOE, MCN, RHO, and WOR are conventionally tilled.

Testing Locations. At STRIPS2 sites, testing locations were determined using USDA Natural Resources Conservation Service (NRCS) Web Soil Survey data (Soil Survey Staff n.d.). We randomly selected three replications of paired PS and RC testing points within each soil series and phase present at each site. For PS points, testing was performed in the center of the strip. For RC points, testing was performed 3 m directly upslope from the PS edge between crop rows.

At STRIPS1 sites, a similar procedure was used to determine paired testing points; however, landscape position was the basis for selection rather than soil series and phase. Two landscape positions were identified within each site—summit and footslope—and two repetitions of paired PS and RC points were randomly placed at each landscape position. PS points were placed 3 m into the strip from its upslope edge, and RC points were placed 3 m upslope of that edge.

Paired treatment points were tested on the same day so that environmental conditions remained consistent, ensuring an accurate comparison between PS and RC treatments. Additionally, to avoid the influence of mechanical compaction, testing never occurred within obvious wheel tracks.

Cornell Sprinkle Infiltrometer. We measured field-saturated infiltration rate and approximate sorptivity with the Cornell Sprinkle Infiltrometer system (Ithaca, New York) at STRIPS2 sites. This system allowed us to capture the effects of rain drop impacts on early and steady-state infiltration. We collected data at ARM, RHO, and WOR in fall of 2020, summer of 2021, and fall of 2021, and at HOE, MCN, and WHI in summer of 2021 only. The summer testing period spanned from mid-June to early August, while the fall testing periods spanned from early October to early November (supplemental figures S1 and S2). Briefly, the Cornell Sprinkle Infiltrometer procedure involved simulating rainfall over a metal ring inserted into the soil and measuring the subsequently observed rainfall and runoff rates to calculate the infiltration rate. Specific information regarding the equipment and its operation is outlined in van Es and Schindelbeck (2015).

To prepare each testing location for sprinkler operation, loose residues within the ring area were removed to prevent clogging in the runoff tube, and vegetation was clipped to below the ring's inserted height (7.5 cm). Per van Es and Schindelbeck's (2015) recommendations, simulated rainfall rates were maintained near 0.5 cm min^{-1} for the duration of the wetting period at each testing point to ensure runoff generation. At 3-minute intervals during sprinkler operation, the height of water in the infiltrometer and generated runoff volume were measured simultaneously to calculate rainfall and runoff rates. We concluded sprinkler operation at each testing point once measured runoff volumes were within 10 mL of each other for three consecutive time intervals, indicating that steady-state conditions had been reached. Steady-state conditions were generally achieved within an hour of initial rainfall simulation. The measured rainfall and runoff rates for each time interval were smoothed using a moving average. The average of the last three measured infiltration rates was used to calculate the field-saturated infiltration rate at each testing point. It was necessary to multiply this value by a conversion factor of 0.80 to correct for three-dimensional flow at the base of the metal ring (equation 1):

$$i_{fs} = i_t \times 0.80 \,, \tag{1}$$

where i_{fs} is the field-saturated infiltration rate (cm min^{-1}) and i_t is the infiltration rate (cm min^{-1}). The conversion factor of 0.80 is based on numerical modeling presented in Reynolds and Elrick (1990) on three-dimensional flow effects at the base of a single ring and represents a ring insertion depth of 7.5 cm, ring diameter of 7.5 cm, and a loam soil texture to best represent our soil conditions (van Es and Schindelbeck 2015).

Additionally, we calculated approximate sorptivity to describe the early stages of infiltration independent of rainfall rate using equation 2 (Kutilek 1980):

$$S = (2T_{RO})^{0.5} \times r \,, \tag{2}$$

where S is approximate sorptivity (cm min$^{-0.5}$), T_{RO} is time to runoff (min), and r is the initial rainfall rate (cm min^{-1}). This equation provides an estimation of sorptivity that varies with initial soil water conditions since soil water is negatively related to time to runoff. Without initial soil water content data available, the difference in approximate sorptivity between paired treatment points is the primary concern for this study.

On rare occasions, runoff generation did not occur in response to the simulated rainfall rate of 0.5 cm min^{-1}. In these instances, the infiltration rate was conservatively estimated as 0.5 cm min^{-1} to reflect the complete infiltration of the simulated rainfall. In the absence of runoff generation, approximate sorptivity was not calculated for these testing points (table S1).

Tension Infiltrometer. Concurrent to summer of 2021 Cornell Sprinkle Infiltrometer testing at STRIPS2 sites, we estimated soil hydraulic conductivities of RC and PS soils with the Tension Infiltrometer at STRIPS1 sites (figure S3). Summer of 2021 testing replicated the methods and testing locations used for the collection of 2010 and 2011 field data described in Lockett (2012). Tension infiltrometers equipped with a 20 cm diameter tension disc were used to determine hydraulic conductivity (K(ψ)) at tensions of −11, −5, −2, −1, and 0 cm H_2O. Tension infiltrometer testing was conducted in triplicate at each testing point, with three infiltrometers running simultaneously. Operating procedures closely followed those detailed in the operator's manual (Soilmoisture Equipment Corporation 2008). Prior to the operation of the tension infiltrometer, several preparatory steps were taken at each testing point, including the placement of a 20 cm diameter metal ring, removal of any loose residues, and clipping of vegetation within the ring area. Additionally, a piece of cheesecloth was placed on top of the prepared area and a thin layer of slightly moistened, fine sand was applied to the soil surface and leveled. In some instances of extreme soil surface roughness or slope, we removed approximately 2 to 3 cm of soil for leveling purposes. Once the area was adequately prepared, the tension disc was placed, and the operation of the tension infiltrometer began at the −11 cm H_2O tension. Measurements of the water level within the reservoir occurred at 4-minute intervals until water level changes were within 0.2 cm for four consecutive time intervals, indicating steady-state conditions. Once measurements at the −11 cm H_2O cm tension concluded, the tension was sequentially set to −5, −2, −1, and 0 cm H_2O, following the same methodology for determining steady-state conditions at each tension. Time intervals for the −5, −2, −1, and 0 cm H_2O tensions were 2 minutes, 1 minute, 1 minute, and 30 seconds, respectively. The selection of time intervals for water level measurement were based on Lockett (2012) and calibration in the field.

