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The influence of prairie strips sown in midwestern corn and soybean fields on sediment discharge throughout the year

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Abstract: Many crop fields in the United States Corn Belt continue to erode at rates in excess of soil regeneration leading to sediment being transported from farms to adjacent surface water and degrading wildlife habitat. To reduce or eliminate sediment loss, vegetative filter strips can be established perpendicular to the hillslope and at the edge-of-field to intercept and filter surface runoff transporting sediment. The filter strips can be planted with native prairie vegetation to filter sediment out of runoff as well as establishing high quality habitat. A long-term study at Neal Smith Wildlife Refuge Farm in central Iowa found that with as little as 10% of a field converted to prairie filter strips, sediment discharge from fields could be reduced up to 95%. To improve our understanding of prairie filter strips and erosion processes over a broader range of landscapes, this study was conducted at six farm sites throughout Iowa. Following a paired treatment approach, each farm site was broken into two different subcatchments; one subcatchment was fully cropped (control) while the other had a portion of the field sown with native prairie vegetation. Each subcatchment had an H-flume installed to sample runoff water and determine the total suspended sediment (TSS) load and a rain gauge to monitor rainfall amount, frequency, and duration. Between 2016 and 2021, subcatchments with prairie strips median TSS load was 89.5% lower (95% CI, 69.2% to 96.4%, $p < 0.001$) than the control subcatchments. In fields when corn was planted, the subcatchments with prairie strips had significantly lower TSS discharged, with a median TSS load 97.6% less (95% CI, 92.1% to 99.3%, $p < 0.001$) compared to the control subcatchments. The TSS loads were significantly influenced by the amount of rainfall ($p < 0.001$) despite the treatment. To investigate effects of seasonality and rainfall amount, the data set was parsed out based on the growing season of the dominant cropping system. There was no prairie strip effect during the primary growing months (PGS) (May to August); however, outside of the primary growing months (OPGS) (March to April and September to November) the prairie strip subcatchments median TSS load was 96.1% less (95% CI, 82.5% to 99.1%, $p < 0.001$) than the controls. The significant interaction of crop planted with prairie strip treatment and the differences between PGS and OPGS suggest that prairie strips have the capacity to reduce sediment leaving a field when they are the most vulnerable to effects of splash erosion (i.e., low ground cover and higher rainfall amount). Climate change models predict that areas like Iowa will continue to trend toward higher frequency and intensity rain events, so the compounded benefits of prairie planted in cropped fields could promote biodiverse landscapes that increase resilience to predicted effects from climate change during parts of the year when the land is more susceptible to erosion.

Key words: conservation management—Corn Belt—prairie strips—rainfall—sediment transport

Water erosion is a major contributor to degradation of agricultural land and streambanks in the midwestern United States in the absence of soil conservation practices, and will continue to be exacerbated as rainfall amount and intensity continue to increase due to climate change (O'Neal et al. 2005; Hatfield et al. 2013; Pryor et al. 2014; Feng et al. 2016; USGCRP 2018; IPCC 2022). The primary drivers of erosion in agroecosystems are water, wind and tillage processes (Renard 1997; Ritter 2018). In this paper we will focus on water erosion and ways to mitigate it in corn (*Zea mays* L.) and soybean (*Glycine max* [L.] Merr.) fields. Water erosion comprises three parts: soil detachment due to the force of falling raindrops (i.e., splash erosion), soil transport via surface flow paths, and soil deposition. Where soil is bare, it is vulnerable to splash erosion and as water accumulates and momentum builds, water will concentrate into a flow path that accrues sediment as it moves downslope. Sediment is then deposited in low-lying areas of fields and floodplains, and sometimes directly into lakes and streams when filtering practices are absent (Renard 1997; Toy et al. 2002).

Feng et al. (2016) observed rainfall patterns associated with mesoscale convective systems (MCS) that make up 30% to 70% of warm-season rainfall in the Midwest. They modeled MCS to predict the trends of MCS under climate change conditions and found that the Midwest will endure increased frequency and intensity of rainfall in the spring when land planted with summer crops like corn and soybeans is the most vulnerable to erosion processes (April through June) (Kaspar and Singer 2011). The optimal corn and soybean planting dates are from mid-April to mid-May so there are millions of acres with bare soils during a time of the year currently and forecasted to receive increased

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frequency and intensity rainfalls. Many soil erosion experts agree that bare soils are the most erosive soils (Fernández-Raga et al. 2017), and land cover management for prevention and structural filtering practices for mitigation are essential to control soil erosion rates.

Slow adoption of soil conservation practices has been partially attributed to a lack of well-defined consequences for crop yield or production efficiencies (FAO 2015). Although the extent of long-term effects from soil degradation is not commonly considered in agronomic sciences (Borrelli et al. 2017), some research highlights the long-term negative economic impacts of soil erosion on yield (Al-Kaisi et al. 2002; Cruse 2016; Thaler et al. 2021). The midwestern Corn Belt region produces 75% of US corn and recent estimates on soil erosion indicate that roughly a third of cultivated land in the region has lost A-horizon soil completely (Thaler et al. 2021). The A-horizon is the most fertile layer of soil and Thaler et al. (2021) estimated that approximately 1.4 Pg of carbon (C) is released annually along eroding hillslopes with concomitant economic losses of US$2.8 billion annually across the region. Iowa is one of the largest corn producing states in the US Corn Belt and is not immune to topsoil thinning and the long-term negative economic impacts. Cruse (2016) reported an annual average rate of 12.8 Mg ha^{-1} for soil erosion in Iowa, which is considered as an unsustainable amount of soil erosion (>10 Mg ha^{-1}). Thaler et al. (2021) reported that crop field topsoil eroded by an average rate of 1.9 mm y^{-1}, which is above the national estimated average rate of soil formation, approximately 0.25 mm y^{-1} (Montgomery 2007; Wischmeier and Smith 1998). As topsoil is reduced, so is the soil's capacity to provide rooting space and store water for crops throughout the growing season (Borreli et al. 2017). Fifty percent of plant available nitrogen (N), phosphorus (P), and potassium (K) are located in the A-horizon, therefore, soil's inherent fertility declines with erosion, increasing production costs and reducing yield significantly (Al-Kaisi et al. 2002).

Borrelli et al. (2017) noted that tillage and inappropriately placed agricultural practices coupled with chronic disruption of native ecosystems are the primary causes of soil erosion. The consequences of these human-induced disturbances on the landscape have cascading effects on soil resources, including but not limited to nutrient loss, reduced C storage, and declining biodiversity and soil ecosystem stability (Borrelli et al. 2017; Fernández-Raga et al. 2017). Studies have demonstrated that erosion rates and sediment transport can be reduced or mitigated in nearly every situation through the application of appropriate agricultural management practices (e.g., conservation tillage, cover crops, and contour farming) and structural measures (e.g., terraces and vegetative filter strips) (Renard 1997; Nearing et al. 2004; Fernández-Raga et al. 2017; Lenhart and Peterson 2017; Borrelli et al. 2017; Ritter 2018).

