

Response of soil sulfur availability to elevation and degradation in the Wugong Mountain meadow, China

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ABSTRACT

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Vegetation restorations of degraded meadows have been widely implemented. The evaluation of soil nutrient changes as affected by degradation is vital for efficient restorations. However, while macronutrients (nitrogen, phosphorus and potassium) have been widely investigated, sulfur (S) as one important element correlated tightly with other nutrients has not been thoroughly studied. Two studies were conducted to determine changes of sulfur as affected by degradation and elevation gradients. The results showed that available S (AS) changed non-linearly with elevation and the first principal component based on other soil nutrient variables. Soil AS depended on degradation levels and contributed substantially to the separation of meadows with different degradation levels. Moreover, AS responded stronger to changes in elevation gradients and degradation levels compared with other major nutrients. Thereby, AS could be an important nutrient responding to meadow disturbance, which should be considered in future studies on meadow soil nutrients cycling and vegetation restorations. The findings have implications for ecological restoration of degraded meadows with respect to soil nutrient management and conservations.

Keywords: anthropogenic disturbance; cycling process; plant species; stoichiometry

Alpine meadows are important carbon (C) and nitrogen (N) pools and are more sensitive to human-induced changes in environmental factors (e.g., agricultural management or trampling) (Kopeć 2002, Deng et al. 2016). Changes in macronutrients C, N and phosphorus (P) were widely studied in meadows or other ecosystems (Kopeć 2002). Sulfur (S) is important in protein formation, functioning of enzymes and stoichiometric interactions with other nutrients (Droux 2004, Scherer 2009, Shi et al. 2016). Changes in C, N and P might also induce altered S in meadow soils (Schmidt et al. 2012). Indeed, due

to the stoichiometric correlations among C, N and P or other elements, changes in one of these important elements will also arouse potential changes in the soil element cycling process (Tipping et al. 2016). For example, under the context of N deposition that potentially alter soil N availability and hence changes in N, P and other related nutrients, S cycling was demonstrated to be decreased (Chen et al. 2016). Soil N related gas emissions were reported to be stimulated (Cai et al. 2012) or suppressed (Fan et al. 2017) by S deposition. Thereby, soil S availability and its cycling may alter in response to changes in

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other major nutrients (Schmidt et al. 2012). However, no study has been developed to determine changes in S availability and its relationship with other soil nutrients with elevation and degradation in alpine meadows, limiting our understanding of nutrients cycling in meadows.

In addition, more meadows are degrading due to anthropogenic disturbance (Zhao et al. 2014, Deng et al. 2016). During degradation, plant coverage and species composition, and availability of soil S, as well as related major nutrients (potassium (K), calcium (Ca) and magnesium (Mg)) might change in response to altered plant biomass and species composition. While vegetation restorations were demonstrated more economic and efficient in restoring degraded meadows (Liu et al. 2011), understanding changes of nutrient availability in soils with different elevation and degradation level will be important for successful restorations. Due to the importance of soil S in soil element cycling and plant growth, clarifying correlations between soil S and other major nutrients and their response to elevation and degradation will improve our understanding of nutrient distributions in degrading meadows and support successful vegetation restorations (Droux 2004).

Thus, the studies were conducted examining available S and its response to elevation and degradation by answering the following questions: How does AS change with elevation gradient and correlate with N, P, K, Ca and Mg in alpine meadows? How would S, N, P, K, Ca and Mg respond to meadow degradations?

MATERIAL AND METHODS

The studies were conducted in alpine meadows of the Wugong Mountain (27°27'N, 114°10'E; 1920 m a.s.l.), Jiangxi, China. Alpine meadows mainly distribute above the elevation of 1600 m a.s.l. Due to excessive tourist trampling, the Wugong Mountain meadows have been degrading seriously. Soil samples were collected along an elevation gradient from 1600 m to 1900 m a.s.l. dominated by meadows by soil cores from the top 20 cm in the first study. To control potential variations caused by plant species, soils were collected from meadows dominated by the most common species (*Miscanthus*) with six replications. In the second study, changes of AS affected by meadow degradation were investigated.