Steady-state infiltration rates measured with tension infiltrometers were then used to determine hydraulic conductivity at each tension (Ankeny et al. 1991). First, the infiltration rate was converted to an infiltration flux, Q (cm^3 h^{-1}), and applied to the Wooding (1968) equation for steady-state infiltration from a circular source (equation 3):

$$Q(\psi_i) = \pi r^2 K_{sat} e^{\alpha\psi}\left(1 + \frac{4}{\pi r \alpha}\right), \tag{3}$$

where $Q(\psi)$ is the steady infiltrating flux (cm^3 h^{-1}), ψ is the pressure potential at the infiltrometer disc (cm), r is the radius of the infiltrometer disc (cm), K_{sat} is the field-saturated hydraulic conductivity (cm h^{-1}), and α is an empirical fitting parameter described in equation 4. K_{sat} is calculated using the Gardner (1958) equation describing an exponential relationship between hydraulic conductivity and pressure potential (equation 5):

$$\alpha = \frac{\ln\left[\frac{Q(\psi_i)}{Q(\psi_{i+1})}\right]}{\psi_i - \psi_{i+1}}, \text{ and} \tag{4}$$

$$K(\psi) = K_{sat}\, e^{\alpha\psi}. \tag{5}$$

Soil Sampling. In addition to infiltration testing, soil samples were collected from select STRIPS2 sites to measure SOM content and bulk density. At ARM, RHO, and WOR, soil samples were collected from approximately the same locations of concurrent Cornell Sprinkle Infiltrometer testing in the fall of 2021. Following Moebius-Clune et al.'s (2016) recommendations, we used a spade to extract 5 cm by 15 cm soil slices. At each sampling point, three slices were taken from an approximate 5 m radius around the point and mixed to create a composite 0 to 15 cm depth sample. The samples were stored in sealed zip-top bags and kept in a 4°C cooler before shipment to a commercial laboratory (Cornell Soil Health Lab, Ithaca, New York) for analysis. At the MCN site, data were taken from Dutter (2022), where soil was collected from the center of the prairie strip and 3 m into the RC field upslope from the strip edge in the fall of 2020. Multiple 0 to 15 cm depth soil cores were collected with a hand probe and mixed to create a composite sample at three randomly placed paired sampling points. In the laboratory, loss on ignition with a 500°C furnace was used to determine the percentage of SOM in oven-dried soil. Bulk density samples were collected at a 0 to 15 cm depth using a 5 cm diameter soil core sampler (AMS Inc., American Falls, Idaho) and dried in a 105°C oven.

Statistical Analysis. All statistical analysis was run using R software (R Core Team 2020), and plots were generated with the ggplot2 package (Wickham 2016). Field-saturated infiltration rate, approximate sorptivity, bulk density, and SOM data from STRIPS2 sites were log-transformed to normalize the data set and facilitate between-site comparison. We used a linear model testing paired differences to determine treatment effects at each site and testing period combination, and contrasts and comparisons were determined with estimated marginal means (Lenth 2020). For the ARM, RHO, and WOR sites, analysis was also performed for all testing periods combined. Analysis of STRIPS1 hydraulic conductivity data also utilized the linear model to test paired treatment differences with estimated marginal means. Additionally, an analysis of variance table was generated for STRIPS1 to determine the effects of landscape position, site, year, and site-year on paired treatment differences. Statistical significance was categorized as marginal ($p < 0.1$), significant ($p < 0.05$), and strongly significant ($p < 0.01$).

Results and Discussion

Field-Saturated Infiltration Rate. Across all testing periods at STRIPS2 sites, field-saturated infiltration rates varied widely within each site and treatment group (table 2). In fall of 2020, the average field-saturated infiltration rate of PS soils was greater than that of RC soils at ARM, RHO, and WOR. At RHO, this difference was strongly significant ($p < 0.01$), and at WOR, it was marginally significant ($p < 0.1$). Differences between PS and RC rates were minimal during the summer of 2021 and fall of 2021 testing periods. The only statistically significant difference observed during these two testing periods occurred at RHO in summer of 2021 ($p < 0.05$), where the PS field-saturated infiltration rate was 2.6 times greater than RC. For the three sites tested in fall of 2020, summer of 2021, and fall of 2021—ARM, RHO, and WOR—treatment differences analyzed across all testing periods combined varied by site (figure 2). We did not find a significant difference in field-saturated infiltration rate between PS and RC treatments at ARM and WOR. However, the field-saturated infiltration rate was 3.6 times greater in PS than RC at RHO.

Overall, differences in field-saturated infiltration rate were only evident at one of the six STRIPS2 sites: RHO. Although determining the difference between PS and RC land covers was the primary objective of this study, specific site characteristics such as soil texture, tillage practices, and SOM content likely

Table 2

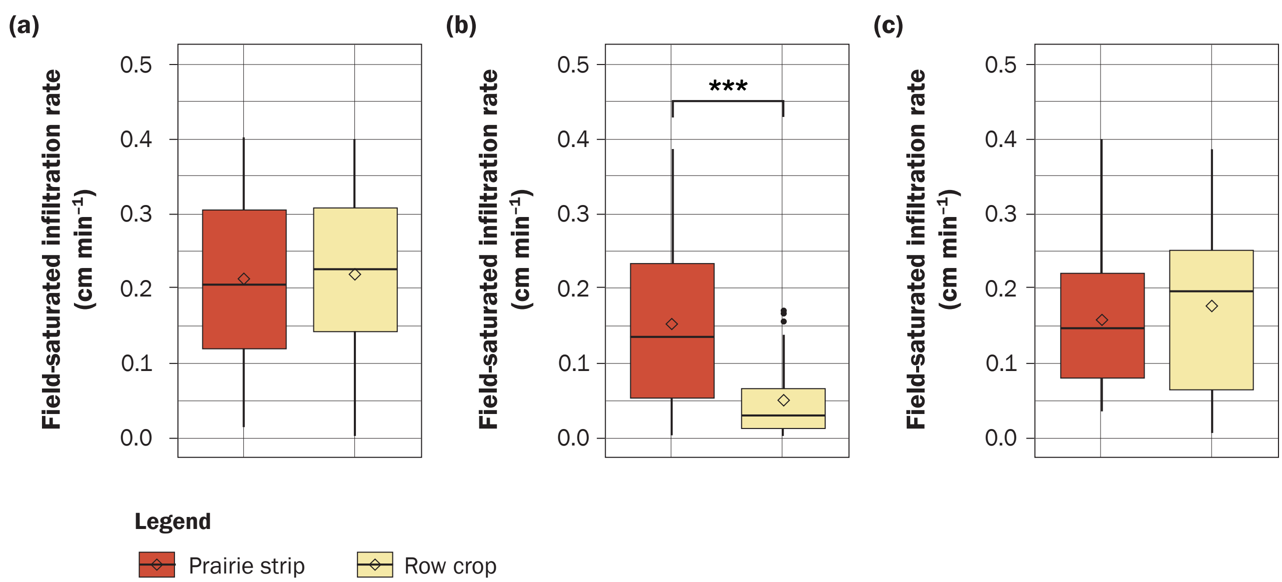
Field-saturated infiltration rates in prairie strip (PS) and row crop (RC) treatments over three testing periods at STRIPS2 sites.