In addition to soil resource concerns, several states throughout the Midwest have experienced substantial degradation and loss of native plant and wildlife species since European settlement (Henningsen 2005; Campbell et al. 2017), and the small percentage that remains is vulnerable to effects of climate change (IPCC 2022; Schulte et al. 2022). Beginning in 2007, researchers in Iowa piloted the enhancement of vegetative filter strips by planting and managing the strips with diverse native prairie vegetation in a corn–soybean rotation at the Neal Smith Wildlife Refuge Farm to explore the functionality of prairie strips for managing surface runoff while also increasing wildlife habitat and connectivity (Schulte et al. 2016). Vegetative filter strips are a common best management practice (BMP) for reducing sediment and other agriculture pollutants in surface water runoff from a field (Dillaha et al. 1987; Robinson et al. 1996; Munoz-Carpena and Parsons 2004; Ramler et al. 2022). The practice is installed along the contour of hillslopes and edge-of-field to intercept overland flow, thus reducing flow velocity and dissipating some of the energy that drives erosion and sediment transport as well as providing area for increased water infiltration. Conventional vegetative filter strips are designed with fixed widths of cool season exotic grasses such as Kentucky bluegrass (*Poa pratensis* L.) and smooth brome (*Bromus inermis* Leyss) (Henningsen 2005). A prairie vegetative filter strip incorporates warm season grasses such as Indiangrass (*Sorghastrum nutans* [L.] Nash), big bluestem (*Andropogon gerardi* Vitman), little blue stem (*Schizachyrium scoparium* [Michx.] Nash), and several forb species blooming each season throughout the year (Blanco-Canqui et al. 2005; Meissen et al. 2020).

The pilot project at Neal Smith Wildlife Refuge Farm found disproportionate benefits for water quality and increases in biodiversity; that is, proportional gains in environmental indicators (i.e., reduced pollutant runoff from fields, water infiltration, increased wildlife habitat and pollinator forage, etc.) were greater than the proportion of fields converted from cropland to prairie (Liebman et al. 2013; Schulte et al. 2017), at a relatively low cost compared to alternative practices (Tyndall et al. 2013). The stiff-stemmed vegetation in a prairie filter strip is more adapted to the Corn Belt's climate and soils and it is more resilient to heavy rainfall events relative to vegetation found in conventional filter strips; in addition, the prairie vegetation provides more plant diversity and supports wildlife communities (Hirsh et al. 2013; Schulte et al. 2016; Kordbacheh et al. 2020). Schulte et al. (2017) reported multiple benefits with as little as 10% of cropland planted with prairie filter strips comprised of native prairie vegetation, including up to 95% of total suspended solids (TSS) load reduction, meaning higher retention of sediment. However, since the study was conducted at only one site, an important question remained: how well does native prairie vegetation used as filter strips perform in cropland with varying topographic features, soils, rainfall patterns, and farms? In the present study our objectives were the following:

- Determine the impact of prairie filter strips on sediment transport in corn–soybean fields in Iowa, United States, using a paired comparison approach
- Evaluate rainfall patterns and sediment transport in subcatchments annually and seasonally between 2016 and 2021

Materials and Methods

To determine the effect of native prairie filter strips on soil movement in corn–soybean fields, a study was conducted using a paired comparison approach (Kendall and Babington Smith 1940; Glickman and Jensen 2005) that included two treatments: a control treatment where subcatchments were managed with 100% row-crops and a prairie strip treatment where subcatchments were managed with row-crops and prairie. The size of the subcatchments ranged from 2.7 to 13.0 ha, with the mean slopes ranging from 4.3% to 12.7%. The paired subcatchments were

Table 1

Site characteristics of each paired subcatchment (Sub): control (Ctrl) and prairie strip (Strp), including the crop rotation (C = corn and S = soybean), residue cover, other best management practices (BMP) (GW = grass waterway), subcatchment area, the mean slope gradient, and information on the prairie filter strip. Subcatchments within a paired watershed were located within 1.6 km from one another to keep climatic and soil characteristics similar to one another yet far enough away so there were no intersecting hydrologic patterns.

Site	Sub	Crop rotation	Residue cover	BMP	Area (ha)	Mean slope gradient (%)	Prairie filter strip (% of Sub)
ARM	Ctrl	SCSCSC	30% to 50% crop residue†	GW	5.7	9.7	—
	Strp			GW	4.3	10.5	12.0
EIA*	Ctrl	SCS - -	15% to 30% crop residue‡	GW	4.1	6.6	—
	Strp			GW	9.4	6.0	6.0
HOE	Ctrl	CSCSCS	30% to 50% crop residue‡	—	8.7	6.6	
	Strp			—	13.0	6.4	6.9
RHO*	Ctrl	CCCCCC	0% crop residue†	GW	2.7	7.4	—
	Strp			GW	3.2	6.6	5.4
WHI	Ctrl	CSCSCS	75% to 100% residue†	—	4.9	10.8	—
	Strp			GW	3.8	12.7	29.5
WOR*	Ctrl	CSCCSC	15% to 30% crop residue†	GW	5.3	4.9	—
	Strp			GW	5.3	4.5	9.5

*Denotes paired subcatchments where the location of the treatment was randomly assigned.

- Crop planted at a research site removed for years when no measurements were taken.

†2019 and 2020 percentage crop residue estimated following and Conservation Technology Information Center's (CTIC) National Crop Residue Management Survey (CRM) guidance.

‡Percentage crop residue estimated based on landowner's tillage practices.

monitored between 2016 and 2021 at six commercial farms throughout Iowa to capture different environmental and hydrologic characteristics. Each farm site was given a unique three-letter identification to ensure anonymity of a site in this study while reporting results (table 1). Across research sites, farm management ranged from continuous corn and intensive tillage, to a corn–soybean rotation with cover crops and zero tillage, as well as varying proportions of prairie strips to cropped acres ranging from 5.4% to 29.5% of a subcatchment (table 1). Crop management practices (e.g., crop sequences and tillage regimes) and soil characteristics were consistent between paired subcatchments, while structural BMPs, such as terraces and grass waterways, varied among all subcatchments (table 1). Following Prior's (1991) classification of landform regions in Iowa, the present research sites were situated on the Southern Iowa Drift Plain, the Iowan Surface, and the Des Moines Lobe. These landforms consist primarily of dissected till plains and rolling hills with some broad ridgetops but mostly long slopes. Due to labor and logistical limitations, each year varied in the number of sites studied.

