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# 草灌植被转变对草地生态系统及其水碳过程的影响研究进展

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**摘要:** 气候变暖和过度放牧的共同作用使全球草地出现明显的灌丛化现象, 灌木去除是草地灌丛化控制的重要方式, 识别这些草灌植被转变对生态系统、生态水文、土壤侵蚀和侵蚀碳流失的影响对草地可持续管理具有重要意义。综述了草地灌木入侵及其控制对植物群落和土壤功能(如土壤有机碳)的影响, 以及这些草灌植被变化对生态水文、土壤侵蚀和土壤侵蚀碳流失等水碳耦合过程的影响机制。针对目前草地灌木入侵和去除对植物群落、植被格局、水土过程和功能影响研究的薄弱环节, 对未来相关研究提出以下建议: (1) 需深化草灌植被转变对碳、氮等生物地球化学循环的影响机制研究, (2) 需重视核磁共振光谱、生物标志物、同位素等新技术和植被格局的指数与连通性等新方法在草灌植被转变的水、碳等生态效应研究中的应用, (3) 需加强草灌植被格局和生态水文、土壤侵蚀与土壤侵蚀碳等水碳过程的多要素、多过程和多尺度的综合研究。本文旨在为灌丛化草地科学有效的生态恢复与多目标的土地利用管理提供理论支撑。

**关键词:** 灌木入侵; 灌木去除; 生态水文; 土壤侵蚀; 土壤碳库

## Research progress on the effect of the transition between shrub and grass vegetation on grassland ecosystem and its water-carbon processes

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**Abstract:** The combined effects of overgrazing and climate warming drive shrubs to encroach into grassland ecosystems worldwide, while removal of the shrub is an important controlling measure for shrub encroachment. It is meaningful for sustainable grassland management to identify the impacts of transitions between grass and shrub vegetation on the ecosystem, eco-hydrology, soil erosion, and soil erosional carbon loss. In this paper, we reviewed the effects of shrub encroachment and its removal on the plant community and soil function (e.g., soil organic carbon), and the impact mechanism of these transitions between grass and shrub vegetation on the water-carbon coupling processes such as the ecohydrological, soil erosional, and erosional carbon loss processes. According to the weakness of previous research on the impacts of shrub

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encroachment and its removal control on plant community, vegetation pattern, and soil-water processes and functions, we provided several suggestions for future research directions: further studying the influence mechanism of transitions between grass and shrub vegetation on biogeochemical cycles such as carbon and nitrogen cycle, paying more attention to applying new techniques such as nuclear magnetic resonance (NMR) spectroscopy, biomarker, isotopes, and methods (e.g., indicators and connectivity of vegetation pattern) to determine the ecological effects of water and carbon for transitions between grass and shrub vegetation, and strengthening the multi-factor, multi-process and multi-scale comprehensive study among grass-shrub vegetation pattern and water-carbon processes such as eco-hydrology, soil erosion and soil erosional carbon loss. These can provide theoretical support for scientific and practical ecological restoration and multi-objective land-use management of shrub-encroached grassland.

**Key Words:** Shrub encroachment; Shrub removal; Eco-hydrology; Soil erosion; Soil carbon storage

草地占陆地面积的一半,贡献了三分之一的陆地净初级生产力,支撑着世界畜牧业生产,是人类福祉和全球生态系统可持续性的关键。由于不合理的土地利用(如过度放牧)和气候变化导致草地灌木入侵,常被称为草地灌丛化,成为草地生态系统退化的重要路径之一,直接影响草地生态系统功能及服务供给<sup>[1-3]</sup>。在半干旱区,草地灌木入侵程度的增加对土壤肥力有正效应(如土壤碳、氮),而减少林下草本覆盖度,土壤肥力、林下植被生长和总体的植被组成存在明显的权衡<sup>[4]</sup>。同时,草地灌丛化也改变了植被覆盖类型,致使水文功能的改变,从而影响土壤侵蚀控制和土壤肥力<sup>[5]</sup>。灌木人为机械去除被认为是草地灌丛化控制的重要方式,但是这些草地管理方式对水土生态功能的影响存在多重权衡关系,如灌木去除增加草生物量和地被层的多样性,却减少了凋落物、生物结皮覆盖和土壤养分,这与土壤保持和养分循环存在潜在的权衡<sup>[6-7]</sup>。而草地灌木入侵和去除控制引起的草灌植被格局变化对植物群落特征、生态水文和土壤侵蚀的影响及其权衡与协同关系尚不清楚。