		Fall 2020				Summer 2021				Fall 2021			
Site	Treatment	*n*	Mean (cm min^{-1})	CV (%)	*p*-value	*n*	Mean (cm min^{-1})	CV (%)	*p*-value	*n*	Mean (cm min^{-1})	CV (%)	*p*-value
ARM	PS	12	0.27	41	0.39	12	0.19	77	0.41	12	0.18	55	0.82
	RC	12	0.22	50		12	0.21	51		12	0.23	56	
HOE	PS	—	—	—	—	15	0.15	78	0.17	—	—	—	—
	RC	—	—	—		15	0.22	48		—	—	—	
MCN	PS	—	—	—	—	11	0.03	77	0.15	—	—	—	—
	RC	—	—	—		11	0.09	89		—	—	—	
RHO	PS	9	0.20	40	<0.01***	9	0.11	77	0.02**	9	0.07	86	0.26
	RC	9	0.02	84		9	0.07	89		9	0.04	87	
WHI	PS	—	—	—	—	12	0.17	72	0.53	—	—	—	—
	RC	—	—	—		12	0.10	82		—	—	—	
WOR	PS	9	0.19	48	0.08*	9	0.08	72	0.29	9	0.15	67	0.69
	RC	9	0.14	64		9	0.20	67		9	0.19	77	
All	PS	30	0.24	42	<0.01***	68	0.09	88	0.42	30	0.11	67	0.82
	RC	30	0.14	86		68	0.10	72		30	0.10	77	

Note: Asterisks indicate significance of treatment difference.
*$p < 0.1$; **$p < 0.05$; ***$p < 0.01$.

Figure 2

Field-saturated infiltration rates (cm min^{-1}) for (a) ARM, (b) RHO, and (c) WOR sites from fall of 2020, summer of 2021, and fall of 2021 testing periods combined. Note: Asterisks indicate significance of treatment difference (*$p < 0.1$; **$p < 0.05$; ***$p < 0.01$).



played a substantial role in the observed results. Along with their location on the Des Moines Lobe landform region, the relatively higher sand content at HOE and WOR, 35% and 42% in the top 15 cm, respectively, set them apart from the other sites (table 1). Under saturated flow conditions, sandier soils generally have greater hydraulic conductivities than finer-textured soils (Rawls et al. 1982). Since field-saturated infiltration rates were relatively high for both treatments at HOE and WOR compared to other sites, the effect of relatively coarse soils may have outweighed any potential effects of vegetative cover. No-till farming practices may have contributed to the absence of differences observed between PS and RC soils at ARM and WHI. A recent review showed that no-till increases water infiltration between 17% and 86% compared to conventional tillage, and increased saturated hydraulic conductivity is also expected in no-till environments; however, results have been less consistent (Blanco-Canqui and Ruis 2018). Much like the establishment of perennial vegetation, no-till farming leaves residue on the soil surface and reduces soil disturbance. These factors enhance macropore development by protecting the soil surface from raindrop impacts and increasing SOM and biological activity (Kumar et al. 2012). While PS could provide additional mechanisms for infiltration enhancement past those shared with no-till, the impact may not be strong enough to differentiate after five to seven years since PS establishment. However, it should also be noted that tillage has been shown to improve soil hydraulic properties in the near term (weeks), although these effects often do not persist over longer periods of time due to surface sealing from raindrop impacts and the formation of a "plow pan" after repeated tillage (Haruna et al. 2018). While the exact dates of tillage operations at STRIPS2 sites are unknown, most spring tillage in the region takes place before May planting (USDA NASS 2022), at least one month before our summer testing. Our fall testing occurred before any postharvest tillage, which typically takes place in October and November (USDA NASS 2022). Therefore, during the summer testing period at tilled sites (HOE, MCN, RHO, and WOR), the positive infiltration effects of tillage could have also offset potential PS enhancements.

While the RHO site possessed potential infiltration-limiting factors such as relatively fine textured soils and a conventionally tilled RC field, its distinction as the only site to display consistently greater field-saturated infiltration rates in PS than RC is likely due to differences in SOM. Of the four sites with SOM data, RHO was also the only site to have significantly greater SOM in PS than RC (table 3). Higher SOM is associated with greater soil aggregation and pore size distributions favorable to infiltration (Boyle et al. 1989). Since RHO also had the lowest SOM of these four sites across treatments, it likely had the greatest potential to experience rapid improvement in SOM and, therefore, field-saturated infiltration rate due to PS establishment as the rate of management-induced SOM increase is negatively related to SOM content (Knops and Tilman 2000).

Overall, a combination of factors limiting macroporosity and therefore saturated infiltration like fine-textured soils, conventional tillage, and lower SOM were all present at RHO. Together, these circumstances positioned RHO to have the greatest potential for the fast and marked improvement of field-saturated infiltration rate within PS relative to other sites. At the five other sites—ARM, HOE, MCN, WHI, and WOR—several components may have dampened any differences in saturated infiltration capacity between RC and PS at five to seven years since PS establishment. While our results do not support native prairie species' ability to enhance saturated infiltration capacity as strongly as Bharati (2002), the observed differences at RHO suggest PS can improve saturated infiltration capacity relatively quickly in certain locations.

Table 3
Soil organic matter and bulk density in prairie strip (PS) and row crop (RC) treatments at select STRIPS2 sites.

