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补播模式对喀斯特地区草地土壤养分和酶化学计量特征的影响

冯 阳¹, 高小叶^{1,2*}, 杨学东³, 王春梅⁴, 罗 彬³, 张 涛⁵

(1. 贵州民族大学生态环境工程学院, 贵州 贵阳 550025; 2. 天津大学地球系统科学学院, 天津 300072; 3. 贵州省草地技术试验推广站, 贵州 贵阳 550025; 4. 贵州大学动物科学学院, 贵州 贵阳 550025; 5. 贵州大学乡村振兴研究院, 贵州 贵阳 550025)

摘要:为探究补播模式对退化草地土壤养分和酶化学计量特征的影响,以贵州独山退化草地为研究对象,以退化草地(CK)为对照,设置燕麦(*Avena sativa* L.)+黑麦草(*Lolium perenne* L.)(AL)和燕麦+黑麦草+三叶草(*Trifolium* L.)(ALT)补播2个处理。结果表明:AL和ALT显著增加0~10 cm土层有机碳、全氮和速效磷含量,增幅分别为42.66%和57.29%、75.54%和116.30%、90.78%和155.59%。ALT处理下0~10 cm土层C/N显著降低,N/P提高,缓解了土壤氮缺乏; β -1,4-葡萄糖苷酶和 β -1,4-N-乙酰葡萄糖氨糖苷酶活性分别显著增加182.21%和186.85%,且增幅高于AL。ALT显著增加0~10 cm土层酶的矢量长度,加剧了微生物碳限制。相关分析表明,胞外酶活性主要受全氮和有机碳的共同调控。综上,该区域选择ALT补播模式可有效提高退化草地土壤有机碳和有效养分,缓解氮缺乏,提高土壤碳、氮循环相关酶活性,但是增强了表层土壤微生物的碳限制。

关键词:豆科;退化草地;可利用养分;胞外酶活性

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Effects of Reseeding Modes on Soil Nutrient and Enzymatic Stoichiometry Characteristics of Karst Grassland

FENG Yang¹, GAO Xiao-ye^{1,2*}, YANG Xue-dong³, WANG Chun-mei⁴, LUO Bin³, ZHANG Tao⁵

(1. College of Ecological and Environmental Engineering, Guizhou Minzu University, Guiyang, Guizhou Province 550025, China; 2. School of Earth System Science, Tianjin University, Tianjin 300072, China; 3. Guizhou Grassland Technology Experiment and Promotion Station, Guiyang, Guizhou Province 550025, China; 4. College of Animal Science, Guizhou University, Guiyang, Guizhou Province 550025, China; 5. Institute of Rural Revitalization, Guizhou University, Guiyang, Guizhou Province 550025, China)

Abstract: To investigate the effects of reseeded patterns on soil nutrients and enzyme stoichiometry of degraded grasslands, a study was conducted in the Dushan of Guizhou, China, using a degraded grassland (CK) as the control. Two reseeded treatments were established: oat (*Avena sativa* L.) + ryegrass (*Lolium perenne* L.) (AL) and oat + ryegrass + clover (*Trifolium* L.) (ALT). The results showed that both AL and ALT significantly increased the contents of organic carbon, total nitrogen, and available phosphorus in the 0~10 cm soil layer, with increasing by 42.66% and 57.29%, 75.54% and 116.30%, and 90.78% and 155.59%, respectively. Under the ALT treatment, the C/N ratio in the 0-10 cm soil layer significantly decreased, while the N/P ratio increased, alleviating soil nitrogen deficiency. The activities of β -1,4-glucosidase and β -1,4-N-acetylglucosaminidase significantly increased by 182.21% and 186.85%, respectively, with a higher increase than

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作者简介:冯阳(2000-),男,汉族,贵州遵义人,硕士研究生,主要从事农业资源与环境研究,E-mail:fengyang3920@163.com;*通信作者
Author for correspondence, E-mail:gaoxiaoye1220@163.com

that in the AL treatment. ALT significantly increased the enzyme vector length in the 0~10 cm soil layer, intensifying microbial carbon limitation. Correlation analysis indicated that extracellular enzyme activities were mainly regulated by the combined effects of total nitrogen and organic carbon. In conclusion, the ALT reseed-ing pattern could effectively improve soil organic carbon and available nutrients, alleviate nitrogen deficiency, and enhance soil enzyme activities related to carbon and nitrogen cycling in degraded grasslands in this region. However, it also strengthened the carbon limitation of surface soil microorganisms.

Key words: Legume; Degraded grasslands; Available nutrients; Extracellular enzyme activities

草地在维持生物多样性、降低水土流失和保持土壤肥力方面发挥关键作用^[1],中国约90%天然草地出现退化迹象,其中超过60%达到中到重度退化程度^[2]。草地退化削弱生态系统服务功能,导致土壤容重增加^[3],土壤水分^[4]、有机碳^[5]、氮磷^[6]等养分含量下降,进而降低草地生产力^[7]。目前国内外草地生态修复有免耕补播、合理放牧、人工草地建植、围栏封育、耕翻和施肥等措施^[8-9],补播改良是有效且易于实施的恢复措施之一^[10]。通过在退化草原上播种具有高营养价值和适应性强的优良草种,可有效改善土壤养分质量和牧草营养品质^[11-12],增加植被覆盖和草地植物群落物种多样性,进而提升草地生产力^[13]。其次,在补播后草地恢复过程中,有机质的输入增加,促进了土壤团聚体的形成,提高了团聚体的稳定性^[14]。在贵州喀斯特地区研究发现,赫章县退化天然草地3种补播改良处理,显著提高土壤全氮、速效钾含量和脲酶活性,并在一定程度上改善土壤肥力和提高产草量^[15];晴隆县退化草地补播白刺花,土壤有机质、全量和速效养分增加19.52%~27.08%^[16]。Wu等^[17]在青藏高原沙地草甸补播羊茅,显著增加土壤有机碳和全氮。在伊犁天然割草地补播通过增加地上植物量,植物根系改变了土壤微环境,间接作用于土壤养分,全氮含量提高38.10%^[18]。但也有研究发现,不同补播处理下内蒙古荒漠草原土壤养分含量无显著差异^[19]。因此,以化学计量学视角深入研究补播措施对喀斯特地区天然退化草地的影响,对于揭示土壤养分对补播草地生态系统恢复的响应具有重要的科学意义。

胞外酶参与土壤有机质的分解、养分转化和循环^[20],是评价土壤质量的重要指标^[21]。当前关注较多的胞外酶包括参与碳循环的 β -1,4-葡萄糖苷酶、参与氮循环的 β -1,4-N-乙酰葡萄糖苷酶和亮氨酸氨基肽酶,以及参与磷循环的酸性磷酸酶等^[22]。土壤酶化学计量可有效表征土壤养分限制状况^[23-24],其矢量长度和矢量角度可揭示微生物受到的碳、氮和磷等养分限制状况^[25]。王廖庆等^[26]研究发现,通过补播虎尾草和野大麦可以提高土壤脲酶、蔗糖

酶、纤维素酶、碱性磷酸酶和过氧化氢酶活性。在东北黑土区退化草甸研究发现,补播与施肥处理可降低土壤盐分含量,增加土壤脲酶、碱性磷酸酶活性和速效养分含量^[27]。云南退化高寒草甸研究发现,鸭茅、黑麦草、苜蓿等混播可提高脲酶和蛋白酶活性,从而提高土壤全量养分和速效氮含量^[28]。Wang等^[29]研究发现植被恢复显著提高了土壤淀粉酶、碱性磷酸酶、脲酶和蔗糖酶的活性。崔新等^[30]研究发现补播牧草和覆盖秸秆可以提高土壤脲酶、蔗糖酶、纤维素酶和碱性磷酸酶活性。此外,补播后凋落物输入增加会强烈刺激土壤酶的合成^[31]。虽然有关补播对退化草地土壤酶活性的影响开展了很多研究,有关酶化学计量的研究相对缺乏。并且,研究土壤酶化学计量可深入理解草地植被恢复过程中土壤养分限制的变化特征。本文研究通过分析不同补播模式下贵州喀斯特地区退化草地土壤理化性质、酶活性及其酶化学计量特征,探究退化草地补播后土壤养分限制状况,为石漠化地区草地生态修复及可持续管理提供科学依据。

