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封面图说: 塞罕坝地处内蒙古高原南缘向华北平原的过渡带,地势分为坝上、坝下两部分。解放初期,这里是“飞鸟无栖树,黄沙遮天日”的荒原沙丘,自 1962 年建立了机械化林场之后,塞罕坝人建起了 110 多万亩人工林,造就了中国最大的人工林林场。这是让人叹为观止的落叶松人工林海。

彩图提供: 陈建伟教授 国家林业局 E-mail: cites.chenjw@163.com

何念鹏, 韩兴国, 于贵瑞. 长期封育对不同类型草地碳贮量及其固持速率的影响. 生态学报, 2011, 31(15): 4270-4276.

He N P, Han X G, Yu G R. Carbon and nitrogen sequestration rate in long-term fenced grasslands in Inner Mongolia, China. Acta Ecologica Sinica, 2011, 31(15): 4270-4276.

长期封育对不同类型草地碳贮量及其固持速率的影响

何念鹏^{1,2,*}, 韩兴国², 于贵瑞¹

(1. 中国科学院地理科学与资源研究所, 生态系统网络观测与模拟重点实验室, 北京 100101

2. 中国科学院植物研究所, 植被与环境变化国家重点实验室, 北京 100093)

摘要: 基于 4 个长期封育草地, 采用成对取样方法(封育-自由放牧草地)分析了长期封育和自由放牧草地地上生物量、地表凋落物、0—100 cm 根系和土壤的碳氮贮量, 探讨了长期封育草地的碳固持速率。实验结果表明: 长期封育显著提高了草地碳氮贮量; 经 30a 围封处理后, 草地碳固持量为 1401—2858 g C m⁻², 平均 2126 g C m⁻²; 草地碳固持速率为 46.7—129.2 g C m⁻² a⁻¹, 平均 84.2 g C m⁻² a⁻¹。长期封育草地氮固持速率为 2.8—14.7 g N m⁻² a⁻¹, 平均 7.3 g N m⁻² a⁻¹。封育草地碳和氮固持速率表现为: 针茅草地 < 羊草草地 < 退化羊草草地 < 补播黄花苜蓿 + 羊草草地。长期封育草地 0—40 cm 土壤碳固持速率相对较高, 但下层土壤对草地碳固持的贡献也比较大, 因此, 未来的相关研究应给予下层土壤更大关注。内蒙古典型草地具有巨大的碳固持潜力, 长期封育(或禁牧)是实现其碳固持效应最经济、最有效的途径之一。

关键词: 草地; 碳固持; 氮贮存; 固持速率; 土地利用变化; 围封

Carbon and nitrogen sequestration rate in long-term fenced grasslands in Inner Mongolia, China

HE Nianpeng^{1,2,*}, HAN Xingguo², YU Guirui¹

1 Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographic Sciences and Natural Resources Research, CAS, Beijing 100101, China

2 Key Laboratory of Vegetation and Environmental Change, Institute of Botany, CAS, Beijing 100093, China

Abstract: Land-use change is considered to have a significant impact on the global C balance by profoundly altering biota, land cover, and biogeochemical cycles. Therefore, the impact of land-use change on the storage or sequestration of carbon (C) and nitrogen (N) is one of the most important domains to global change research. As a dominant form of landscape and an integral component of the Eurasian landmass, grasslands of northern China, which account for 40% of the land area in China, play important roles in servicing the ecological environment and in the socio-economy of the region. Furthermore, an increase in the soil C and N storage in the grasslands of northern China is anticipated with the implementation of measures aimed at encouraging grassland protection. However, there is little information regarding the potential of C and N storage (or C sequestration rate) due to the absence of long-term grazing exclusion plots in multiple sites.

In this present research, using pair-sampling methods, we investigated the C and N storage in aboveground biomass, litter, roots and soil organic matter in the 0—100 cm soil layer in the fenced grasslands and free-grazing grasslands in 4 sites. The main objectives of this study was to assess the effect of long-term grazing exclusion on the storage of C and N in temperate grasslands of northern China, and further determined the sequestration rates of C and N in fenced grasslands by comparing with the data of free grazing grasslands.

