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Pyric-herbivory and Hydrological Responses in Tallgrass Prairie☆

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ABSTRACT

Pyric-herbivory is the spatial and temporal interaction of fire and grazing on area resources that results in site selection by animals on recently burned areas. Pyric-herbivory promotes heterogeneity by increasing bare ground on some patches and litter and aboveground biomass on other patches. The influences of this heterogeneity on hydrological properties and sediment transport are not well documented. We monitored the pattern of cattle occupancy on annually burned and patch burned pastures under moderate stocking rates of steers in the Tallgrass Prairie Preserve and quantified surface runoff and sediment transport for simulated rainfall of 10-year return storm intensity applied to different phases of the fire-grazing interaction in 2011 and 2012. Results showed that patch burn altered grazing distribution with cattle spending 70% of their time within the most recently burned areas. Our rainfall simulation results showed the high-intensity grazing following a spring fire did not have a prolonged, ecologically meaningful detrimental impact on hydrological properties of the burned patch in comparison with annually burned grazing pasture. Instead, the increased spatial and temporal heterogeneity of hydraulic properties could potentially enhance resource conservation through runoff and runon interactions within the patch-burned pasture. Further study focusing on quantifying pyric-herbivory effects on runoff and sediment transport at watershed scale will provide needed insights for managing tallgrass prairie for improving ecosystem services.

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Introduction

In tallgrass prairie ecosystems, grazing and fire are interactive disturbances that play a primary role in shaping rangeland communities. This interaction, called *pyric-herbivory*, occurs with varied frequency and intensity across multiple spatial scales and defines prairie structure and function, which regulates prairie ecosystem services (Fuhlendorf et al., 2012). Improved understanding of the underlying mechanisms of pyric-herbivory has assisted development of a new rangeland management scheme commonly called *patch burning* or *patch burn grazing* (Fuhlendorf and Engle, 2004). Under patch burn management, pastures are delineated into patches, which are then burned on a rotation across years. Grazers are drawn to and then spend the majority of their time within recently burned patches. For a pasture on a 3-year fire return interval, a patch may experience an increased grazing pressure by up to threefold within the same year of being burned but will have 2 subsequent years of minimal grazing pressure when cattle are attracted to other more recently burned patches. This variable site selection has been shown to result in increases of aboveground biomass accumulation as time since fire increases (Fuhlendorf and Engle, 2004).

Recent studies have investigated topics ranging from the effect of patch burning on biological responses, such as vegetative structure and composition, to changes in bird, mammal, and insect species diversity and richness, to more abiotic responses such as soil nitrogen and shifts in soil temperatures (Coppedge and Shaw, 1998; Fuhlendorf and Engle, 2004; Anderson et al., 2006; Coppedge et al., 2008; Limb et al., 2009; Fuhlendorf et al., 2010). However, there are very few studies that have considered the potential effects of burning and focal herbivory on hydrological functions in tallgrass prairies (Fuhlendorf et al., 2010).

Focal grazing can influence aboveground biomass accumulation and soil disturbance. Increased grazing pressure for recently burned grasslands decreases cover, which will lead to an increase of raindrop impact and soil detachment (Kinnell, 2005). In addition, extensive trampling from increased cattle occupancy exacerbates the break-up of aggregates (Warren et al., 1986). The excessive loss of cover and an increase in soil surface disturbance as a collective effect of fire and intense grazing were documented to accelerate runoff and sediment transport in sand sagebrush mixed prairie in northwestern Oklahoma (Vermeire et al., 2005) and semidesert grassland in Arizona (O'Dea and Guertin, 2003; Field

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et al., 2011). All of these factors, along with increased soil bulk density from trampling, have the potential to decrease the soil's hydraulic conductivity and increase sediment transport into aquatic systems (Wilcox et al., 1990; Hester et al., 1997; Kato et al., 2009; Casali et al., 2010; Gonzalez-Pelayo et al., 2010).

Tallgrass prairies in the Flint Hills and Osage Hills regions within the southern Great Plains comprise highly productive rangeland and can have adequate residue biomass to support annual burning under average precipitation amounts and appropriate grazing management. The convention in these regions is to burn the entire pasture in spring to uniformly increase palatable forage for cattle (Fuhlendorf and Engle, 2001). This contrasts the historic, more stochastic fire return frequency and interactive grazing that occurred in this region (Fuhlendorf et al., 2009). Burning portions of a landscape to create a patchlike disturbance pattern on both spatial and temporal levels has demonstrated an increase of landscape heterogeneity and biodiversity while simultaneously maintaining cattle production (Fuhlendorf and Engle, 2004). However, the added disturbance of immediate high-intensity grazing following a spring fire has the potential to substantially decrease infiltration capacity, resulting in increased runoff and sediment transport compared with rates observed under fire or grazing disturbance alone, especially under extreme precipitation events.