Meadows with more than 90% total vegetation coverage were used as control (control), 30–90% as degradation 1 (degra 1) and those with less than 30% as degradation 2 (degra 2) plots. All plots were distributed in places with similar slope and exposure to control variations caused by position. Soils were air-dried and processed by removing visible roots and other materials and passing through 2 mm sieve for determination of pH (using a glass electrode; 1:2.5, soil/water ratio), soil organic carbon (SOC) by a wet digestion method.

Available N (AN), available Ca (ACa) and available Mg (AMg) were extracted using 2 mol/L KCl solution. For AN determination colorimetric techniques were used; for ACa and AMg it was atomic absorption spectrometry; AN, ACa and AMg were extracted using KCl solution. Available P (AP) and available K (AK) were extracted by 0.2 mol/L NaHCO_3 + 0.01 mol/L EDTA + 0.01 mol/L NH_4F . Available P and AK were determined by colorimetric method and atomic emission spectroscopy, respectively. Available S (mineral S in soil solution and adsorbed) was extracted using 0.01 mol/L $\text{Ca}_3(\text{PO}_4)_2$ solution and determined by turbidimetric procedure.

Principal component analysis (PCA) was used to obtain simple structure of soil pH, SOC and all measured soil available nutrients except AS. Second order polynomial function was used to determine the relationship between AS and the dominating soil nutrient gradient (PC1) estimated by PCA. The same function was also used to examine the relationship between AS and elevation, AN, AP, AK, ACa as well as AMg. Analysis of covariance with elevation as the covariate was conducted to test whether soil available nutrients varied among degradation levels. Post-hoc means comparisons were conducted when significant difference was detected. Discriminant analysis was performed to examine whether plots with different degradation level were separated in multivariate space based on soil pH, SOC and six soil available nutrients. A variable that contributed the most to these separations was determined using a follow-up pairwise correlation analysis. All analyses were performed by JMP 9.0 (Cary, USA).

RESULTS AND DISCUSSION

While AS decreased non-linearly with the studied elevation gradient, changes in other major nutrients

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Table 1. Soil available nutrients (mg/kg) along elevation gradient in alpine meadow of the Wugong Mountain

Variable	Elevation (m a.s.l.)						
	1600	1650	1700	1750	1800	1850	1900
N	45.42 ± 2.32	29.78 ± 4.06	38.03 ± 4.10	51.12 ± 3.28	47.14 ± 5.06	31.47 ± 2.59	42.80 ± 4.56
P	4.87 ± 2.14	1.55 ± 0.47	2.50 ± 0.48	7.16 ± 1.03	7.26 ± 0.81	5.32 ± 1.33	5.16 ± 0.44
K	42.49 ± 2.17	36.70 ± 4.20	45.60 ± 3.61	69.54 ± 5.46	60.79 ± 1.77	44.77 ± 2.28	39.28 ± 1.32
Ca	82.08 ± 7.41	91.28 ± 6.82	135.76 ± 30.51	152.28 ± 20.55	76.54 ± 9.15	98.88 ± 9.81	101.47 ± 16.70
Mg	14.93 ± 0.95	10.57 ± 1.42	14.15 ± 1.57	22.84 ± 1.68	16.58 ± 0.82	15.29 ± 0.34	16.95 ± 1.64
S	34.61 ± 5.40	40.47 ± 5.60	23.09 ± 1.82	19.18 ± 1.10	16.42 ± 1.13	16.97 ± 1.98	7.26 ± 0.70

Means ± standard error of 50 m elevation intervals are shown

with elevation were not consistent (Table 1, Figure 1). The decreased trend in the second order polynomial function might be caused by decreasing temperature

since soil microbial activities would decrease with increased elevation due to lower temperature in higher places. Moreover, except for microbial com-