The prairie strips were planted along the hillslope and edge-of-field (figure 1) with diverse seed mixes (table 2) and managed as a prairie. Vegetative surveys were conducted in 2018 and 2019 and reported by English (2020a) and English (2020b). They reported that four of the six subcatchments sown with prairie had greater than 50% of the strip established in prairie, while two subcatchments had vegetative strips that were less than 50% prairie vegetation. These two sites required additional maintenance from the landowner to suppress weeds so prairie vegetation could become more established (English 2020b). All six sites were kept in the analysis to represent prairie strip sites at all stages of maintenance and establishment timelines.

Sediment Transport Measurements. H-flumes were installed at the outlet of each subcatchment to monitor water quality and runoff volume between 2016 to 2021. At most sites, H-flume outlets coincided with a grassed waterway due to farm management (table 1). The sizing and installation of flumes were determined based on the runoff volume and peak 10-year flow rate for a 24-hour storm event. The Soil Conservation Service Curve Number (SCS-CN) method was used to calculate the CN for cultivated lands with conservation present (Hernandez-Santana et al. 2013). H-flume installation included plywood wing walls to guide surface runoff to the flumes. Automated water samplers (ISCO 6712, Inc., Lincoln, Nebraska) equipped with pressure transducers (720 submerged Probe Module) were installed at each flume to record runoff rate and collect water samples. The pressure transducers were calibrated annually in the laboratory during the winter and checked throughout the monitoring season. The H-flumes were installed at the edge-of-field as to not interfere with any farm management activities and downslope from the treated area. The installations were intended to be placed in similar locations between paired subcatchments so as to assess the impact of prairie filter strips as closely as possible in field conditions found on commercial-scale farms.

Runoff measurements were taken at 5-minute intervals during nonfreezing parts of the year. The samplers were removed from the fields during colder months (November to March) to prevent damage due to freeze-thaw cycles. At the start of each sampling year, equipment was put back in the field and flumes were checked to ensure they were level. The flow discharge rate at each flume was determined according to the *Field Manual for Research in Agricultural Hydrology* (Brakensiek et al. 1979). Using the rating created for each flume, the volume of flow could be calculated for each flume at 5-minute intervals and was calculated and summed

Figure 1

Research sites were distributed throughout Iowa. Each site consisted of paired subcatchments that included a control (no prairie strips) and prairie strips sown within the field. The management of the field was the same between paired subcatchments, including crop management, structural practices, and slopes.

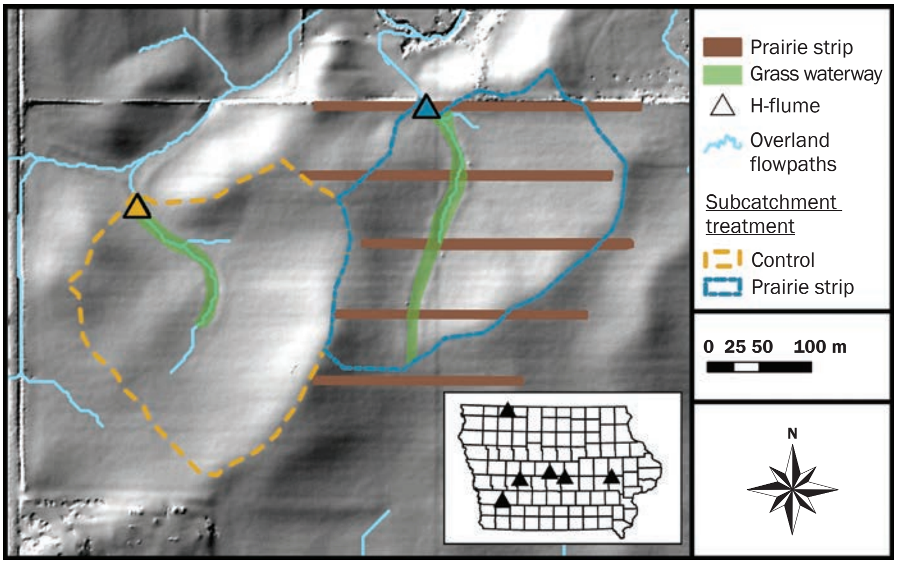


Table 2

Information on prairie strip planting date, number of species seeded, the proportion of prairie grass seed to prairie forb seed, where the seed was purchased, and how much of the strip had prairie vegetation established based on a vegetative survey conducted in 2018 and 2019 by English et al. (2020a).

Site	Year planted	Species seeded	Prairie seed grass:forb	Seed mix source	Area of strip established prairie (%)
ARM	2014	40	0.37	Allendan	77.6
EIA*	2015	—	—	—	76.0†
HOE	2016	28	0.72	The Prairie Flower	73.8
RHO*	2015	40	0.37	Allendan	30.0
WHI	2015	54	0.35	Jon Judson	41.0
WOR*	2015	40	0.37	Allendan	84.6

*Denotes paired subcatchments where the location of the treatment was randomly assigned.

†Vegetative survey of strip to determine area established in prairie vegetation in 2017.

— Data missing on original seed mix.

to obtain the total flow volume for each sampling event.

A water sampling event was initiated when runoff occurred, and samples were collected at 5-minute intervals until there was no more runoff detected. Sediment was cleared from flumes after a sampling event, as needed. The initiation of a sampling event was dependent on flow discharge measured at a flume that was directly connected with a rain event. Runoff due to snowmelt was disregarded. For the purposes of this paper only the TSS loads and rainfall will be reported. Sediment transport was measured as TSS concentrations in milligrams per liter per sampling event and converted to a load weighted by contributing area (ha) and converted to a mass (kg). The mass of TSS was then adjusted for the subcatchment size divided by the area (ha) contributing to the H-flume to get a load value in kilograms per hectare. In cases where runoff was measured at a flume for only one subcatchment within a research site pairing, the paired subcatchment without runoff had a TSS load of zero recorded. Measurements were summed to compare TSS loads annually, during a sampling event, and seasonally.

Rainfall and Seasonal Sediment Transport Patterns. Rainfall was measured using rain gauge installations co-located with an H-flume per site. Rain gauges were calibrated to collect every 5 minutes (ISCO 674, Teledyne ISCO, Inc., Nebraska), which allowed us to measure rainfall accumulation during the sampling season and for each rain event (table 3). When rain gauge equipment malfunctioned, hourly rain data collected from the nearest Iowa Mesonet (https://mesonet.agron.iastate.edu/) rain gauge station were used as a substitute. Rainfall accumulation and intensity was determined for each sampling event. Rain events were defined as precipitation ≥6.35 mm (Osterholz et al. 2021) separated by at least 12 hours with no precipitation (Dunkerley et al. 2008; Hernandez et al. 2016).