The results showed that, compared with free-grazing grasslands, there were significant increases in the C and N storage

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* 通讯作者 Corresponding author. E-mail: E-mail: henp@igsnrr.ac.cn

in the fenced grasslands. It was estimated that, after 3-decades grazing exclusion, the quantity of C sequestration ranged from 1401 to 2858 g C m⁻² in the 4 sites, averaging 2126 g C m⁻²; and the rates of C sequestration in fenced grasslands ranged from 46.7 to 129.2 g C m⁻² a⁻¹, averaging 84.2 g C m⁻² a⁻¹. The rates of N sequestration in fenced grasslands varied from 2.8 to 14.7 g N m⁻² a⁻¹, averaging 7.3 g N m⁻² a⁻¹. From the view of C and N sequestration rates, there is a total trend as follows: *Stipa grandis* grassland < *Leymus chinensis* grassland < degraded *L. Chinese* grassland < Sowing *Medicago falcata* and *L. chinensis* grassland. Moreover, we found that the lower soil layers (40—100 cm) had also play an important role in the total C and N sequestered in fenced grasslands although sequestration rates were relative higher in the upper soil layer (0—40 cm). Together, the study demonstrated that temperate grasslands of northern China have the vast potential to increase C storage, and long-term grazing exclusion should be the most valuable and feasible approach to make true the C sequestration of temperate grasslands in future.

Key Words: grassland; carbon sequestration; nitrogen storage; sequestration rates; land-use change; fenced

土壤有机碳库是陆地生态系统最大的碳库,其总贮量约为大气碳库的3倍^[1]。如能提高生态系统土壤碳贮量,可部分抵消(或减缓)人为活动释放CO₂对大气CO₂浓度升高的影响^[2]。大量研究表明:优化的生态系统管理措施或土地利用方式可显著提高草地土壤碳贮量^[2-5];其中,施肥、播种豆科植物、恢复原生植被等措施均具有明显效果^[6]。适宜的管理措施是当前提高生态系统碳贮量、实现生态系统碳增汇最经济且最具操作性的途径之一^[7-9]。

我国草地约4亿hm²,约占国土陆地面积40.6%;其中北方天然草地是其主体,对该地区畜牧业和生态环境保护等均具有重要作用^[10]。然而,自20世纪80年代以来,伴随该地区人口数量和牲畜数量的急剧增长,以及长期不合理的土地利用方式,我国北方草地出现了大面积退化和沙化,生产力明显下降^[11-13]。2000年以来,中央政府和北方草地大面积分布的省区均采取了积极的应对策略,如大面积地实施退耕还草、退耕还林、延迟放牧和围封转移等,改良或恢复了大部分严重退化的北方温带草地生态系统。随着一系列国家重大生态工程的实施,可以预见中国北方温带草地碳贮量将会逐渐增加,并成为一个重要碳汇。目前,过去30a我国北方温带草地碳贮量是否发生了明显的变化,科学家们还存在较大争议^[8-9,14-17],如何更好地实现温带草地的碳固持功能,是当前亟待解决的重要科学问题。

封育是当前推广范围最广的草地恢复措施之一。然而,由于缺乏长时间尺度的研究/监测数据,科学家很难准确地评估长期围封对不同类型草地碳贮量和碳固持速率的影响。本文采用成对取样的方法,基于4个长期封育草地(封育时间约30a)及其对应的自由放牧草地,分析了长期封育对温带典型草地碳贮量的影响,并探讨了长期封育状态下温带草地的碳固持速率。

1 实验样地与方法

1.1 实验样地

野外实验在中国科学院内蒙古草原生态系统定位研究站进行。该区海拔高度1200—1250m,属大陆性温带半干旱草原气候;年均温度0.4℃,年均降水量345mm左右,且降雨主要集中在6—8月份。植被类型为温带典型草原,以羊草和针茅等多年生旱生禾本科植物为优势种。本研究共设置4个实验点,8个实验样地;即在每个实验点分别选择围栏封育草地和自由放牧草地,封育年限21—30a(表1)。

1.2 野外取样和数据测定

2009年8月中旬,在围栏封育草地和围栏外自由放牧草地(距围栏15m)分别设置一条100m取样样带,在样带上间隔10m设置一个1m×1m样方(每个样地共10样方)。在每个样方内进行地上生物量取样、地表凋落物收集;随后,采用根钻(直径10cm)进行根生物量取样,用土钻(直径4cm)进行土壤取样,根和土壤分0—10cm、10—20cm、20—40cm、40—60cm、60—80cm和80—100cm共6层进行收集。此外,为了计算土壤碳氮贮量,采用土壤培面法测定土壤容重,土壤容重测定按每层10cm进行,每个样地重复3次。经预处理的植物、凋落物、根系和土壤