1 材料与方法

1.1 研究区概况

本研究位于贵州省独山县(107°17'~107°52'E, 25°13'~26°01'N),80%以上为25°以上坡地,海拔1000 m左右,属中亚热带湿润季风性气候,年平均气温15℃,年降雨量为1429.9 mm,植被类型主要为常绿阔叶落叶混交林,灌木丛林、高乔木灌草丛,优势物种为白茅(*Imperata cylindrica*)和狗牙根(*Cynodon dactylon*),主要土地类型为黄壤土。研究地属于典型的喀斯特地貌区域,草地资源相对丰富,全县草地面积达4.1万hm²,是中国南方畜牧业重点县,但过度开展放牧等活动导致草地退化。为维持草地生产力,该县致力于发展人工草场20年,采取补播等措施恢复退化草地,主要措施为禾本科+禾本科按1:1比例混播,禾本科+禾本科+豆科按3:4:3比例混播等。

1.2 试验设计与样品采集

选择退化草地(CK)为对照,燕麦(*Avena sativa* L.)+黑麦草(*Lolium perenne* L.)(AL)和燕麦+黑麦草+三叶草(*Trifolium* L.)(ALT)补播2个试验处理,补播始于2017年,采用条播,AL处理下燕麦和黑麦草播种比例为1:1,分别为 $75\text{ kg}\cdot\text{hm}^{-2}$ 和 $10\text{ kg}\cdot\text{hm}^{-2}$,ALT处理下燕麦、黑麦草和三叶草按照3:4:3比例播种,分别为 $45\text{ kg}\cdot\text{hm}^{-2}$, $8\text{ kg}\cdot\text{hm}^{-2}$ 和 $1.5\text{ kg}\cdot\text{hm}^{-2}$ [32]。燕麦、黑麦草和三叶草单播量分别为 $150\text{ kg}\cdot\text{hm}^{-2}$, $20\text{ kg}\cdot\text{hm}^{-2}$ 和 $5\text{ kg}\cdot\text{hm}^{-2}$,混播比例均以单播为参考。每个处理设置3个重复,每个样地(重复)为 $10\text{ m}\times 10\text{ m}$ 。于2021年3月,采用5点法,用直径5 cm土钻采集0~10 cm和10~20 cm土层样品,采用四分法将样品分为两份,一份过2 mm土筛后,4℃冷藏用于测定土壤酶活性,一份风干后过筛测定土壤理化性质。

1.3 土壤分析测试方法

土壤pH值采用土水比1:2.5 pH计测定,土壤有机碳(Soil organic carbon, SOC)采用重铬酸钾氧化外加热法测定,土壤全氮(Total nitrogen, TN)采用半微量凯氏定氮法测定,全磷(Total phosphorus, TP)采用NaOH碱溶-钼锑抗比色法测定,速效磷(Available phosphorus, AP)采用 NaHCO_3 浸提-钼锑抗比色法测定[33]。

采用96孔板荧光法对土壤中的胞外酶活性进行定量分析。包括酸性磷酸酶(Acid phosphatase, ACP)、 β -1,4-葡萄糖苷酶(β -1,4-Glucosidase, BG)、 β -1,4-N-乙酰氨基葡萄糖苷酶(β -1,4-N-acetylglucosaminidase, NAG)和L-亮氨酸氨基肽酶(L-leucine aminopeptidase, LAP)。试验中,4-甲基伞形酮酯用作BG,AP和NAG活性的检测底物,而7-甲基香豆素盐酸盐用于LAP活性的检测。使用365 nm波长的激发光,在450 nm波长处测量吸光度,具体步骤参照Su等人[34]的研究方法。

土壤胞外酶活性(Extracellular enzyme activities, EEA)的生态化学计量特征计算[35]如下所示:

$$\text{EEA}_{\text{C/N}} = \ln(\text{BG}) / \ln(\text{LAP} + \text{NAG}) \quad (1)$$

$$\text{EEA}_{\text{C/P}} = \ln(\text{BG}) / \ln(\text{ACP}) \quad (2)$$

$$\text{EEA}_{\text{N/P}} = \ln(\text{LAP} + \text{NAG}) / \ln(\text{ACP}) \quad (3)$$

土壤胞外酶活性的向量特征计算[35]如下所示:

$$\text{VL} = \text{SQRT}(x^2 + y^2) \quad (4)$$

$$\text{VA} = \text{Degrees}[\text{ATAN2}(x, y)] \quad (5)$$

矢量长度(Vector length, VL)和矢量角度(Vector angle, VA)表征不同处理下土壤微生物的养分限制情况。式中,x表示 $\ln(\text{BG})/\ln(\text{ACP})$,y表示 $\ln(\text{BG})/\ln(\text{NAG} + \text{LAP})$,SQRT为开平方函数,Degrees为弧度转角度函数,ATAN2为反正切函数。矢量长度VL增加表明微生物C限制增加;土壤微生物N,P限制用矢量角度VA表示,矢量角度 $>45^\circ$ 和 $<45^\circ$ 分别表示磷和氮的限制,微生物磷限制随矢量角度增大而增大,微生物氮限制随矢量角度减小而减小[36]。

1.4 数据处理

所有数据经过Excel软件处理整合后,采用SPSS 27.0通过最小显著差数法(LSD)基于 $P < 0.05$ 对土壤理化性质、酶活性及其化学计量比等指标进行显著检验。用双因素方差(Two-Way ANOVA)分析比较不同处理和不同土层土壤养分的差异显著性,通过计算土壤特性与矢量长度和矢量角度的相关系数来评估相对重要性,用Pearson相关分析解析土壤碳氮磷化学计量比与酶活性指标的关系,用Origin 2021制图。

2 结果与分析

2.1 不同补播模式对土壤养分及化学计量特征的影响

与CK相比,0~20 cm土层AL和ALT处理提高土壤pH值,但差异不显著。补播显著提高0~20 cm土壤SOC和TN含量,且ALT处理增幅高于AL。补播处理增加土壤TP和AP含量,不同土层间TP含量均为AL最高,其中0~10 cm土层AL处理TP和AP含量显著高于CK,0~20 cm土层ALT处理AP含量显著高于CK。不同土层间AN含量在ALT下显著高于AL处理和CK,AL处理下仅10~20 cm土层AN含量显著高于CK(表1)。补播处理对土壤养分有显著影响,土层对除pH值和TP外其他养分的影响显著,补播与土层的交互作用仅对土壤AP产生显著影响(表2)。与CK相比,0~10 cm土层AL和ALT处理显著降低C/N(图1a),不同处理C/P差异不显著(图1b),ALT处理下0~20 cm土层N/P显著高于AL处理和CK(图1c)。