Burning on rotation leads to changes in both the spatial and temporal dynamics of vegetative cover and grazing intensity, ultimately leading to changes in hydrological properties and function such as saturated hydraulic conductivity, which describes the amount of water that will infiltrate the soil under saturated conditions. A burned grassland will experience increases in bare soil and decreases in litter and vegetative cover the first 10 months after fire (Hart and Frasier, 2003; Fuhlendorf and Engle, 2004) and usually takes about 3 years to reach prefire levels depending on rangeland types and vegetation cover (Fuhlendorf et al., 2006; Spasojevic et al., 2010). Under heavy grazing intensity, vegetative cover in tallgrass prairies has been noted to recover in 6 to12 months once grazing is removed; bulk density has been observed to decrease within 1 year of rest after heavy trampling (Townsend and Fuhlendorf, 2010). Using burned patches to encourage focal cattle grazing behavior is considerably different from intensive rotational grazing management where grazing intensity is focused for a few months followed by several months of rest. Burning patches on rotation involves uniformly stocking the area every year and rotating the burn location to encourage the movement of focal grazing from one area to the next. It has not been adequately documented how vegetation, ground cover, and saturated hydraulic conductivity in tallgrass prairie will be affected by the spatial and temporal dynamics associated with pyric-herbivory.

The overall objective of our study was to understand how rangeland management, specifically the use of fire paired with grazing, alters hydrologic functions within native tallgrass prairie. The specific objectives were to contrast the spatial and temporal variability of surface runoff, saturated hydraulic conductivity, and sediment yield under uniform grazing pressure from an annual burn and focal, rotating grazing pressure from an annually rotating patch burn. Vegetative cover, biomass, and litter cover were measured on the plots at each sampling period to assist in interpretation of observed differences in hydrological responses.

Methods

Study Site

Our study site was within the Nature Conservancy's Tallgrass Prairie Preserve (36°50′46′N, 96°25′22′W), located in the southern edge of the Flint Hills region of the Great Plains in Osage County, Oklahoma, United States (Fig. 1). The bedrock is composed of shale, sandstone, and limestone (Web Soil Survey, 2011). The landscape is rolling hills with a high percentage of rock in the uplands. As a result, this land has never been cultivated and is one of the largest remnants of the historic tallgrass prairie ecosystem. The mean annual precipitation from 1999 to 2013 was 953 mm with typically 64% occurring from April through September on the basis of data from the Foraker station, Oklahoma Mesonet (Mesonet, 2014). Vegetation is dominated by C_4 native grasses such as big bluestem (*Andropogon gerardii* Vitman), indian grass [*Sorghastrum nutans* (L.) Nash], switchgrass [*Panicum virgatum* (L)], and little bluestem [*Schizachyrium scoparium* (Michx.) Nash].

Two large adjacent pastures were selected (see Fig. 1). The pasture to the north (604.5 ha in size) was burned annually in the spring, and the pasture to the south (534.7 ha) was part of a patch burn grazing experiment started in 2006 (Fuhlendorf et al., 2009). The annual burn pasture represented the conventional grazing management approach in the Osage Hills region, which was to burn pastures every year in the spring (Fuhlendorf et al., 2009). The whole annual burn pasture was viewed as a single treatment. The pasture directly south had one third of the pasture burned every year so that, in a 3-year span, the whole pasture experienced fire at some point. This created patches within the field that were at different stages of recovery from fire disturbance and were variable in the distribution of grazing disturbance (see Fig. 1). Each third was considered a separate treatment so that results could be analyzed in relation to time since fire. There were no fences present within the southern pasture, but the burn patches were consistent from year to year. For both the annual burn pasture and patch burn pasture, burning occurred in April and cattle were allowed to graze from after the burn to September. Cattle were stocked at the rate of one steer per two hectares within both pastures.

Experimental Design

To meet our overall objective of evaluating the interactions of burning regimen, grazing pressure, and hydrological function, we chose to use a rainfall simulator to deliver consistent known amounts of rainfall to small plots within our treatment patches. For the annual burn pasture, three temporary plots were selected for each simulated rainfall run. For the patch burn pasture, three plots were selected within each of the three patch burn patches for a total of nine plots for each simulated rainfall run. For both pastures, temporary rainfall simulation plot locations were randomly selected from within areas that had similar slope (3–8%), soil type (sandy loam), and percent rock (3–5%) in order to isolate the hydrological response from fire and grazing disturbance. All plots were within a Lucien–Coyle soil complex (Web Soil Survey, 2011), the major soil type of the Tallgrass Prairie Preserve.

For the initial rainfall simulation in October 2011, simulation plots measured 2 × 2 meters and were constructed by carefully inserting metal borders 5–10 cm into the soil. Borders tapered to a flume at the downslope side of the plot for water collection, and the edges were sealed with wax. In order to increase replicates, the 2 × 2 plots were divided lengthwise, creating temporary plots measuring 2 meters in length × 1 meter in width for the runs in 2012. Each half mirrored the other in spatial variation.

