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REGULAR ARTICLE

Effects of wildfire and topography on soil nutrients in a semiarid restored grassland

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Abstract
Background Wildfire and topography each have significant effects on soil biogeochemical cycles, but their interactive effects on soil nutrients remain largely unclear, hindering the precise prediction of the effects of fire on soil biogeochemical cycles in a larger spatial scale.
Methods We examined soil nutrient contents from restored grass slopes that had suffered wildfires and adjacent restored grass slopes without any wildfire. Topographic factors included slope aspects (north and south slopes) and positions (upper, middle and lower slopes).
Results Fire significantly increased the contents of soil organic carbon (OC), total nitrogen (TN) (0–10 cm), ammonium (NH_4^+), and extractable phosphorous (EP), decreased the contents of nitrate (NO_3^-) and available potassium (AK), and had minimum influence on total phosphorus (TP) content. Slope aspect and position also affected soil nutrients, with higher contents in the north slope than the south slope and at the upper slope than the lower slope. The effects of fire on soil OC, TN, and NO_3^- were consistent across north and south slopes, but the effects on soil NH_4^+, TP, EP and AK varied with slope aspect. However, the effects of fire on soil nutrients were not influenced by slope position.
Conclusion These results indicate that slope aspect should be considered in predicting the response of soil biogeochemical cycles to fire.

Keywords Fire · Semiarid restored grassland · Slope aspect · Slope position · Soil nutrients

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Introduction

As a global 'herbivore', fire has been burning ecosystems for half billion years, since the Late Silurian Period (420 Myr) when vascular plants began to cover the Earth's surface (Bond and Keeley 2005), helping to shape global vegetation distribution and to maintain the structure and function of fire-prone communities (Collins 1992; Flannigan 2015; Pellegrini et al. 2015). Restored grasslands, usually characterized by the high plant productivity and soil fertility (Cheng et al. 2016; He et al. 2009), suffer a great fire risk due to the accumulation of stand/fall litter (Davies et al. 2010), particularly in semiarid regions that may suffer high temperature and prolonged droughts due to climate change (Pitman et al. 2007). Previous studies in sagebrush grassland showed that fire increased aboveground biomass and soil inorganic N concentrations but decreased soil moisture (Davies et al. 2007; Davies et al. 2008). However, the studies about the effects of fire in semiarid restored steppe are still rare. The lack of evidence regarding the effects of fire on restored ecosystems limits our understanding of the biogeochemical cycles and the sustainable use of restored grasslands.

Soil nutrients play important roles in maintaining the structure and function of grassland ecosystems (Reich and Hobbie 2013; See et al. 2015; Turner and Wright 2014). Long-term grazing exclusion increased soil organic carbon (OC) and nutrients, which resulted from the increased primary production that in turn increased the organic materials inputs through surface litter and roots (He et al. 2009; Jing et al. 2014; Mofidi et al. 2013), but these positive effects depended on plant productivity, precipitation, and grassland status before exclusion (Davies et al. 2014; Fernández-Lugo et al. 2013; Hu et al. 2016; Jones and Carter 2016). Given the aboveground biomass and stand/fall litters were greater in the restored grassland than unrestored grasses (e.g., grazing), the effects of fire on nutrients cycling in soils may differ in restored versus unrestored grassland (Davies et al. 2010). Understanding how soil nutrients respond to fire would, therefore, provide essential knowledge about biogeochemical cycles, ecosystem succession, and management in grasslands. The responses of soil nutrients to fire vary with different factors, included of vegetation type, fire intensity, fire duration, time after fire, topography, climate, and soil sampling depth (Bodí et al. 2014; Ficken and Wright 2017; Grierson et al. 1999; Wan et al. 2001), and thus no consensus has yet been reached. For example, N availability was observed not to be affected by frequent fire in a South African savanna (Coetsee et al. 2008), decreased in an Australian mesic savanna (de Souza et al. 2016), but increased in an American big sagebrush steppe (Davies et al. 2007). Soil organic carbon (OC) was decreased up to 50% in the upper 10 cm of a Humic Cambisol under a pine forest after a wildfire (Fernández et al. 1997), was not affected in a semiarid grassland (Novara et al. 2013) and was increased in a savanna after annual and intermediate burnings (da Silva and Batalha 2008). Furthermore, leaching, rainfall, soil erosion, and the plant regrowth post-fire affect the response of soil nutrients to fire (Balfour et al. 2014; Ficken and Wright 2017; Hanan et al. 2017). Therefore, those factors that influence the response of soil nutrients to fire should be disentangled to improve our ability to understand and predict soil biogeochemical cycles.

Slope aspect and position are well documented to cause variability in soil microclimates (solar radiation, temperature, and soil moisture) (Bennie et al. 2008; Burnett et al. 2008). In the Northern Hemisphere, the south slope receives more solar radiation than the north slope, which resulted in the higher temperature and lower soil moisture in south slope (Burnett et al. 2008; Wang et al. 2011). Soil moisture and temperature influence plant growth, community composition, litter quality, the decomposition of litter, and the mineralization of soil organic matter, which ultimately affects soil nutrients status (Del Grosso et al. 2008; Gershenson et al. 2009; Liu et al. 2007; Liu et al. 2009). Solar radiation also influences soil nutrients due to its effects on the photodegradation of litter and microbial activities (Austin and Vivanco 2006; Brandt et al. 2010). Therefore, slope aspect affects soil nutrients. For example, the contents of soil nitrate (NO_3^-) and ammonium (NH_4^+) in north slope were higher than those in south slope in the Loess hilly regions (Huang et al. 2015). Slope position affects soil nutrients through its effects on soil moisture and the transportation of sediments along the slope, resulting in the redistribution of nutrients and vegetation (Fu et al. 2004). Generally, the lower slope has higher soil moisture and nutrient contents than the upper slope (Hook and Burke 2000).