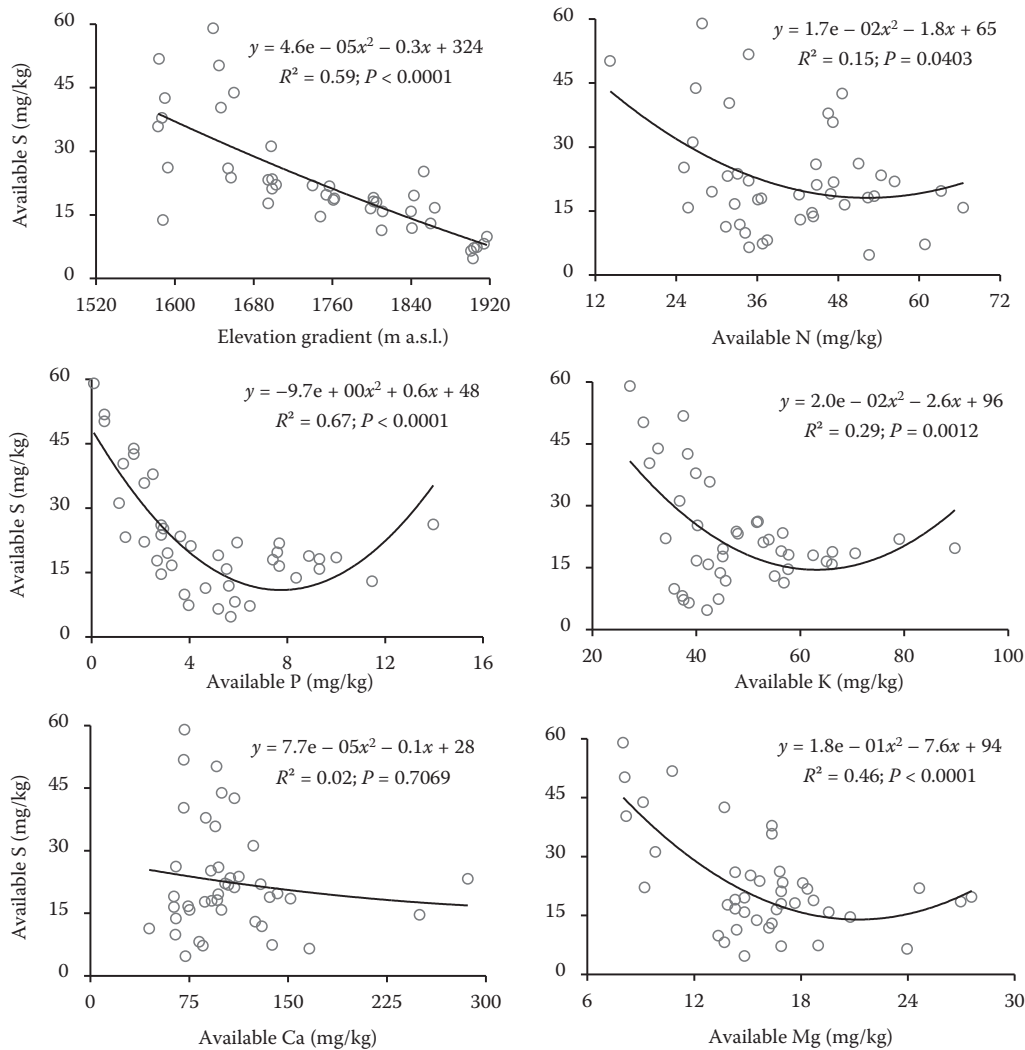


Figure 1. Correlations between available sulfur (AS) and elevation gradients and five major nutrients. Results by fitting $y = ax^2 + bx + c$ are shown

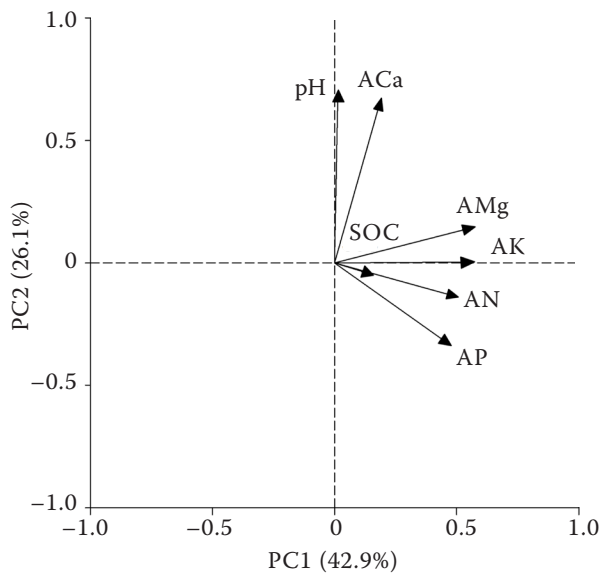


Figure 2. Principal component (PC) analysis of soil available nutrients, pH and soil organic carbon (SOC). A Ca – available calcium; AMg – available magnesium; AK – available potassium; AN – available nitrogen; AP – available phosphorus

