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高寒放牧草地碳循环研究进展

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摘要:叠加食草野生动物和人类需求驱使家畜牧食的放牧草地碳循环是食草动物-草地植物-土壤耦合系统吸收、储存和释放碳的过程。食草动物通过牧食、踩踏和粪尿归还等途径影响草地碳循环过程,但其发挥促进碳吸收和增加碳汇的正效应还是促进碳释放的负效应,仍然存在较大不确定性。鉴于此,通过文献综述阐明食草动物对草地碳循环过程的可能影响及作用机制,提出可能的未来研究方向,以期为青藏高原高寒草地碳循环过程与机理研究,及碳增汇管理提供基础。研究发现,虽然高寒草地净生态系统生产力和碳汇强度可观,但由于观测站点分布和草食动物等因素的影响,目前的结果可能存在高估固碳速率的情况,同时基于不同方法所得的结果也存在一定差异;特别在放牧条件下,高寒草地碳固存过程更为复杂,食草动物通过改变草地群落组成、植物多样性、生产力和地上/地下碳分配,显著影响草地植被碳储量和碳循环过程,这些影响同时还收到气候和土壤等多种因素的调控,具有复杂性和不确定性。目前对高寒放牧草地碳循环的研究仍然缺乏考虑食草动物再分配的影响和强度,同时对植被碳分配如何响应放牧强度的机制和认识、以及放牧管理对草地碳循环的影响机理仍然缺乏深入探究。因此,在未来研究中仍需要深入研究食草动物-植被-土壤之间的碳耦联机制,不断整合地面观测与过程模型模拟,发展针对草地碳汇功能管理模式及不同气候情景的遥感-生态过程模型,为未来高寒草地碳汇功能的演变趋势提出适应性的管理对策。

关键词:青藏高原;食草动物;碳固存;气候变化;草地管理

Review of grazing effect on carbon cycling in alpine grasslands

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Abstract: The carbon cycle of grasslands grazed by herbivorous wildlife and human demand-driven domestic animal is a process of carbon uptake, storage and release in the coupled herbivore-grassland plant-soil system. Herbivores influence the grassland carbon cycle through grazing, trampling, and feces and urine return, but there remains significant uncertainty about whether they enhance carbon uptake and promote carbon sequestration or stimulate carbon release. This paper reviewed the possible effects and mechanisms of herbivores on the carbon cycle process in grassland, and proposes possible future research directions, with a view to providing a basis for the study of the carbon cycle process and mechanism in the alpine grassland of the Qinghai Tibetan Plateau, as well as the management of carbon sequestration. Research findings indicate that while alpine grasslands exhibit substantial net ecosystem productivity and carbon sink intensity, current results may overestimate carbon sequestration rates, influenced by observational site distribution and the impact of herbivores.

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Discrepancies exist among results derived from different methodologies. Carbon sequestration in alpine grasslands becomes more intricate under herbivore grazing. Herbivores significantly affect carbon storage and cycling in alpine grasslands by altering community composition, plant diversity, productivity, and above/below-ground carbon allocation. These effects are further regulated by climate and soil factors, introducing complexity and uncertainty. Current studies on carbon cycling in grazed alpine grasslands lack consideration of herbivore redistribution effects and intensity. Furthermore, the mechanisms of how vegetation carbon allocation responds to grazing intensity and the influence of grazing management on grassland carbon cycling necessitate further research. Future research should focus on the carbon coupling mechanisms among herbivores, vegetation, and soil, integrating field observations with process model simulations. Developing remote sensing-ecological process models for grassland carbon sink function management under various climate scenarios is crucial to propose adaptive management strategies for the evolution of alpine grassland carbon sink function.

Key Words: Qinghai Tibetan Plateau; herbivorous; carbon sequestration; climate change; grassland management

应对和减缓气候变化已成为全球共识,且多个国家相继采取了碳达峰和碳中和的国家自主减排目标[1]。草地约占陆地面积的40.5%,贡献了全球1/3的碳储量,其中约90%贮存在土壤和根系中,对全球碳贮存发挥着至关重要的作用[2]。草地不仅是野生动物的栖息地,也是畜牧生产用地,维持上亿人口的生活和生计[3]。在兼顾生物多样性维持和畜牧生产功能前提下,如何保持其土壤碳稳定持久地固存而不被释放的碳库功能,可能超过其有限的碳增汇量的贡献[4]。因此,探索草地碳库稳定性和持久性维持机制,维持其碳汇功能并能提升其生产功能,实现保护与发展双赢目标,不仅是我国生态文明建设的目标,也是联合国可持续发展目标,具有重要的科学和现实意义[5—7]。