样品,采用重铬酸-浓硫酸外加热法测定有机碳含量、采用半微量凯氏定氮法测定全氮含量。

表 1 实验样地及土地利用历史
Table 1 Experimental sites and land-use history

实验点 Site	地理坐标 Location	样地类别 Types	优势植物种类 Dominant species	土地利用历史 Land-use type
A	43°33' N 116°40' E	围栏封育草地	羊草 (<i>Leymus chinensis</i>)、大针茅 (<i>Stipa grandis</i>)、 西伯利亚羽茅 (<i>Achnatherum sibiricum</i>)	1979—至今,围栏封育,围封前草地状态 良好
		自由放牧草地	羊草 (<i>L. chinensis</i>)、大针茅 (<i>S. grandis</i>)、糙隐子 草 (<i>Agropyron cristatum</i>)	自由放牧,草地轻度退化
B	43°32' N 116°33' E	围栏封育草地	大针茅 (<i>S. grandis</i>)、羊草 (<i>L. chinensis</i>)、冰草 (<i>Cleistogenes squarrosa</i>)	1979—至今,围栏封育,围封前草地状态 良好
		自由放牧草地	大针茅 (<i>S. grandis</i>)、羊草 (<i>L. chinensis</i>)、糙隐子 草 (<i>A. cristatum</i>)	自由放牧,草地轻度退化
C	43°35' N 116°44' E	围栏封育草地	羊草 (<i>L. chinensis</i>)、大针茅 (<i>S. grandis</i>)、糙隐子 草 (<i>A. cristatum</i>)	1984—至今,围栏封育,围封前草地中度 退化
		自由放牧草地	羊草 (<i>L. chinensis</i>)、大针茅 (<i>S. grandis</i>)、糙隐子 草 (<i>A. cristatum</i>)	自由放牧,草地严重退化
D	43°38' N 116°42' E	围栏封育草地	羊草 (<i>L. chinensis</i>)、黄花苜蓿 (<i>Medicago falcata</i>)、 糙隐子草 (<i>A. cristatum</i>)	1989—至今,围栏封育,混播黄花苜蓿和 羊草
		自由放牧草地	羊草 (<i>L. chinensis</i>)、糙隐子草 (<i>A. cristatum</i>)、黄 囊苔草 (<i>Carex korshinskyi</i>)	自由放牧,草地严重退化

1.3 数据分析与处理

采用如下公式计算土壤有机碳贮量(SOC, g C/m²)和土壤全氮(STN, g N/m²):

$$SOC = \sum D_i \times B_i \times OM_i \times S \tag{1}$$

$$STN = \sum D_i \times B_i \times TN_i \times S \tag{2}$$

式中, D_i 、 B_i 、 OM_i 、 TN_i 和S分别是土层厚度(cm)、土壤容重(g/cm³)、土壤有机碳含量(%)、土壤全氮含量(%)和对应面积(cm²); i 代表土壤的分层数,并且*i* = 1, 2, 3, ..., 6。

草地碳氮固持量是根据封育草地和自由放牧草地碳氮贮量的数值之差进行计算(g C/m²或 g N/m²),草地碳氮固持速率是固持量除以围封年限(g C m⁻² a⁻¹或 g N m⁻² a⁻¹)。采用成对*T*检验方法来确定围封对草地碳和氮贮量是否具有显著性(*P* < 0.05),统计分析均由SPSS11.0软件完成。

2 结果

2.1 土壤碳贮量

实验结果表明:长期封育显著地提高了温带草地碳贮量(图1);在4个实验点,封育草地碳贮量均显著高于对应的自由放牧草地(*P* < 0.01)。不同实验点草地碳贮量变化也很大,自由放牧草地碳贮量(地表植被、凋