表 1 不同补播模式 0~20 cm 土层土壤养分含量

Table 1 Soil nutrient content in 0-20 cm with different reseeding modes

土层深度 Soil depth/cm	处理 Treatment	pH 值 pH	有机碳 SOC/(g·kg ⁻¹)	全氮 TN/(g·kg ⁻¹)	全磷 TP/(g·kg ⁻¹)	有效氮 AN/(mg·kg ⁻¹)	速效磷 AP/(mg·kg ⁻¹)
0~10	CK	4.42±0.18 ^a	18.59±0.18 ^b	1.84±0.04 ^b	0.43±0.03 ^b	51.59±2.50 ^b	11.28±0.62 ^b
	AL	5.05±0.37 ^a	26.52±1.01 ^a	3.23±0.15 ^a	0.71±0.13 ^a	51.96±4.47 ^b	21.52±2.68 ^a
	ALT	4.61±0.24 ^a	29.24±3.80 ^a	3.98±0.44 ^a	0.54±0.02 ^{ab}	81.44±5.22 ^a	28.83±2.50 ^a
10~20	CK	4.29±0.12 ^a	10.84±0.61 ^b	1.32±0.09 ^b	0.35±0.03 ^a	35.31±1.12 ^c	7.20±1.18 ^b
	AL	5.00±0.29 ^a	16.45±1.89 ^a	1.89±0.12 ^a	0.56±0.09 ^a	43.19±0.91 ^b	7.94±1.58 ^b
	ALT	4.66±0.20 ^a	17.58±1.90 ^a	2.37±0.22 ^a	0.41±0.04 ^a	58.88±2.78 ^a	16.08±1.49 ^a

注:同列不同小写字母表示同一土层深度不同处理间差异显著($P<0.05$),AL,燕麦+黑麦草;ALT,燕麦+黑麦草+三叶草;CK,退化草地。下同

Note: Different lowercase letters indicate significant differences among treatments at the same soil depth ($P<0.05$). AL, Oat+ryegrass; ALT, Oat+ryegrass+clover; CK, Degraded grassland. The same as below

表 2 不同处理和不同土层土壤养分间的双因素方差分析

Table 2 Two-way ANOVA of soil nutrients across different reseeding treatments and soil layers

因素 Factor	pH 值 pH	有机碳 SOC	全氮 TN	全磷 TP	有效氮 AN	有效磷 AP
T	*	**	***	*	***	***
D	ns	***	***	ns	***	***
T×D	ns	ns	ns	ns	ns	*

注:T,处理;D,土层深度;ns表示没有显著性,*表示 $P<0.05$,**表示 $P<0.01$,***表示 $P<0.001$

Note: T, Treatment; D, Soil depth, ns indicates no significance, * indicates $P<0.05$, ** indicates $P<0.01$, *** indicates $P<0.001$

2.2 不同补播模式对土壤酶活性的影响

AL 和 ALT 处理各土层土壤酶活性均高于对照(图 2),0~10 cm 土层 BG 酶活性在 ALT 处理下显著高于 CK($P<0.05$),增幅为 182.21%(图 2a)。0~10 cm 土层 NAG 酶活性在 ALT 处理下显著高于 CK;10~20 cm 土层在 AL 处理下最高,但各处理差异不显著(图 2b)。各层 LAP 酶活性 AL 处理最高,不同处理间无显著差异(图 2c)。0~10 cm 土层 ACP 酶活性在 AL 处理下显著高于 CK($P<0.05$),增幅为 122.31%,10~20 cm 土层各处理差异不显著(图 2d)。

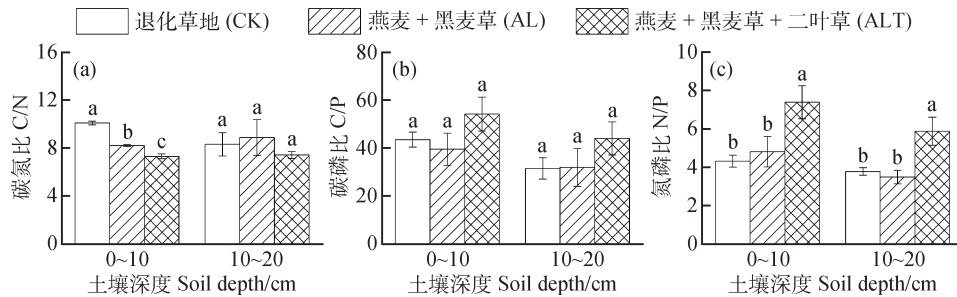


图 1 不同补播模式土壤碳氮磷化学计量特征

Fig. 1 Characteristics of changes in soil elemental stoichiometric ratios under different reseeding modes

注:C/N为土壤有机碳与全氮含量的比值;C/P为土壤有机碳与全磷含量的比值;N/P为土壤全氮与全磷含量的比值

Note: C/N is the ratio of soil organic carbon to total nitrogen content; C/P is the ratio of soil organic carbon to total phosphorus content; N/P is the ratio of soil total nitrogen to total phosphorus content

2.3 不同补播模式酶化学计量比和矢量特征

0~10 cm 土层酶 C/N 和 C/P 值在 ALT 处理下显著高于 CK($P<0.05$),10~20 cm 土层不同处理间差异不显著(图 3a 和 3b);不同处理间酶 N/P 无显著差异,且不同土层间无显著变化(图 3c)。矢量分

析结果表明,0~10 cm 土层矢量长度 ALT 处理显著高于 CK($P<0.05$)(图 4a),说明补播导致 0~10 cm 土层微生物碳限制增加;所有处理矢量角度均大于 45°(图 4b),表明该地区土壤微生物主要受磷限制,但不同处理间并无显著差异。

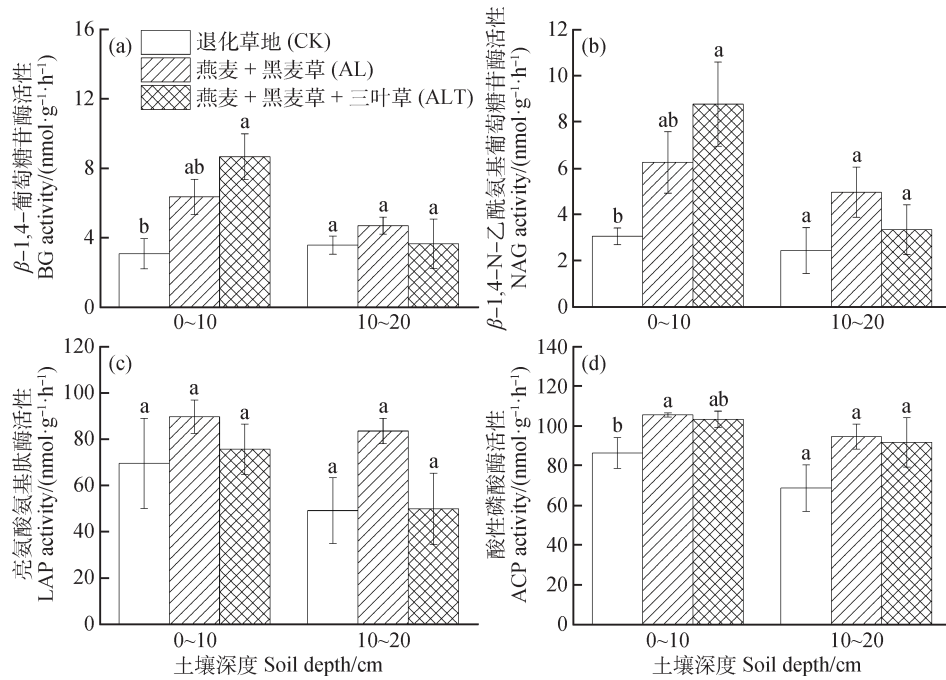


图2 不同补播模式土壤酶活性差异

Fig. 2 Differences in soil enzyme activities between reseeding modes

注: BG, β -1,4-葡萄糖苷酶; NAG, β -1,4-N-乙酰葡萄糖胺酶; LAP, 亮氨酸氨基肽酶; ACP, 酸性磷酸酶。下同

Note: BG, β -1,4-Glucosidase; NAG, β -1,4-N-Acetylglucosaminidase; LAP, Leucine Aminopeptidase; ACP, Acid phosphatase. The same as below