munities, both the availability and decomposability of substrates releasing S also control soil AS levels (Xiao et al. 2015). Indeed, as was demonstrated, AS in uncultivated soil generally originated from mineral weathering, S deposition and decomposition of organic matter (Scherer 2009). Even though not considered in this work, atmospheric deposition of S in this area was reported ranging from 95 to 140 kg S/ha/year more than ten years ago (Wang et al. 2005, Cai et al. 2012). If the deposition levels change with elevation gradients, altered soil AS levels might also be induced by S deposition as this source was also an important component of soil S cycling (Xiao et al. 2015).

Importantly, changes in species composition and productivity with elevation would also affect soil nutrient cycling, and hence AS levels. For example, changes in plant functional groups were generally followed by altered C fixing and soil nutrient assimilation abilities (De Deyn et al. 2008). In alpine meadow ecosystems, AS might be more sensitive to these changes compared with macronutrients C, N, P, and K due to its relatively small amounts but functionally important role played in plant growth (Shi et al. 2016). Thereby, AS level changes with elevation might be the synthetic results of temperature, microbial activity and substrate in meadow ecosystems.

Moreover, changes in other nutrients could also induce alterations in AS due to the tight stoichiometric correlations between S and other elements (Figure 1). In addition to correlations between AS and elevation, significant correlations between AS and AN, AP, AK and AMg were also observed (Figure 1). While previous studies proposed stoichiometric correlations between S and other major soil elements (Shi et al. 2016, Tipping et al. 2016), the correlations vary with nutrients in our study (Figure 1). For example, the fitness and significant level of the model describing relationships between AS and AN were significant, and in line with tight correlations between S and N reported by previous studies (Gebauer et al. 1994) but not as strong as that between AS and AP, AMg or AK (Figure 1b–f). In general, soil AN included soluble nitrate N and ammonium N, which achieve their interconvertible balance by nitrification and other processes that are extremely sensitive to changes in soil pH, temperature and also plant species (Jiang et al. 2016). Similar soil environmental factors could be preferred by only one component of AN with AS. In contrast, while AP fractions could be any of solution P, adsorbed P and organic P, AK could be any exchangeable K or soluble K. Moreover, AMg was generally dominated by exchangeable Mg. Hence, correlations between AS and AN might be different to those between AS and AP, AK or AMg. However, the significant correlations that were observed here suggest AS may alter in response to changes in availabilities of N, P, K and Mg. Indeed, soil S cycling has been reported to decrease by N deposition via suppressing arylsulfatase activity, which was ascribed to decreased pH following N

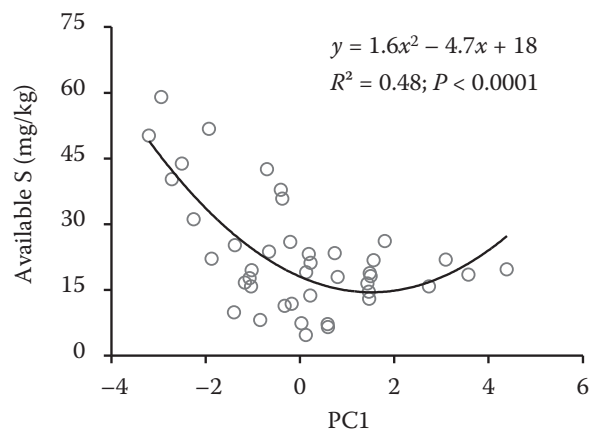


Figure 3. Correlations between available sulfur (AS) and principal component (PC1). Results by fitting $y = ax^2 + bx + c$ are shown