Site	Treatment	Soil organic matter (%)	*p*-value	Bulk density (g cm^{-3})	*p*-value
ARM	PS	3.5	0.682	1.02	0.128
	RC	3.5		0.99	
MCN	PS	3.6	—	0.93	0.251
	RC	3.3		0.95	
RHO	PS	2.8	<0.01***	1.05	0.130
	RC	2.5		1.08	
WOR	PS	2.9	0.98	—	—
	RC	2.9		—	

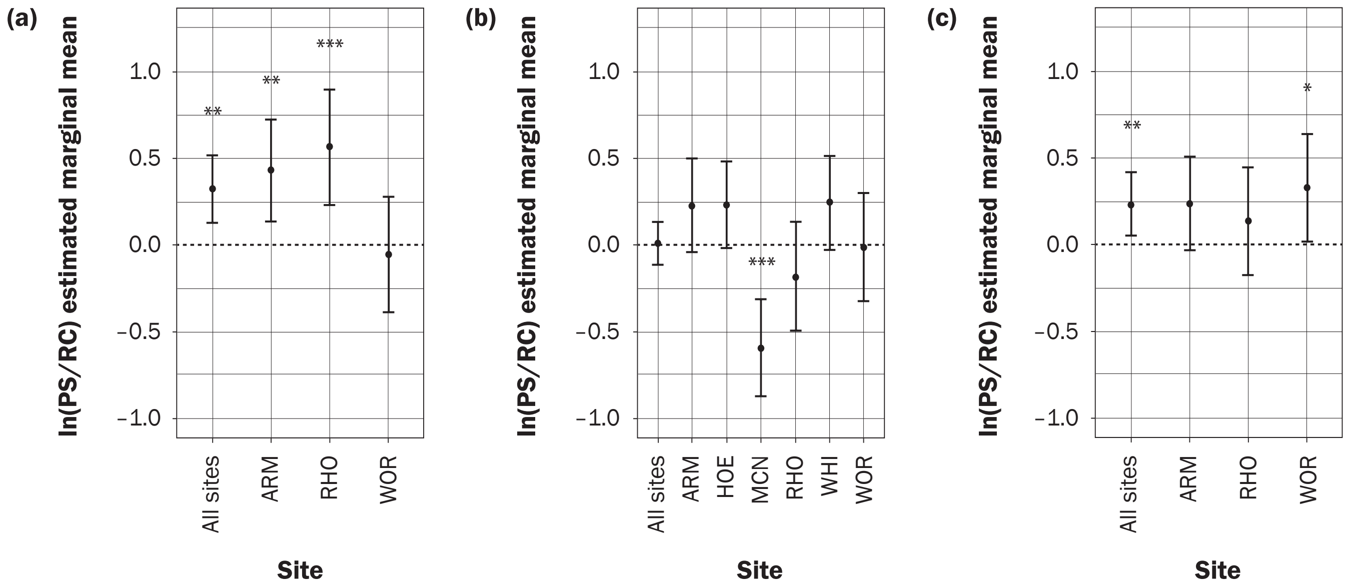
Notes: Asterisks indicate significance of treatment difference. Treatment differences in soil organic matter at MCN were not statistically analyzed due to lack of replication.
$*p < 0.1$; $**p < 0.05$; $***p < 0.01$.

Approximate Sorptivity. As our estimation of soil sorptivity using the Cornell Sprinkle Infiltrometer system varies with antecedent moisture content, the comparison of descriptive statistics between STRIPS2 sites and testing periods (table S1) in the absence of soil moisture measurements is null. However, near simultaneous testing of paired treatment points permits the analysis of treatment differences as both points experienced nearly identical environmental conditions leading up to testing. Therefore, our analysis effectively compares the differences in early infiltration between PS and RC at our sites at any given point in time. For the majority of the site and testing period combinations, the PS treatment had greater approximate sorptivity than RC (figure 3). This difference was especially evident in the fall testing periods as we observed significantly greater approximate sorptivity in PS than RC in the fall of 2020 at ARM ($p < 0.05$), RHO ($p < 0.01$), and across all three fall 2020 sites combined ($p < 0.05$). Additionally, in the fall of 2021, PS had greater approximate sorptivity than RC at WOR ($p < 0.1$) and across the three fall 2021 sites combined ($p < 0.05$). Contrarily, during the summer of 2021 testing period, the only significant result occurred at MCN where RC approximate sorptivity was significantly greater than PS ($p < 0.01$).

Given the method used to approximate sorptivity trends in this study, it is possible that our observation of a treatment difference being evident in the fall stems from disparities in initial soil moisture content rather than soil structural changes. Previous studies have indicated that the increased evapotranspiration associated with perennial vegetative cover can lead to lower soil moisture content than soil in agricultural fields and that this difference is most pronounced in the spring and fall (Zhang and Schilling 2005; Gutierrez-Lopez et al. 2014; Remigio 2015). While we did not measure soil moisture at the time of testing, given the ample repetition over time and space, we can assume a wide range of initial soil moisture conditions for treatment pairs at each site (figures S1 and S2). The observed approximate sorptivity differences may also be influenced by surface roughness as it is negatively related to time-to-runoff as well (Zhao et al. 2018). Recent tillage can temporarily increase surface roughness; however, over time, raindrop impacts on bare soil can cause surface sealing and limit infiltration. Additional time for surface sealing to occur on bare soil in the RC treatment could also contribute to the fall differences in approximate sorptivity trends observed between PS and RC. While we cannot conclusively say that the PS treatment has greater sorptivity than the RC treatment when adjusted for soil moisture, our observation of greater approximate sorptivity in PS than RC during the fall is meaningful nonetheless. A postponement in

Figure 3

Paired differences between log-transformed prairie strip (PS) and row crop (RC) approximate sorptivity (cm $min^{-0.5}$) at each site and all sites combined during (a) fall of 2020, (b) summer of 2021, and (c) fall of 2021 testing periods. Error bars represent the 90% confidence interval. Notes: Asterisks indicate significance of treatment difference (*$p < 0.1$; **$p < 0.05$; ***$p < 0.01$). Log-transformation was necessary for optimal statistical analysis of treatment differences and absolute values calculated for approximate sorptivity (cm $min^{-0.5}$) are inconsequential in this study.



runoff generation has favorable soil and water quality conservation outcomes regardless of the mechanism causing it. Since it is likely that approximate sorptivity trends between PS and RC arise from soil moisture and/or surface roughness differences, we can deduce that PS have greater early infiltration than RC at the end of the annual growing season and potentially the beginning as well. Therefore, we can say that a field would generate less surface runoff if it contains PS than if it is 100% RC during a given rainfall event in the fall.