草地生态系统是人—食草动物—草地长期演化相互影响相互适应而形成的自然与社会耦合系统,其碳循环过程不仅包括与森林和农田生态系统相似的植被光合碳固定、植被和土壤碳储存等生物地球化学循环过程,也包括其动物生物地球化学过程、人类社会利用家畜产品所形成的独特的碳循环过程[4, 8—10]。目前对草地碳循环过程及其驱动机制已进行了大量系统综述,也基于控制实验文献数据分析了放牧强度和围栏封育等对草地碳储量和通量的影响[11—14]。但食草动物牧食对草地碳库稳定性和持久性的作用机制仍不清晰,可能导致对其碳库功能定位的较大不确定性。

高寒草地是被誉为"世界第三极"的青藏高原的主要植被类型,由于对气候变化极为敏感而又脆弱[9],其碳循环及碳汇功能成为研究热点。自1970年代以来,青藏高原气温以0.4℃ $10a^{-1}$的速率变暖,几乎是全球变暖速率的2倍,而降水变率也在增大,气候变化及以放牧为主的人类活动正在剧烈地影响着青藏高原高寒草地固碳过程[15]。本文围绕高寒放牧草地碳循环过程梳理研究进展,分析高寒草地碳库稳定性和持久性的影响因素,揭示其维持机制,将有助于草地恢复治理措施和放牧管理的优化,促进青藏高原绿色高质量发展和国家落实"双碳"战略行动落实。

1 高寒草地碳储量与通量

基于机器学习的青藏高原植被碳储量中地上和地下生物量分别为1.03 Pg和1.37 Pg,其中草地植被碳储量为0.86 Pg,地上和地下植被碳库分别0.16 Pg和0.7 Pg,远低于早期基于有限地面调查数据估计的草地植被碳储量(1.87 Pg)[16]。青藏高原土壤有机碳储量较高[17],早期估计的范围约为38.4—79.4 Pg C[18—21],最新基于7196个调查数据,利用机器学习算法估算的土壤1 m深SOC为19.69—47.9 Pg C,平均为32.01 Pg C;土壤SOC主要由高寒草地贡献,其中草地土壤1 m深SOC为15.52 Pg C,0—0.3 m深为7.8 Pg C[16]。

基于遥感估算的青藏高原高寒草地现存净初级生产力(NPP)约为136—344 Tg C/a[22—25],其中,约30%分配于地上茎叶,65%分配地下根系;约31 Tg C地上生物量碳被草食动物采食,其中仅有0.38 TgC以畜产品进入社会系统,而大部分或释放到大气,或返回到土壤[26]。

根据涡度相关法观测和生态系统过程模型模拟研究,高寒草地具有显著的碳汇功能,每年的碳汇强度在 17—130 Tg C/a[27—29],但因不同方法估算的高寒草地碳汇大小仍然存在较大不确定性[22, 29—38](图 1)。基于 32 个涡度相关法碳通量站点观测数据估计的整个青藏高原的固碳速率为(130.0±53.6) Tg C/a[29];基于 5 个通量观测塔资料的青海省草地碳汇速率为 36.08 Tg C/a[39]。整合清查法、生态系统过程模型、大气反演和涡度相关方法的研究表明,青藏高原当前碳汇大小为每年 26.5—33.7 Tg C/a,占全国陆地生态系统碳汇的 9.9%—19.6%[40]。因大部分通量观测站通常处在植被生长状况较好、相对未退化的区域,而高原有相当大比例的草地处于不同程度的退化之中,因此,可能总体高估了固碳速率[40]。另外,草食动物对草地碳储量和碳汇的影响,也仍然缺乏系统地定量研究。