土壤碳库是陆地最大有机碳库,在气候变化和土地利用转变背景下土壤碳库在全球碳循环中起着重要作用<sup>[8]</sup>。由于陆地表层多以不平坦的坡面景观组成,在土壤侵蚀和成土过程的共同作用下土壤再分布和生物地球化学循环过程对土壤碳库的影响至关重要,这直接导致陆地表层土壤碳源-汇格局的改变<sup>[9]</sup>。非 CO<sub>2</sub> 的土壤碳通量(如颗粒有机碳的侵蚀和溶解性有机碳的输出)显著影响全球碳收支,在不考虑这些土壤碳通量时模型会高估全球碳收支量,且土地覆盖显著影响土壤侵蚀导致的土壤碳流失<sup>[10-11]</sup>。草地灌木入侵会直接影响草地生态系统的土壤有机碳,一般认为灌木使原生草地成为碳汇,但是草地木本植物入侵对土壤碳、氮的影响显著受降雨的调节,越干旱的区域显示净增加,而越湿润的区域体现为净流失<sup>[12-13]</sup>。草地植被、土壤、水文、侵蚀对灌木去除的响应也受局地条件(如气候、土壤、灌木特征和土地利用等)的影响,使草地灌木去除控制对土壤碳库的影响不确定性大<sup>[14-15]</sup>。由于草地灌木入侵和去除对土壤碳库的影响全球分异性大,草地灌木扩张和去除管理致使植物群落和植被格局演变,影响水文和侵蚀等水土过程,从而导致土壤碳库由于水文和侵蚀等生物物理过程影响的流失定量观测和机理认识不足。

因此,本文综述草地灌木入侵和去除控制对植物群落和土壤功能的影响,草灌植被变化如何影响生态水文和土壤侵蚀过程,以及水文、侵蚀和土壤侵蚀碳流失等水碳耦合过程的研究进展,并提出以后主要研究热点方向,为草地多目标的土地利用优化管理和流域、区域的碳收支模型构建与模拟提供理论支撑。

## 1 草地灌木入侵及其控制对植物群落和土壤功能的影响

### 1.1 草地灌木入侵对植物群落和土壤功能的影响

在全球整合分析发现灌木入侵使草本覆盖度呈现减少趋势,而对土壤碳、氮呈现出一致性增加的规律(图1)<sup>[12]</sup>。北美半干旱草地生态系统灌木的密度和盖度都显著增加,减少约45%的物种丰富度,增加了年净初级生产力,且物种丰富度和年净初级生产力的权衡关系受降雨量制约<sup>[16-17]</sup>。在全球干旱地的研究发现植

物多样性和生态系统多功能性显著受灌木盖度的影响,当灌木盖度达到中间水平(41%—60%)时,植物多样性、丰富度和生态系统多功能性等特征达到峰值,物种丰富度与灌木盖度正相关关系在气候越湿润区域更加明显<sup>[18]</sup>。草地灌木入侵的植物性状对植物群落有明显影响,也受气候和土壤差异的影响,如结构性状(如高大的、混合的牙根和须根)高的入侵木本植物降低了生态系统组成、结构和功能性状主要调节木本植物入侵过程中的土壤稳定性<sup>[19]</sup>。因此,灌木入侵对植物群落的影响全球分异性大,受局地因子的显著影响,特别是气候因子。