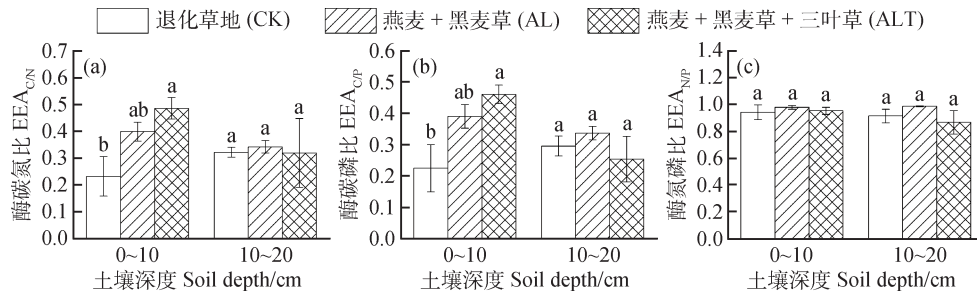


图3 不同补播模式酶化学计量特征

Fig. 3 Enzymatic stoichiometry characteristics under different reseeding modes

注: 与 C、N 循环相关酶活性的化学计量比 ($EEA_{C/N}$): $\ln(BG)/\ln(LAP+NAG)$, 与 C、P 循环相关酶活性的化学计量比 ($EEA_{C/P}$): $\ln(BG)/\ln(ACP)$; 与 N、P 循环相关酶活性的化学计量比 ($EEA_{N/P}$): $\ln(LAP+NAG)/\ln(ACP)$

Note: The stoichiometric ratio of enzyme activities related to the C and N cycles ($EEA_{C/N}$) is $\ln(BG)/\ln(LAP+NAG)$, the stoichiometric ratio of enzyme activities related to the C and P cycles ($EEA_{C/P}$) is $\ln(BG)/\ln(ACP)$, and the stoichiometric ratio of enzyme activities related to the N and P cycles ($EEA_{N/P}$) is $\ln(LAP+NAG)/\ln(ACP)$

2.4 土壤酶活性和土壤养分关系

Pearson 相关分析表明 (图 5), BG 活性与 SOC 和 TN 显著正相关 ($P < 0.05$); NAG 活性与土壤 pH 值、SOC、TN 显著正相关, 与 C/N 显著负相关 ($P < 0.05$); ACP 活性与 SOC, TN, BG 和 NAG 显著正相关 ($P < 0.05$)。矢量长度 VL 与

TN, BG, ACP, $EEA_{C/N}$ 和 $EEA_{C/P}$ 显著正相关; 矢角角度 VA 与 LAP 和 $EEA_{N/P}$ 呈显著负相关 ($P < 0.05$)。由图 6 可知, 土壤养分对于 C 限制和 N 限制的贡献存在差异, TN, SOC 和 AP 对 C 限制的影响相对较大, 而 pH 值和 TP 对 P 限制的影响较大。

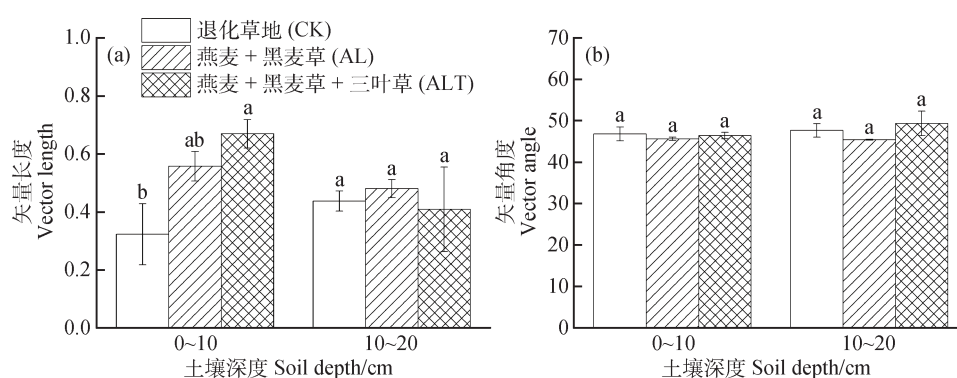


图 4 不同补播模式矢量特征

Fig. 4 Vector characteristics of different reseeding modes

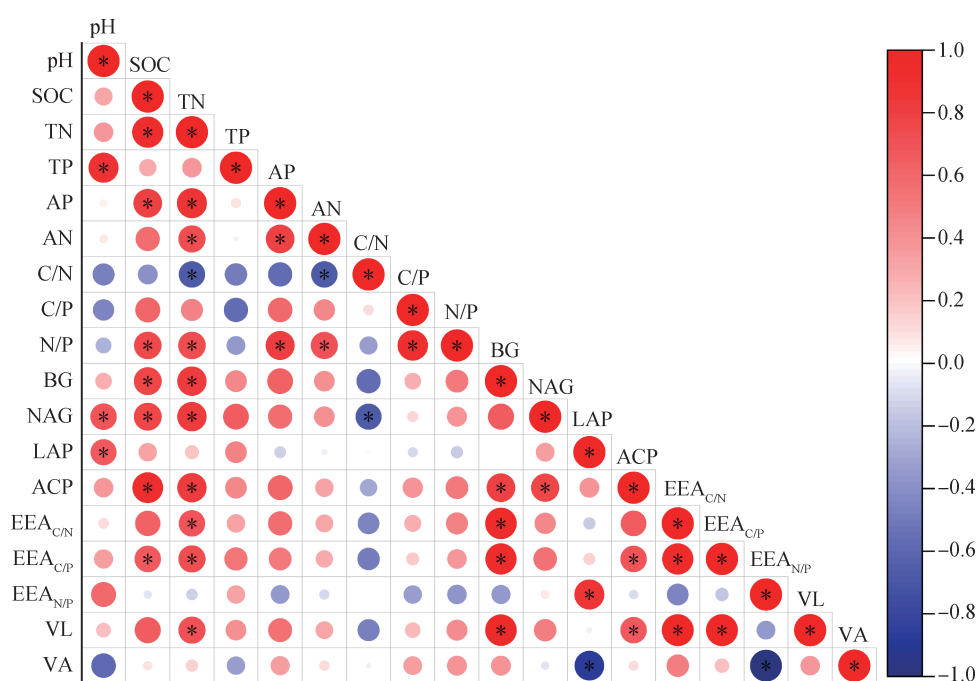


图 5 土壤酶活性及其化学计量比与土壤养分的相关分析

Fig. 5 Correlation analysis of soil enzyme activity and its stoichiometric ratio with soil nutrients

注:数值表示相关性,蓝色和红色分别代表正相关和负相关,颜色深浅代表相关性大小,*表示 $P < 0.05$,**表示 $P < 0.01$,***表示 $P < 0.001$,pH表示pH值,SOC表示土壤有机碳,TN表示全氮,TP表示全磷,AP表示有效磷,AN表示有效氮,C/N表示土壤有机碳比全氮,C/P表示土壤有机碳比全磷,N/P表示全氮比全磷,BG表示 β -1,4-葡萄糖苷酶,NAG表示 β -1,4-N-乙酰氨基葡萄糖苷酶,LAP表示L-亮氨酸氨基肽酶,ACP表示酸性磷酸酶, $EEA_{C/N}$ 表示 $\ln(BG)/\ln(LAP+NAG)$, $EEA_{C/P}$ 表示 $\ln(BG)/\ln(AP)$, $EEA_{N/P}$ 表示 $\ln(LAP+NAG)/\ln(ACP)$,VL表示矢量长度,VA表示矢量角度