To further explore treatment effects and make seasonal comparisons in sediment transport, the surface runoff data were divided into two subsets and analyzed separately. These two subsets represented two periods of measurement for the full data set and randomized location subset: TSS load measurements taken during the primary growing season (PGS) (May to August) and TSS loads taken outside of the primary growing season (OPGS) (March to April and September to November), when crops are not planted, just planted, or are dormant. The TSS loads were summed per sampling event within each period, and these two data sets were analyzed across years between paired treatments to investigate the effect of prairie strips on seasonal sediment transport patterns (table 4). In addition, the rainfall rate was classified into four different intensity classes, including light (≤2.5 mm h^{-1}), medium (2.6 to 7.5 mm h^{-1}), heavy (7.6 to 50 mm h^{-1}), and violent (≥50 mm h^{-1}) (Environment Canada 2013) (figure 2).

Subcatchment Characterization. Surface flow patterns, terrain attributes, and subcatchments were modeled using Agricultural Conservation Planning Framework (ACPF) Version 3 (https://acpf4watersheds.org/) (Porter et al. 2018) in ArcMap 10.8.2 using a 1 m digital elevation model (DEM) derived from the State of Iowa's LiDAR data set (https://geodata.iowa.gov/dataset/iowa-lidar-project-2007-2010) at each study location. The location of each flume outlet was collected using the GPS represented

Table 3

Total rainfall (mm) at a research site per year during the sampling period. In parentheses is the total annual rainfall (mm) from January through December estimated from the nearest Iowa Mesonet rain gauge to a research site. In addition, the 30-year average (1991 to 2021) rainfall was calculated using the Iowa Mesonet rain gauge network.

	Total rainfall within a year (mm)						30-year average for yearly annual rainfall total (mm)
Site	2016	2017	2018	2019	2020	2021	1991 to 2020
ARM	631 (1,088)	559 (902)	606 (1,115)	653 (1,113)	216 (479)	422 (730)	940
EIA*	724 (1,095)	210 (891)	738 (1,232)	—	—	—	987
HOE	188 (1,016)	226 (937)	413 (1,259)	645 (1,085)	253 (613)	363 (760)	748
RHO*	—	—	735 (1,233)	486 (1,034)	306 (777)	337 (625)	960
WHI	352 (947)	425 (904)	549 (1,209)	554 (1,096)	191 (589)	158 (744)	896
WOR*	532 (955)	345 (755)	359 (1,264)	546 (917)	227 (586)	170 (627)	911

*Denotes paired watersheds where the treatment location was randomly assigned.

Table 4

The total and average total suspended solids (TSS) load measured within a year by treatment within the full data set (F) and randomized location subset (R). The data are summarized for the three different sampling periods: annual sampling period, primary growing season (PGS), and outside of PGS (OPGS).

		Annual sampling season		Primary growing season		Outside of primary growing season	
		TSS load (kg ha^{-1})		TSS load (kg ha^{-1})		TSS load (kg ha^{-1})	
Year		Ctrl	Str	Ctrl	Str	Ctrl	Str
2016	F	103.4	7.9	53.6	1.3	46.0	6.6
	R	29.4	7.6	11.5	1.2	14.1	6.4
2017	F	72.2	0.3	40.3	0.3	32.0	0
	R	—	—	—	—	—	—
2018	F	367.4	240.4	161.0	106.1	206.4	134.3
	R	175.2	154.8	97.5	99.6	77.7	55.2
2019	F	1,169.9	649.9	1,108.8	559.7	61.2	90.2
	R	1,135.7	619.1	1,086.0	559.0	49.6	60.1
2020	F	29.6	4.7	10.7	2.0	18.9	2.7
	R	10.9	4.7	10.7	2.0	0.2	2.7
2021	F	52.5	32.3	—	—	32.3	52.5
	R	52.5	32.3	—	—	52.5	32.3
Average	F	299.2	155.9	274.9	133.9	66.1	47.7
	R	280.7	163.7	301.4	165.5	38.8	31.3

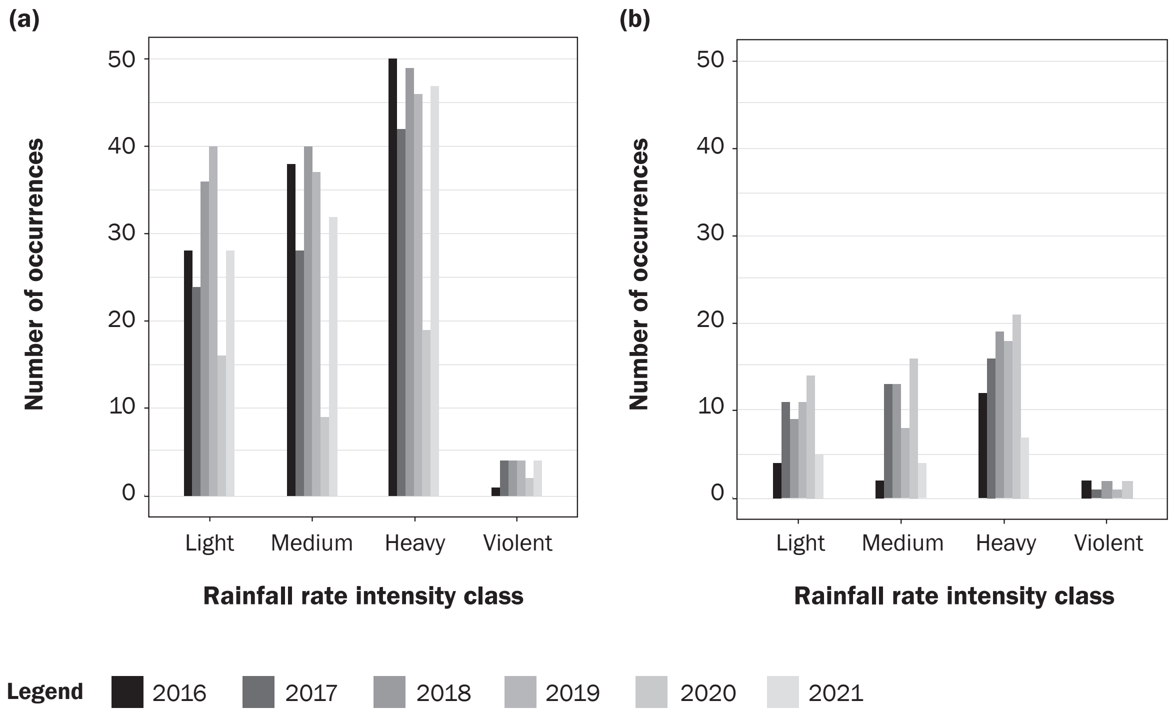
watershed outlet in the surface model so that all upslope contributing areas draining to that point could be delineated to estimate the area-weighted TSS load.