Rainfall Simulation

A rainfall simulator based on the design by Miller (1987) was used to control the amount, rate, and duration of rainfall, so hydrological responses to a large storm event could be quantitatively assessed (Humphry et al., 2002). One TeeJet nozzle, with a maximum flow rate of 210 $mL \cdot s^{-1}$ was located in the center of the simulator 305 cm above the soil surface. Rainfall intensity was controlled using a solenoid and an electrical box that controlled water flow. The rainfall intensity was calibrated using an array of small cups distributed around the entire plot at the beginning of the simulation, which also helped check the spatial variation of our simulated rainfall. Three rain gauges were placed within the plot during the simulation to provide the true rainfall used in the result. Wind effect was minimized by surrounding the rainfall simulator with tarps staked down to the ground. Because grasslands are known to be resilient and the greater danger of erosion occurs under high-intensity rainstorms (Elliott and Vose, 2005), we selected

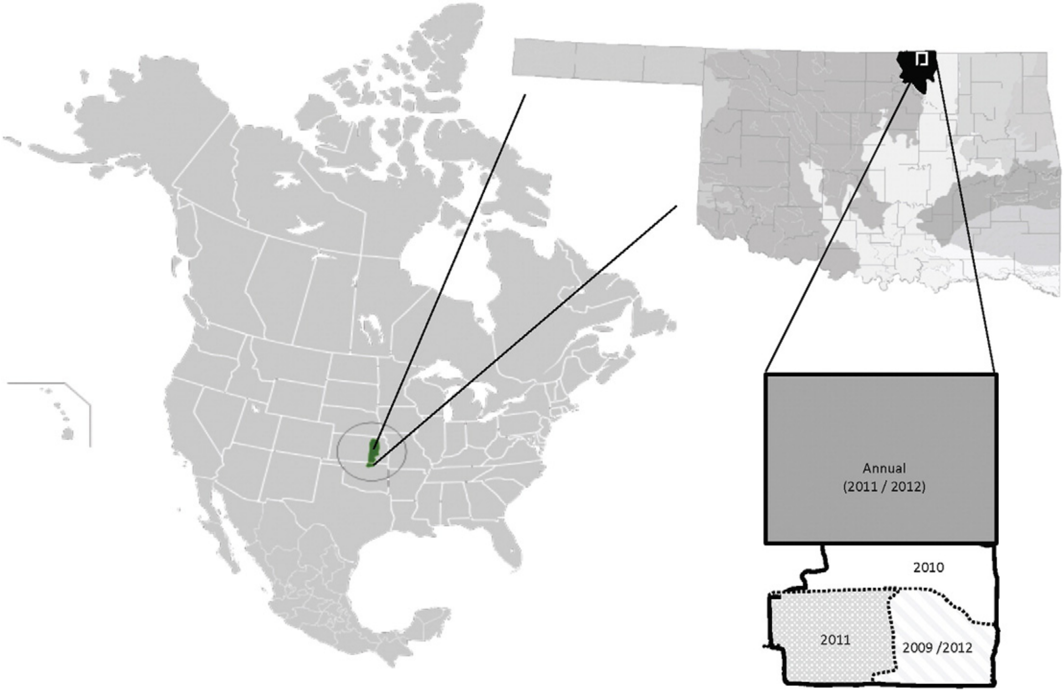

Figure 1. Flint Hills Tallgrass Prairie Ecoregion in the United States. Study sites were located at the Tallgrass Prairie Preserve in Osage County, Oklahoma. Study sites consisted of one annually burned pasture (annual burn pasture) and one pasture that was burned patch by patch on a 3-year rotation (patch burn pasture). The dotted line illustrated the boundary of three patches in the patch burn pasture. The year denotes the year burn occurred for individual patch.

a 1-hour 10-year return storm intensity of 68 mm · h^{-1} (Hershfield, 1961; Tortorelli et al., 1999).

For each plot, simulated rainfall runs were conducted for 30 minutes at the nominal intensity of 68 mm · h^{-1} and under antecedent soil moisture conditions. Runs were conducted in October 2011, at the end of the grazing season under dry soil moisture conditions, in April 2012 two weeks after burning under saturated soil moisture conditions and in October 2012 under low soil water content conditions. In October 2012, a second run of 30 minutes was conducted 2 hours after the initial run on the same plots. This wet run provided saturated hydraulic conductivity for comparison across seasons. The two October dry runs provided information on unsaturated hydraulic conductivity at antecedent soil moisture and served to saturate the surface soil profile for the second run in 2012.

Prescribed burns were conducted in spring. Thus, on the annual burn (AB) pasture, we collected data from rainfall simulations conducted