Fire usually occurs in ecosystems that have complex landforms (Heyerdahl et al. 2001; Schoennagel et al. 2004). The effects of fire on ecosystem processes are thus affected by the topography, which determines the microclimate, fuel quantity, and fire severity (Alexander et al. 2006). However, to date, the influence of topography (slope aspect and position) on the responses of soil nutrients to fire (and thus the interactive effects between fire and topography) have rarely been studied, hindering the precise prediction of the biogeochemical cycles in those fire-affected ecosystems, the extrapolation of current knowledge to a larger spatial scale, and the identification of a universal pattern of influences.

On the basis of the above considerations, we generated the following hypotheses: (1) fire would increase soil nutrient contents due to the ash deposition (Marion et al. 1991), the enhanced mineralization of organic materials (Choromanska and DeLuca 2002), rainfall, and changes in soil moisture post fire (Balfour et al. 2014; Hanan et al. 2017); (2) the effects of fire on soil nutrients would vary with slope aspect due to the differences in microclimate (radiation, temperature, and soil moisture) and biomass distribution between north and south slopes (Huang et al. 2015; Måren et al. 2015; Suggitt et al. 2011); (3) the effects of fire on soil nutrients would be greater in the lower slope than the upper slope, because fire accelerates soil erosion and then soil nutrients tend to accumulate in the lower slope (Johansen et al. 2001). To test these hypotheses, we examined soil nutrients and moisture from restored grass slopes that had suffered wildfire in the previous year (fire treatment) and adjacent restored grass slopes that did not suffer any wildfire (the control). Soil samples were collected in south and north slopes and in the upper, middle and lower slope positions of both slopes for the control and fire treatments to examine whether the effects of fire vary with slope aspect or position. These factors have not been previously assessed but are essential to understand given the role of topography in mediating the effects of fire on soil biogeochemical processes in grassland ecosystems.

Materials and methods

Study area

This study was conducted in the Yunwu Mountain National Natural Grassland Protection Zone in the Loess Plateau (106°21′-106°27′E, 36°10′-36°17′N, altitude 1800–2148 m), near Guyuan City, Ningxia Hui Autonomous Region, China. To prevent soil erosion and protect grassland plant diversity from overgrazing during the restoration, a protectionary zone excluding grazing and/or other disturbances was established in 1982. With longer time scales of grazing exclusion, the fire risk increases. Fires were recorded in 1999 and 2008 in two areas of the protection zone (Wu et al. 2014), but not in the study sites of this paper. The area is characterized by a continual monsoon climate, with a mean annual temperature of 6.9 °C. The annual maximum and minimum temperatures occur in July (22–25 °C) and January (−14 °C), respectively. The mean annual precipitation is 448 mm (from 1957 to 2011), approximately 60–75% concentrated in July–September, while the mean potential evaporation is 1330–1640 mm. There are significant topographic variations, with hills and gully slope shapes in this area. The plant community is dominated by *Stipa grandis*, *S. przewalskyi*, and *Artemisia sacrorum*. According to the Chinese taxonomic system, the soil in the research area is a mountain grey-cinnamon soil classified as a Calci-Orthic Aridisol, equivalent to a Haplic Calcisol in the FAO/UNESCO system (Qiu et al. 2015).

Field investigation, sampling design, and laboratory analysis

In October 2012, a wildfire occurred in the restored grassland with an area of ca. 2 ha (Fig. 1). The fire in our research area was typically a surface head fire, which quickly burned the aboveground vegetation, included of aboveground biomass and stand/fall litter, and was characterized by relatively lower temperatures and shorter duration compared to the forest fire. As the fire without human control, no data of fire characteristic (e.g. temperature and wind speed) was recorded.

To test the effects of fire, we chose the burned slopes as the fire treatment and the adjacent unburned slopes as the control treatment. The burned and unburned grassland have been in natural restoration condition (excluded from grazing, fire, and any human disturbances) for at least 31 years. Two sampling slopes (north and south slopes) were established in each of the fire and control treatment for detecting the effects of slope aspect. In each slope, 2–7 plots (1 m × 1 m) were set at each slope position (upper, middle and lower) for examining the effects of slope position. The details of each sampling slope are presented in Table 1. As the fire treatment was not far from the control treatment and all the sampling plots had the similar slope gradients, the vegetation type and soil condition of each sampling plot were similar before the fire. Therefore, any differences in soil nutrient contents in our study could be ascribed to the effects of fire and topography (slope aspect and slope position).

On August 5, 2013, the canopy cover was estimated, and all the aboveground biomass was cut at the surface of the ground and dried at 65 °C for 24 h to measure the aboveground biomass in each sampling plot. Three soil cores in each plot were collected from the 0–10 and 10–20 cm depths with an auger (0–20 cm depth, 5 cm diameter) and then mixed into one composite sample. A total of 110 soil samples were collected. Large pieces of roots and litter were removed, air dried and ground to pass through 2 mm sieve for the measurement of soil NO_3^-, NH_4^+, extractable P (EP), and available potassium (AK), and through 0.25 mm sieve for the measurement of soil OC, total nitrogen (TN), and total

Table 1 Characteristic of sampling plots

Treatment	Slope aspect	Slope length (m)	Slope (°)	Number of sampling plots in each slope position			Altitude of each slope position (m)		
				Upper	Middle	Lower	Upper	Middle	Lower
Control	North	70	15	3	3	2	2100	2097	2094
	South	180	15	7	6	6	2102	2092	2080
Fire	North	150	15	6	5	5	2102	2096	2092
	South	110	17	4	4	4	2102	2093	2087

phosphorus (TP). The soil moisture at the 0–6 cm depth was measured in each sampling plot on July 22, July 30, Aug 3, Aug 9, and Aug 15, 2013, using an impedance probe (theta probe soil moisture sensor, type ML2 and HH2 recording device, Delta-T Devices, Cambridge, England). We measured three times randomly in each plot and reported the average value. Precipitation was recorded by a weather station near the study area.