Statistical Analyses. Data management and statistical analyses were performed using RStudio 4.2.0 (R Core Team 2022). A linear mixed effects model was built to estimate the prairie strip effect using *lmer* function in the *lmerTest* package (v3.1-3) (Kuznetsova et al. 2017). The statistical model was created to compare the effect of the two treatments on sediment transport in paired subcatchments, using year, rainfall, and crop planted as fixed effects. Site and its interaction with treatment, year, and sampling event were modeled as random effects to take into consideration the unique characteristics within a paired treatment location. The model was designed to include covariates representing total rainfall per sampling event and the crop planted at the time of measurement to estimate their influence on sediment transport and interaction with the treatments. The total rainfall value was log-transformed using the natural log before being included in the model. The interaction of year and sampling event was modeled as a random effect because each year varied in event frequency and duration. A Type III Sums of Squares analysis of variance (ANOVA) using Satterthwaite's method was conducted in R to compare the estimated influence each fixed effect in the statistical model had on sediment transport using the *anova* function in the *stats* package (v4.2.0) (R Core Team 2022). The *contrast* and *confint* functions (v1.7.5) in the *emmeans* package (Lenth 2022) were used to estimate the multiplicative effect of each fixed effect identified as significant in the Type III ANOVA Table and determine the confidence intervals.

Three of the research sites included a randomized prairie strip location between the two subcatchments (EIA, RHO, and WOR), while the other three sites were not randomized and followed the landowner's farm management and resource concerns (ARM, HOE, and WHI). The "full data set" included all six paired subcatchments sown with prairie seed, while the "randomized location subset" included only the three paired subcatchments that were randomized. Experimental design and statistical best practices require that treatments are randomly assigned, therefore the full data set will be discussed as the observed differences between paired treatments while the randomized location subset can support claims of a causal relationship between treatments and sediment transport. Throughout the results section, both data sets will be reported for predictor variables that are identified as statistically significant drivers of the TSS load response in at least one of the two data sets.

Figure 2

The frequency of a rainfall rate intensity class (a) outside of the primary growing season (OPGS) and (b) the primary growing season (PGS) for each year measurements were taken. There was higher occurrence of light (<2.6 mm h^{-1}), medium (2.6 to 7.6 mm h^{-1}), heavy (7.6 to 50 mm h^{-1}), and violent (>50 mm h^{-1}) intensities OPGS.



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Results and Discussion

The rainfall and TSS load were monitored from thaw in early spring to freeze in late fall and the data were analyzed for three periods to explore seasonal and annual differences in the treatment effect. These periods included the annual sampling, PGS, and OPGS. Examination of the main effects for treatment, year, rainfall, and crop planted followed similar trends in the full data set and randomized location subset, whereas the interaction of predictor variables varied between the three different subsets. Those differences provide insight into better understanding how prairie strips affect seasonal sediment transport patterns. All results for each data subset by period are reported in table 5.

Annual Sampling Period. Analysis of the full data set detected a significant difference between the paired treatments. The subcatchments sown with prairie had a median TSS load 89.5% lower (95% CI, 69.2% to 96.4%, $p < 0.001$) (figure 3) than the control subcatchments, while the randomized location subset found no significant differences between paired treatments ($p = 0.74$) (table 5). There were significant differences in TSS loads across years, regardless of treatment (full data set: $p = 0.02$; randomized location: $p = 0.001$) (table 5). Analysis of the full data set suggests that the interaction of year with treatment significantly influenced the effects on the response variables ($p < 0.001$) (table 5), but there was no significant interaction for the randomized location subset ($p = 0.27$). In the full data set, 2016 and 2017 had significant differences between paired subcatchments in TSS load discharged. There was 94.5% (95% CI, 70.0% to 99.0%, $p = 0.001$) and 100% (95% CI, 99.5% to 100%, $p < 0.001$) less TSS load discharged in the subcatchments treated with prairie strips, respectively (figure 3).

In years when corn was planted, prairie strips subcatchments had significantly lower sediment loads (full data set: $p < 0.001$; randomized location subset: $p = 0.01$) (table 5). In the full data set there was 97.6% (95% CI, 92.1% to 99.3%, $p < 0.001$) (figure 3) less TSS load discharged from subcatchments with strips sown with prairie vegetation compared to control subcatchments. Analysis of the randomized location subset indicated that the prairie strips reduced the sediment load by 81% (95% CI, 31.6% to 94.8%) (figure 3). There were no differences in TSS load discharged between paired treatments when the crop planted was soybean (full data set: 0.34; randomized location subset: $p = 0.06$) (table 5).

There was a strong, positive relationship between rainfall accumulation and TSS loads during a sample event (full data set: $p = 0.003$; randomized location subset: $p = 0.002$) (table 5). There was no significant interaction between treatment and rainfall in the full data set and randomized location subset.

Seasonal Sediment Transport Patterns. The TSS load measurements taken during the PGS indicated that there were no significant differences between paired treatments (full data set: $p = 0.32$; randomized location: $p = 0.87$) (table 5), except in 2017 and when majority of the fields were planted in corn (figure 4). In contrast, TSS loads recorded in the full data set for OPGS period indicated that there was 96.1% (95% CI, 82.5% to 99.1%, $p < 0.001$) (figure 5) less sediment

Table 5

ANOVA table for the paired subcatchment analysis evaluating prairie strips effects on total suspended solids (TSS) load measurements taken between 2016 and 2021. Results from three different sampling periods are represented for both the full data set (F) and randomized location (R) subset and are summarized, including the main effects, covariates, and interaction of main effects. The outputs were derived from a Type III Analysis of Variance Table using the Satterthwaite's method.

			Annual sampling season		Primary growing season		Outside of primary growing season	
Variable		df	*F*-statistic	*p*-value	*F*-statistic	*p*-value	*F*-statistic	*p*-value
Fixed factor								
Treatment	F	1	7.055	0.009*	1.942	0.174	7.007	0.010*
	R		0.049	0.826	0.354	0.560	0.000	0.994
Rainfall	F	1	9.007	0.003*	2.419	0.131	5.365	0.023*
	R		10.44	0.002*	7.251	0.016*	4.764	0.035*
Crop	F	1	1.093	0.298	0.023	0.880	0.739	0.393
	R		0.306	0.582	0.016	0.900	0.866	0.357
Year	F	4	2.897	0.017*	2.216	0.092	1.687	0.147
	R		5.467	0.001*	4.835	0.014*	3.009	0.028*
Interaction								
Treatment: Rainfall	F	1	2.624	0.108	1.186	0.285	2.571	0.113
	R		0.096	0.758	0.326	0.576	0.053	0.819
Treatment: Crop	F	1	9.938	0.002*	1.386	0.249	9.496	0.003*
	R		8.053	0.006*	0.308	0.587	5.935	0.019*
Treatment: Year	F	4	5.225	<0.001*	2.259	0.087	4.705	0.001*
	R		1.336	0.267	0.418	0.743	2.317	0.072

Notes: Values with an asterisk (*) next to them are statistically significant ($p < 0.05$). The degrees of freedom (df) are the number of levels of a fixed factor in the statistical model minus one.

transported from cropland with prairie strips than the control. The randomized location subset did not indicate a difference between the two treatments during this period ($p = 0.41$) (table 5).