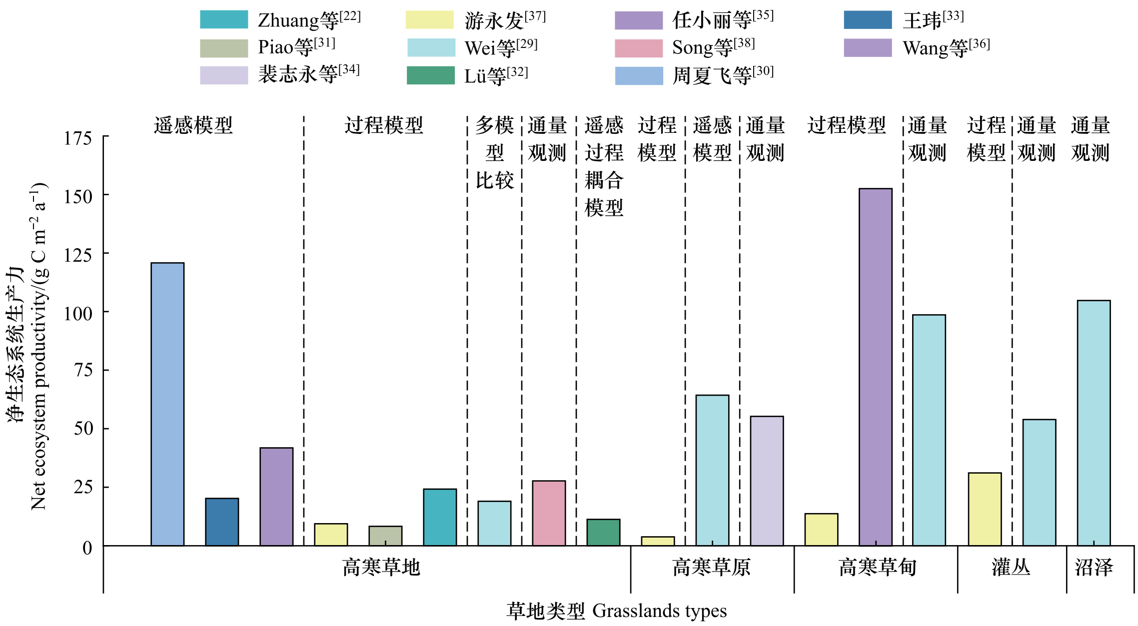

图 1　青藏高原高寒草地碳汇研究在不同方法间存在较大差异

Fig.1　Carbon sinks in alpine grasslands on the Tibetan Plateau show large differences between methods

基于未来气候情景数据以生态系统过程模型的模拟研究,认为高寒草地未来仍将发挥碳汇功能。尽管也有个别模型模拟认为有可能成为碳源,但总体上基于不同模型的模拟的净生态系统生产力为 16—38 Tg C/a;但由于气候持续变暖但降水变化不显著而导致暖干化的未来气候变化,将导致高寒草地 NEP 在 2069 年左右到达峰值,然后可能会出现下降趋势且稳定性也将降低[41]。然而这些模型均未能考虑未来气候变化下植被演替和适应性,更为突出的是,这些模型通常都不考虑草地管理,特别是草地退化恢复治理及家畜放牧管理的效应。

2　放牧对草地植被碳的影响

2.1　对草地群落组成及植物多样性的影响

放牧方式和放牧强度通过食草动物对草地群落的偏好性采食和物理践踏,直接影响草地植物多样性,进而影响草地植被生产力及地上和地下的碳分配,从而影响草地生态系统碳固定[42]。总体上适度放牧有利于植物物种多样性的提高,而过度放牧或者不放牧会导致物种多样性降低。根据 Sheng 等人的文献综述,青藏高原高寒草地放牧样地物种丰富度、香农—维纳指数和皮鲁均匀度指数较之围封样地分别高 9.89%、7.28%和 3.74%[43];然而,在全球尺度的文献数据整合分析却认为放牧历史和放牧强度对物种丰富度没有显著影响[44]。这表明了放牧对物种多样性的影响受多种因素的复杂影响。通常认为,在低放牧强度下,放牧使植物高度和覆盖度等降低,光照供应增加,进而增强草地群落的生态位,促进物种共存,最终导致草地植物物种多

样性增加[45—46];但过度放牧会导致草地群落结构受到损害、生物多样性显著下降、甚至导致草地永久性退化[47—48]。然而,因为不同植物个体或者植物群落对食草动物的采食和践踏可能存在不同的应激响应,可能会从生长缓慢的保守性状转变为快速生长的激进性状[49],由此导致在轻度放牧和适度放牧下,可能会遵从中度干扰假说,物种丰富度和多样性具有正向响应[50],但也可能对群落结构和生物多样性没有显著影响[51]。但对全球 10 个实验点的联网对照研究表明,长期放牧对事物多样性的影响取决于气候干旱程度,越干旱的地区放牧对植物多样性的负面影响越大[52]。而生物多样性的丧失会导致严重的碳排放,进而会导致更严重的气候变化,而气候变化又导致更严重的生物多样性丧失,最终形成自我强化的反馈循环[53]。因此,需要进一步开展研究,以探索不同地区植物多样性对放牧强度、放牧方式等的响应,在现有草地碳循环模型中考虑生物多样性模块,以积极开展放牧管理情景模拟,以保护生物多样性,促进草地碳储存的稳定性和持久性。

2.2　对草地生产力及地上/地下碳分配的影响

放牧家畜通过直接采食草地地上牧草而直接影响草地植被生产力[46, 51]。由于存在家畜的啃食、踩踏等牧食作用,如图 2 所示,放牧动物的啃食和踩踏可导致地上生物量降低约 41.91%,地下生物量降低约17.68%,导致植被碳生产显著下降[42, 51]。但是相比于过度放牧和轻度放牧,适度放牧对植被碳的影响程度相对较小[54],也可能会对植被碳固定起促进作用[55]。在三江源开展的研究中发现,包括野生食草动物和家畜的牧食作用对草地碳固定存在补偿效应,大小约为 14%[56]。但也有研究发现,放牧强度对草地生产的影响可能因草地类型不同而有所差别[13, 57]。并且,食草动物的粪便施肥作用对草地生产极其重要,特别是在高寒草地这一低投入的天然系统中成为主要的养分输入[58],使得草地固碳过程通过食草动物再分配,而使其重要性不容忽视。