The contents of soil OC, TN, TP, EP, and AK were measured according to the standard methods described by Page et al. (1982). Soil OC was determined using the Walkley-Black method, TN was measured using the Kjeldahl method, TP was analyzed colorimetrically after wet digestion with sulphuric acid and perchloric acid, EP was measured by the Olsen method, and AK was measured by flame photometry after extraction by ammonium acetate. Soil NO_3^- and NH_4^+ were determined by a Lachat Flow Analyzer (AutoAnalyzer3-AA3, Seal Analytical, Mequon, WI) after extraction by potassium chloride (Kachurina et al. 2000).

Data analysis

Multi-way analysis of variance (MANOVA) was conducted using SPSS for Windows (Version 23.0, SPSS Inc., Chicago, IL, USA) to test the direct and interactive effects of fire, soil depth, slope aspect and position on soil nutrients.

Results

The effects of fire on soil nutrients

Fire significantly affected the contents of soil OC and nutrients, and the effects varied with soil depth (Table 2). Averaged across slope aspects and slope positions, soil OC and NH_4^+ contents were significantly higher in the fire treatment than the control (+11% and + 10% for OC, $P < 0.01$; +29% and + 16% for NH_4^+, $P < 0.05$, at the 0–10 cm and 10–20 cm depths, respectively), while the NO_3^- content was significantly lower in the fire treatment than the control (−26% and − 27% at the 0–10 and 10–20 cm depths, respectively, $P < 0.01$) (Table 3). However, the effects of fire on TN, EP, and AK varied with soil depth. The contents of TN and EP were significantly higher in the fire treatment than the control at the 0–10 cm depth (+7% and + 44%, $P < 0.05$) but was not affected by the fire at the 10–20 cm depth. The AK content was significantly decreased by fire at the 10–20 cm depth (−15%, $P < 0.01$), but was not altered at the 0–10 cm depth. TP was not affected by the fire at either soil depth.

The effects of topography on soil nutrients

Most soil nutrients varied with slope aspect in this grassland (Table 2). Soil OC and TN contents in the north slope were significantly higher than those in the south slope ($P < 0.05$) regardless of soil depth and fire treatment (Fig. 2). The contents of soil TP, EP and AK in the north slope were also significantly higher than those in the south slope ($P < 0.01$) for the control treatment but were similar between two slope aspects for the fire treatment at two soil depths (Fig. 2). However, slope aspect did not affect the contents of NO_3^- and NH_4^+ (Table 2). For example, the NO_3^- content was similar between north and south slopes at both treatments and both soil depths (Fig. 2).

Slope position significantly affected the contents of soil OC, TN, NH_4^+, TP, and EP (Table 2), with the higher contents at the upper slope and lower contents at the lower slope (Fig. 3) across fire treatment and slope aspect. The effects of slope position on OC, TN and TP were significant at both 0–10 cm and 10–20 cm depths, but the effects on NH_4^+ and EP were only significant at the 10–20 cm depth (Fig. 3).

Table 2 Multi-way analysis of variance (MANOVA) for soil organic carbon (OC), total nitrogen (TN), nitrate (NO_3^-), ammonium (NH_4^+), total phosphorus (TP), extractable phosphorus (EP), and available potassium (AK) as affected by fire (F), slope aspect (SA), slope position (SP), and soil depth (D) in a semiarid restored grassland (Variance contribution (%))

	OC	TN	NO_3^-	NH_4^+	TP	EP	AK
F	3.18**	1.01*	16.02**	7.47**	3.36**	2.88**	4.75**
SA	18.67**	22.81**	0.49	0.14	10.92**	5.21**	4.21**
SP	4.37**	12.55**	1.65	8.76**	4.20**	4.32**	0.01
D	27.18**	23.32**	29.41**	14.06**	17.65**	33.74**	59.59**
F*SA	0.82	0.08	0.37	2.56*	10.92**	4.35**	5.88**
F*SP	1.71	0.97	0.32	1.15	4.20**	0.08	0.44
F*D	0.24	0.42	0.24	1.31	0.00	6.80**	0.29
SA*SP	2.78**	3.89**	0.08	1.49	1.68	0.84	0.84
SA*SD	0.06	0.02	0.24	4.77**	0.00	0.61	0.06
P*SD	0.16	0.07	0.60	0.73	0.00	1.33	0.52
F*SA*SP	1.07	0.25	0.08	0.29	5.04**	0.01	3.35**
F*SA*D	0.00	0.01	0.44	15.32**	0.01	0.70	0.04
F*SP*D	0.29	0.02	0.18	0.83	3.36*	0.23	0.77
SA*SP*D	0.13	0.31	0.71	5.31**	0.84	0.75	0.27
F*SA*SP*D	0.11	0.16	0.23	4.03**	0.01	0.07	0.14

All the value present here is the variance contribution of each factor and their interaction according to the result of the MANOVA by GLM model

* and ** represent the P value <0.05 and < 0.01, respectively

Furthermore, these effects were consistent across the slope aspect and fire treatment as evidenced by the lack of interactions between slope position and fire treatment or slope aspect (Table 2).