Hydraulic Conductivity. While paired design permitted the analysis of treatment differences for each tension, comparisons of raw hydraulic conductivity values between years at STRIPS1 sites were limited to K(0), since it represents saturated hydraulic conductivity and circumvents most effects of antecedent soil moisture. However, notable differences in hydraulic conductivity between PS and RC were relatively sparse across all site years (figure 4). Additionally, the magnitude of measured saturated hydraulic conductivities varied considerably within and between years (figure 5), making it difficult to detect any trends. Although differences in soil hydraulic properties between landscape positions have been reported in prairie and agricultural systems (Guzman and Al-Kaisi 2011), an analysis of variance test determined that the treatment difference in hydraulic conductivity was not affected by landscape position, while interactions between site, year, and site:year occasionally occurred (table 4).

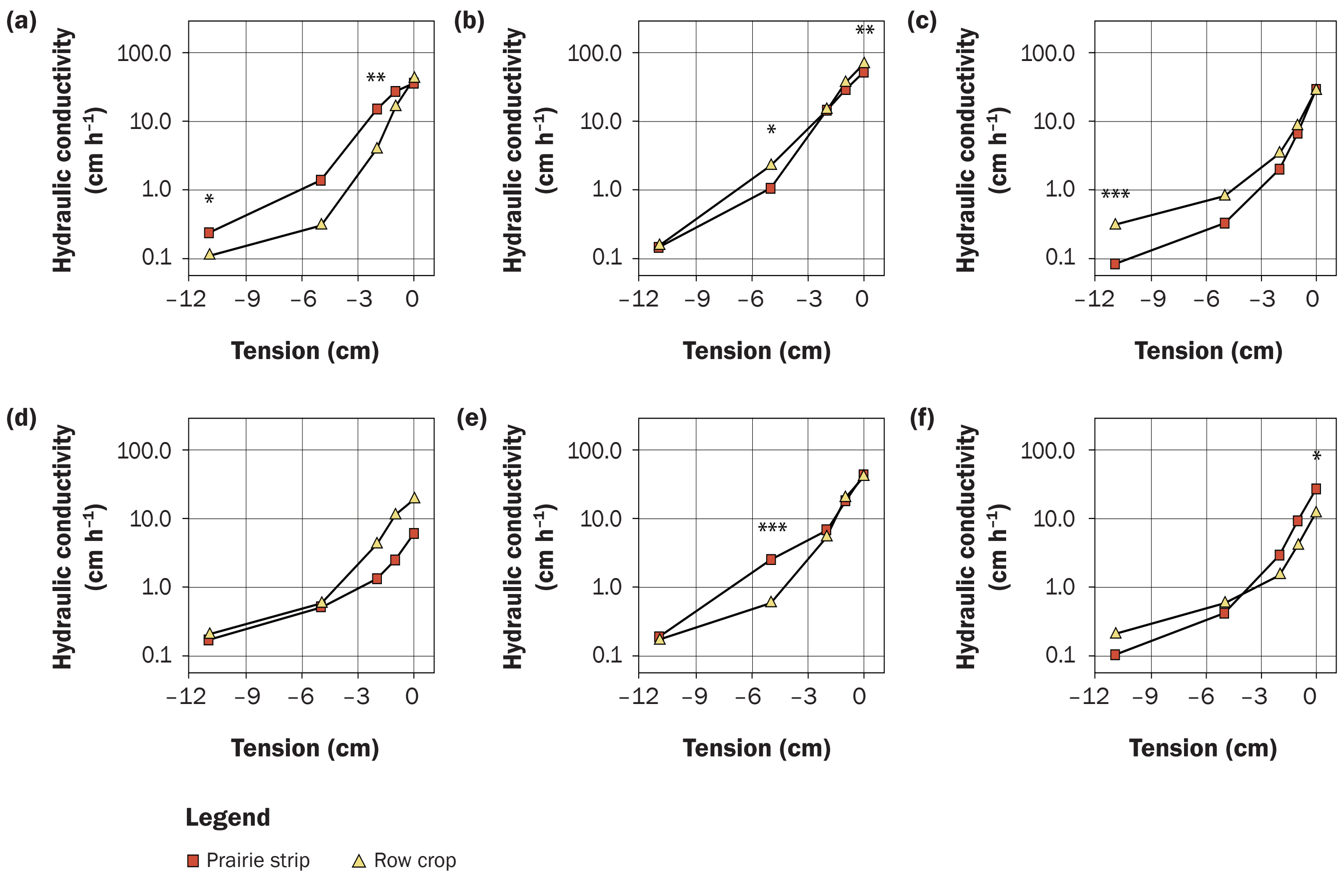
Only two statistically significant treatment differences occurred in the 2021 testing period (figure 4). At IN1, K(–11) was 0.21 cm h^{-1} less in PS than in RC ($p < 0.01$), and at WE2, K(0) was 16.18 cm h^{-1} greater in PS than in RC ($p < 0.1$). While not always statistically significant, unsaturated hydraulic conductivities were lower in PS than RC at the smallest tensions (–5 and –11 cm H_2O) for both sites in 2021. At the higher tensions (–2, –1, and 0 cm H_2O), the general direction of treatment differences (PS – RC) varied by site as WE2 maintained positive differences and IN1 was slightly negative. The 2021 results differed from those collected 10 and 11 years prior. Between 2010 and 2011, the direction of treatment differences in hydraulic conductivity was inconsistent at most tensions, and no tension values had consecutive statistically significant differences in hydraulic conductivity at either site (figure 4). Further, only two trends in treatment differences between 2010 and 2021 were moderately evident. At IN1, the difference in K(–11) appears to have decreased over time, as PS had 0.11 cm h^{-1} greater hydraulic conductivity than RC in 2010 ($p < 0.1$) and 0.21 cm h^{-1} less conductivity than RC in 2021 ($p < 0.01$). On the other end of the spectrum, the treatment difference in K(0) was –11.5 (PS < RC) at WE2 in 2010 and 16.18 cm h^{-1} in 2021 (PS > RC) ($p < 0.1$).

The increase in saturated hydraulic conductivity differences between PS and RC treatments observed at WE2 over time can be attributed to a combination of previously mentioned factors like SOM, biological activity, and disturbance. Slightly greater sand content at IN1 than WE2 may play a role in IN1 not displaying any treatment contrasts in saturated hydraulic conductivity. The decrease in differences observed for the –11 cm H_2O tension at IN1 likely relates to a greater abundance of smaller pores within the RC treatment, possibly caused by compaction. Disparities in antecedent soil moisture could factor into the hydraulic conductivity observations at the –11 cm H_2O tension. However, literature and the concurrent approximate sorptivity analysis would suggest drier conditions within the PS treatment. Despite this, the RC treatment had greater conductivity at –11 cm H_2O than PS, reinforcing the notion of a greater fraction of smaller pores within the RC treatment.