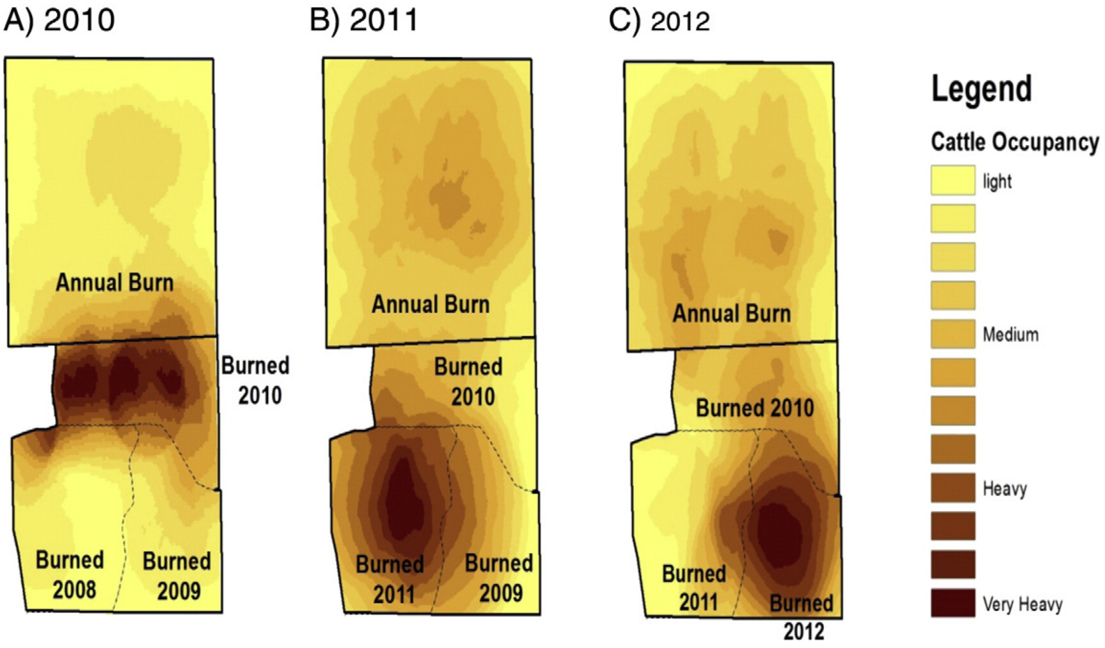

Figure 2. Cattle occupancy within annual burn pasture and individual patches within patch burn pasture for 2010 (**A**), 2011 (**B**), and 2012 (**C**). The patch burn pasture had no fencing between patches and cattle were free to move between patches. Lighter colors represent overall little cattle occupancy while dark colors represent overall intense cattle occupancy throughout the grazing season from April to October for that year.

within the first month after fire in April (AB-0) and 6 months after fire in October (AB-6). For the patch burn pasture (PB), our runs were conducted on patches burned in different years, allowing us to collect hydrological responses over time since fire (in months): PB-0, PB-6, PB-12, PB-18, PB-24, and PB-30.

Runoff Characteristics and Sediment Transport Using Rainfall Simulations

Runoff water leaving the plots was collected during set timespans at set intervals to provide samples throughout the rain event. These samples were used for calculating runoff amounts and rates and for measuring suspended solids leaving the plots. The total volume of water that flowed off of the plot during the 30-minute simulation was converted to total runoff depth in mm by dividing volume by plot area. Saturated hydraulic conductivity was calculated by subtracting the last 2-minute flow rate of the 30-minute simulation from the rainfall application rate. Sediment yield was quantified as the total suspended solids (TSSs) per hectare transported downslope by surface runoff during 30 minutes of simulated rainfall at nominal 68 $\mathrm{mm \cdot hr^{-1}}$ storm intensity.

Soil and Vegetation Metrics

Soil water content within the top 12 cm was measured at three locations in each plot using a portable TDR (Hydrosense, Campbell Scientific Inc., Logan, Utah, USA) before and after each rainfall simulation. Before each rainfall simulation, percent rock, bare ground, litter, plant basal area, and total vegetative cover were estimated within each plot using modified Daubenmire cover classes (Daubenmire, 1959). Vegetative cover was further separated into either grass cover or forb cover to capture the general vegetative community. Biomass was estimated by clipping all aboveground vegetation and raking up all down litter in an area of 0.25 m^2 within the plot after rainfall simulations. Vegetation samples were then dried at 65°C and weighed for biomass calculations.

Grazing Distribution

At the individual pasture scale, the primary difference between an annual burn approach and a patch burn approach is found in the spatial variability of grazing distribution and the temporal evolution of such spatial variability associated with individual patches. To record grazing occupancy throughout the grazing season, we fitted one steer in the annual burn pasture and one steer in the patch burn pasture with a global positioning system collar (GPS3300, Lotek Wireless Inc., Newmarket, Canada) that recorded the animal's location every 10 minutes from April to September in 2010, 2011, and 2012. Collars were retrieved in September of each year when cattle were removed from the pastures. The use of only one steer fitted with a GPS collar has been used successfully to identify the trend of a whole herd due to herd mentality found in domestic cattle (Allred et al., 2011).

Data Analysis and Statistics

Cattle occupancy maps were created in ArcGIS 10.0 using point density analysis of all the GPS points recorded within each treatment during each year of the study. Cattle occupancy per treatment area was calculated using the equation $\mathrm{E_t = r_t/p}$ where r_t = total number of data points within the treatment (t) and p = total number of data points within the pasture unit. The cattle occupancy number, as a percentage of time spent within each treatment, was converted into an index of 0-100 for use in analysis of variance as an independent variable. We used this index as a surrogate visualizing cattle treading, dung deposit, and grazing influences at a landscape scale.

All statistic analyses were conducted using Proc Mixed model in SAS (SAS 9.2, SAS Institute Inc., Cary, NC, USA). Differences between means of total runoff depth and sediment yield by time since fire for the same pasture type were tested using LSMEAN with Duncan's Multiple Range Test as a post-hoc test. Difference between total runoff depth and sediment yield between treatments at the same time since fire was analyzed using Student's *t* test. Exponential regression model fitting was completed using the statistical software SigmaPlot 11 (Systat software Inc, San Jose, CA, USA).