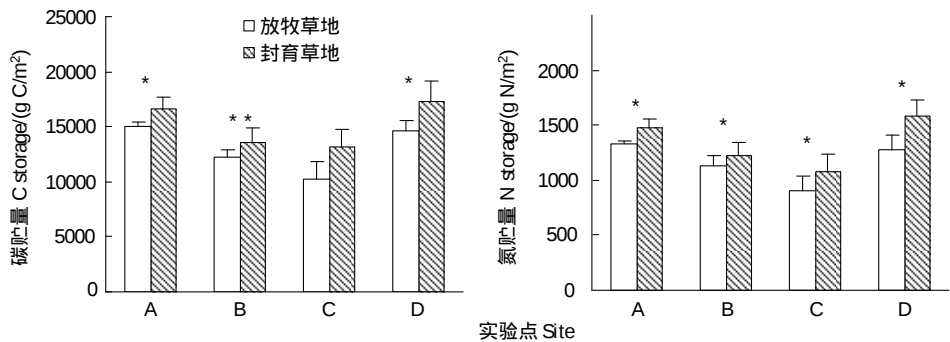


图 1 长期封育后温带草地碳氮贮量变化

Fig. 1 Changes in C and N storage in temperate grasslands (including aboveground biomass, litter, roots and soil in the 0—100 cm depth
* 表示封育草地和自由放牧草地间显著差异 (T-test, *P* < 0.05)

落、0—100 cm 根系和土壤)介于 10243.4—15059.3 g C/m²之间,平均 13030.3 g C/m²;围封草地碳贮量介于 13101.6—17315.9 g C/m²之间,平均为 15157.0 g C/m²。另外,草地不同碳库间差异非常大,地上植被和凋落物碳贮量不到草地碳贮量的 1%,碳主要分布在土壤有机碳库(表 2)。土壤碳贮量具有明显的垂直分布特征,0—10 cm 和 10—20 cm 土层有机碳含量相对较高,随着土层深度增加碳储量明显降低(图 2)。

表 2 长期封育对温带草地上植被、凋落物、0—100 cm 根系和土壤碳氮贮量的影响

Table 2 Effects of long-term fenced treatment on the storage of C and N in aboveground biomass, litter, 0—100 cm roots and soil

实验点 Site	样地类别 Types	碳贮量 C storage/(g C/m ²)				氮贮量 N storage/(g N/m ²)			
		地上植物 Aboveground biomass	凋落物 Litter	根系 Roots	土壤 Soil	地上植物 Aboveground biomass	凋落物 Litter	根系 Roots	土壤 Soil
A	围栏封育草地	21.3±10.4 *	15.5±6.4 *	709.2±63.7 *	14313±71 *	1.5±0.2 *	0.5±0.2 *	24.8±2.9 *	1297±71 *
	自由放牧草地	67.9±7.4	55.8±12.0	763.3±132.3	15707±77	4.3±0.5	1.8±0.3	23.5±4.8	1446±77
B	围栏封育草地	21.2±4.7 *	5.4±2.0 *	558.0±69.3 *	11630±80 *	0.7±0.2 *	0.2±0.1 *	23.3±3.3 *	1111±80 *
	自由放牧草地	57.9±4.2	27.5±10.5	1118.4±197.3	12407±120	3.6±0.2	1.1±0.5	49.1±9.5	1165±120
C	围栏封育草地	13.5±1.3 *	2.4±1.1 *	512.9±164.9 *	9715±167 *	1.0±0.1 *	0.1±0.02 *	22.7±7.8 *	882±167 *
	自由放牧草地	71.1±15.1	27.3±10.2	864.6±136.7	12139±161	4.4±2.2	0.8±0.4	36.8±6.1	1035±161
D	围栏封育草地	29.0±8.2 *	2.5±0.6 *	617.7±47.2 *	13954±138 *	1.7±0.6 *	0.1±0.02 *	22.5±2.8 v	1251±138 *
	自由放牧草地	124.8±30.2	43.8±18.3	732.5±136.6	16415±43	4.0±1.1	1.9±0.8	28.8±5.9	1549±43

同一列中围栏封育草地数据具有星号,则表示围封和自由放牧草地间差异显著(Paired samples T-test, P < 0.05)