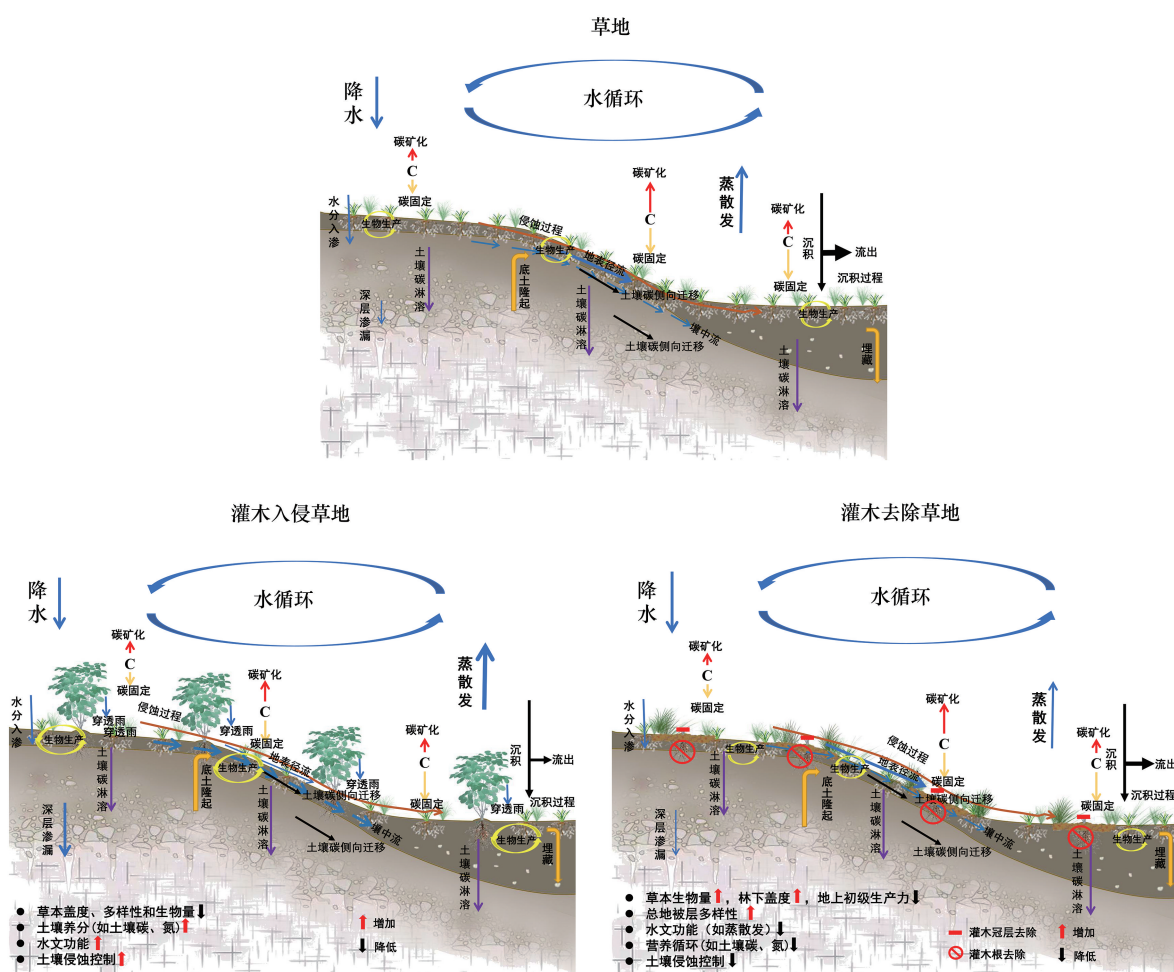


图1 草灌木植被转变对草地生态系统及其水碳过程的影响概念图

Fig.1 The conceptual framework of the effect of the transition between shrub and grass vegetation on grassland ecosystem and its water-carbon processes