Overall, the high variability of hydraulic conductivity measurements across sites and testing years was more notable than any treatment effect. These results corroborate literature descriptions of challenges associated with measuring field hydraulic conductivity

Figure 4

Average hydraulic conductivities (cm h⁻¹) at each tension at STRIPS1 sites ([a] IN1 2010, [b] IN1 2011, [c] IN1 2021, [d] WE2 2010, [e] WE2 2011, and [f] WE2 2021). Note: Asterisks indicate significance of treatment difference at the corresponding tension value (*$p < 0.1$; **$p < 0.05$; ***$p < 0.01$).



due to spatial and temporal variability (Deb and Shukla 2012). This inconsistency of measured hydraulic conductivity values caused difficulties in assessing any possible trends. As a result, the overall lack of distinction between PS and RC treatments in observed hydraulic conductivity suggests that the effects of PS are limited at 14 years since PS establishment at these sites. Our field results differ from previous studies in which laboratory-measured saturated hydraulic conductivity was significantly greater in restored prairie soils than row crop soils (Udawatta et al. 2008; Alagele et al. 2019).

Summary and Conclusions

This study analyzed differences in soil infiltration dynamics between prairie strips (PS) and row crops (RC) at two PS establishment stages (STRIPS1, 14 years; STRIPS2, 5 to 7 years). We did not find universal improvements in soil hydraulic properties due to PS; however, supporting evidence was found in specific circumstances. Prairie strips increased saturated infiltration relative to RC at two sites (one STRIPS1 and one STRIPS2). Greater saturated hydraulic conductivity in PS than RC at the STRIPS1 site appeared to develop over time, but the difference was only moderately significant after 14 years since PS establishment. The STRIPS2 site that had greater field-saturated infiltration rate in PS than RC possessed several RC infiltration-limiting factors like fine-textured soils, conventional tillage, and low SOM, which likely contributed to greater contrast between the two treatments at its relatively early stage of PS establishment. These results suggest that any changes in saturated infiltration capacity induced by management practices such as PS occur slowly, probably on at least a decadal timescale, unless certain site-specific factors are present. Contrary to saturated infiltration capacity observations, early infiltration improvements after PS implementation were more prevalent. Differences in approximate sorptivity were most pronounced in the fall when prairie land cover has greater rates of evapotranspiration than comparable cropland. Therefore, soil moisture dynamics and surface roughness differences may explain approximate sorptivity disparities between treatments. Greater rates of early infiltration within PS support their utility as a surface runoff inhibitor and soil and water quality conservation tool. Due to higher sorptivity trends within PS, we could expect a corn or soybean RC field with embedded PS to infiltrate more water and export less surface runoff than a comparable 100% RC field during a given rainfall event in the fall and potentially early spring. While we may not expect any difference between PS and RC in the summer, this result is less consequential as summer soil erosion rates are generally low for both land covers. Future research should revisit infiltration dynamics of PS at times further since establishment and with additional methodologies. Also, since disparities between locations were evident, prairie reconstruction infiltration studies should be expanded to more locations to assess site-specific trends.

Figure 5

Distribution of measured hydraulic conductivities (cm h⁻¹) at each tension infiltrometer tension value ([a] –11 cm, [b] –5 cm, [c] –2 cm, [d] –1 cm, and [e] 0 cm) for IN1 and WE2 sites combined during 2010, 2011, and 2021 testing periods.

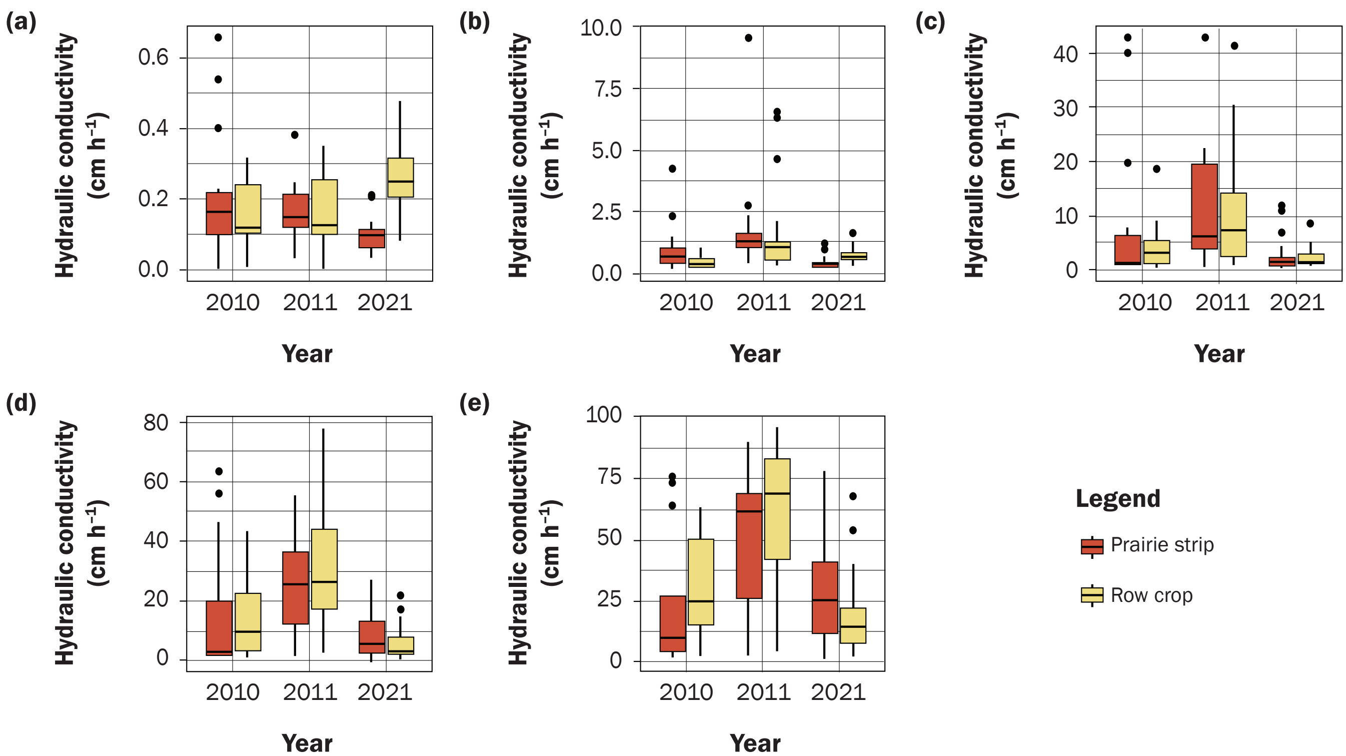


Table 4

Analysis of variance table of effects on hydraulic conductivity paired treatment differences (prairie strip – row crop) at STRIPS1 sites across three testing periods.