Results

Grazer Behavior in Annual Burn and Patch Burn Pastures

The pattern of cattle occupancy differed between the annual burn and the patch burn pastures (Fig. 2). Grazing in the annual burn pasture was more uniform across the entire pasture. In contrast, cattle spent on average 70% of their time in the most recently burned patch within the patch burn pasture (Table 1). During years of below-average precipitation (2011 and 2012), cattle moved more frequently out of the burned patch to utilize other patches compared with the year of average precipitation (2010) (see Fig. 2).

Surface Runoff and Sediment Transport under a Simulated Rainfall Event

Total runoff depth and associated sediment transport generated from a simulated 30-minute rainfall event decreased exponentially as the time since fire increased (Fig. 3). Total runoff depth was highest after fire and was significantly different between the annual burn pasture (AB-0) and patch burn pasture (PB-0) ($P = 0.05$) (Table 2). Six months after fire, runoff depth in the annual burn pasture (AB-6) decreased ($P < 0.001$) from 19.7 to 5.1 mm whereas within the recently burned patch (PB-6), runoff depth remained relatively high at 16.7 mm. Eighteen months after fire (PB-18), the runoff depth was 5.5 mm, similar to the amount from the annual burn site at 6 months after fire (AB-6). At the 30th month (PB-30), just before the patch was going to be burned again, the runoff depth was on average 0.03 mm, almost

Table 1

Ecological variables sampled in 2011 and 2012. Percent ground cover was estimated with a Daubenmeire rank class system. Forbs and graminoids are percent of vegetative cover. Cattle occupancy was calculated from number of data points in each patch divided by the total number of data points collected from one cow from April to September. Values are means ± standard error ($n = 3$ for October 2011 and $n = 6$ for April and October 2012). Means noted with different letters are significantly different based on Duncan's Multiple Range Test ($P < 0.1$).

		Biomass ($\mathrm{g \cdot m^{-2}}$)	Bare ground (%)	Plant basal (%)	Forb (%)	Graminoid (%)	Cattle occupancy (% time)
Oct. 2011	AB-6	75 ± 8 b	45 ± 7 a	–	11 ± 3 d	86 ± 10 a	100
	PB-6	93 ± 11 b	23 ± 7 b	–	23 ± 6 c	38 ± 0 b	66.4
	PB-18	346 ± 20 a	0 ± 0 d	–	38 ± 0 b	78 ± 6 a	8.7
	PB-30	127 ± 21 b	1 ± 1 c	–	53 ± 13 a	34 ± 14 b	25.1
April 2012	AB-0	38 ± 9 b	48 ± 3 a	27 ± 4 c	38 ± 0 a	63 ± 0 b	–
	PB-0	17 ± 5 b	29 ± 3 b	31 ± 2 c	13 ± 2 b	85 ± 0 a	–
	PB-12	38 ± 3 b	28 ± 4 b	45 ± 4 b	37.5 ± 0 a	58 ± 4 b	–
	PB-24	127 ± 21 a	1 ± 1 c	55 ±3 a	34 ± 7 a	58 ± 7 b	–
Oct. 2012	AB-6	143 ± 21 b	10 ± 7 b	56 ± 4 a	13 ± 2 c	70 ± 11 a	100
	PB-6	57 ± 4 d	24 ± 2 a	43 ± 2 b	54 ± 5 a	48 ± 5 b	74.4
	PB-18	93 ± 7 c	8 ± 1 b	65 ± 2 a	23 ± 4 b	78 ± 4 a	20.1
	PB-30	182 ± 10 a	1 ± 0 c	61 ± 6 a	23 ± 4 b	66 ± 7 a	5.6

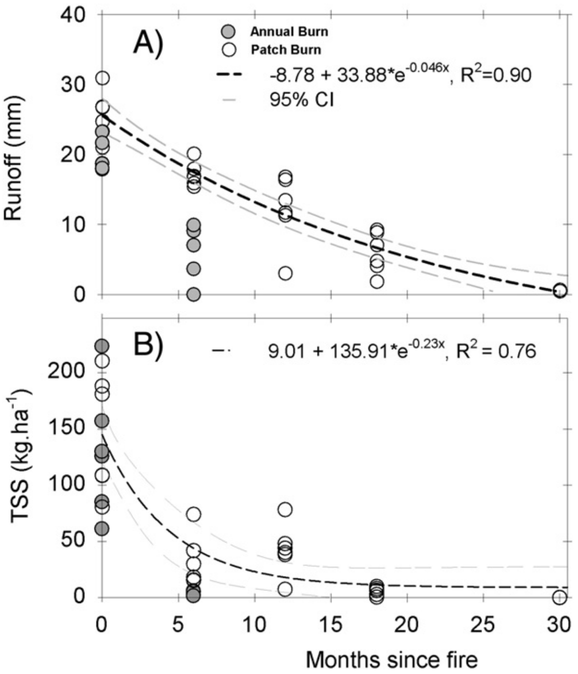

Figure 3. Responses of total runoff depth (mm) (**A**) and total suspended solids (TSS) (kg · ha^{-1}) (**B**) to a simulated rainfall event (30 minutes at a nominal 68 mm · h^{-1} storm intensity) over time since fire under saturated soil conditions.

negligible (see Table 2). The surface runoff from dry run simulations was usually small and variable. Six months after fire, runoff depth in the patch burn pasture was greater than in the annual burn pasture for 2011 and 2012. The runoff depth reached 9.4 mm for patch burn pasture in 2012, which was substantially higher than 1.4 mm in annual burn pasture.