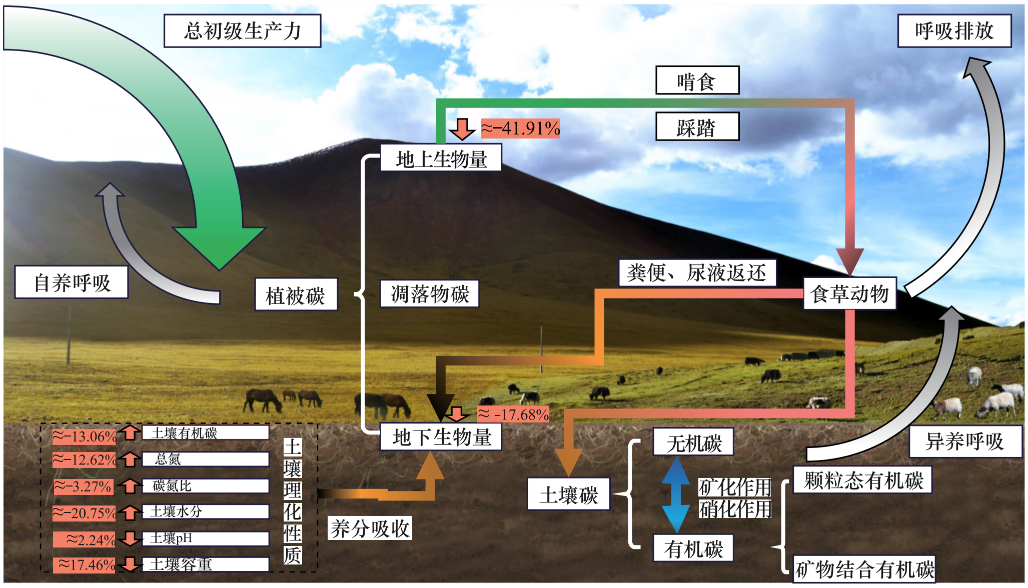

图 2　高寒草地碳循环过程及基于文献整合分析的放牧对高寒草地的影响

Fig.2　Carbon cycling processes in alpine grassland and the impact of grazing on alpine grassland based on literature integration analysis

地上/地下碳分配模式是植被碳形成的关键因素之一[59]。由于根部取样的难度,基于根茎比(*R/S*)测定的生物量分配的估计显示出很大的不确定性[60—63]。青藏高原地上地下生物量空间格局存在显著差异,根据在 80 个点位测定的数据,高寒草甸具有较低的 *R/S*,中值为 13.35,变化范围为 1.72—66.56;荒漠草地的 *R/S* 较高,为 36.06(9.23—69.10),温性草原和草甸草原的 R/S 居中,分别为 16.60(7.49—70.64)和 19.46(3.20—39.97)[62];但这一结果远高于早期在青藏高原地区 16 个点位测定并计算的高寒草甸和高寒草原群落的 *R/S*

值(5.2 和 6.8)[64]。而这种差异可能更多来自对地下生物量取样和测定的不确定性。

植物地上与地下碳分配的变化是植物及群落适应外界环境压力的一种重要调节机制[60]。基于经严格筛选配对的全球 1467 个地上和地下净初级生产力样方数据,经机器学习得到的地下和地上净初级生产力比(f_{BNPP},raction of belowground net primary production)[65],经提取和统计青藏高原草地f_{BNPP},得到全区平均值为 3.10,即地下碳固定速率是地上的 3.10 倍,不同草地类型间以高寒荒漠的f_{BNPP}最高(3.54),而以热性草丛最低(0.97)(图 3)。然而,基于在藏北高原测定的地上生物量与地下生物量计算得到的地上与地下净初级生产力比(图 3),对比分析围栏与放牧对碳分配的研究表明,放牧的影响远不如草地类型的影响显著[66]。此外,放牧对草地地上地下碳分配的影响还可能受到气候、土壤理化性质以及土壤微生物等其他因素的调控[67],导致这一过程和内在驱动机制变得更加复杂。