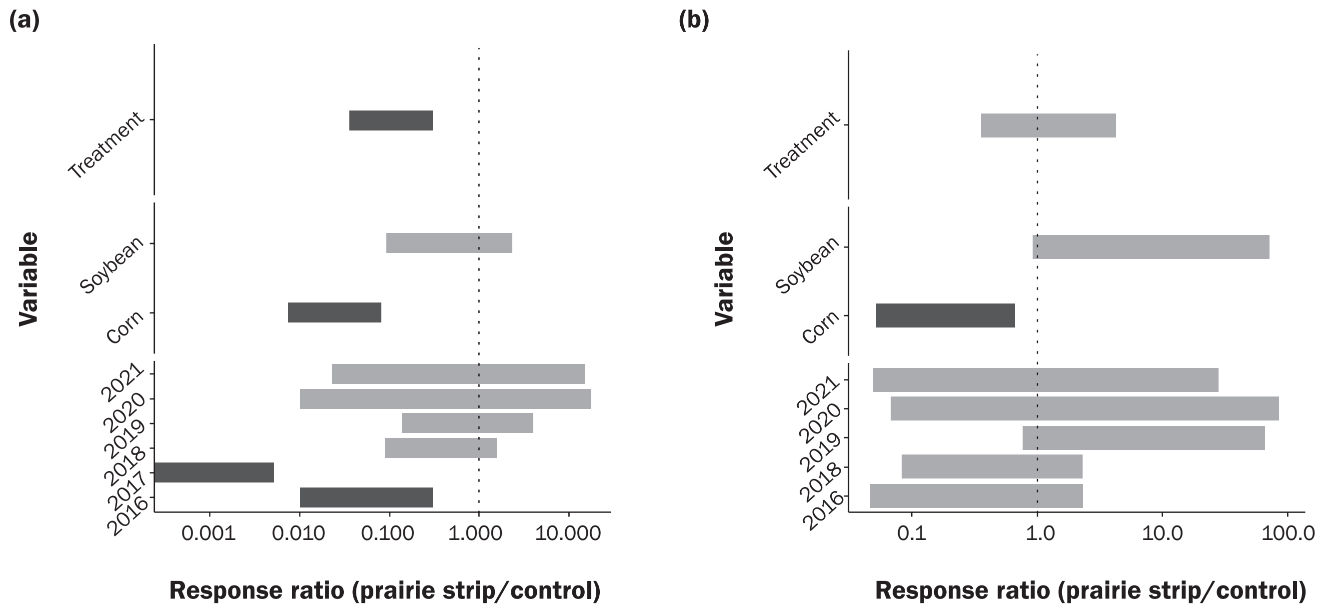
In conditions associated with the OPGS period, analysis of the full data set indicated a significant interaction between treatment and rainfall and roughly half the TSS load measured from subcatchments with prairie strips compared to the control subcatchments ($p = 0.05$) (table 5). Analysis of the randomized location subset did not find a significant interaction between treatment and rainfall ($p = 0.82$) (table 5). The sampling events recorded OPGS period were characterized by more frequent and higher accumulation and intensity rain events than during PGS, and there were over twice as many rain events in all classes compared to the PGS (figure 5). Since rainfall was a significant predictor variable across all data sets, the rainfall frequency and intensity could be contributing to the difference in prairie strip effect between the PGS and OPGS periods.

Discussion. This research sought to expand the inference space for evaluating the use of species-diverse native prairie vegetation as prairie filter strips in agricultural fields and how it influences sediment transport at the outlet of a field. There were several differences in TSS discharge between prairie and control subcatchments; however, not all differences were significant within both data sets. Nonetheless, given the similarity of slope gradients, climatic variables, and crop management between paired subcatchments, comparisons and assertions can be made concerning the influence of prairie vegetation on TSS loads.

We found that TSS loads were determined by an interaction between the crop planted and the presence or absence of prairie strips. The canopy cover and residue amount on the soil surface are integral to reducing erosion and runoff in cropped land (Sturgul et al. 1990; Fernández-Raga et al. 2017), which is of particular concern during the spring and late fall in Iowa. Within the growing season, fields planted in corn have a higher water use efficiency (Kimball et al. 2016) and have some canopy cover to protect the soil from splash erosion compared to when there are either no crops or the crop growing is no longer at evapotranspiration maximum. In our study, the years in which corn was planted, the crop residue in the spring was either soybean, or in the case of the continuous corn site, there was no surface residue due to intensive tillage, therefore there wasn't much residue protecting the soil surface from erosive processes. In these conditions there was 96.8% less sediment discharge measured in subcatchments with prairie, which suggests that fields with low residue cover have more erosion and greater sediment discharge, and that prairie filter strips are an important mode of promoting rainfall infiltration and reducing transport. As reported previously, the main effect of rainfall and interaction between treatment and crop planted were significant predictors for TSS loads for the annual sampling period and this pattern was observed seasonally as well. The location of prairie vegetation was studied at the Neal Smith Wildlife Refuge Farm and they found that prairie strip placement at the footslope position, in particular, is effective at preventing sediment discharge to other fields and waterways (Helmers et al. 2012; Hernandez-Santana et al. 2013).

Without sufficient groundcover protecting the earth's surface, soils are more susceptible to detachment due to splash erosion (Uri 2021). Since rainfall amount was a significant factor affecting sediment discharge, practices reducing splash erosion help to reduce the amount of sediment transported; in cases where no erosion control measures are being taken within the cropped fields, prairie strips

Figure 3
For sampling events across all years, the ratio of total suspended solids (TSS) load measured for the prairie strip subcatchment to the control was calculated and reported as the response ratio by interaction variable (year and crop planted) and the main effect of treatment. The prairie strip subcatchments had significantly lower TSS loads compared to the control, especially when the crop was planted in corn. However, the interaction between year and treatment indicates there were no measured differences between paired treatments from 2018 to 2021 and when the crop was planted in soybeans. Note: Gray bars represent the 95% confidence interval (CI) for contrasts of the response ratios. The dashed vertical line is x = 1. When the 95% CI doesn't intersect the vertical line (dark grey bars), then the effect of the variable is considered significant ($p < 0.05$). (a) Full data set (n = 6) and (b) randomized location subset (n = 3) are depicted. There are no randomized paired treatments analyzed in 2017.



could significantly reduce sediment being transported. In this study, both the full data set and randomized location subset had comparable magnitude in differences between the prairie strip and control subcatchment TSS load discharged. The filter strips not only changed the flow patterns and shortened flow lengths within a subcatchment (Renard 1997; Schmitt et al. 1999; Muñoz-Carpena and Parsons 2004; Gathagu et al. 2018), but also facilitated water infiltration and sediment deposition upslope of the filter strip during varying degrees of rainfall accumulation and intensities. Thoughtful placement of prairie strips along the contour of fields with slopes greater than 3% and along edges of cropped fields to intercept water runoff carrying high sediment loads could help improve the filtering effectiveness of prairie vegetation.