灌木入侵也直接影响土壤功能(如土壤碳、氮),对地下部分影响更为复杂。在北美干旱地草地灌木入侵影响生态系统碳平衡,土壤有机碳平均积累  $385 \text{ g C/m}^2$ ,年平均降雨  $336 \text{ mm}$  是影响地上净初级生产力增加或减少的重要阈值,且火烧、土地管理和干旱等干扰因素显著抵消土壤碳积累效应<sup>[20]</sup>。也有研究表明草地灌木入侵使地上生物固碳增加,且  $\text{C}_4$  功能群草本植物有助于土壤固碳能力的增加<sup>[21]</sup>。在我国北方典型草原灌木入侵改变植被格局,通过降低草本植物的丰富度、地上生物量和增加土壤碳氮含量增加了景观异质性,且受灌木种类与特征、气候等因素影响<sup>[22]</sup>。灌木入侵对土壤有机碳的影响又受土层深度和草地类型决定,深层土壤有机碳含量显示灌丛高于草地<sup>[23]</sup>。高寒草甸向灌木为主的群落演替减弱了高寒草甸产草和固碳功能<sup>[24]</sup>,而有研究表明金露梅灌丛草甸斑块贡献了主要的固碳,与灌木生物量密切相关<sup>[25]</sup>。灌木入侵的菌根类型及根际微生物在生物地球化学循环具有重要作用。菌根类型的改变影响着冻原生态系统灌木入侵后土壤长期

碳、氮储量,外生菌根真菌和欧石南类菌根真菌对土壤有机质积累和分解具有相反的作用<sup>[26]</sup>。同时,土壤真菌及其多样性与灌丛的土壤有机碳和总氮密切相关,也受灌丛地上生物量和年平均降雨的调节<sup>[27]</sup>。木本植物入侵也影响土壤微生物丰富度和群落组成,其中根共生体类型起着重要作用,如氮固定的木本植物具有高的土壤真菌丰富度,杜鹃花类菌根则有较高的土壤细菌丰富度<sup>[28]</sup>。草地入侵灌木的结构和功能性状对木本植物入侵过程中的土壤稳定性具有重要的调节作用<sup>[19]</sup>,但是草地灌木入侵过程中土壤稳定性机制仍然不明,特别是土壤碳库的稳定性。目前,固体核磁共振、生物标志物和放射性同位素(<sup>14</sup>C)等先进手段相结合解析土壤碳库组分及其来源为揭示灌木入侵过程中的土壤碳库稳定性机制提供了新方法、新途径<sup>[29-30]</sup>。有研究通过以木质素和氨基糖作为植物残体和微生物残体的生物标志物解析了草地和林地土壤有机碳的生物来源明显不同,微生物残体碳对土壤有机碳贡献在草地中比林地大,而植物残体是林地土壤有机碳的主要来源<sup>[31-32]</sup>。因此,将核磁共振、生物标志物和放射性同位素(<sup>14</sup>C)等新技术应用到灌木入侵过程对土壤碳组分及其来源的影响研究,以及入侵灌木菌根类型和根际微生物过程在土壤碳库的稳定性和生物地球化学过程中的作用将会是热点研究方向。