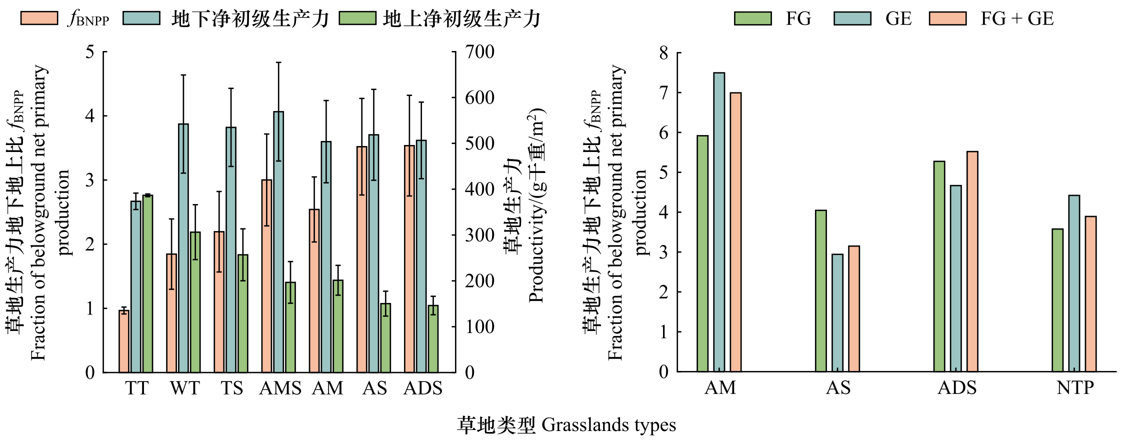

图 3　青藏高原地区草地地下与地上净初级生产力及其比值

Fig.3　Grassland net primary productivity (NPP) and its ratio in the Tibetan Plateau region

左图基于全球尺度经机器学习得到的地下和地上净初级生产力比数据统计的青藏高原草地生产力及其比值;右图基于在藏北高原测定的地上生物量与地下生物量,通过周转率计算得到的地上与地下净初级生产力比(根据文献[66]数据重新绘制);TT:热性草丛;WT:暖性草丛;TS:典型草原;AMS:草甸草原;AM:高寒草甸; AS:高寒草原;ADS:荒漠类;NTP:全青藏高原草地;FG:放牧;GE:禁牧;FG+GE:全部数据

目前,对于草地地上地下碳分配的内在机制解释,其主要假说有两种:最优分配假说(即植物优先分配生物量以优化资源利用)[68]和等距假说(即假设根和芽之间的生物量分配是固定的)[60, 69],在不同的研究区域或研究背景存在争议。青藏高原高寒草地的控制实验表明升温、降水的减少和氮沉降的增强对地上、地下生物量及其分配均会产生影响[67, 70—71],高寒退化草地的恢复实验也表明植物在高营养环境中会将更多的生物量分配给芽,在低营养环境中它们会将更多的生物量分配给根[72],与最优分配假说一致。

3　放牧对草地土壤碳的影响

3.1　对土壤有机碳及其周转的影响

放牧动物直接或间接地影响植被碳的同时,以粪便和尿液的投放以及放牧动物的践踏,改变凋落物的分解、土壤有机碳的矿化、土壤理化性质以及微生物群落的组成和活动[73—75],从而影响土壤有机碳动态及固存[42]。放牧活动可能导致土壤容重增加 17.46%,土壤酸碱度增加 2.24%,土壤水分持水量降低 20.75,导致土壤有机碳、总氮含量分别降低约 13.06%和 12.62%,碳氮比降低 3.27%[76—77]。对于不同强度的放牧水平,禁牧显著提高了土壤有机碳(14.74%)以及土壤总氮(28.35%)[11],随着放牧强度的增加,土壤有机碳含量逐渐下降,重度放牧导致土壤有机碳含量下降了 16.77%[13]。

土壤微生物既可以通过降解矿化土壤有机碳,又可以通过同化合成稳定土壤有机碳,这被认为是土壤碳库维持稳定的一个重要机制[78]。土壤有机碳来源主要分为植物碳源(凋落物、根系以及根系分泌物)和微生

物碳源(微生物残体和其代谢产物)。传统的“热力学理论”和“凋落物降解实验”都认为难分解的木质素是土壤碳库保持稳定的重要因素,而新的土壤生物标志物显示微生物残体对土壤碳库的贡献也十分重要[79]。在碳输入方面,地下生物量与根系分泌物和土壤物理结构密切相关,放牧活动通过食草动物采食等行为迫使植物调整光合产物分配[80],从而影响根系数量和质量[81],造成微生物群落营养和食物网变化,调控土壤活性有机碳[82]。土壤养分方面,家畜的粪便沉积通过为微生物提供额外的底物或外源性酶和微生物刺激土壤有机质分解[83],改善土壤营养状况,从而影响草地土壤碳封存。土壤物理特性方面,牲畜践踏压实土壤可能破坏土壤团聚体,土壤水分减少并增加土壤侵蚀风险[84—85],进一步降低了土壤微生物多样性;而合理放牧可以增加较高质量的根系碳(较低的碳氮比)投入和氮保留[73],从而促进土壤中矿物相关有机物的形成和持续。

土壤有机碳周转时间可以反映土壤有机碳稳定性的变化,是生态系统模型中确定土壤有机碳储量的重要参数[86—88],为预测土壤对气候变暖的潜在反应提供了可能[89—90]。常用的土壤有机碳周转研究方法包括碳稳定同位素(^{13}C)、放射性碳同位素(^{14}C)、碳平衡等方法;其中,碳平衡法是大尺度上衡量 SOC 周转时间有效且低成本的手段,主要通过 SOC 库与 SOC 的输出或输入的比值获得土壤有机碳周转时间[91—92]。