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Table 2. Pairwise correlations between principal component (PC1) and soil available nutrients (mg/kg), pH and soil organic carbon (SOC, mg/kg)

Variable	PC1	
	<i>R</i>	<i>P</i>
N	0.8065	< 0.0001
P	0.7596	< 0.0001
K	0.8998	< 0.0001
Ca	0.3189	0.0396
Mg	0.9091	< 0.0001
pH	0.0226	0.8868
SOC	0.1925	0.2219

Table 3. Dependence of soil available nutrients (mg/kg) on degradation and elevation

Factor	Degradation		Elevation		Model	
	<i>df</i>	<i>F</i>	<i>df</i>	<i>F</i>	<i>df</i>	<i>F</i>
N	2	0.28	1	0.17	3	0.24
P	2	1.63	1	0.01	3	1.09
K	2	2.69	1	6.89*	3	4.09*
Ca	2	1.4	1	0.69	3	1.17
Mg	2	6.84**	1	0.11	3	4.59*
S	2	10.59***	1	5.35*	3	8.84****

P* < 0.05; *P* < 0.01; ****P* < 0.001; *****P* < 0.0001

input (Chen et al. 2016). In addition, in areas with heavy sulfur dioxide-formed acid deposition, AS would be further altered as soil S and pH could be directly changed by S input and acidification of soil, respectively (Cai et al. 2012, Xiao et al. 2015).

The significant correlation between AS and PC1 based on pH, SOC and five other major nutrients suggesting substantial relationships between AS and soil environmental conditions or AS and other soil elements cycling (Figures 2 and 3) (Chen et

al. 2016, Fan et al. 2017). In addition, among all the variables, AMg, AK and AN correlated the most with PC1, indicating stronger contribution of AMg to PC1 and hence potential changes in AS across elevation gradients. However, significant correlations between pH, SOC and PC1 were not observed (Table 2). While pH and SOC both regulate the environmental conditions controlling microbial community activities, there might be no substantial change along the investigated short elevation gradient that was dominated by meadow

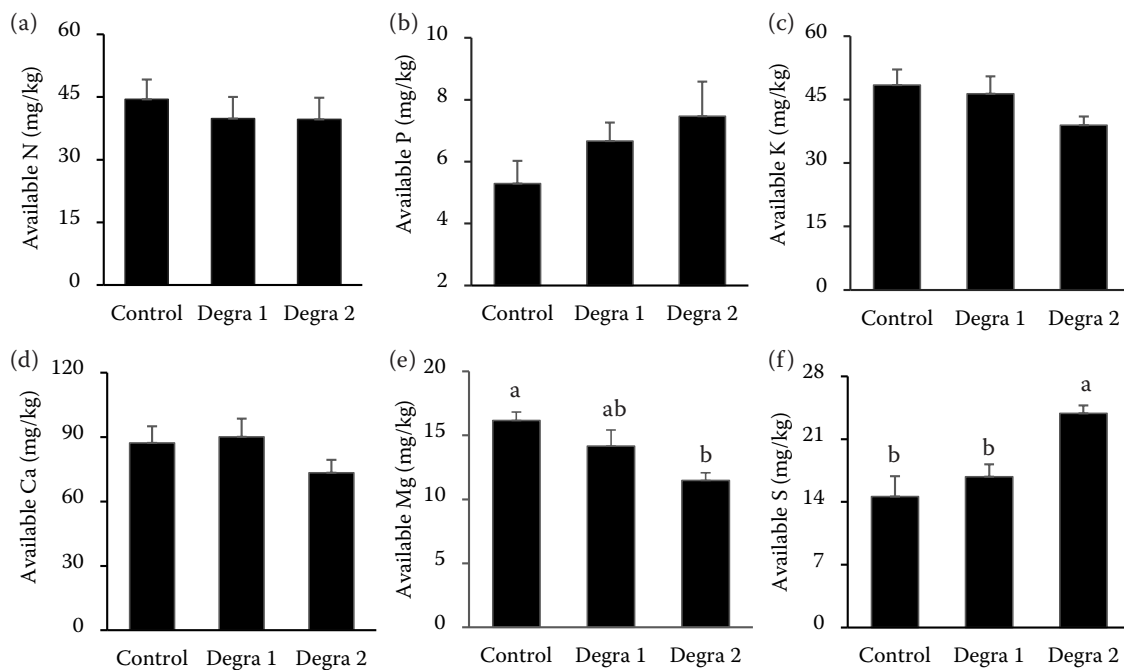


Figure 4. Dependence of soil available nutrients on degradation levels. Means with different letters are significantly different. Means + standard errors are shown. Control – more than 90% total vegetation coverage, degra 1 – 30–90%, degra 2 – less than 30% total vegetation coverage