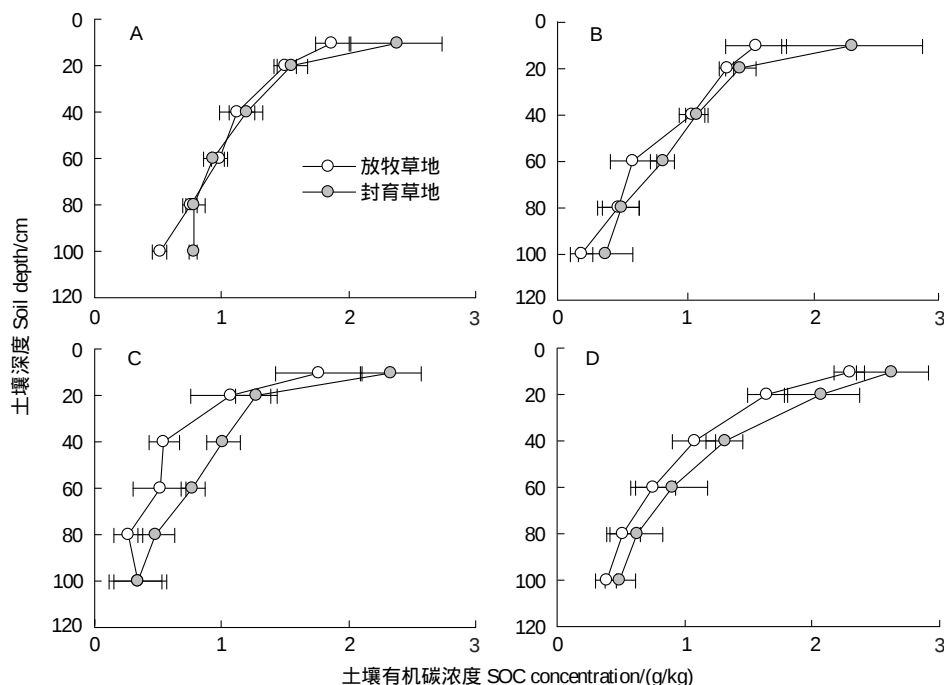


图 2 长期封育对温带草地 0—100 cm 土壤碳含量的影响

Fig. 2 Effect of long-term fenced approach on the C concentration in the 0—100 cm soil layer in temperate grasslands

A、B、C、D 为实验样点

长期封育状态下,温带草地可固持大量有机碳,4 个实验点碳固持量介于 1401.5—2858.2 g C/m²之间,平均为 2126.7 g C/m²;碳固持速率介于 46.7—129.2 g C m⁻² a⁻¹,平均为 84.2 g C m⁻² a⁻¹(表 3)。从碳固持速率上看,针茅草地<羊草草地<退化羊草草地<补播黄花苜蓿+羊草草地。0—40 cm 土壤碳固持速率相对较大,但下层土壤(40—100 cm)碳固持速率也很可观;因此,今后的相关研究需要对下层土壤给予更大关注。

表 3 长期封育草地的碳固持量及其碳固持速率

Table 3 The quantity and rate of C and N sequestration in long-term fenced grasslands in Inner Mongolia

土层 Soil depth	实验点 Site	碳固持 C sequestration		氮固持 N sequestration		碳氮比 C : N
		碳固持量 Quantity /(g C/m ²)	碳固持速率 Speed /(g C m ⁻² a ⁻¹)	氮固持量 Quantity /(g N/m ²)	氮固持速率 Speed /(g N m ⁻² a ⁻¹)	
0—40 cm	A	790.0 ± 292.1	26.3 ± 9.7	68.4 ± 29.2	2.3 ± 1.0	11.5
	B	1008.4 ± 518.1	33.6 ± 17.3	31.4 ± 33.0	1.0 ± 1.1	32.1
	C	1633.5 ± 888.2	62.8 ± 34.2	104.1 ± 93.3	4.0 ± 3.6	15.7
	D	1636.6 ± 759.9	77.9 ± 36.2	150.2 ± 131.7	7.2 ± 6.3	10.9
	平均值 Average	1267.1 ± 324.9	50.2 ± 24.3	88.5 ± 37.9	3.6 ± 2.6	14.3
0—100 cm	A	1534.6 ± 737.9	51.2 ± 24.6	151.4 ± 69.0	5.0 ± 2.3	10.1
	B	1401.5 ± 771.0	46.7 ± 25.7	84.9 ± 72.0	2.8 ± 2.4	16.5
	C	2858.2 ± 888.4	109.9 ± 34.2	171.0 ± 108.5	6.6 ± 4.2	16.7
	D	2712.5 ± 883.4	129.2 ± 42.1	308.0 ± 50.1	14.7 ± 2.4	8.8
	平均值 Average	2126.7 ± 536.1	84.2 ± 41.6	178.8 ± 41.8	7.3 ± 5.2	11.9