基于青藏高原高寒草地样带调查,高寒草地有机碳周转时间为 4—289a,其中高寒草甸 95%置信区间为 63—78a,平均为 71a;高寒草原的变化范围为 65—87a,平均为 76a,主要受土壤化学计量特征和气候(降水)的影响[93]。然而基于全球尺度的研究结[88],提取并统计得到青藏高原全区及主要草地类型的土壤有机碳周转时间(图 4),基于全球土壤数据库及卫星遥感 NPP 数据,估算的 0.3 米以下底土层中的土壤有机碳周转时间高原全区平均为 284a,其中高寒草甸和高寒草原分别为 135a 和 544a;而基于长期土壤培养实验数据经空间尺度外推估计的全区及两种草地类型的对应值分别为 249a、268a 和 197a。而部分可能是由于放牧绵羊通过践踏和排泄尿液和粪便影响土壤特性,较之超过 10a 禁牧样地(12.1a),持续放牧的高寒灌丛土壤有机碳具有更长的周转时间(29.5a)。

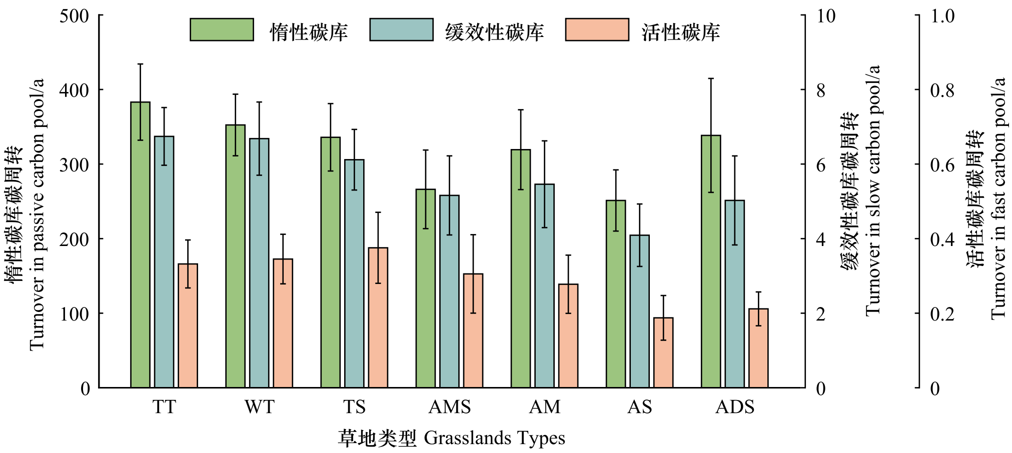

图 4 基于全球尺度的研究结果[88, 94]提取并统计得到青藏高原全区及主要草地类型的土壤有机碳周转时间

Fig.4 Based on the results of global-scale studies[88, 94] the soil organic carbon turnover time of the whole Tibetan Plateau and the major grassland types were extracted and statistically obtained

这些有限研究结果表明,一方面不同研究方法导致对青藏高原土壤有机碳周转时间估计的较大不确定性;另一方面,正如 Ren 等[94]指出的,目前地球系统模式可能因为未能考虑诸如微生物的热驯化过程等而高估了高纬度生态系统所有碳库该参数,可能低估了目前生态系统碳释放而高估了全球碳排放空间,使得应对和减缓全球气候变化面临着更大的挑战。其次,放牧对土壤有机碳周转时间的影响研究,还需要更多的不同地点不同草地类型以及不同研究方法的系统性研究。

3.2 土壤有机碳物理组分

放牧强度对土壤微生物介导下的碳组分合成和转化产生重要影响,不同有机碳组分对放牧强度的响应存

在差异。放牧通过改变植被地上、地下输入物的数量与性状及土壤状况,调控微生物的群落组成、生理性状及残体数量[95],影响土壤有机碳含量及密度与酶活性[96]。相较于轻度放牧,中度和过度放牧促使高寒草甸有机碳物理组分的集中分布从宏观团聚体(>1 mm)逐渐分解为微团聚体(<0.05 mm)[97],化学组分从有惰性特性的烷氧碳向相对活性芳香碳转变,降低了微生物生物量碳对土壤有机碳的贡献[98]。基于有机碳物理组分(颗粒态有机碳 POC 和矿物结合态有机碳 MAOC)研究土壤对生态系统变化的响应是一种简单且有效的手段[99]。POC 是土壤中与砂粒结合的有机碳,主要来源于植物残体,周转速率较快,易受土地利用影响。有限的研究表明,相较于轻度放牧和过度放牧,适度放牧影响植物的生长和土壤的碳输入,又提高了土壤微生物和酶的总活性,导致 POC 含量上升[100]。MAOC 是有机碳与金属氧化物、黏土矿物形成的高稳定性的有机矿物复合体[101],矿物结合有机碳变化主要取决于矿物吸附与解吸附的非生物过程和微生物生长速率变化所引起的微生物残体形成和转化的生物过程[102—103]。由放牧强度引起的植被—土壤—微生物协同变化是一个复杂过程,土壤有机碳库容和组分的响应具有强烈的深度依赖性,深入探究该耦合机制有助于认识土壤 POC 和 MOC 的驱动强度和生态机理,是评估放牧管理下草地固碳过程的关键。