## 1.2 草地灌木去除对植物群落和土壤功能的影响

草地灌木去除对植物群落和土壤功能也有显著影响,且灌木机械去除对草地灌丛化控制的成效受气候、土壤、地形和年限等因素影响。在全球整合分析发现草地灌木去除增加草本生物量和草本丰富度,减少凋落物、生物结皮覆盖和土壤碳氮含量<sup>[6]</sup>。在灌木去除后长期演替过程中增加了本地草本覆盖度,以及冠层间的草本植物,受土壤因素显著影响<sup>[33-34]</sup>。而灌木去除的有效性是短暂的(<5年),对生产力、水文和土壤碳氮等生态功能的影响周期更长(持续10年以上)<sup>[7]</sup>。如灌木林通过13年的去除控制后对生态系统碳储量和土壤有机碳储量都无显著的影响<sup>[35]</sup>。也有研究发现功能性状(如氮固定、落叶等)高的木本植物去除减弱了生态系统功能,木本植物结构和功能性状主要调节木本植物去除过程中的草本盖度,从而影响木本植物去除的生态效应,且受气候和土壤等非生物因素显著影响<sup>[19]</sup>。而在高寒区,通过灌木去除控制试验发现灌木入侵影响苔原生态系统功能主要是灌木冠层作用,而不是凋落物输入质量和数量<sup>[36]</sup>。高寒灌丛草甸去除灌丛和禾本科草在短期内对群落水平的非禾本科草和生物量无显著影响,而物种水平的相互作用显著影响群落组成<sup>[37]</sup>,同时灌丛冠层和根的去除对灌木林下草地植物群落组成有显著影响,与灌木根呈正效应,而与冠层呈负效应,特别是物种多样性、丰富度和草产量<sup>[38-39]</sup>。在亚高山草灌群落斑块6年去除试验发现,优势草去除减缓了与次优势草的竞争压力,而优势灌木去除对次优势种的生物量无影响,优势草和灌木去除对物种丰富度都无显著影响,植物功能群决定优势物种间的相互作用<sup>[40]</sup>。树线群落过渡带外来木本植物去除增加了物种多样性和物种丰富度,需光和氮低的植物种成为主导物种<sup>[41]</sup>。目前,灌木去除对植物群落、土壤碳和草产量等生态系统结构和功能的影响区域分异明显,而对于灌木冠层和根去除的植被格局与土壤功能长期演变,以及对生物地球化学循环影响的长期研究不足。

## 2 草地灌木入侵及其控制对生态水文和土壤侵蚀过程的影响

### 2.1 草地灌木入侵及其控制对生态水文过程的影响

草地灌木入侵及其控制引起植被覆盖类型和土地利用的改变,从而影响生态水文过程(图1)。在全球尺度灌木入侵使植被变绿,提高了生态系统水分利用效率<sup>[42]</sup>。也有研究表明降雨、蒸散发和产水等生态水文背景决定草地与灌丛转变的可能性以及优先的替代转变机制,优先级高于人为干扰<sup>[43]</sup>。因此,降雨、林冠截留、地表入渗、深层渗漏和植被水分利用(蒸散发)等生态水文过程及其动态变化与植被覆盖密切联系<sup>[44-45]</sup>。草地灌木入侵使植物群落组成、植被格局改变,从而影响生态水文过程<sup>[46]</sup>,但是草地灌木入侵对土壤水分动态影响的内在生态水文机理尚未明晰。如草地灌木入侵未增加植被土壤水可获得性,而是以灌丛树干茎流作为优先流增加了土壤深层入渗,从而影响土壤资源的空间分布<sup>[47-48]</sup>。灌丛植被的冠层集水效应有利于土壤聚集降水资源,但是土壤水分的有效性浅层化明显<sup>[49]</sup>。也有研究表明灌木斑块土壤田间持水量和植物可利用

水高于草地,有利于土壤水分保持,且随着灌木覆盖度增加而增加<sup>[50]</sup>。草地向灌丛转变又将进一步影响入渗和蒸散发等生态水文过程,使灌丛植被增加约 65% 的水分入渗,也增加了约 30% 的蒸散发量<sup>[51]</sup>。同时,草地灌木入侵在一定程度上可以减缓过度放牧影响土壤孔隙度和入渗过程而引起的土壤水文功能减弱,其中灌木特征、有机质覆盖起着重要作用<sup>[52]</sup>。在内蒙古高原和黄土高原利用氢、氧稳定性同位素研究草本和灌木水分利用来源表明草本植物主要利用土壤表层的土壤水分,而灌木主要利用中深层土壤水分,且灌木和草本植物对水分的竞争格局主要受水资源限制<sup>[53-54]</sup>。因此,稳定同位素技术为揭示草地灌木入侵对土壤水分动态的生态水文机理提供了重要的技术手段。