Sediment yield mimicked runoff behavior and decreased exponentially as time since fire increased for both the annual burn pasture and patch burn pasture (Fig. 3). Two weeks after being burned in spring 2012, the sediment yield calculated from the wet run simulation on the annual burn pasture (AB-0) was not different from the recently burned patch in patch burn pasture (PB-0) ($P = 0.324$) (see Table 2). Six months since fire, with moderate stocking density, sediment yield in the annual burn pasture reduced to only about 2% of the amount observed at 2 weeks after fire while the patch burn pasture still had a sediment yield of 20% of that observed right after fire. Even with large decreases in sediment transport, the sediment yield in PB-6 was greater than that in AB-6 ($P = 0.02$). Eighteen months since fire, sediment yield from the burned patch was less and at a level similar to that from AB-6. The sediment yield in patch burn pasture dropped to 12.1 kg · ha^{-1} by 24 months and was negligible by 30 months.

Response of Saturated Hydraulic Conductivity to Fire and Grazing Interaction

Soon after spring fires in 2012, the saturated hydraulic conductivity of PB-0 was not different from AB-0 ($P = 0.49$). Six months later, average saturated hydraulic conductivity for the recently burned patch (PB-6) was less than the annual burn pasture (AB-6) ($P < 0.001$) (see Table 2). At 18 months, saturated hydraulic conductivity of the patch burn pasture (PB-18) was similar to the annual burn pasture (AB-6). Thirty months after fire with low-grazing pressure, the saturated hydraulic conductivity of the burned patch (PB-30) approached or exceeded the 1-h 10-yr return rainfall intensity of 68 mm · h^{-1}, resulting in little to no surface runoff even during an extended rainfall simulation.

Soil and Vegetation Parameters and Hydrological Responses

Although there were differences in the percentage of the vegetation cover that was in forbs or graminoids based on time since fire, the differences were not consistent across the years or seasons (see Table 1).

Aboveground biomass was the variable that best predicted total runoff depth ($P < 0.001$) and sediment yield ($P < 0.001$) (Fig. 4). When biomass was below 20 g · m^{-2}, the total runoff depth and sediment yield averaged across all plots were 24.27 mm and 173.13 kg · ha^{-1}, respectively. Mean runoff decreased by 50% when biomass reached 46 g · m^{2} or more, and sediment yield decreased by 50% when biomass reached 26.6 g · m^{-2} or more. As biomass increased to 160 g · m^{-2}, the average runoff depth approached zero (1.58 mm). Sediment yield showed similar responses but a much more rapid decrease as aboveground biomass increased. As aboveground biomass approached 80 g · m^{-2}, sediment yield was negligible (0.10 kg · ha^{-1}).

Percent bare ground showed a relationship with total runoff depth and sediment yield. The response of total runoff depth to the amount of bare ground was best fitted to a logarithmic curve ($P = 0.01$), but an exponential growth relationship best described the relation between sediment yield and bare ground ($P < 0.001$) (see Fig. 4). As the amount of bare ground reached 40%, the variance in the data increased, suggesting that variables other than bare ground started to have substantial effect on variability of observed total runoff depth and sediment yield.

Table 2
Change of surface runoff characteristic, infiltration rate, and sediment yield measured based on dry run and wet run from a simulated rainfall event (30 min at a nominal 68 mm · h^{-1} storm intensity) from 2011 to 2012. Saturated hydraulic conductivity was calculated by subtracting runoff amounts from rainfall amount for the last 2 min of simulation. Initial volumetric soil content was the mean soil water content in the top 10 cm of soil. Values reported are means ± standard error ($n = 3$ for October 2011 and $n = 6$ for April and October 2012). Means noted with different letters are significantly different at a level of $P < 0.1$.

			Total runoff depth (mm)	Hydraulic conductivity (mm · h^{-1})	Initial soil water content (cm^{3} · cm^{-3})	Total sediment (kg · ha^{-1})
DRY	Oct. 2011	AB-6	0.5 ± 0.4 ab	60.5 ± 4.4b	7.4 ± 0.2 a	0.4 ± 0.2 b
		PB-6	2.1 ± 1.2 a	66.5 ± 0.8b	8.2 ± 0.8 a	5.6 ± 2.1 a
		PB-18	0.1 ± 0.0 b	71.6 ± 3.7a	7.1 ± 1.1 a	0.0 ± 0.0 c
		PB-30	0.8 ± 0.3 a	66.4 ± 1.2b	8.7 ± 0.8 a	0.4 ± 0.3 b
	Oct. 2012	AB-6	1.4 ± 1.5 bc	46.3 ± 5.4 b	8.7 ± 1.5 ab	1.2 ± 0.60 c
		PB-6	9.4 ± 0.6 a	23.6 ± 2.6 c	7.4 ± 0.6 b	36.6 ± 10.6 a
		PB-18	3.4 ± 1.1 b	51.8 ± 3.5 b	8.3 ± 0.4 b	6.1 ± 2.3 b
		PB-30	0 ± 0.0 c	76.2 ± 2.1 a	9.6 ± 0.4 a	0 ± 0.2 d
WET	April2012	AB-0	19.7 ± 0.8 b	8.5 ± 2.2a	39.8 ± 0.8 a	128.8 ± 21.3 a
		PB-0	25.1 ± 1.3 a	6.2 ± 1.4a	39.8 ± 0.9 a	153.8 ± 19.9 a
		PB-12	11.7 ± 1.9 c	11.1 ± 3.9a	36.0 ± 0.7 b	42.7 ± 8.4 b
		PB-24	22.3 ± 0.8 a	12.6 ± 2.0a	39.8 ± 1.5 a	12.1 ± 3.03b
	Oct. 2012	AB-6	5.1 ± 1.5 b	46.5 ± 4.7 b	25.0 ± 1.5a	2.1 ± 0.7 b
		PB-6	16.7 ± 0.6 a	28.1 ± 2.5 d	22.5 ± 2.7b	32.5 ± 8.5 a
		PB-18	5.5 ± 1.1 b	52.7 ± 3.5 c	24.5 ± 0.6b	5.7 ± 1.3 b
		PB-30	0.03 ± 0.03 c	76.2 ± 2.1 a	28.3 ± 2.5a	0.03 ± 0.02 c