The effects of fire, soil depth, slope aspect and position on soil nutrients and their interaction

Fire, soil depth, slope aspect, and position could significantly affect soil nutrients in this study. Soil depth explained the most variation in soil nutrients than other factors (Table 2). For example, soil depth explained 27% of the total variance in soil OC, while fire, slope aspect, and position explained 3%, 19% and 4% of them, respectively. Meanwhile, the effects of topography (slope aspect and position) were larger than the effects of fire on most soil nutrients. For example, topography explained 35% of the total variance in soil TN, while fire explained 1%. Furthermore, most of the interactive effects among fire, topography, and soil

Table 3 Effects of fire on soil organic carbon (OC), total nitrogen (TN), nitrate (NO_3^-), ammonium (NH_4^+), total phosphorus (TP), extractable phosphorus (EP), and available potassium (AK) at 0–10 and 10–20 cm depths in a semiarid restored grassland

	OC ($g \cdot kg^{-1}$)	TN ($g \cdot kg^{-1}$)	NO_3^- ($mg \cdot kg^{-1}$)	NH_4^+ ($mg \cdot kg^{-1}$)	TP ($g \cdot kg^{-1}$)	EP ($mg \cdot kg^{-1}$)	AK ($mg \cdot kg^{-1}$)
0–10 cm							
Control	32.1 ± 0.9B	3.3 ± 0.1B	25.4 ± 0.9A	12.0 ± 0.7B	0.72 ± 0.01A	12.6 ± 0.8B	296 ± 9A
Fire	35.7 ± 0.8A	3.5 ± 0.1A	18.9 ± 0.9B	15.5 ± 0.9A	0.72 ± 0.00A	18.2 ± 0.78A	283 ± 6A
10–20 cm							
Control	27.1 ± 0.8B	2.9 ± 0.1A	17.2 ± 0.7A	10.4 ± 0.4B	0.69 ± 0.01A	10.0 ± 0.5A	187 ± 9A
Fire	29.7 ± 0.5A	3.0 ± 0.1A	12.5 ± 0.7B	12.1 ± 0.6A	0.69 ± 0.01A	9.6 ± 0.4A	160 ± 39B

Values represent the means ± standard errors; different uppercase letters indicate significant differences (P < 0.05) between control and fire treatments at the same soil depth

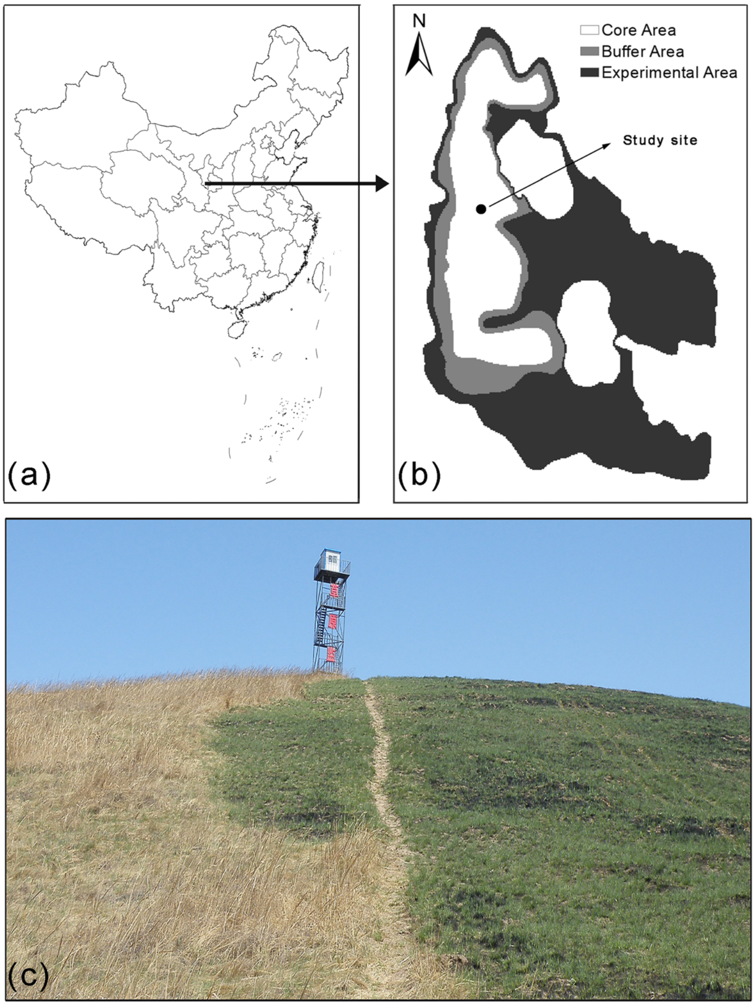

Fig. 1 Location of the study area (**a** and **b**) and photograph of burned and unburned grasslands (**c**)

depth did not affect soil nutrients contents, except the interaction between fire and slope aspect.

The effects of fire on soil OC, TN, and NO_3^- contents were similar between north and south slopes ($P > 0.05$ for the interactions between fire and aspect) (Fig. 4a, Table 2). The fire resulted in +9%, +3%, and − 28% changes in OC, TN, and NO_3^- in the south slope and + 3%, +2%, and − 22% changes in the north slope, respectively. However, the effects of fire on NH_4^+, TP, EP, and AK contents varied with slope aspect ($P < 0.05$ for the interactions between fire and aspect) and even with soil depth ($P < 0.01$ for the interactions between fire and soil depth on EP and the interactions among fire, aspect and soil depth on NH_4^+) (Fig. 4a, Table 2). For example, the fire resulted in an increase of TP in the south slope but a decrease in the north slope and these effects were consistent across 0–10 and 10–20 cm depths. Similarly, fire resulted in a 73% increase ($P < 0.01$) in NH_4^+ at the 0–10 cm depth and a 7% decrease ($P > 0.05$) at the 10–20 cm depth in the south slope but an 11% decrease ($P > 0.05$) at the 0–10 cm depth and a 34% increase ($P < 0.01$) at the 10–20 cm depth in the north slope. Furthermore, the effects of fire on most soil nutrients (OC, TN, NO_3^-, NH_4^+, and EP) were greater in the south slope than the north slope for the 0–10 cm soils but were lower in the south slope than the north slope for the 10–20 cm depth (NO_3^-,NH_4^+, TP, EP, and AK) (Fig. 4a).