2.2 土壤氮贮量

草地总氮贮量,包括地上生物量、地表凋落物、0—100 cm 根系和土壤,在不同草地间差异显著 ($P < 0.01$);长期封育显著提高了草地氮贮量 ($P < 0.01$),自由放牧草地氮贮量介于 906.2—1324.1 g N/m²之间,平均为 1160.4 g N/m²;围封草地氮贮量介于 1077.2—1583.7 g N/m²之间,平均为 1339.2 g N m⁻²。与碳贮存规律基本相似,氮主要存贮在土壤和根系内,地上植物和地表凋落物氮贮量非常有限(表 2);氮贮量存在明显的剖面分布特征(图 3)。从草地氮固持速率角度分析,封育草地氮固持速率约为 2.8—14.7 g N m⁻² a⁻¹;整体趋势:针茅草地<羊草草地<退化羊草草地<补播黄花苜蓿+羊草草地(表 3)。

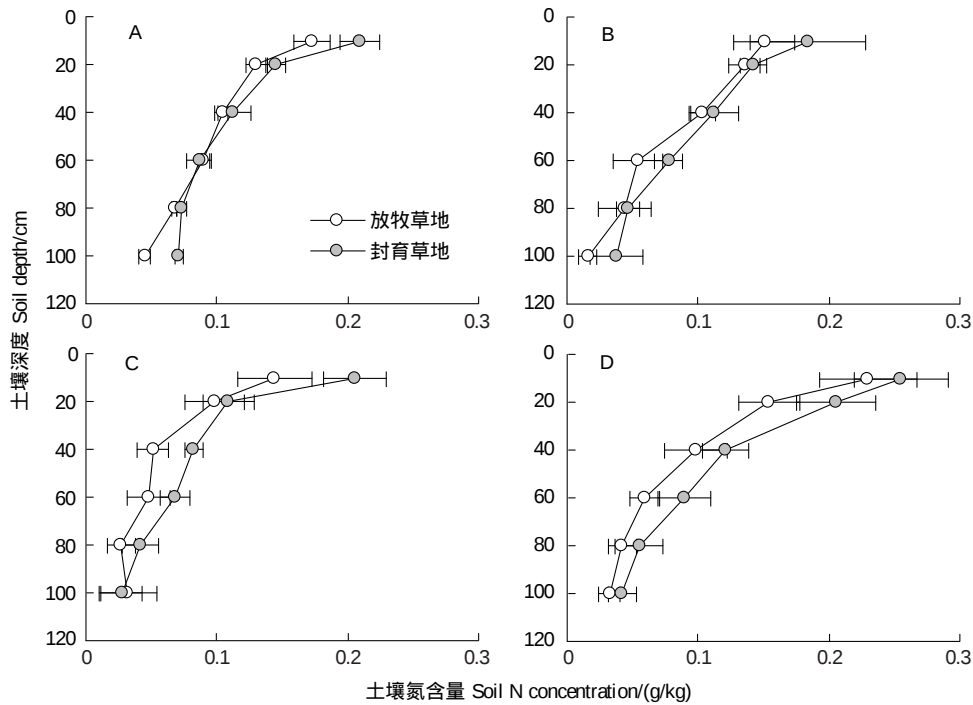


图 3 长期封育对草地 0—100 cm 土壤氮含量的影响

Fig. 3 Effect of long-term fenced approach on the N concentration in the 0—100 cm soil layer

3 结论与讨论

长期封育可显著地提高温带草地碳氮贮量,温带草地具有巨大的碳固持潜力;封育状况下,草地碳固持速

率介于 $46.7\text{--}129.2\text{ g C m}^{-2}\text{ a}^{-1}$, 平均为 $84.2\text{ g C m}^{-2}\text{ a}^{-1}$ 。必须指出:本文的分析是基于封育-自由放牧草地的数据,其结果可揭示了长期封育温带草地具有巨大的碳固持潜力,但它并未揭示封育后草地碳氮固持过程或未来发展趋势。通常,随着生态系统的发育(或恢复)进程,其碳固持能力(或速率)会逐渐下降,并最终达到一个相对平衡状态,其变化趋势大多可用对数函数来拟合^[15,18-21]。以内蒙古羊草草地为例,经过 27a 围封后,羊草草地生态系统净生产力处于一个相对平衡状态,即草地生态系统处于弱碳源-弱碳汇相互转换的状态,这种转换过程和强度主要受当年降水量的调控^[22]。因此,在更长时间尺度上,围封是否还能进一步提高温带草地碳贮量,仍有待进一步深入研究。