再者,草地灌木去除管理措施减少冠层影响,从而减少了降雨截留和蒸腾,而增加了蒸发<sup>[55]</sup>。灌木林下植被盖度增加又可以增加部分蒸散发,从而降低草地灌木去除对土壤入渗的影响<sup>[56]</sup>。但是由于气候、土壤等因素全球分异,草地灌木去除对土壤水分深层补给的影响机理尚不明确。如北美草地灌木去除使灌丛向草地转变增加了深层土壤水分和深层排水,其中植物功能群对水分平衡有显著影响<sup>[57-58]</sup>。草灌植被转变多归因于大气 CO<sub>2</sub> 浓度升高、放牧和火烧等因素干扰,土壤水文属性对这一过程的影响常被忽视<sup>[59]</sup>。有研究表明木本植物去除改善了冠层间水力传导度和土壤水文功能,促进了冠层间入渗,限制了产流<sup>[60]</sup>。木本和草本植物根系垂直分布格局直接影响根系对土壤水分的获得和水文生态位的分配,深层分布的根可以获得更多的土壤水分,而草本仅能利用表层土壤水分<sup>[61-63]</sup>。由于年均降雨、干燥度、土壤属性等水文背景差异,草地灌木去除引起的草灌植被变化对土壤水分、入渗和持水能力等生态水文过程的影响机制研究仍不完善,未来需要更多固定、长期的野外观测试验研究作为基础支撑。

## 2.2 草地灌木入侵及其控制对土壤侵蚀过程的影响

由于坡度、气候、尺度、土地利用等因素作用,使土壤侵蚀在空间上高度分异。坡面土地利用对土壤侵蚀的影响更显著,林地和灌丛具有最低的土壤侵蚀率<sup>[64]</sup>。灌丛比草地的径流系数低,减少了地表径流和地下壤中流,草地向灌丛转变也使产流机制从饱和产流向非饱和产流转变<sup>[65]</sup>。草地灌木去除引起的植被类型变化也会影响关键的径流和产沙过程,区域分异明显。如在流域尺度伐木管理减少了径流量,随着降雨量增加而增加<sup>[66]</sup>。也有研究发现草地树木机械去除增加了本土草种的密度和覆盖度,而坡面低的覆盖度增加了裸地面积又导致高的产流和产沙量<sup>[60]</sup>。灌木入侵和去除改变植被格局,植被格局也是水文和侵蚀过程重要的控制因素,显著影响产流和土壤侵蚀的时空分布(图 1)。如植被空间聚集与分布显著影响水分再分配过程,这与土壤入渗、产流能力密切相关,植被聚集与植物物种丰富度、植被覆盖范围呈现显著的正相关关系<sup>[67]</sup>。植被斑块类型与土壤水分含量密切相关,更高的土壤水分有利于提升植物多样性和土壤属性,土壤水分含量与产流能力又呈现负相关<sup>[68]</sup>。景观格局分析中格局指数研究为定量植被覆盖类型转变对产流和土壤侵蚀机制研究提供了有效的解决工具,如通过人工测量以斑块连通性、植被覆盖类型和景观位置改进的景观格局指数对于揭示植被恢复类型对水文过程的影响机制有较好的解释度<sup>[69]</sup>。也有研究表明跨尺度的结构和功能连通性反馈有助于解释灌丛草地状态转变,灌木化学控制使草地的水文连通性变化不明显,结构连通性减弱了径流和泥沙输移的能量,从而降低了泥沙连通性<sup>[70]</sup>。因此,未来研究应考虑景观尺度上草地灌木入侵与去除引起的植被格局变化对径流、壤中流和产沙的影响机制,特别是景观指数和连通性来揭示植被格局、水文和侵蚀过程的相互作用机理。