	Ψ = 0		Ψ = –1		Ψ = –2		Ψ = –5		Ψ = –11	
Effect	**F**	***p***	**F**	***p***	**F**	***p***	**F**	***p***	**F**	***p***
Position	0.60	0.45	0.19	0.67	0.97	0.34	0.00	0.95	0.57	0.46
Site	1.90	0.18	0.25	0.78	0.39	0.68	0.75	0.49	6.43	0.01***
Year	4.11	0.06*	0.01	0.93	0.37	0.55	1.97	0.18	0.00	0.98
Site:Year	2.21	0.14	2.68	0.10*	1.97	0.17	5.68	0.01**	2.31	0.13

Note: Asterisks indicate significance level.
*$p < 0.1$; **$p < 0.05$; ***$p < 0.01$.

Supplemental Material

The supplementary material for this article is available in the online journal at https://doi.org/10.2489/jswc.2024.00146.

Acknowledgements

Funding for this research was provided by the Iowa Department of Agriculture and Land Stewardship Division of Soil Conservation, USDA Farm Services Agency (AG-3151-P-14-0162), US Forest Service Northern Research Station, USDA Farm Services Agency (19CPT0010516), and the Foundation for Food and Agriculture Research award number – Grant ID: CA18-SS-0000000278. In-kind support was from the Committee for Agricultural Development, the US Fish and Wildlife Service Neal Smith National Wildlife Refuge, Iowa State University and ISU Research and Demonstration Farms, Whiterock Conservancy, and one private commercial farm as hosts to the project.

References

Alagele, S.M., S.H. Anderson, and R.P. Udawatta. 2019. Biomass and buffer management practice effects on soil hydraulic properties compared to grain crops for claypan landscapes. Agroforestry Systems 93:1609-1625.

Anderson, R., K. Brye, and L. Wood. 2020. Landuse and soil property effects on infiltration into Alfisols in the Lower Mississippi River Valley, USA. Geoderma Regional 22:e00297.

Ankeny, M.D., M. Ahmed, T.C. Kaspar, and R. Horton. 1991. Simple field method for determining unsaturated hydraulic conductivity. Soil Science Society of America Journal 55:467-470.

Ankeny, M.D., T.C. Kaspar, and R. Horton. 1990. Characterization of tillage and traffic effects on unconfined infiltration measurements. Soil Science Society of America Journal 54:837-840.

Bharati, L., K.H. Lee, T.M. Isenhart, and R.C. Schultz. 2002. Soil-water infiltration under crops, pasture, and established riparian buffer in Midwestern USA. Agroforestry Systems 56:249-257.

Blanco-Canqui, H., and S.J. Ruis. 2018. No-tillage and soil physical environment. Geoderma 326:164-200.

Boyle, M., W.T. Frankenberger Jr., and L.H. Stolzy. 1989. The influence of organic matter on soil aggregation and water infiltration. Journal of Production Agriculture 2:290-299.

Brady, N.C., and R.R. Weil. 2008. The Nature and Properties of Soils, 14th edition. Upper Saddle River, NJ: Prentice Hall.

Brittenham, B.A. 2017. Effect of Converting Row Crop to Prairie on Nutrient Concentration in Shallow Groundwater and Soil Properties. Master's thesis, Iowa State University.

Bugeja, S.M., and M.J. Castellano. 2018. Physicochemical organic matter stabilization across a restored grassland chronosequence. Soil Science Society of America Journal 82:1559-1567.

Deb, S.K., and M.K. Shukla. 2012. Variability of hydraulic conductivity due to multiple factors. American Journal of Environmental Sciences 8:489.

Dutter, C. 2022. The Spatial and Temporal Effects of Prairie Strip Restoration on Soil Health. [Unpublished Doctoral dissertation]. Iowa State University.

Fuentes, J.P., M. Flury, and D.F. Bezdicek. 2004. Hydraulic properties in a silt loam soil under natural prairie, conventional till, and no-till. Soil Science Society of America Journal 68:1679-1688.

Gardner, W.R. 1958. Some steady-state solutions of the unsaturated moisture flow equation with application to evaporation from a water table. Soil Science 85:228-232.

Gutierrez-Lopez, J., H. Asbjornsen, M. Helmers, and T. Isenhart. 2014. Regulation of soil moisture dynamics in agricultural fields using strips of native prairie vegetation. Geoderma 226:238-249.

Guzman, J.G., and M.M. Al-Kaisi. 2011. Landscape position effect on selected soil physical properties of reconstructed prairies in southcentral Iowa. Journal of Soil and Water Conservation 66(3):183-191. https://doi.org/10.2489/jswc.66.3.183.

Haruna, S.I., S.H. Anderson, N.V. Nkongolo, and S. Zaibon. 2018. Soil hydraulic properties: Influence of tillage and cover crops. Pedosphere 28:430-442.

Helmers, M.J., X. Zhou, H. Asbjornsen, R. Kolka, M.D. Tomer, and R.M. Cruse. 2012. Sediment removal by prairie filter strips in row-cropped ephemeral watersheds. Journal of Environment Quality 41:1531-1539.

Hernandez-Santana, V., X. Zhou, M.J. Helmers, H. Asbjornsen, R. Kolka, and M. Tomer. 2013. Native prairie filter strips reduce runoff from hillslopes under annual row-crop systems in Iowa, USA. Journal of Hydrology 477:94-103.

Knops, J.M., and D. Tilman. 2000. Dynamics of soil nitrogen and carbon accumulation for 61 years after agricultural abandonment. Ecology 81:88-98.