本研究未能区分过去 30 a 自由放牧对温带草地碳贮量的影响,从而将大大增加对长期封育草地碳固持速率评估的误差和不确定性。由于缺乏围封处理前草地碳贮量的本底数据,只能假设近过去几十年自由放牧对草地碳贮量影响较小,不会对实验结果产生重要影响。关于放牧对草地土壤碳氮贮量的影响,科学界还存在争议。最近的研究结果表明轻度放牧可提高内蒙古温带典型草地土壤碳氮贮量,随着放牧强度增加,土壤碳氮贮量降低;随着放牧强度变化,温带草地存在碳固持/碳流失的内在转化阈值(即放牧强度阈值)^[9]。Derner 等研究表明:长期轻度放牧和中度放牧,北美矮草草原有机碳贮量可提高 24%,但类似的实验处理却使北美高草草原土壤有机碳贮量降低 8%^[23];Schuman 等研究表明轻度放牧对 0—60 cm 土壤碳氮贮量影响非常小^[24]。大量实验结果表明:长期过度放牧将显著降低土壤碳氮贮量^[7-9,19,25-26]。放牧对土壤碳贮量的影响途径可概括如下:(1)通过增加营养循环或营养的可利用性,轻度放牧可促进植被更新和土壤碳氮贮存^[23];(2)通过牲畜的大量取食、降低土壤的通透性和营养可利用性,重度放牧抑制了草地生产力、显著地降低了通过地上植被和地下根系的有机质输入^[27];(3)过度放牧时,牲畜对土壤团聚体和地表结皮的严重破坏,提高了土壤有机质分解速率,并使土壤更易于水蚀和风蚀^[28-30]。因此,本研究所报告的草地碳固持速率存在上述不确定性,尤其是自由放牧草地可能因退化而使碳贮量降低的现象,有可能会高估内蒙古温带草地碳固持能力和速率。

从草地碳和氮固持速率来看,整体规律为针茅草地<羊草草地<退化羊草草地<补播黄花苜蓿+羊草草地。在内蒙古地区,羊草草地通常分布在水肥条件更好地区域,具有更大的地上-地下生产力^[10],从而比针茅草地具有更大的碳固持能力或速率。从增加碳固持潜力角度而言,如能采取合理的草地恢复措施,退化草地具有更大的固碳潜力^[31]。播种黄花苜蓿和羊草后,改良了植物群落结构、增加了植物固氮输入,显著提高草地生产力,使苜蓿+羊草混播草地具有更大的碳固持速率。多年监测数据也表明:播种黄花苜蓿+羊草草地上生产力远高于围栏外自由放牧草地,且生产力稳定性也更高,生产力稳定在 $310\text{--}456\text{ g/m}^2$ 之间。然而,受本文研究方法的局限(封育草地-自由放牧草地成对取样法),自由放牧草地是否退化及其退化程度,将对实验结论造成较大的影响。总体而言,本文的研究结论可提供不同地点/不同管理途径下温带草地碳固碳速率的粗略比较,但并未能深入揭示不同类型封育草地的碳固持机理,在未来工作中有待加强。

围封(或禁牧)将显著提高内蒙古地区温带草地的碳氮贮量,鉴于我国北方温带草地巨大的面积,任何提高草地碳贮量的管理措施,均可对区域甚至全球碳固持形成重要影响^[2];例如,通过合理地调节放牧强度,内蒙古草地碳氮贮量也将会明显增加,达到其碳增汇的目的^[9]。总之,我国北方温带草地具有巨大的碳固持潜力,在合理的草地管理制度下,未来一段时间内将成为一个重要的碳汇;其中,围封禁牧将是实现温带草地巨大碳汇效应最经济、且最具有操作性的途径之一。

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