Note: The values indicate correlation, with blue and red representing positive and negative correlations, respectively, and the shade of color representing the magnitude of the correlation, * indicates $P < 0.05$, ** indicates $P < 0.01$, *** indicates $P < 0.001$, pH represents the pH value, SOC represents soil organic carbon, TN represents total nitrogen, TP represents total phosphorus, AP represents available phosphorus, AN represents available nitrogen, C/N represents the ratio of soil organic carbon to total nitrogen, C/P represents the ratio of soil organic carbon to total phosphorus, N/P represents the ratio of total nitrogen to total phosphorus, BG represents β -1,4-glucosidase, NAG represents β -1,4-N-acetylglucosaminidase, LAP represents L-leucine aminopeptidase, ACP represents acid phosphatase, $EEA_{C/N}$ represents $\ln(BG)/\ln(LAP+NAG)$, $EEA_{C/P}$ represents $\ln(BG)/\ln(AP)$, $EEA_{N/P}$ represents $\ln(LAP+NAG)/\ln(ACP)$, VL represents vector length, VA represents vector angle

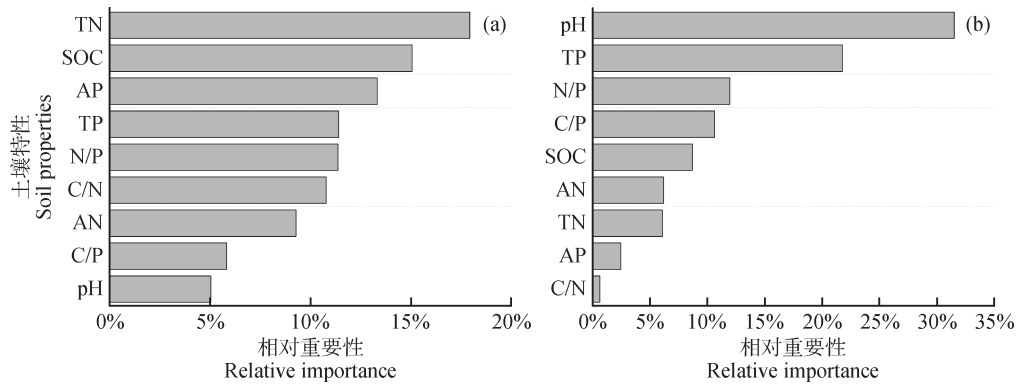


图6 土壤特性对矢量长度(a)和对矢量角度(b)的相对重要性

Fig. 6 Relative importance of soil properties on vector length (a) and vector angle (b)

3 讨论

3.1 补播模式对土壤碳氮磷及其化学计量比的影响

草地恢复是改善生态环境、促进土壤养分循环的重要措施, SOC和TN是评估土壤肥力及草地生产力的关键指标。本研究发现, 补播显著提高了土壤SOC, TN和AN含量, 尤其是禾本科+豆科的混播模式, 这与王星^[37]和王伟^[38]等人的研究相似, 王星研究发现浅翻耕+补播处理显著提高了退化荒漠草原0~20 cm土层SOC和TN含量, 王伟研究发现高寒草甸补播禾本科植物2年后土壤SOC, TN和AN含量显著提高。其原因可能是补播后凋落物归还, 使得土壤SOC含量提高, 促进氮硝化作用^[39]; 另外, 补播后植物根系增加, 根系分泌物也是SOC的重要来源^[40]。此外, 相较CK, AL和ALT一定程度上提高了土壤pH值, 可能会促进土壤微生物的活性, 有利于可利用养分的释放, 促进牧草生长, 从而对土壤SOC, TN和AN产生正反馈效应^[41]。本研究ALT处理TN含量增幅最高, 其原因可能是三叶草属于豆科植物, 能与根瘤菌共生, 能够固定大气中的氮气, 转化为植物可利用的氮源, 从而提高土壤TN^[42]。本研究中补播提高土壤TP和AP含量, 这与孙波等^[15]在贵州赫章阿西里大草原的研究结果类似, 该研究显示补播黑麦草+鸭茅+三叶草后土壤TP和AP显著提高。可能是因为植物可以覆盖土壤表面, 减少雨水冲刷和地表径流导致土壤磷素流失^[43]。另外, 本研究中补播提高了土壤pH值, 一定程度上能够释放土壤中与 Ca^+ , Mg^+ , Fe^+ , Al^+ 等阳离子结合的固化态磷, 进而提高土壤可利用磷含量^[44]。在本研究中, 补播显著降低了0~10 cm土层C/N, 较低的C/N可加速SOC的分

解, 不利于碳的积累^[45], 其原因可能是补播处理土壤TN含量增幅高于SOC增幅。类似研究显示, 采用早熟禾对中度退化草地进行补播后, 0~10 cm土层C/N降低^[46]。因此, 禾本科与豆科补播对于土壤氮的贡献可能高于碳的贡献。较低的C/P意味着土壤中磷的有效性较高, 速效磷的转化速率也较强^[47]。段成伟等^[48]研究发现免耕补播牧草提高了高寒草甸土壤C/P, 本研究也发现ALT处理提高了土壤C/P, 但是却缓解了土壤AP的缺乏, 尤其是禾本科与豆科混播。可能是因为ALT处理下SOC提高幅度高于TP。前人研究发现混播促进SOC积累与固氮作用, 这种协同效应可能间接提升土壤C/P和N/P^[49]。本研究发现ALT处理提高了0~20 cm土层N/P, 可能是因为豆科植物三叶草通过共生固氮作用(与根瘤菌共生)增加了氮的供给。综上, 禾本科+豆科的混播模式能够有效提高土壤SOC, TN以及可利用养分, 进而调节土壤碳、氮和磷的化学计量特征。

3.2 补播模式对土壤酶化学计量的影响

土壤酶活性是衡量土壤微生物代谢强度和物质循环效率的重要指标, 土壤胞外酶活性受到土壤基质质量和土壤养分平衡状态的影响^[50]。段成伟等^[51]研究发现补播降低了BG和NAG活性, 可能是因为试验年限较短, 在短期内没有明显效果。本研究发现, 两种补播方式均提高了0~10 cm土层BG和NAG酶活性, 其可能原因是补播可促进植物生长, 增加凋落物、根系分泌物等有机物输入, 从而改善土壤养分来源, 提高碳获取酶活性^[52]。而随着凋落物输入的增加, 导致大量的C元素输入到土壤中, 土壤微生物需吸收更多的N和P以保持其内部元素的稳定状态, 从而增加NAG和LAP等氮磷获取酶

活性^[53]。本研究中AL处理显著提高了0~10 cm土层土壤ACP活性,刘国富等^[27]研究也发现补播羊草可以提高土壤磷酸酶的活性。土壤胞外酶化学计量比反映了微生物在面临养分限制时的相对能量分配情况^[54-55],本研究发现,0~10 cm土层补播处理总体上提高了 $EEA_{C/N}$ 和 $EEA_{C/P}$,表明土壤微生物在面对养分限制时,增加了对碳、氮和磷的相对能量分配。微生物对分解底物化学计量比变异性的响应和调节的机制包括产生特定的胞外酶以获取受限制的资源^[54]。本研究发现补播增加了0~10 cm土层酶活的矢量长度,说明补播增强了土壤微生物的碳限制,原因可能是微生物在分解凋落物时会消耗自身储存的碳以提供能量,导致微生物的碳限制加剧。所有处理土壤酶活矢量角度均大于45°,表明该区域草地恢复过程中土壤微生物受到磷限制。邓竹辛等^[25]也发现在草地恢复过程中,0~20 cm土层的矢量角度始终大于45°,土壤微生物代谢始终受到磷限制。Pearson相关分析发现,TN含量与BG,NAG和ACP显著正相关,表明土壤碳、氮、磷相关酶受土壤TN含量调控。土壤氮元素增加可通过增强植被生物量来增加土壤中碳的输入,提高微生物对养分和能量的获取,并依据资源分配的原则,对酶的分泌进行调节,改变酶的生化特性,从而提高酶的活性^[56]。此外,SOC也与BG,NAG和ACP呈显著正相关,表明磷相关酶对土壤有机碳的变化敏感,因此,土壤BG,NAG和ACP活性,可作为衡量土壤肥力的生物学指标^[57]。