## 3 草地灌木入侵及其控制对土壤侵蚀碳流失的影响

### 3.1 水文和土壤侵蚀过程对土壤碳库的影响

土壤碳流失除了以 CO<sub>2</sub> 气态形式流失外,水文过程通过激发碳在土壤剖面、坡地以及流域的物理和化学过程交换,主要以地表径流和碳淋溶的途径流失(图 1)<sup>[71-72]</sup>。全球土壤碳在人为加速侵蚀和沉积过程的净碳量相当于 1/3 由于土地覆盖改变引起的碳排放<sup>[73]</sup>。而坡面降雨过程中土壤碳通量的生物物理过程和生物地球化学过程影响生态系统碳循环,生物地球化学过程是通过土壤微生物作用或土壤矿化作用,土壤碳被分

解反应形成  $\text{CO}_2$ ,最终以垂直通量的形式释放到大气中,而生物物理过程是通过侵蚀和水文过程形成的碳通量,土壤侵蚀不仅使土壤微小颗粒及其输移的颗粒碳流失,也会导致可溶性碳的流失,称为土壤侵蚀碳流失<sup>[74-76]</sup>。在次降雨过程中,水文过程碳通量主要受到降雨、入渗、径流、壤中流和产沙等坡面水文和土壤侵蚀过程影响,由降雨和入渗过程控制的碳通量为垂直碳通量,而由地表径流和产沙过程控制的各组分碳通量为侧向碳通量,以地表径流、壤中流、地下径流流失的碳进入流域水体<sup>[77-78]</sup>。地形因素直接影响土壤侵蚀过程和土壤有机碳的再分布,坡面自上而下存在侵蚀区和沉积区,使土壤碳的垂直和侧向碳通量差异显著,而由于侵蚀的搬运作用在沉积区使土壤有机碳积累<sup>[79-80]</sup>。而这些过程也与坡面的植被覆盖类型、土壤水分动态和土壤质地(如团聚体粒径分布)等因素密切相关<sup>[81-83]</sup>。由于全球气候、植被、土壤和地形等因素的空间异质性,土壤碳库由于水文和侵蚀等物理过程引起的碳及组分流失,以及微生物过程引起的土壤碳动态耦合机制还缺乏系统认识。