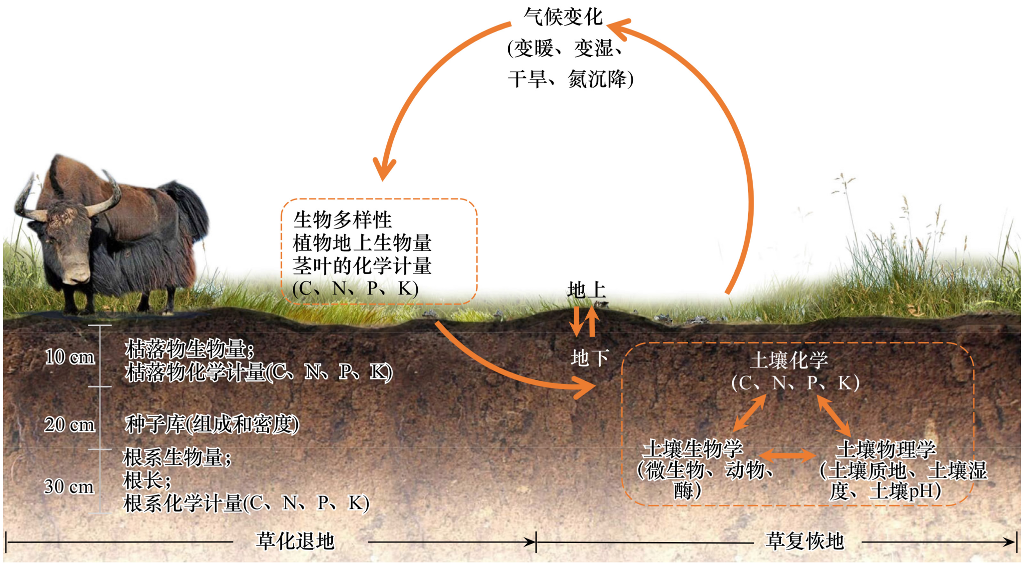

图 5　退化恢复草地碳循环过程及主要影响因素

Fig.5　Carbon cycling processes in degraded and restored grasslands and its main affecting factors

3.3　放牧管理

放牧改良可以增加较高质量的根系碳(较低的碳氮比)投入和氮保留[73],从而促进土壤中矿物相关有机物的形成和持续[104]。轻度放牧和适度放牧绵羊提高了半干旱高寒草原的植物多样性,但降低了植物生产力[105]。草地禁牧将显著提高高寒草甸植被地上生产力,但有可能导致物种多样性降低。牛羊混合放牧下土壤呼吸和微生物呼吸的温度敏感性要低于其他放牧处理。此外还有研究表明放牧可以缓解变暖导致的高寒草甸植物产量和营养质量的下降,适度放牧可以抵消变暖对高寒草甸灌丛群落的某些影响[106]。在持续干旱条件下,暖季放牧减少了高寒草甸中 CO_2 的封存,但在未来青藏高原变暖变湿条件下,暖季牧草地对生长季节的 CO_2 封存影响很小[107]。然而目前的多数研究都是基于有限空间范围的控制实验,仍然缺乏区域尺度现实放牧强度、放牧方式和放牧制度对草地碳固定影响研究,而生态系统过程模型可能是解决这一问题相对可行途径之一。

生态系统过程模型通过模拟生态系统碳循环过程及其与水、热、养分循环间的相互作用,而成为诊断和预测碳循环过程对气候变化和管理措施响应的有力工具,能够弥补野外试验研究难以实现的多管理情景响应研

究[108—109]。20 世纪 90 年代以来开发了大量的动态草原模拟模型,如 Century 模型、LPJmL 模型、PaSim 模型、SPACSYS 模型等,为草地碳循环过程、温室气体排放、及草地放牧管理研究提供了模型工具基础[110]。近年来,模拟植被生长、分配、凋落,及土壤养分动态过程的生物地球化学循环过程模型,正逐渐向耦合家畜采食和代谢过程模拟的方向发展[56, 111—112]。从样地、牧户到区域尺度,开展了草地温室气体排放、放牧强度影响模拟及放牧的生态和生计效应分析[3, 113—115]。在区域尺度,基于早期发展的生态系统过程—遥感耦合模型[116],通过对比围封样地内外的产草量,提出了家畜采食量模块,为放牧强度估算提供了方法基础[112]。根据早期的试验数据,对青藏高原主要草食动物的采食和代谢过程进行了模拟研究,量化了草食动物的碳通量,发现牲畜占草原上消耗的碳的主要部分[56]。