The effects of fire on most soil nutrients were not affected by slope position as suggested by the lack of significant interactions between them (Table 2). Only the effect of fire on TP content was influenced by slope position ($P < 0.05$), with a 5% decrease ($P < 0.01$) from fire at upper slope and a 4% increase ($P < 0.05$) at the lower slope but unvaried at middle slope at the 0–10 cm depth and unvaried in all 3 slope positions at the 10–20 cm depth (Fig. 4b). Therefore, the effects of fire on

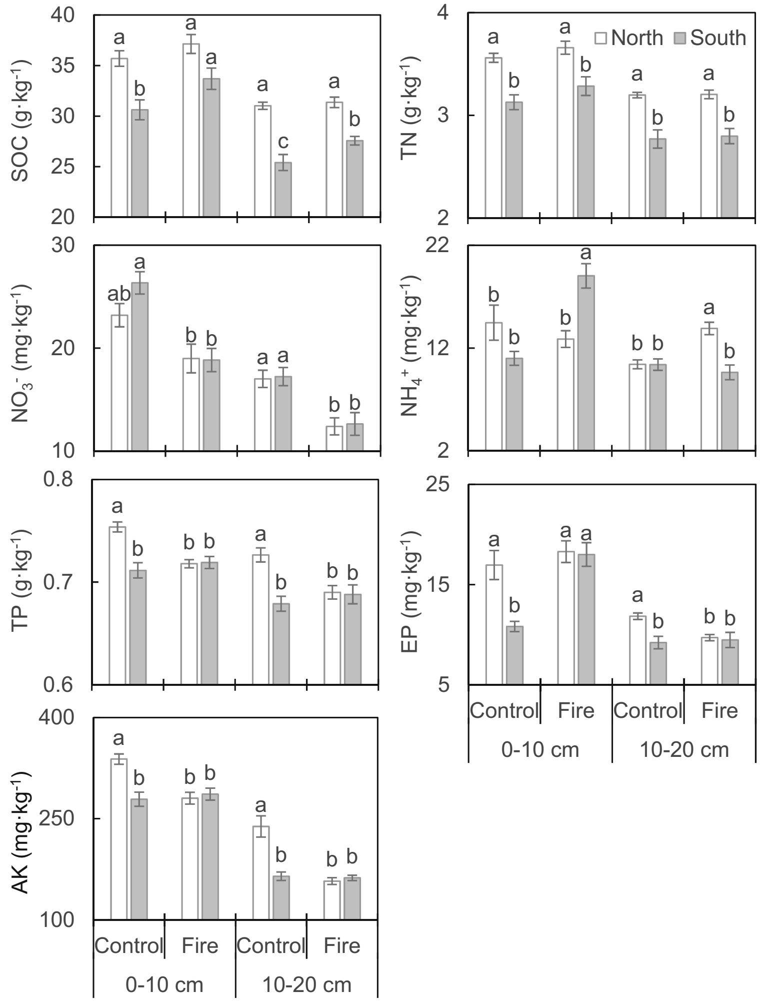

Fig. 2 Effects of slope aspects (north vs. south slopes) on soil organic carbon (OC), total nitrogen (TN), nitrate (NO_3^-), ammonium (NH_4^+), total phosphorus (TP), extractable phosphorus (EP), and available potassium (AK) in control and fire treatments at 0–10 and 10–20 cm depths in a semiarid restored grassland. Error bars denote two standard errors of the mean; means with different lowercase letters indicate significant at $P < 0.05$ within the same soil depth

soil nutrients were consistent across slope position for this semiarid restored grassland.

The effects of fire, slope aspect and position on soil moisture

The fire significantly decreased soil moisture during the measurement period, which was 7% ($P < 0.05$) lower in the fire treatment than the control. The effect of fire on soil moisture was increased by rain events (Fig. 5). For example, after 4, 3, and 4 days of rain (in the 5 days preceding measurement), soil moisture was 7%, 7%, and 11% lower in the fire treatment than the control ($P < 0.05$) at days 11, 15, and 21, respectively.

Soil moisture varied significantly with slope aspects, with higher soil moisture in the north than the south slope (+16%, $P < 0.05$) across the control and fire treatments (Fig. 6). However, slope aspect did not affect the response of soil moisture to fire, with 10.4% lower soil moisture in the fire treatment than the control in both north and south slopes. The effect of slope position on soil moisture varied with slope aspect but was not influenced by fire treatment (Fig. 7). Although not statistically significant, soil moisture decreased with slope position in the south slope but increased with slope position in the north slope.