### 3.2 灌木入侵和去除对草地土壤碳流失过程的影响

草地灌木入侵和去除措施影响植被覆盖、水文和侵蚀过程,从而也改变土壤碳的土壤剖面格局和空间分布(图1)<sup>[84]</sup>,但是由于气候、植被、土壤等环境异质性使土壤侵蚀碳的通量定量研究不确定性很大。由于土地利用的改变,土壤侵蚀使土壤-植被系统表层土壤及土壤碳的再分布加剧,从而影响陆地土壤碳的源-汇格局<sup>[71]</sup>。在黄土高原,退化草地转变为灌木林地更有利于水土保持,显著减少土壤有机碳的损失<sup>[85]</sup>。灌木入侵草地火烧干扰去除灌木第一年后土壤侵蚀导致土壤碳库损失  $1474 \text{ kg/hm}^2$ <sup>[86]</sup>。不同植被类型及坡面位置的产沙和土壤侵蚀碳流失有显著差别,进而影响坡面土壤碳流失各组分比例,如灌木群落由于其高的植被覆盖度,土壤侵蚀碳流失量最小,也减轻土壤有机碳富集程度,入渗碳通量是表层土壤碳输出中最重要的渠道,总入渗碳通量占总碳输出通量近 96%<sup>[87]</sup>。在北美的奇瓦瓦沙漠,草地灌木入侵使灌丛的土壤有机碳含量显著高于其周边裸地,土壤侵蚀作用增加了土壤有机碳的空间异质性,且灌木地比草地的土壤有机碳损失高 3 倍<sup>[88]</sup>。在阿根廷巴塔哥尼亚东北部,也发现灌木草地比草地的土壤流失和土壤有机碳富集率更高<sup>[89]</sup>。草灌植被变化也直接影响土壤碳组分及其比例变化,而水文和土壤侵蚀过程加剧土壤碳库的不稳定性。欧洲亚高山草地灌木入侵 40 年使原有草地的土壤有机碳储量从  $100 \text{ t C/hm}^2$  降低到  $81 \text{ t C/hm}^2$ ,且灌丛增加了矿质土壤中颗粒有机物和不受保护的碳浓度,易以可溶性有机碳的形式流失<sup>[90]</sup>。也有研究表明草地灌木入侵不仅加剧了土壤侵蚀碳流失,也促使草地中原有的稳定有机碳的流失,该区域草地向灌丛植被转变使土壤碳库极不稳定<sup>[91]</sup>。草地灌木入侵也影响土壤碳库组分使土壤无机碳流失,如灌木入侵导致土壤酸化程度增加,导致 0—100 cm 土层的土壤无机碳库减少<sup>[92]</sup>。灌木入侵后深层根系影响水文过程,这直接提升了土壤碳的碳酸盐风化率<sup>[93]</sup>。高寒灌丛和草地的土壤碳库组分直接影响水文和侵蚀过程对土壤碳流失过程的影响,如高寒草地的颗粒有机碳、轻组有机碳、碳水化合物等土壤碳组分高于灌丛,灌丛草甸土壤中非保护性碳含量较高<sup>[94-95]</sup>。也研究发现坡面高寒草甸和灌丛草甸土壤有机质组分及其侧向流失直接影响流域河流中颗粒有机质的组分<sup>[96]</sup>。目前大部分研究多集中于灌木入侵及其控制对土壤碳库及其组分状态量的量化及其影响因素的解释,而定量灌木入侵及其控制引起的草灌植被转变对土壤有机碳侵蚀侧向流失的生物物理过程的系统解释不足,特别是土壤侵蚀碳流失的有机和无机碳组分及其比例关系的研究。

## 4 展望

全球草地灌丛化问题突出,直接影响草地产草量,威胁畜牧业发展。灌丛化草地灌木去除是恢复草地重要的草地管理方式。草地灌丛化和草地灌木去除引起草灌植被变化,直接影响水文、侵蚀和土壤碳流失等水碳过程,威胁土壤碳库的稳定性。由于全球草地灌丛化的气候、土壤、灌木特征和草地管理方式等分异大,使草地灌丛化及其控制的植被格局、水文、土壤侵蚀和土壤侵蚀碳的耦合作用具有复杂性、综合性。通过对草地灌木入侵和机械去除引起的草灌植被转变对植物群落和土壤功能、生态水文和土壤侵蚀过程以及土壤侵蚀碳流失的影响研究进展的回顾,未来仍需对如下研究方向进一步加以考虑:

1)需深化草灌植被转变对草地生态系统碳、氮等生物地球化学循环的影响机制研究,特别是入侵和去除灌木的菌根类型和根际微生物过程对土壤碳、氮库组分、来源及稳定性的影响。

2)需重视新技术、新方法在草灌植被转变的水、碳等生态效应中的应用,如生物标志物和放射性同位素( $^{14}\text{C}$ )结合分析草地灌木入侵和去除对土壤碳库稳定性的影响机制;稳定同位素技术应用于草灌植被转变对土壤水分利用格局影响的生态水文机理研究;应用植被格局指数和连通性来定量草灌植被变化对坡面水碳过程的影响。

3)需加强多要素、多过程和多尺度的综合研究,如草灌植被格局和生态水文、土壤侵蚀与土壤侵蚀碳等水碳过程耦合作用机理研究,特别是土壤碳库由于水文和侵蚀等物理过程引起的碳及组分流失,以及微生物过程引起的土壤碳动态耦合机制。

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