4 结论

退化草地补播黑麦草+燕麦+三叶草可显著提高0~10 cm土层SOC,TN,AN和AP含量以及土壤碳氮循环相关的BG和NAG活性;补播黑麦草+燕麦则可以显著改善土壤SOC,TN,TP和AP与土壤磷循环相关的ACP酶活性。0~10 cm土层燕麦+黑麦草+三叶草补播处理显著提高了土壤酶活性化学计量比 $EEA_{C/N}$ 和 $EEA_{C/P}$,表明土壤微生物在面对养分限制时,增加了对碳、氮和磷的相对能量分配。0~10 cm土层补播增加矢量长度,说明补播增强了微生物的碳限制,且TN和SOC对碳限制的影响相对较大。所有处理的矢量角度都大于45°,表明补播未能有效改善草地土壤微生物磷限制,pH值和TP对于磷限制的影响最大。研究结果

表明燕麦+黑麦草+三叶草补播更适用于氮素严重缺乏的退化草地,而AL在缺磷型土壤中更具优势。

参考文献

- [1] 喻岚晖,王杰,廖李容,等. 青藏高原退化草甸土壤微生物量、酶化学计量学特征及其影响因素[J]. 草地学报,2020,28(6):1702-1710
YU J H, WANG J, LIAO L R, et al. Soil microbial biomass, enzyme activities and ecological stoichiometric characteristics and influencing factors along degraded meadows on the Qinghai-Tibet Plateau[J]. Acta Agrestia Sinica, 2020, 28(6): 1702-1710
- [2] 白永飞,潘庆民,邢旗. 草地生产与生态功能合理配置的理论基础与关键技术[J]. 科学通报,2016,61(2):201-212
BAI Y F, PAN Q M, XING Q. Fundamental theories and technologies for optimizing the production functions and ecological functions in grassland ecosystems[J]. Chinese Science Bulletin, 2016, 61(2): 201-212
- [3] 其曼古丽·帕拉提,刘丹,毛军,等. 不同退化程度高寒草地土壤碳氮磷含量及生态化学计量特征[J]. 生态学杂志,2024,43(6):1612-1620
PALATI Q, LIU D, MAO J, et al. Contents and eco-stoichiometric characteristics of soil carbon, nitrogen, and phosphorus in alpine grasslands with different degradation degrees[J]. Chinese Journal of Ecology, 2024, 43(6): 1612-1620
- [4] 郝爱华,薛娴,彭飞,等. 青藏高原典型草地植被退化与土壤退化研究[J]. 生态学报,2020,40(3):964-975
HAO A H, XUE X, PENG F, et al. Different vegetation and soil degradation characteristics of a typical grassland in the Qinghai-Tibetan Plateau[J]. Acta Ecologica Sinica, 2020, 40(3): 964-975
- [5] 邵建翔,刘育红,马辉,等. 退化高寒草地浅层土壤理化性质Meta分析[J]. 草地学报,2022,30(6):1370-1378
SHAO J X, LIU Y H, MA H, et al. Meta-analysis of physical and chemical properties of shallow soils in degraded alpine grasslands[J]. Acta Agrestia Sinica, 2022, 30(6): 1370-1378
- [6] 贺有龙. 不同退化程度高寒灌丛草甸植物量及土壤养分的变化[J]. 西北农业学报,2014,23(7):184-190
HE Y L. Changes of biomass and soil nutrients in the differently degraded alpine *Salix paraqpleisia* shrub meadows[J]. Acta Agriculturae Boreali-Occidentalis Sinica, 2014, 23(7): 184-190
- [7] 宋淑珍,熊康宁,池永宽,等. 中国南方喀斯特石漠化治理中的退化草地改良研究综述[J]. 家畜生态学报,2019,40(3):82-87,96
SONG S Z, XIONG K N, CHI Y K, et al. Study on improvement of degraded grassland in rocky desertification control in the karst areas of Southern China[J]. Journal of Domestic Animal Ecology, 2019, 40(3): 82-87, 96
- [8] 罗晓宇,王顺霞,石薇,等. 利用方式与施氮对黄土高原无芒雀麦农艺性状、产量和品质的影响[J]. 草地学报,2022,30(11):3119-3131

- LUO X Y, WANG S X, SHI W, et al. Effects of using methods and nitrogen application on agronomic characters, yield and quality of *bromus inermis* in Loess Plateau[J]. Acta Agrestia Sinica, 2022, 30(11): 3119-3131
- [9] 古琛, 贾志清, 杜波波, 等. 中国退化草地生态修复措施综述与展望[J]. 生态环境学报, 2022, 31(7): 1465-1475
- GU C, JIA Z Q, DU B B, et al. Reviews and prospects of ecological restoration measures for degraded grasslands of China[J]. Ecology and Environmental Sciences, 2022, 31(7): 1465-1475
- [10] 姬万忠, 王庆华. 补播对天祝高寒退化草地植被和土壤理化性质的影响[J]. 草业科学, 2016, 33(5): 886-890
- JI W Z, WANG Q H. Effects of over-seeding on plant community and soil physical and chemical properties of degraded grassland in Tianzhu County[J]. Pratacultural Science, 2016, 33(5): 886-890
- [11] 刘伟, 赵越, 杨龙, 等. 补播优良牧草对新疆昭苏退化草地生产性能和牧草品质的影响[J]. 草地学报, 2025, 33(1): 231-240
- LIU W, ZHAO Y, YANG L, et al. Effects of reseeding fine forage on production performance and forage quality of degraded grassland in Zhaosu, Xinjiang[J]. Acta Agrestia Sinica, 2025, 33(1): 231-240
- [12] 徐然然, 常生华, 贾倩民, 等. 施氮和利用方式对黄土高原禾豆混播草地产量、品质和水分利用的影响[J]. 草地学报, 2020, 28(6): 1744-1755
- XU R R, CHANG S H, JIA Q M, et al. Effects of nitrogen application and utilization methods on yield, quality and water use of Grass-Legume mixed grassland in Loess Plateau[J]. Acta Agrestia Sinica, 2020, 28(6): 1744-1755
- [13] 张海娟, 周学丽, 芦光新, 等. 有机肥与补播对退化人工草地植被与土壤的影响[J]. 中国草地学报, 2023, 45(2): 67-75
- ZHANG H J, ZHOU H L, LU G X, et al. Effect of organic fertilizer and reseeding on vegetation and soil in degraded artificial grassland[J]. Chinese Journal of Grassland, 2023, 45(2): 67-75
- [14] SHI P, REN M X, LI P, et al. Effects of 15-year vegetation restoration on organic carbon in soil aggregates on the Loess Plateau, China[J]. Archives of Agronomy and Soil Science, 2023, 69(3): 344-357
- [15] 孙波, 吴瑛, 周大荣, 等. 复合改良措施对喀斯特山区退化天然草地土壤性质和植被特征的影响[J]. 草业科学, 2024, 41(10): 2263-2274
- SUN B, WU Y, ZHOU D R, et al. The impact of composite improvement measures on soil properties and vegetation characteristics of degraded natural grasslands in Karst Mountainous Areas[J]. Pratacultural Science, 2024, 41(10): 2263-2274
- [16] 陈芝能, 龙忠富, 马培杰, 等. 补播盘江白刺花对岩溶山区退化草地植被和土壤性质的影响[J]. 农技服务, 2022, 39(9): 47-50
- CHEN Z N, LONG Z F, MA P J, et al. The impact of replanting panjiang white thornflower on vegetation and soil properties in degraded grasslands of Karst Mountain Areas[J]. Agricultural Technology Service, 2022, 39(9): 47-50
- [17] WU G L, LI W, ZHAO L P, et al. Artificial management improves soil moisture, C, N and P in an alpine sandy meadow of western china[J]. Pedosphere, 2011, 21(3): 407-412
- [18] 霍倩倩, 宋洋洋, 段震宇, 等. 补播对伊犁天然割草地土壤理化性质及微生物群落结构的影响[J]. 草地学报, 2025, 33(2): 429-439
- HUO Q Q, SONG Y Y, DUAN Z Y, et al. Effects of reseeding on soil physicochemical properties and microbial community structure in Yili natural mowing land[J]. Acta Agrestia Sinica, 2025, 33(2): 429-439
- [19] 姚敏, 赵佳乐, 王忠武, 等. 不同补播模式对荒漠草原植物群落特征及土壤养分的影响[J]. 中国草地学报, 2024, 46(5): 14-22
- YAO M, ZHAO J L, WANG Z W, et al. Effects of reseeding patterns on plant community characteristics and soil nutrient in desert steppe[J]. Chinese Journal of Grassland, 2024, 46(5): 14-22
- [20] 乔文静, 戴银月, 张伟, 等. 黄土丘陵区撂荒恢复过程中植物群落组成与土壤养分及酶活性变化的关系[J]. 环境科学, 2018, 39(12): 5687-5698
- QIAO W J, DAI Y Y, ZHANG W, et al. Relationship between the vegetation community and soil nutrient and enzyme activity during the restoration of abandoned land in the Loess Hilly Region[J]. Environmental Science, 2018, 39(12): 5687-5698
- [21] 高瑞敏, 严君, 韩晓增, 等. 不同有机物料还田对白浆土土壤化学计量特征及胞外酶活性的影响[J]. 干旱地区农业研究, 2024, 42(5): 198-205, 15
- GAO R M, YAN J, HAN X Z, et al. Effects of returning different organic materials to soil on stoichiometric characteristics and extracellular enzyme activities of albic soil[J]. Agricultural research in the arid areas, 2024, 42(5): 198-205, 15
- [22] 苗宇, 侯瑞星, 裴浩, 等. 有机物料还田对黑土胞外酶化学计量特征的影响[J]. 农业工程学报, 2023, 39(22): 207-215
- MIAO Y, HOU R X, PEI H, et al. Impact of organic material incorporation on the chemical stoichiometry characteristics of extracellular enzymes in black soil[J]. Transactions of the Chinese Society of Agricultural Engineering, 2023, 39(22): 207-215
- [23] GHOSH A, SINGH A B, KUMAR R V, et al. Soil enzymes and microbial elemental stoichiometry as bio-indicators of soil quality in diverse cropping systems and nutrient management practices of Indian Vertisols[J]. Applied Soil Ecology, 2020, 145: 103304
- [24] 张延文, 周雅洁, 张不染, 等. 固沙林恢复土壤酶化学计量特征与养分限制效应[J]. 水土保持研究, 2023, 30(6): 102-111
- ZHANG Y W, ZHOU Y J, ZHANG B R, et al. Soli enzymatic stoichiometry and nutrient limitation during revegetation in sand-fixing forest[J]. Research of Soil and Water Conservation, 2023, 30(6): 102-111
- [25] 邓竹辛, 类延宝, 孙庚, 等. 川西北高寒退化草地恢复过程中土壤酶活性及其化学计量特征[J]. 应用与环境生物学报, 2025, 31(3): 463-475