Researchers have modeled and collected empirical data that support long-held climate change predictions that precipitation patterns in humid areas, like Iowa and other parts of the Corn Belt, would have increased frequency of high intensity rain events (Nearing et al. 2004; Feng et al. 2016; O'Neal et al. 2005; IPCC 2022), and we are seeing that these changes are negatively affecting crop performance and downstream water quality (Zurek et al. 2022; Malhi et al. 2021; FAO 2015; Foley et al. 2011). Rainfall and sediment transport were strongly, positively correlated in this study, raising concern about soil resiliency and quality that are essential for supporting productive landscapes in rain-fed systems. There were more than twice the high-intensity rain events (figure 5) that occurred during the OPGS period compared to during the PGS. The TSS loads discharged from fields in the full data set OPGS indicated that there was 92.9% less sediment transported from areas with prairie compared to the control. The results suggest that prairie strips were effective during times of year when erosion control and trapping field sediments are the most crucial, whereas in other parts of the year prairie strips may not have a strong effect because of limited soil detachment and transport occurring. Hernandez-Santana et al. (2013) also observed that when the crops were absent there was less runoff from cropped areas with prairie planted. Cover crops and high residue management would provide benefits to address splash erosion (Fernández-Raga et al. 2017; Kavian et al. 2020; Seitz et al. 2020), while using prairie vegetation in a filter strip would be effective at filtering sediment loads and mitigating sediment transport in surface runoff.

In the present study, the effect of higher rainfall amount on TSS discharge in both treatments resulted in more sediment discharged from a field. Prairie vegetation did have a measurable effect on TSS load compared to subcatchments without prairie under certain conditions, and other studies have demonstrated that prairie strips help stabilize and reduce sediment transported from a field more generally (Helmers et al. 2012). Depending on the slope of a field and priorities of the landowner, prairie strips distributed throughout the field in addition to the field edge could be advantageous to filter out sediment moving along the hillslope and trapping it higher in the drainage area. Additional research needs to be pursued to explore the relationship between rainfall intensity, frequency, and antecedent soil conditions in order to fully capture the soil and water dynamics within these cropped fields to help with future design and placement of prairie strips.

Figure 4
During the primary growing season (PGS) the ratio of total suspended solids (TSS) load measured for the prairie strip subcatchment to the control was calculated per sampling event and reported as the response ratio by interaction variable (year and crop planted) and the main effect of treatment. The prairie strips did not significantly vary from TSS loads measured in the control, except there was significantly lower TSS loads measured from prairie strip subcatchments when the crop was planted in corn and in 2017. Gray bars represent the 95% confidence interval (CI) for contrasts of the response ratios. The dashed vertical line is $x = 1$. When the 95% CI doesn't intersect the vertical line (dark grey bars), then the effect of the variable is considered significant ($p < 0.05$). (a) Full data set ($n = 6$) and (b) randomized location subset ($n = 3$) are depicted. There were no observations recorded in the randomized location subset in 2017 and 2021.

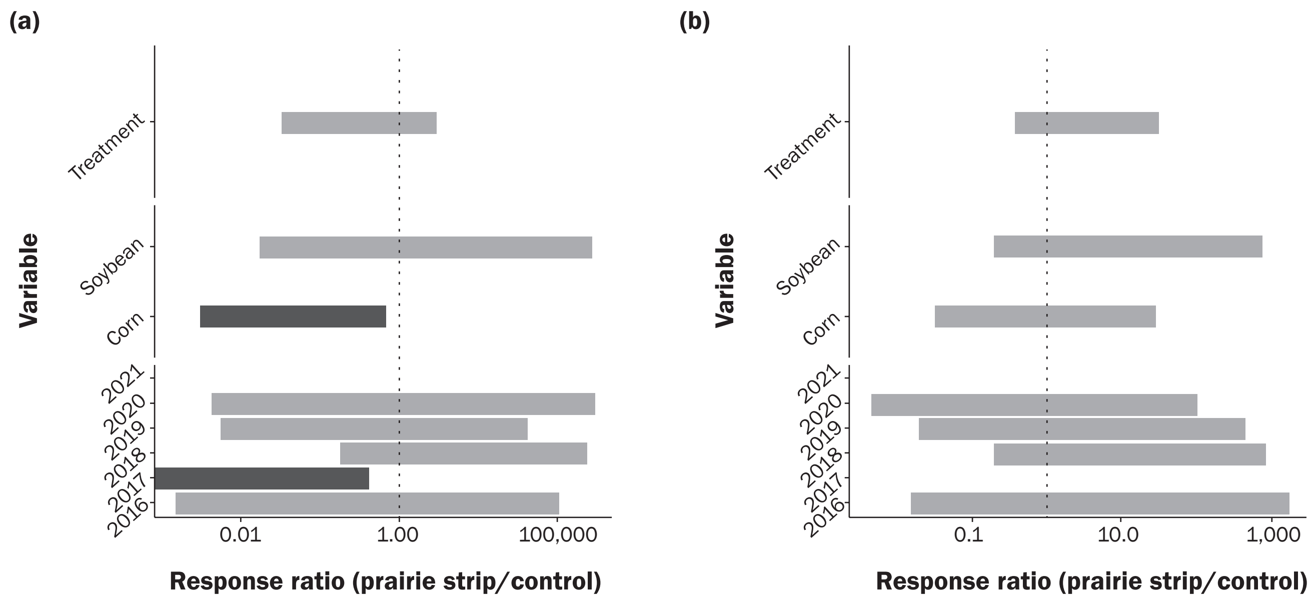
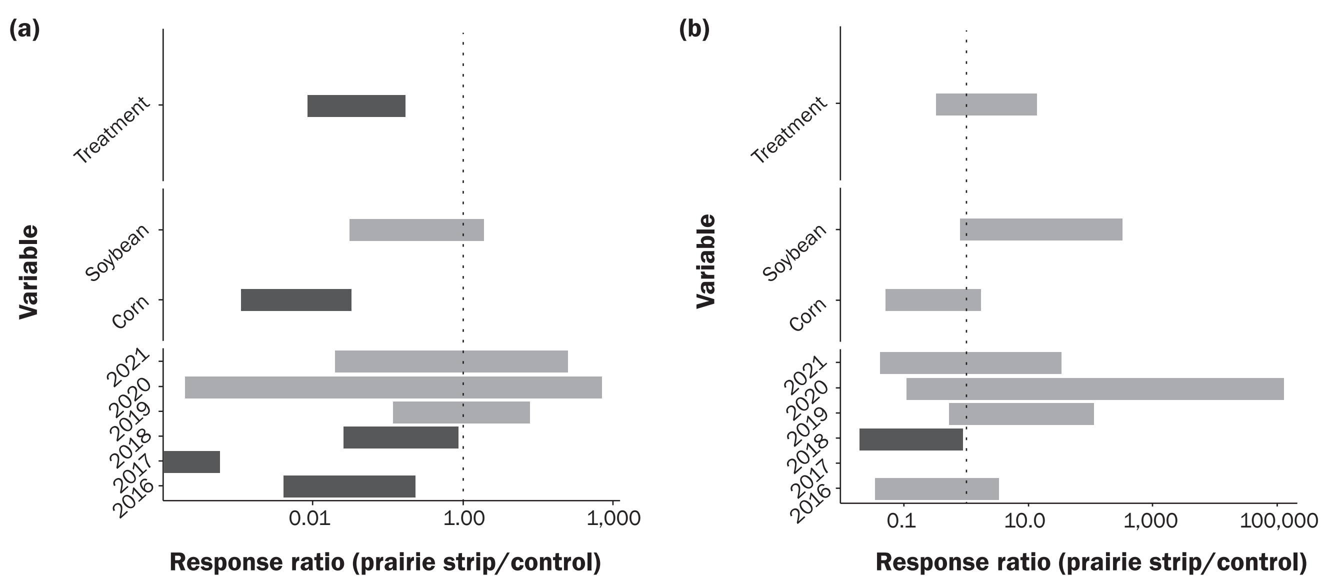