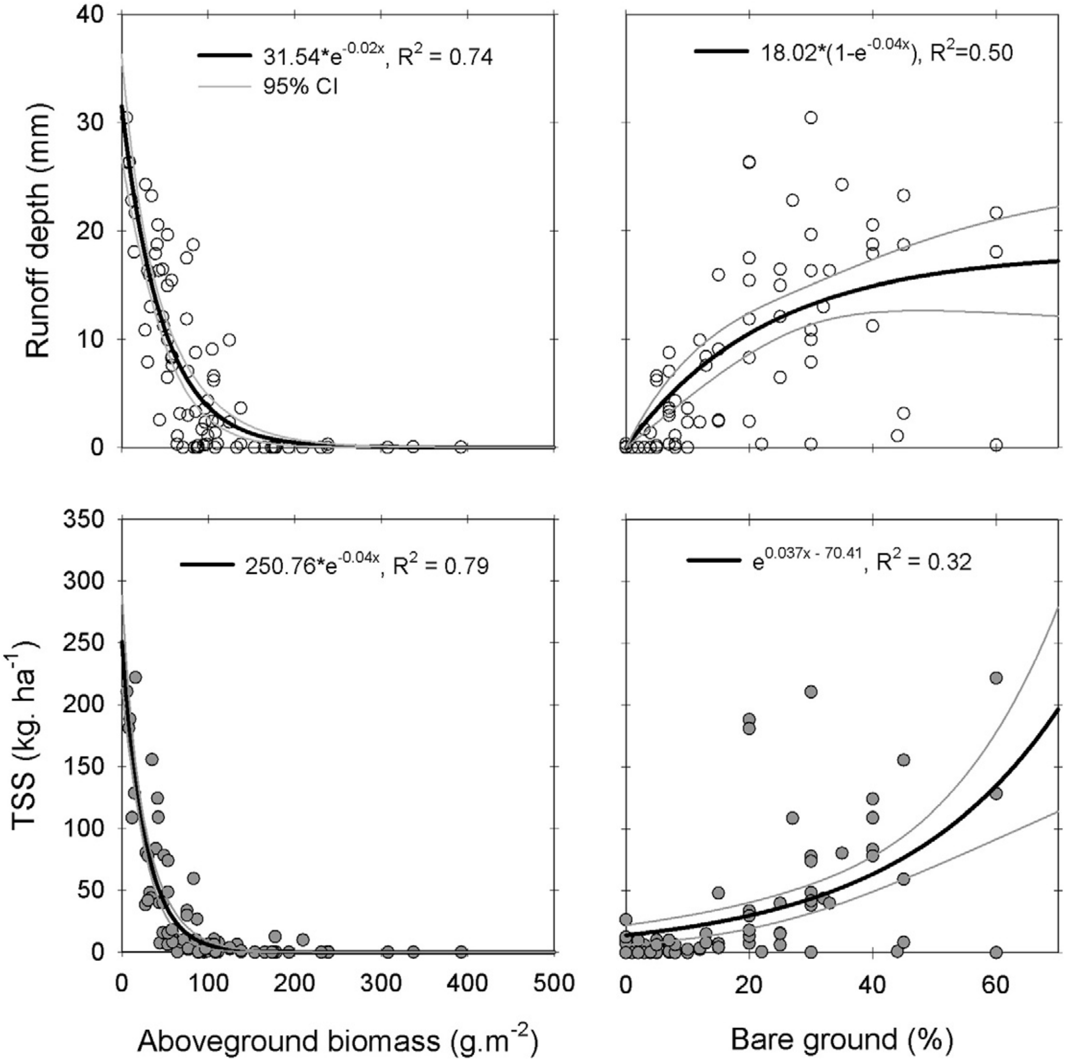

Figure 4. Relationships between runoff depth (upper panel) and sediment yield (lower panel) generated from a simulated rainfall event (30 minutes at a nominal 68 mm · h^{-1} storm intensity) and the aboveground biomass (g · m^{-2}) and bare ground (%). Data were from both wet and dry runs with 95% confidence intervals identified.

All other ecological variables including vegetative composition, plant basal area, and cattle occupancy showed slight to no direct relationship with runoff or sediment yields.