虽然这些草地管理模型对不同环境和管理强度下的产量和温室气体排放的模拟,表现出了足够高的准确性[109],但这些模型涉及大量的植被、土壤和管理方面的参数,这些模型参数的本地化,特别是管理过程参数的本地化,是这些模型进一步发展和应用的难点[117—121]。如针对欧洲人工草地占多数情况而发展的草地管理模型,更多地考虑刈割、施肥和灌溉等[108]。而对于我国草地,特别是青藏高原天然草地,更多是围封保护、及不同放牧强度管理,是较为突出的问题[122]。

4 存在的问题及可能解决途径

高寒草地是在全新世以来人类活动干扰下形成的,合理地放牧利用被认为有利于草地的更新、物种多样性的维系和草地碳汇功能的可持续维持[123]。青藏高原高寒草地一直是当地牧民维持生计的基础,同时需维持草地碳库稳定并提升固碳潜力,因此,在全球气候变化背景下,构建放牧草地碳汇管理模型,开展多管理情景模拟和诊断,是草地生态系统可持续管理的基础[9]。

在自然过程中,草地群落结构和地上地下碳生产影响着土壤碳输入,进而调节微生物活动和土壤养分循环,从而调节草地生态系统的固碳过程。但是由于野生食草动物和家畜在不同的强度下介入,草地碳生产发生了再分配,植物群落结构、碳生产以及土壤过程也相应发生了不同程度的改变。目前针对高寒草地净初级生产和植被碳固存过程的定量研究并没有考虑食草动物再分配的影响,同时仍然缺乏不同草地类型下的大尺度范围放牧强度影响研究。植被地上地下碳分配对不同放牧强度的响应机制目前仍然缺乏系统性的认识,特别是在高寒草地自由放牧条件下,叠加气候、土壤等因素,其内在驱动机制研究仍然不足。因此,在食草动物牧食再分配的影响下,自由放牧草地食草动物—植被—土壤之间的碳耦联机制将仍然是需要深入开展研究的核心科学问题。

放牧强度是改变微生物群落和土壤理化性质的一个重要影响因素,并对土壤固碳过程产生重要的调节作用[124]。由于区域之间的环境存在差异性,放牧强度对土壤微生物以及土壤碳氮循环的影响也不总是呈现负相关。例如,食草动物的排泄物会提高土壤养分并增加微生物生物量,在一定程度上抵消了放牧带来的负面影响,土壤微生物群落结构不因放牧强度和植物物种丰富度而改变[125]。除此之外,微生物对土壤有机碳积累的影响还受微生物群落结构与土壤团聚体稳定性之间的相互作用的控制[126],放牧强度与地区土壤特性的不同可能塑造多样化微生物生境。由放牧强度引起的土壤团聚体稳定性与微生物间协同变化是一个复杂过程,深入探究该过程机制有助于认识土壤 POC 和 MOC 的驱动强度和生态机理,是评估放牧管理下草地固碳过程的关键。

放牧管理对草地植物、土壤和生态系统碳循环有着复杂的影响作用,但因放牧对照试验地点、年限设置及观测指标等的差异,不同放牧强度、制度下高寒草地碳收支响应机理仍不明确,增加了模型模拟结果的不确定性。整合地面观测和模型模拟,探究高寒草地放牧管理方式下从植被层到土壤层的碳储量及收支的响应过程,评估不同草场围封和不同放牧强度的增汇速率和潜力,发展草地管理模式及气候情景的草地碳汇功能的遥感—生态过程模型,预测未来高寒草地碳汇功能的演变趋势并提出适应性的管理对策,不仅将促进全球变化科学研究发展,也为评估放牧管理方式下的碳增汇潜力及草地碳中和提供数据和方法基础,为合理规划草

地资源保护与利用提供理论支撑。然而,也必须要指出,区域尺度的模型研究,需要样地尺度不同管理措施下草地的植被和土壤背景及其变化过程的数据支持,以校验模型参数和评价模型不确定性,才有可能准确的模拟和预测结果。

5　总结

放牧管理对草地植物、土壤和生态系统碳循环有着复杂的影响作用,但因放牧对照实验地点、实验控制条件、以及研究尺度等的差异,不同放牧强度下高寒草地土壤碳固存机理仍不明确,并增加了模型模拟结果的不确定性。建议今后在放牧控制实验基础上,进一步开展自由放牧强度草地碳固存的草食动物—植被—土壤碳过程耦合机制研究,探究高寒草地从植被层到土壤层的碳固存对牧食强度的响应,评估不同放牧强度的增汇速率和潜力,发展草地管理模式及气候情景的草地碳汇功能的遥感—生态过程模型,预测未来高寒草地碳汇功能的演变趋势并提出适应性的管理对策。研究不仅将促进全球变化科学研究发展,也为评估放牧管理方式下的碳增汇潜力及草地碳中和提供数据和方法基础,为合理规划草地资源保护与利用提供理论支撑,因而具有非常重要的科学和现实意义。

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