Figure 5
Outside of the primary growing season (OPGS) the ratio of total suspended solids (TSS) load measured for the prairie strip subcatchment to the control was calculated per sampling event and reported as the response ratio by interaction variable (year and crop planted) and the main effect of treatment. The prairie strip subcatchments had significantly lower TSS loads compared to the control; however, 2019 to 2021 there were no measured differences between paired treatments and when the crop was planted in soybeans. Gray bars represent the 95% confidence interval (CI) for contrasts of the response ratios. The dashed vertical line is $x = 1$. When the 95% CI doesn't intersect the vertical line (dark grey bars), then the effect of the variable is considered significant ($p < 0.05$). (a) Full data set ($n = 6$) and (b) randomized location subset ($n = 3$) are depicted. There were no observations recorded in the randomized location subset in 2017.



Prairie filter strips were incorporated in the 2018 Farm Bill as conservation practice (CP) 43 and funding was made available in 2020 so that landowners can take advantage of financial and technical assistance to implement this practice on their farms. Landowners, farmers, conservation professionals, planners, and policymakers have an opportunity to address a major challenge of the twenty-first century by putting an emphasis on modifying conventional practices, such as grassed filter strips and contour buffer strips, to address major resource concerns and support a biodiverse agroecosystem. At regional scales, the costs to implement some common conservation practices do not outweigh the estimated negative economic impacts to cultivated land due to soil degradation (Basche et al. 2020). However, at field or farm-scale the cost of conservation remains a significant barrier (Ranjan et al. 2019). Because of this situation, cost-share through the US federal government along with technical assistance make these practices more accessible.

The average erosion rates in the United States have declined from 10.8 Mg ha^{-1} y^{-1} in 1982 to 7.4 Mg ha^{-1} y^{-1} in 2007 (FAO 2015), but we are still degrading more soil than what is being regenerated (Montgomery 2007; Thaler et al. 2021). The reduction between 1982 and 2007 was largely due to an investment in experimentation, targeted resource planning for croplands, and documentation and standardization of BMPs. Historically, structural BMPs installed to reduce runoff and filter sediment have been designed with only one goal in mind—reducing in-field erosion to increase productivity (Farooq and Siddique 2015; Uri 2021); with prairie strips, other conservation concerns, such as wildlife habitat, can be prioritized.

Practices that provide multiple benefits are desirable to achieve conservation and agronomic goals. Two of the prairie subcatchments in our study had greater than 10% of the drainage area converted to prairie (12.0% and 29.5%), whereas the other four subcatchments ranged from 5.4% to 9.5% prairie coverage. Despite the majority of the subcatchments being planted in less than 10% prairie, there was an effect of treatment in several years, especially in corn fields. Determining the influence of percentage prairie coverage within a prairie strip and a subcatchment was not a primary research objective of this study, so further research and consideration of this type of design specification is worth exploring to help target locations in the field and design future CP43 installations.

Looking forward, researchers have outlined several ways to address challenges of global food, fiber, and fuel production at various scales including being more strategic with existing cropland and technology to maximize production on the most productive land (Lipper et al. 2014; Campbell et al. 2017; Porter et al. 2019; Gerten et al. 2020). The competing interests between cropland expansion and land dedicated to conservation practices have been debated for over a century in the United States. The collective results from other research studying prairie strips extends the idea of intensification to conservation practices to create a complementary strategy that dovetails environmental priorities with agronomic goals. Past research has demonstrated that filter strips using prairie seed mixes provide benefits for stabilizing hillslopes and infiltrating surface runoff, as well as increasing biodiversity on farms, including insects, pollinators, and birds; reductions in surface runoff; and higher retention of sediment and nutrients in the field (Helmers et al. 2012; Hernandez-Santana et al. 2013; Hirsh et al. 2013; Cox et al. 2014; Perez-Suarez et al. 2014; Zhou et al. 2014; Schulte et al. 2016; Kordbacheh et al. 2020). Greater adoption of prairie strips could be an important means to achieve conservation goals in the US Corn Belt.

Summary and Conclusions

Our results indicate that small amounts of prairie strips installed in corn–soybean systems can be used to effectively reduce sediment loss from row cropped fields. The crop planted, rainfall, and year-to-year variations in growing conditions and farm management influenced the significance of the prairie strip treatment effect on soil loss. The differences in sediment discharge between paired treatments were greater in the spring and fall (OPGS), which can be attributed to crops either absent in the field or there was limited living ground cover. Consequently, subcatchments with prairie filter strips provided significant benefits at filtering sediment before surface water runoff left a field. Year-to-year variations influenced the effect of prairie strip treatments. There is ongoing research to understand what causes these annual and seasonal variations in sediment transport, nutrient and P loading, water runoff, and soil moisture conditions. These long-term data sets will provide insight into how prairie strip establishment will function over time.

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