Discussion

Native prairie soils are highly permeable, exhibiting high hydraulic conductivities (Hester et al., 1997; Vadilonga et al., 2008). Lucien–Coyle soil complex, the major soil type of the Tallgrass Prairie Preserve, is well drained with moderately rapid permeability, usually substantially higher than the 1-h, 10-yr return rainfall intensity of 68 mm · h^{-1} reported for the tallgrass prairie region of the south-central Great Plains (Hershfield, 1961). When we simulated this 68 mm · h^{-1} rate of rainfall on our plots, the measured saturated hydraulic conductivity for the burned patch was well below this level 1 year after fire (see Table 2). The saturated hydraulic conductivity for the annual burn pasture never reached beyond 60 mm · h^{-1}, providing evidence that the combination of uniform fire application and grazing could have reduced the soil's capacity to absorb rainfall within a Lucien–Coyle soil complex. The trends observed in this study suggest that patch burn grazing management allows a section of the pasture to reach a very high hydraulic conductivity (PB-30) representative of historical rates from native tallgrass prairies due to the spatial and temporal variation in fire and grazing disturbance within the pasture.

Aboveground biomass was the best indicator of runoff volumes and sediment yields (see Fig. 4). Biomass accumulation differed between the annual burn and the patch burn plots; the annual burn pasture experienced a uniformly moderate grazing pressure (see Fig. 2) that allowed accumulation of sufficient aboveground biomass within one growing season to adequately cover the soil surface and in effect reduce runoff and sediment transport. In contrast, it took 12–18 months for burned patches to reach similar biomass amounts because grazing pressure was approximately three times greater on the burned patch within the first year. The increased variability in aboveground biomass and associated runoff and sediment yield in the patch burn pasture both spatially (among each patch) and temporally (for a given patch) that we observed could be the direct result of changing grazing behavior as suggested by Cournane et al. (2010). Because the grazing pressure ranged from very heavy to light within the patch burn pasture, the patch burn treatment had high heterogeneity of aboveground biomass, which allowed for shifts in the runoff and runon relationships between biomass amount and distribution (Wilcox et al., 2003).

Bare ground has been used as a primary indicator of decreased infiltration and increased runoff in rangelands across the globe (Abdel-Magid et al., 1987; Fuhlendorf et al., 2002; Campo et al., 2006; Kato et al., 2009; Wine et al., 2012). In this study, however, bare ground was not the best predictor for runoff or sediment transport due to increasing variance in runoff and sediment as bare ground increased. This variance could be a result of connectivity and location of bare patches. We believe that, as aboveground biomass decreased, the connection between bare areas increased, decreasing the chances of resistance of litter or standing vegetation to runoff or suspended sediments. Previous studies have found that overland flow and sediment transport in rangeland sites exhibit a threshold behavior so that as ground cover decreases below 40%, sediment transport increases substantially (Davenport et al., 1998). This phenomenon is hypothesized to be similar to the percolation theory first described by Stauffer (1985). Percolation theory in relation to hydrology hypothesizes that as connectivity between bare patches decreases, the ability of water and suspended solids percolating through the landscape to reach waterways also decreases (Dunne et al., 1991; Hester et al., 1997; Urgeghe et al., 2010).

Cattle congregation on recently burned prairie resulted in higher sediment transport and overland flow in the recently burned patch. However, this disturbance was isolated due to the small size of one burned patch in a patchwork landscape combined with reduced grazing pressure in other patches of the pasture. Patch burn management is designed to create heterogeneity in surface cover and vegetative structure across the landscape and can also be utilized to minimize sediment movement and maximize water retention. With increased heterogeneity, the probability of surface runoff and sediment reaching areas of high vegetation cover can increase and the probability of sediment reaching riparian areas could decrease. Areas of high vegetation cover can serve as buffers to collect runoff and sediment influx from recently burned and heavily grazed areas. Consequently, patch burning can be designed to control vegetative cover and structure in order to reduce runoff and sediment transport into sensitive areas.

Quantitative comparison of runoff and sediment transport and associated nutrient movement between patches and between pastures was beyond the scope of this study. Our research has provided the first step toward exploring how pyric-herbivory can influence tallgrass prairie hydrology. An interesting research question remains to be answered—could the total amount of water and soil transported off site for the patch burn pasture be lower than an annually burned pasture due to increases in heterogeneity and therefore decrease in connectivity of the disturbance? Spatially distributed hydrological models such as Soil and Water Assessment Tool (SWAT) and Automated Geospatial Watershed Assessment (AGWA, Goodrich et al., 2011) may be used to answer this type of question in the future with more data on varying soil types and slope becoming available.

Implications

Pyric-herbivory promotes heterogeneity by using spatial and temporal variation in fire to encourage spatially and temporally varying grazing pressure within a pasture. Focal grazing on the recently burned patch increases the potential of runoff and sediment transport on that patch but decreases the potential soil and water loss on remaining patches. The increased disturbance of focal grazing following a spring fire does not have a prolonged detrimental impact on hydrological properties for the fine, sandy loam Lucien series soils in the native tallgrass prairie featured in the Tallgrass Prairie Preserve, and there is no ecologically meaningful difference in either runoff and sediment transport between burned patch and annually burned pasture at the end of the first growing season.

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