Discussion

Partially supporting our hypotheses, a fire significantly increased the contents of soil OC, TN (0–10 cm), NH_4^+ and EP (10–20 cm) but decreased NO_3^- and AK (10–20 cm). The contents of soil OC and TN were significantly higher in the north slope than the south slope, but

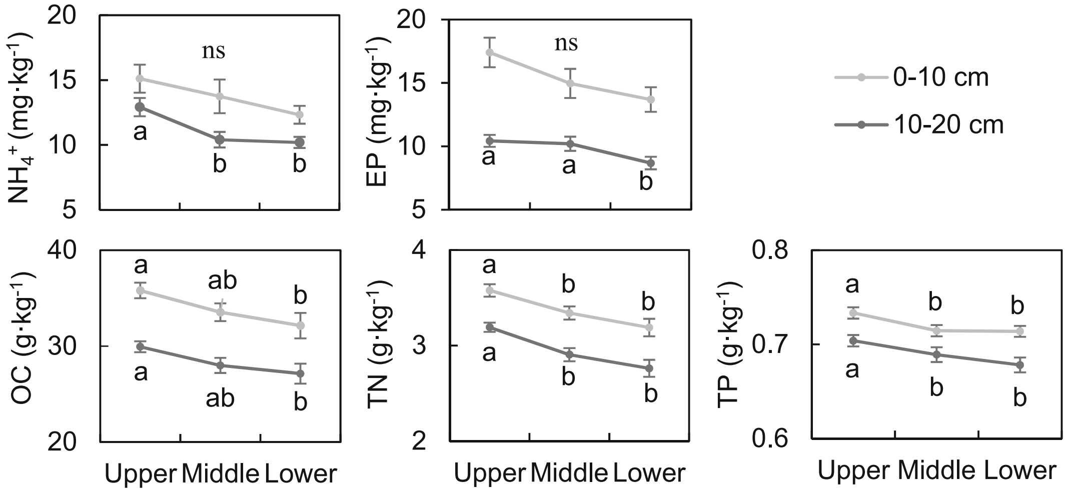

Fig. 3 Effects of slope positions on soil organic carbon (OC), total nitrogen (TN), total phosphorus (TP), ammonium (NH_4^+), and extractable phosphorus (EP) at 0–10 and 10–20 cm depths in a semiarid restored grassland. ns, not significant; error bars denote two standard errors of the mean; means with different lowercase letters indicate significant at $P < 0.05$ within the same soil depth

the contents of soil TP, EP, and AK were significantly higher in the north slope than the south slope only in control treatment. Slope position significantly affected the contents of soil OC, TN, NH_4^+, TP and EP with higher contents in upper slope and lower contents in lower slope. Furthermore, slope aspect significantly affected the effects of fire on soil nutrients (NH_4^+, TP, EP, and AK), but slope position did not affect the effects of fire on most soil nutrients.

The effects of fire on soil nutrients

Our results showed that fire significantly increased the contents of soil OC and TN. The results were attributed

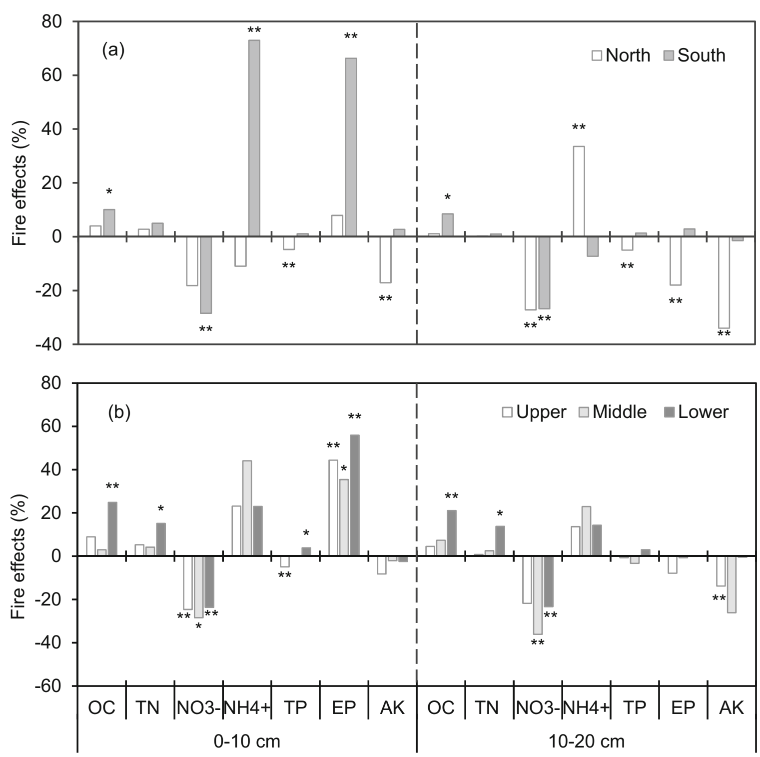

Fig. 4 Effects of fire on soil organic carbon (OC), total nitrogen (TN), nitrate (NO3-), ammonium (NH4+), total phosphorus (TP), extractable phosphorus (EP), and available potassium (AK) in north and south slopes (**a**) and different slope positions (**b**) at 0–10 and 10–20 cm depths in a semiarid restored grassland. Fire effects were calculated by comparing the fire treatment with the control; * and ** indicate significant at $P < 0.05$ and $P < 0.01$, respectively

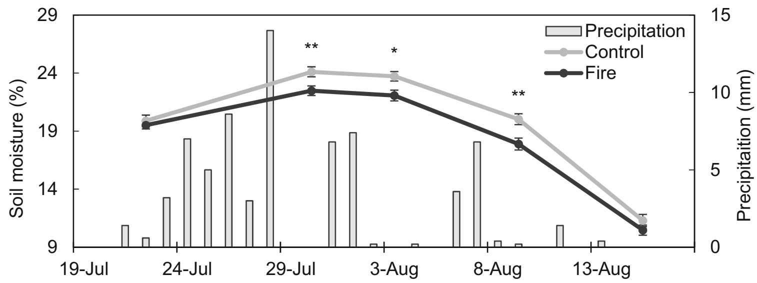

Fig. 5 Effects of fire on soil moisture (the line) at the 0–6 cm depth and the precipitation during the measurement period (the bar) in a semiarid restored grassland. Error bars denote two standard errors of the mean; means with * and ** indicate significant between control and fire treatments at $P < 0.05$ and $P < 0.01$, respectively