- DENG Z X, LEI Y B, SUN G, et al. Soil enzyme activities and their stoichiometric characteristics in the ecological restoration process of a desertified alpine meadow in northwestern Sichuan [J]. Chinese Journal of Applied and Environmental Biology, 2025, 31(3): 463-475
- [26] 王彦庆, 李洪影, 李冰, 等. 盐碱草地补播虎尾草、野大麦同时覆盖秸秆对土壤酶活性的影响[J]. 草地学报, 2015, 23(4): 738-743
- WANG Y Q, LI H Y, LI B, et al. Effects of reseeding *Chloris virgata* and *Hordeum brevisublatum* and mulching pulverized corn straw on the activities of soil enzymes in saline-alkali grassland [J]. Acta Agrestia Sinica, 2015, 23(4): 738-743
- [27] 刘国富, 孙雪, 肖知新, 等. 补播和施肥对退化草甸土壤化学性质及酶活性的影响[J]. 中国草地学报, 2022, 44(11): 66-75
- LIU G F, SUN X, XIAO Z X, et al. Effects of reseeding and fertilizing on the chemical properties and enzyme activities of degraded meadow soils [J]. Chinese Journal of Grassland, 2022, 44(11): 66-75
- [28] 张冉, 杨蔚, 王文, 等. 补播对退化高寒草甸牧草养分及土壤理化性质的影响[J]. 草业科学, 2022, 39(6): 1059-1068
- ZHANG R, YANG W, WANG W, et al. Effects of reseeding on forage nutrition and physical and chemical properties of degraded alpine meadow soils [J]. Pratacultural Science, 2022, 39(6): 1059-1068
- [29] WANG L J, LUO N N, SHI Q L, et al. Responses of soil labile organic carbon fractions and enzyme activities to long-term vegetation restorations in the karst ecosystems, Southwest China [J]. Ecological Engineering, 2023, 194: 107034
- [30] 崔新, 崔国文, 李洪影, 等. 覆盖秸秆和补播牧草对松嫩平原退化盐碱草地土壤酶活性的影响[J]. 中国草地学报, 2014, 36(5): 95-100
- CUI X, CUI G W, LI H Y, et al. Influence of straw covering and reseeding on soil enzyme activity in saline and alkaline grassland in Songnen Plain [J]. Chinese Journal of Grassland, 2014, 36(5): 95-100
- [31] YIN R, DENG H, WANG H L, et al. Vegetation type affects soil enzyme activities and microbial functional diversity following re-vegetation of a severely eroded red soil in sub-tropical China [J]. Catena, 2014, 115: 96-103
- [32] 王世成. 贵州坡地多年生牧草品种混播组合和轮牧放养肥架子牛效果研究[D]. 重庆: 西南大学, 2024: 5-23
- WANG S C. Study on the effects of mixed sowing combinations of perennial forage grasses and rotational grazing for fattening steers on sloping land in Guizhou [D]. Chongqing: Southwest University, 2024: 5-23
- [33] 鲍士旦. 土壤农化分析[M]. 第3版. 北京: 中国农业出版社, 2000: 25-200
- BAO S D. Soil Agrochemical Analysis [M]. 3rd Edition. Beijing: China Agriculture Press, 2000: 25-200
- [34] SU Z X, ZHU X Y, WANG Y B, et al. Litter C and N losses at different decomposition stages of *Robinia pseudoacacia*: the weaker effects of soil enzyme activities compared with those of litter quality and the soil environment [J]. Frontiers in Environmental Science, 2022, 10: 956309
- [35] MOORHEAD D L, SINSABAUGH R L, HILL B H, et al. Vector analysis of ecoenzyme activities reveal constraints on coupled C, N and P dynamics [J]. Soil Biology and Biochemistry, 2016, 93: 1-7
- [36] CUI Y, ZHANG Y, DUAN C, et al. Ecoenzymatic stoichiometry reveals microbial phosphorus limitation decreases the nitrogen cycling potential of soils in semi-arid agricultural ecosystems [J]. Soil and Tillage Research, 2020, 197: 104463
- [37] 王星, 于双, 许冬梅, 等. 不同恢复措施对退化荒漠草原土壤碳氮及其组分特征的影响[J]. 草业学报, 2022, 31(1): 26-35
- WANG X, YU S, XU D M, et al. Effects of different restorative measures on soil carbon and nitrogen and their component fractions in a degraded desert steppe [J]. Acta Pratacultural Sinica, 2022, 31(1): 26-35
- [38] 王伟, 德科加. 不同补播年限下河南县高寒草甸地上生物量、群落多样性与土壤养分特征的相关性研究[J]. 青海畜牧兽医杂志, 2017, 47(2): 12-16
- WANG W, DE K J. Correlation analysis of aboveground biomass, community diversity and soil nutrient characteristics on Alpine meadow in Henan County under different reseed year [J]. Chinese Qinghai Journal of Animal and Veterinary Sciences, 2017, 47(2): 12-16
- [39] 张骞, 张中华, 马丽, 等. 不同牧草混播对退化高寒草甸土壤养分及生物量的影响[J]. 草地学报, 2019, 27(6): 1659-1666
- ZHANG Q, ZHANG Z H, MA L, et al. Effects of mixed sowing of different pasture grasses on soil nutrients and biomass in degraded alpine meadows [J]. Acta Agrestia Sinica, 2019, 27(6): 1659-1666
- [40] LI Y, YANG X, BAI X, et al. Composition and contribution of *Stipa bungeana* root exudates to soil organic carbon fractions in the Loess Plateau [J]. Applied Soil Ecology, 2023, 189: 104957
- [41] 王伟, 徐成体, 曾鹏. 补播对高寒草甸生物量和养分的影响[J]. 青海畜牧兽医杂志, 2017, 47(6): 9-14
- WANG W, XU C T, Z P. Influence of reseeding on aboveground biomass and of nutrients of Alpine meadow [J]. Chinese Qinghai Journal of Animal and Veterinary Sciences, 2017, 47(6): 9-14
- [42] 李志芳, 朱春茂, 吴文良, 等. 白三叶草/根瘤菌共生固氮潜力及干旱限制因素[J]. 农业环境科学学报, 2009, 28(3): 639-644
- LI Z F, ZHU C M, WU W L, et al. Potential capacity of symbiosis nitrogen fixation of white clover-*Rhizobium* interaction and drought limiting factor [J]. Journal of Agro-Environment Science, 2009, 28(3): 639-644
- [43] SOLTANGHEISI A, RODRIGUES M, COELHO M J A, et al. Changes in soil phosphorus lability promoted by phosphate sources and cover crops [J]. Soil and Tillage Research, 2018, 179: 20-28
- [44] GARG S, BAH L G S. Phosphorus availability to maize as influenced by organic manures and fertilizer P associated phosphatase activity in soils [J]. Bioresource Technology, 2008, 99(13): 5773-5777