Table 4. Pairwise correlations between soil available nutrients, pH, soil organic carbon (SOC) and the first two canonical scores of discriminant ordinations shown in Figure 5

Parameter		AN	AP	AK	ACa	AMg	AS	pH	SOC
Canonical 1	coefficient	-0.13	0.38*	-0.45*	-0.34	-0.70****	0.75****	-0.70****	-0.02
Canonical 2	coefficient	-0.18	0.24	0.06	0.28	-0.15	-0.10	-0.03	0.18

The largest coefficients are in bold. * $P < 0.05$; **** $P < 0.0001$. AN – available nitrogen; AP – available phosphorus; AK – available potassium; ACa – available calcium; AMg – available magnesium; AS – available sulfur

ecosystems in the Wugong Mountain. Future studies considering larger elevation gradients might be helpful in examining changes in pH and SOC and hence their contributions to nutrient availability.

AS increased with degradations (Table 3, Figure 4). In general, meadow degradation would be accompanied by decreased plant coverage and productivity, and hence lower absorption of available soil nutrients (Deng et al. 2016). The accumulation of C and N was reported in at least three studied sites in Northern Tibet (Liu et al. 2017) or observed in the Wugong Mountain (Deng et al. 2016) in seriously degraded meadows, respectively. Moreover, degradation of alpine meadows was generally followed by altered microbial community compositions (Li et al. 2016). While the levels of AS in meadow soils were largely controlled by the mineralization of organic matter containing S (Yang et al. 2007), changes in microbial communities could also induce fluctuations in sources of AS (Scherer 2009, Xiao et al. 2015). In addition, the significant correlations between S and organic C or total N indicate

substantial stoichiometric connections among C, N and S (Nguyen and Goh 1992, Wang et al. 2006). Changes in C or N following meadow degradation could also induce altered relationships among them (Tipping et al. 2016). Thereby, changes in AS with meadow degradation would be expected and might be common since changes in other nutrients would cause new balance in degraded meadows (Nguyen and Goh 1992). Changes in S should be considered when evaluating changes in enzyme activities, element limitation and fertilization practice for vegetation restorations.

The canonicals of discriminant analysis suggested substantial separation of meadows with different degradation levels (Figure 5) and the follow-up analysis showed that AS contributed the most to Canonical 1 (Table 4), indicating AS could have been profoundly altered in response to degradation relative to other elements (Nguyen and Goh 1992). Thereby, during the restoration of degraded meadows, AS should be considered in soil nutrient evaluation and fertilization management in degraded meadows.

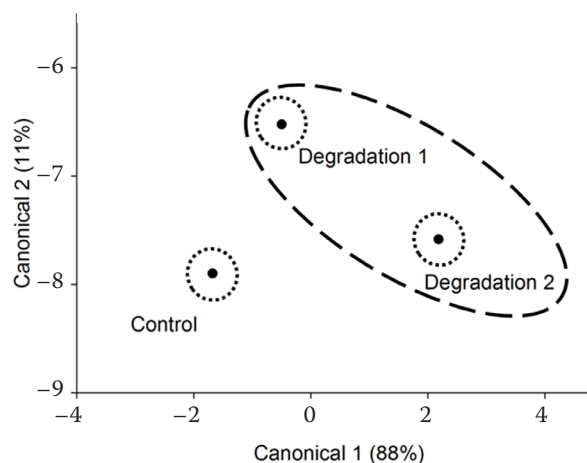


Figure 5. Discriminant analysis ordination of plots with different degradation levels. Control – more than 90% total vegetation coverage, degra 1 – 30–90%, degra 2 – less than 30% total vegetation coverage

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