to the post-fire ash deposition and pyrogenic C input (Pereira et al. 2013). The grassland fire was characterized by lower temperatures (usually lower than 400 °C at the surface) and of shorter duration compared with forest fires (Gibson et al. 1990; Miranda et al. 1993), resulting in the incomplete combustion of organic materials and the residues of organic materials in the ash from the burning of aboveground vegetation, litter, and organic-rich surface soil (Bodí et al. 2014). These residual organic materials are incorporated into the soil by the rainfall (Santín et al. 2012; Schmidt and Noack 2000), which increases the contents of soil OC and TN. In our study, rainfall occurs in a short time after a fire, but no significant runoff was observed. Therefore, the organic materials in the ash were leached into the deeper soil rather than a lateral loss by wind erosion or runoff (Balfour et al. 2014; Fonseca et al. 2017). Our results were in agreement with previous observations in various ecosystems. For example, fire was reported to increase soil TN in a South African coastal fynbos ecosystem (Stock and Lewis 1986), increase organic matter in a grassland of Lithuania (Pereira et al. 2013), and double soil OC and N concentrations in the A horizon in a Dystric Cambisol under a Mediterranean pine forest (Knicker et al. 2005). However, our results differed from the results of intensive and frequent fires, which decreased soil C and N (Cheng et al. 2013; Girona-García et al. 2017). Intensive fires were characterized by higher temperature and longer duration, which highly combusted the organic materials and resulted in the decreases of soil C and N (Girona-García et al. 2017). Frequent fires also decreased soil C and N due to the lower input from the nutrients of aboveground vegetation (Cheng et al. 2013).

We observed a significant increase in soil NH_4^+ but a decrease in soil NO_3^- due to fire, which did not agree with previous studies (Cui et al. 2010; Wan et al. 2001). For example, soil NO_3^- and NH_4^+ were increased throughout the growing season after annual burning in a semiarid grassland (Augustine et al. 2014) and

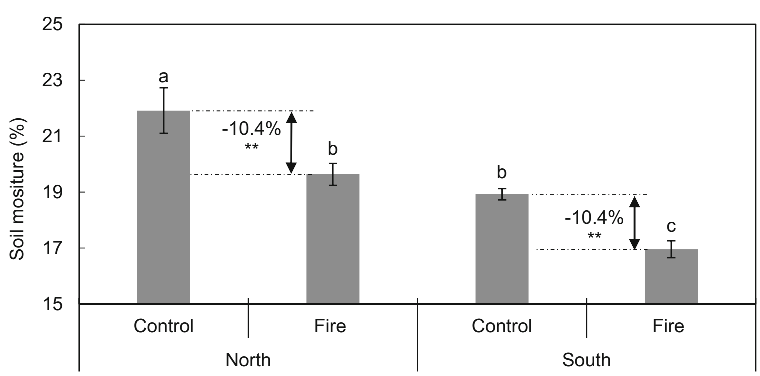

Fig. 6 Effects of fire on soil moisture at the 0–6 cm depth in north and south slopes in a semiarid restored grassland. The percentage indicates the reduction of soil moisture by fire; error bars denote two standard errors of the mean; ** indicates significant differences between control and fire treatments within the same slope aspect at $P < 0.01$; means with different lowercase letters indicate significant at $P < 0.05$

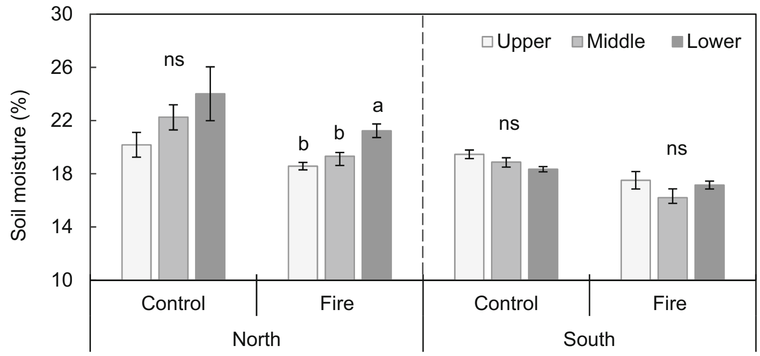

Fig. 7 Effects of slope positions on soil moisture at the 0–6 cm depth in control and fire treatments of north and south slopes in a semiarid restored grassland. ns, not significant; error bars denote two standard errors of the mean; means with different lowercase letters indicate significant differences among slope positions at $P < 0.05$

increased by fire in a temperate steppe (Wei et al. 2014). Increased soil NH_4^+ results from ash deposition and increases in N mineralization caused by altered soil temperature, pH and microbial activities (Knoepp and Swank 1993). The increase in soil NO_3^- is the result of increased nitrification stimulated by increased soil NH_4^+, altered soil pH, temperature and microbial activities, and decreased allelopathy (Andersson et al. 2004; Christensen 1973; Fultz et al. 2016). In our study, a fire significantly increased aboveground biomass (+65%) and accelerated the uptake of inorganic N from the soil (Jensen et al. 2001; Romanyà et al. 2001), which may decrease soil NO_3^-.