Kumar, S., A. Kadono, R. Lal, and W. Dick. 2012. Long-term tillage and crop rotations for 47–49 years influences hydrological properties of two soils in Ohio. Soil Science Society of America Journal 76:2195-2207.

Kutilek, M. 1980. Constant rainfall infiltration. Journal of Hydrology 45:289-303.

Lenth, R. 2020. emmeans: Estimated Marginal Means, aka Least-Squares Means. R package version 1.5.2-1. https://CRAN.R-project.org/package=emmeans.

Li, C., K.S. Veum, K.W. Goyne, M.R. Nunes, and V. Acosta-Martinez. 2021. A chronosequence of soil health under tallgrass prairie reconstruction. Applied Soil Ecology 164:103939.

Liu, Y., Z. Cui, Z. Huang, M. López-Vicente, and G.L. Wu. 2019. Influence of soil moisture and plant roots on the soil infiltration capacity at different stages in arid grasslands of China. Catena 182:104147.

Lockett, D.R. 2012. Soil Hydraulic Property Impacts of Incorporating Prairie Vegetation within a Row Crop Production Area. Master's thesis, Iowa State University.

Matamala, R., Jastrow, J.D., Miller, R.M. and C.T. Garten. 2008. Temporal Changes in C and N Stocks of Restored Prairie: Implications for C Sequestration Strategies. Ecological Applications 18:1470-1488.

McLauchlan, K.K., S.E. Hobbie, and W.M. Post. 2006. Conversion from agriculture to grassland builds soil organic matter on decadal timescales. Ecological Applications 16:143-153.

Moebius-Clune, B.N., D.J. Moebius-Clune, B.K. Gugino, O.J. Idowu, R.R. Schindelbeck, A.J. Ristow, H.M. van Es, J.E. Thies, H.A. Shayler, M.B. McBride, K.S.M. Kurtz, D.W. Wolfe, and G.S. Abawi. 2016. Comprehensive Assessment of Soil Health – The Cornell Framework, Edition 3.2. Geneva, NY: Cornell University.

O'Neal, M.R., M.A. Nearing, R.C. Vining, J. Southworth, and R.A. Pfeifer. 2005. Climate change impacts on soil erosion in Midwest United States with changes in crop management. Catena 61:165-184.

Pérez-Suárez, M., M.J. Castellano, R. Kolka, H. Asbjornsen, and M. Helmers. 2014. Nitrogen and carbon dynamics in prairie vegetation strips across topographical gradients in mixed Central Iowa agroecosystems. Agriculture, Ecosystems and Environment 188:1-11.

Pey, S.L., and H.A.S. Dolliver. 2020. Assessing soil resilience across an agricultural land retirement chronosequence. Journal of Soil and Water Conservation 75(2):191-197. https://doi.org/10.2489/jswc.75.2.191.

R Core Team. 2020. R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing. http://www.R-project.org/.

Rawls, W.J., D.L. Brakensiek, and K.E. Saxton. 1982. Estimation of soil water properties. Transactions of the ASAE 25:1316-1320.

Remigio, V. 2015. Assessing the Ecohydrological Impact of Incorporating Perennial Vegetation into an Agricultural Watershed in Central Iowa, USA. PhD dissertation, Iowa State University.

Reynolds, W.D., and D.E. Elrick. 1990. Ponded infiltration from a single ring: I. Analysis of steady flow. Soil Science Society of America Journal 54:1233-1241.

Samson, F., and F. Knopf. 1994. Prairie conservation in North America. BioScience 44:418-421.

Soil Survey Staff. N.d. Web Soil Survey. Washington, DC: USDA NRCS. https://websoilsurvey.nrcs.usda.gov/.

Soilmoisture Equipment Corporation. 2008. Tension infiltrometer operating instructions. Goleta, CA: Soilmoisture Equipment Corp. https://www.soilmoisture.com/pdfs/Resource_Instructions_0898-2826D20%20Tension%20Infiltrometer%2020%20cm%20D.pdf.

Stone, L.R., and A.J. Schlegel. 2010. Tillage and crop rotation phase effects on soil physical properties in the west-central Great Plains. Agronomy Journal 102:483-491.

Udawatta, R.P., S.H. Anderson, C.J. Gantzer, and H.E. Garrett. 2008. Influence of prairie restoration on CT-measured soil pore characteristics. Journal of Environmental Quality 37:219-228.

USDA NASS (National Agricultural Statistics Service). 2022. Crop Production 2021 Summary. Washington, DC: USDA NASS. https://downloads.usda.library.cornell.edu/usda-esmis/files/k3569432s/sn00c1252/g158cj98r/cropan22.pdf.

USDA NRCS (Natural Resources Conservation Service). 2006. Land Resource Regions and Major Land Resource Areas of the United States, the Caribbean, and the Pacific Basin. Washington, DC: USDA NRCS.

van Es, H.M., and R.R. Schindelbeck. 2015. Field Procedures and Data Analysis for the Cornell Sprinkle Infiltrometer. Department of Crop and Soil sciences Research Series. Ithaca, NY: Cornell University. https://cpb-us-e1.wpmucdn.com/blogs.cornell.edu/dist/7/9922/files/2021/10/Cornell-Sprinkle-Infiltrometer-manual-1xf0snz.pdf.

Wickham, H. 2016. ggplot2: Elegant Graphics for Data Analysis. New York: Springer-Verlag.

Wooding, R.A. 1968. Steady infiltration from a shallow circular pond. Water Resources Research 4:1259-1273.

Wu, G.L., Y. Liu, Z. Yang, Z. Cui, L. Deng, X. F. Chang, and Z.H. Shi. 2017. Root channels to indicate the increase in soil matrix water infiltration capacity of arid reclaimed mine soils. Journal of Hydrology 546:133-139.

Zhang, Y.K., and K.E. Schilling. 2006. Effects of land cover on water table, soil moisture, evapotranspiration, and groundwater recharge: A field observation and analysis. Journal of Hydrology 319:328-338.

Zhao, L., R. Hou, F. Wu, and S. Keesstra. 2018. Effect of soil surface roughness on infiltration water, ponding and runoff on tilled soils under rainfall simulation experiments. Soil and Tillage Research 179:47-53.

Zhou, X., M.J. Helmers, H. Asbjornsen, R. Kolka, M.D. Tomer, and R.M. Cruse. 2014. Nutrient removal by prairie filter strips in agricultural landscapes. Journal of Soil and Water Conservation 69(1):54-64. https://doi.org/10.2489/jswc.69.1.54.