- [45] MARTY C, HOULE D, GAGNON C, et al. The relationships of soil total nitrogen concentrations, pools and C:N ratios with climate, vegetation types and nitrate deposition in temperate and boreal forests of eastern Canada[J]. *Catena*, 2017, 152:163-172
- [46] 尹亚丽, 王玉琴, 李世雄, 等. 补播对退化高寒草甸土壤性质及酶活性的影响[J]. 青海畜牧兽医杂志, 2020, 50(6):1-6
YIN Y L, WANG Y Q, LI S X, et al. Effect of replanting on soil properties and enzyme activities in degraded alpine meadows[J]. *Chinese Qinghai Journal of Animal and Veterinary Sciences*, 2020, 50(6):1-6
- [47] 牛得草, 李茜, 江世高, 等. 阿拉善荒漠区6种主要灌木植物叶片C:N:P化学计量比的季节变化[J]. 植物生态学报, 2013, 37(4):317-325
NIU D C, LI Q, JIANG S G, et al. Seasonal variations of leaf C:N:P stoichiometry of six shrubs in desert of China's Alxa Plateau[J]. *Chinese Journal of Plant Ecology*, 2013, 37(4):317-325
- [48] 段成伟, 李希来, 柴瑜, 等. 人工修复下退化高寒草甸碳、氮、磷生态化学计量特征[J]. 中国草地学报, 2022, 44(7):23-32
DUAN C W, LI X L, CHAI Y, et al. Eco-stoichiometric characteristics of carbon, nitrogen, and phosphorus in degraded alpine meadow under artificial restoration[J]. *Chinese Journal of Grassland*, 2022, 44(7):23-32
- [49] 芦奕晓, 牟乐, 杨惠敏. 豆科与禾本科牧草混播改良土壤的研究进展[J]. 中国草地学报, 2019, 41(1):94-100
LU Y X, MU L, YANG H M. Advances in improved soil fertility with legume-grass mixtures[J]. *Chinese Journal of Grassland*, 2019, 41(1):94-100
- [50] 胡培雷, 王克林, 曾昭霞, 等. 喀斯特石漠化地区不同退耕年限下桂牧1号杂交象草植物-土壤-微生物生态化学计量特征[J]. 生态学报, 2017, 37(3):896-905
HU P L, WANG K L, ZENG Z X, et al. Ecological stoichiometric characteristics of plants, soil, and microbes of *Pennisetum purpureum* cv. Guimu-1 pastures at different rehabilitation ages in a karst rocky desertification region[J]. *Acta Ecologica Sinica*, 2017, 37(3):896-905
- [51] 段成伟, 李希来, 马盼盼, 等. 人工修复措施对退化高寒草甸土壤养分及酶活性的影响[J]. 西北农业学报, 2022, 31(4):431-440
DUAN C W, LI X L, MA P P, et al. Effect of artificial restoration measure on soil nutrients and enzyme activities of degraded alpine meadow[J]. *Acta Agriculturae Boreali-Occidentalis Sinica*, 2022, 31(4):431-440
- [52] 陈雅轩, 张彧璠, 王佳乐, 等. 不同林龄华北落叶松土壤酶活性和碳氮磷化学计量变化[J]. 生态学报, 2025, 45(1):25-41
CHEN Y X, ZHANG Y F, WANG J L, et al. Changes of soil enzyme activity and the stoichiometry of carbon, nitrogen, and phosphorus in *Larix principis-rupprechtii* plantations at different ages[J]. *Acta Ecologica Sinica*, 2025, 45(1):25-41
- [53] 刘宁, 刘佩雯, 何浩勇, 等. 凋落物对喀斯特喀木土壤微生物量和土壤酶活性的影响[J]. 广西师范大学学报(自然科学版), 2025, 43(1):1-16
L N, L P W, H H Y, et al. Effects of litter on soil microbial biomass and soil enzyme activities of *Loropetalum chinense* community in Karst Area[J]. *Journal of Guangxi Normal University (Natural Science Edition)*, 2025, 43(1):1-16
- [54] 周正虎, 王传宽. 微生物对分解底物碳氮磷化学计量的响应和调节机制[J]. 植物生态学报, 2016, 40(6):620-630
ZHOU Z H, WANG C K. Responses and regulation mechanisms of microbial decomposers to substrate carbon, nitrogen, and phosphorus stoichiometry[J]. *Chinese Journal of Plant Ecology*, 2016, 40(6):620-630
- [55] 汪宗飞, 郑粉莉. 黄土高原子午岭地区人工油松林碳氮磷生态化学计量特征[J]. 生态学报, 2018, 38(19):6870-6880
WANG Z F, ZHENG F L. C, N, and P stoichiometric characteristics of *Pinus tabulaeformis* plantation in the Ziwuling Region of the Loess Plateau[J]. *Acta Ecologica Sinica*, 2018, 38(19):6870-6880
- [56] 何斌, 李青, 冯图, 等. 黔西北不同林龄马尾松人工林针叶-凋落物-土壤C、N、P化学计量特征[J]. 生态环境学报, 2019, 28(11):2149-2157
HE B, LI Q, FENG T, et al. Stoichiometry characteristics of C, N, and P in needle leaves, litter, and soil during stand development in a *Pinus massoniana* plantation in northwest Guizhou Province[J]. *Ecology and Environmental Sciences*, 2019, 28(11):2149-2157
- [57] 王芸, 韩宾, 史忠强, 等. 保护性耕作对土壤微生物特性及酶活性的影响[J]. 水土保持学报, 2006(4):120-122, 42
WANG Y, HAN B, SHI Z Q, et al. Effects of conservation tillage on soil microbial characters and soil enzyme activities[J]. *Journal of Soil and Water Conservation*, 2006(4):120-122, 42

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