We observed a significant increase in soil EP at the 0–10 cm depth from fire, consistent with the results of Rau et al. (2007), in which soil EP in topsoils was increased immediately following a fire and remained elevated for 2 years due to the fire's transformation of organic P in the plant into inorganic P. An alternative explanation was that the higher soil temperature and lower soil moisture caused by fire enhanced the mineralization of organic P and result in the increased EP (Grierson et al. 1999). However, soil TP (0–20 cm) and AK (0–10 cm) were not significantly altered by fire (Table 3), probably due to the loss of P and K through particulate or non-particulate during combustion (Kugbe et al. 2015). For example, in northern Ghana, 50% and 75% of P and K were lost in particulate form, and 50% and 25% were lost in non-particulate form during combustion across the savanna, woody savanna, grassland savanna, and shrubland ecosystems (Kugbe et al. 2015). Therefore, less P and K in the ash was added to the soil. Additively, plant absorbed more P and K after fire (Kutiel and Naveh 1987), thus soil TP and AK were not significantly altered. Given that the plant regrowth required lots of soil nutrients, especially for N, P, and K (Kutiel and Naveh 1987), and fire increased soil N (Table 3), the P and K may limit plant growth post-fire.

The nutrients contents in above- and below-ground biomass and litter may affect soil nutrients in the grassland ecosystem, especially for a restored grassland (Deng et al. 2014; Mofidi et al. 2013; Scalon et al. 2014; Villalobos-Vega et al. 2011). For example, soil nutrients contents significantly increased with the increase of grazing exclusion time in a semiarid grassland due to the increased biomass that in turn increased soil organic matter input through litter and roots (Jing et al. 2014). Therefore, further research is needed to examine the effects of fire on the nutrient input from plant and litter into the soils.

The effects of slope aspect on soil nutrients and their responses to fire

We demonstrated that slope aspect significantly affected soil nutrients (Table 2), and the contents of most soil nutrients in the north slope were greater than those in the south slope (Fig. 2), in agreement with previous studies (Gong et al. 2007; Mudrick et al. 1994). For example, higher soil nutrients were observed in the north slope than the south slope in a small catchment in the hilly loess area, China (Gong et al. 2007). Generally, in the Northern Hemisphere, the north slope receives lower solar radiation than the south slope, resulting in the lower soil temperatures (Måren et al. 2015) and the higher soil moisture (Fig. 6). Solar radiation, soil moisture, and temperature could influence soil OC and nutrients status through the direct and indirect effects (Brandt et al. 2010; Hook and Burke 2000; Verhoef et al. 2000; Wang et al. 2006). In this semiarid grassland ecosystem, however, soil moisture may be a limiting factor in controlling the plant growth and microbial activities (D'Odorico et al. 2007; Liu et al. 2009). Therefore, higher aboveground biomass and plant cover were found in the north slope (Fig. A1c, d), which had the higher soil moisture than the south slope. Thus, more litter accumulates in the north slope and releases more nutrients to the soils through the decomposition of litter and the mineralization of organic matter (Huang et al. 2015; Mudrick et al. 1994).

We observed the similar responses of soil OC and TN to fire between north and south slopes ($P > 0.05$ for interactions between fire and aspect, Table 2); thus, the effects of fire on soil OC and TN were independent of slope aspect. However, most P and K metrics were significantly decreased by fire in the north slope but less altered in the south slope (Fig. 4a), possibly because plants take up more P and K from soils in the north slope than the south slope. In this area, fire enhanced the uptake of soil P and K by plants (unpublished data), which might be the reason for the decreased P and K in the north slope after a fire.

The effects of slope position on soil nutrients and their responses to fire

This study showed that soil nutrients varied with slope positions (Fig. 3), and the discrepancies were mainly in the upper and lower slope. Soil nutrients were hypothesized to be higher in the lower slope than the upper slope because lower slope usually have the higher soil moisture, the greater above- and below-ground biomass and the faster decomposition of organic matter, thus leading to the higher return rates of nutrients to the soils (Hook and Burke 2000; Sariyildiz et al. 2005). However, we observed the higher soil nutrient contents in the upper slope than the lower slope (Fig. 3). In this study, the upper slope was characterized by higher canopy cover and aboveground biomass (Fig. A1a and b) than the other slope positions. Slope position did not affect soil moisture (Fig. 7), and the lower slope was not affected by groundwater level (Chen et al. 2008). Furthermore, soil temperature was relatively higher in the upper slope than the lower slope in this region, which may result in a relatively high turnover rate of organic materials and thus the release of nutrients to soils (Tsui et al. 2004). Moreover, due to the higher ground canopy cover (90%, 89% and 87% in upper, middle and lower slopes, respectively) (Fig. A1a) and the rapid recover post-fire, nutrient transport with soil particles along slopes could be neglected, thus favouring the accumulation of nutrients in upper slope soils. Therefore, the higher nutrient contents in the upper soils than lower soils were expected, consistent with observations in a subtropical pasture (Sigua and Coleman 2010).

The effects of fire on soil nutrients were not influenced by slope positions in this study, probably due to the large spatial variations of soil nutrients along the slope (with variance coefficients of 4–39% in the control treatment and 5–31% in the fire treatment for all nutrients, respectively). The spatial patterns of soil nutrients may provide an explicit explanation on the response of soil resources to fire, therefore, these effects merit further investigated. Given that slope positions altered the effects of fire on plant coverage (Pereira et al. 2016), which may regulate nutrients dynamics in soils, further understanding of the variation of fire effects on nutrients among slope positions would provide more evidence about mechanisms behind soil nutrient dynamics in grassland.

Conclusions

Collectively, our results demonstrated that both wildfire and topography (slope aspect and slope position) influence soil nutrients in the semiarid restored grassland. Wildfire significantly increased the contents of soil OC, TN, NH_4^+, and EP. The nutrient contents were higher in the north slope than the south slope but decreased with decreasing slope position. The effects of fire on soil OC, TN, and NO_3^- were consistent across north and south slope, but the effects of fire on soil NH_4^+, TP, EP, and AK varied with slope aspect. However, the effects of fire on soil nutrients were not influenced by slope positions. Future research is recommended to understand the effects of fire on nutrient uptake by plants and their responses to topography, which would provide the mechanism behind the responses of soil nutrients to fire in various topographical conditions.

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