DOI:10.11686/cyxb2022077　　http://cyxb.magtech.com.cn
高丽,丁勇.世界退化草地恢复研究和实践进展.草业学报,2022,31(10):189－205.
GAO Li, DING Yong. Progress in research and practice of restoration of degraded grassland around the world. Acta Prataculturae Sinica, 2022, 31(10): 189－205.

世界退化草地恢复研究和实践进展

高丽*,丁勇*
(中国农业科学院草原研究所,内蒙古草业与草原研究院,内蒙古 呼和浩特 010010)

摘要:草地是地球上最重要的陆地生态系统之一,给人类带来诸如食物生产、调节气候、净化空气、涵养水源、防风、固沙等一系列的生态系统服务。受气候变化和人为因素的影响,全球接近一半的草地出现不同程度的退化,成为世界性生态环境问题之一。世界各地开展了大量的有关退化草地恢复的研究和实践工作,并且取得了巨大的进步。然而,在联合国生态系统恢复10年(2021－2030)启动之际,需要新一代的恢复研究和实践项目来应对全球的环境挑战。本研究对世界各地有关退化草地恢复研究和实践进行了总结,希望从已有的草地恢复工作中学习经验,在此基础上,找出未来退化草地恢复研究的主要方向,制定合理的退化草地恢复计划,进而为全球变化背景下的新的草地恢复研究和实践提供参考依据。

关键词:草地;退化;恢复;研究;实践

Progress in research and practice of restoration of degraded grassland around the world

GAO Li*, DING Yong*
Institute of Grassland Research, Chinese Academy of Agricultural Sciences, Inner Mongolia Academy of Grassland Science, Hohhot 010010, *China*

Abstract: Grassland is one of the most important terrestrial ecosystems on earth, and brings humankind a series of ecosystem services, including food production, climate regulation, air purification, water conservation, wind prevention and sand fixation. Nearly half of the grasslands in the world are affected by climate change and human factors, and thus display different degrees of degradation. This degradation has become one of the world's ecological and environmental problems. Much research on restoration of degraded grasslands has been carried out around the world with findings often leading to change in practice, and great progress has been made. However, at the beginning of the UN Decade on Ecosystem Restoration (2021－2030), a new generation of restoration research and practice projects is needed to cope with global environmental challenges. This paper summarizes the research and practice of degraded grassland restoration around the world, in the hope of learning from the existing grassland restoration work. On this basis, it is anticipated that we can map out the main direction of future research on degraded grassland restoration, and formulate reasonable restoration plans for degraded grassland, so as to provide reference information for new grassland restoration research and practice in the context of global change.

Key words: grassland; degradation; restoration; research; practice

收稿日期:2022-02-18;改回日期:2022-04-18
基金项目:内蒙古自治区自然科学基金项目(2021MS03076;2020ZD06),内蒙古科技计划项目(2020ZD0020;2019ZD008)和中央级公益性科研院所基本科研业务费项目资助。
作者简介:高丽(1980-),女,内蒙古鄂尔多斯人,副研究员,博士。E-mail: gaoli1980@126.com
*通信作者 Corresponding author. E-mail: gaoli1980@126.com,dingyong228@126.com

草地是陆地生态系统的重要组成部分，占全球陆地（除冰盖和冰层外）总面积的40.5%[1-2]，具有重要的生态与食物生产功能[3-4]。受农业发展、城市化、物种入侵、气候变化和其他人为因素的影响，草地出现大规模的退化[5-8]，成为重要的世界性生态环境问题之一[9]。过去几十年，世界各地的政府机构、高等院校、科研院所、企业、社会组织、土地所有者等利益相关者开展了大量有关退化草地恢复的研究和实践工作，草地恢复科学和实践取得了巨大的进步，但恢复工作普遍未能将草原的生物多样性以及其他生态系统属性恢复到原来的状态[7,10]。此外，大气CO_2浓度增加、气温升高、降水格局改变等气候变化因素威胁着草原生态系统的生物多样性和稳定性[11-12]，从而增加了退化草地恢复过程中的不确定性[13]。因此，迫切需要对已有的退化草地恢复研究和实践进行总结，从成功的草地恢复工作中学习经验，同时发现存在的问题，在此基础上，找出未来退化草地恢复研究的主要方向，制定合理的退化草地恢复计划，进而为全球变化背景下的新的草地恢复研究和实践提供参考依据。

1 世界退化草地恢复研究和实践现状

根据气候条件和地理位置，全球天然草原可分为热带、亚热带稀树草原（savannas）、温带草原（steppes）和北极－高山草原（arctic－alpine grasslands）[14]。由于生态系统退化和转换，热带、亚热带稀树草原和温带草原遭受了严重损失[15]。

1.1 退化稀树草原恢复研究和实践现状

稀树草原覆盖了非洲和澳大利亚一半以上的面积，南美洲45%的面积，印度和东南亚10%的面积[16]。由于受密集和长期的农业和商业活动的影响，分布于非洲南部[17-18]、澳大利亚北部[19-20]、巴西中部[21-22]的大面积稀树草原已经退化[23-25]，遭受着外来植物的入侵[26-27]，土壤退化[28-29]、水土流失[24]、生物多样性的丧失[30]，造成许多生态和社会经济的威胁[31]。

1.1.1 非洲稀树草原 非洲稀树草原是南非、博茨瓦纳、纳米比亚和津巴布韦等国的主要植被类型[32]。在非洲南部，稀树草原是关键的资源区，长期以来用于商业和农业发展以及野生动物的保护[17-18]。在南非半干旱地区，由于长期放牧导致许多稀树草原发生退化[17]，遭受着外来植物的入侵[33]。银胶菊（*Parthenium hysterophorus*）是南非稀树草原生态系统及其牧场中主要的入侵草种，其在南非的持续入侵，造成许多生态和社会经济的威胁[31]。来自南非的高校和科研院所的专家们开展了大量退化草地修复研究工作。例如通过减少放牧牲畜数量，可以使牧场恢复，同时降低银胶菊的密度和影响[34-35]。然而，仅仅通过减少放牧压力，达到自然恢复，可能需要很长的时间，而且根据入侵的严重程度，成功率有限[17]。采用化学、机械和生物控制方法来解决银胶菊的入侵[33,36-37]，没有产生明显的效果[38]。在低度到中度放牧的稀树草原和牧场上，同时采用清除银胶菊和播种本地多年生草种可能有助于抑制银胶菊，从而恢复非洲南部和其他国家有类似入侵植物的草原[36]。由于过度放牧，土壤中的种子逐渐枯竭，再加上高的幼苗死亡率，大大降低了半干旱非洲稀树草原土壤种子库和地上植被中多年生草的密度。因此，在过度放牧的影响下，幼苗的存活和随后的建立是决定稀树草原种群成功恢复、生长和长期持续的关键过程[39]。稀树草原生态系统是由连续的草本植物层以及稀疏的乔木和灌木斑块组成[40]。稀树草原生态系统中木本植物的扩散被称为灌木侵占[41]，灌木丛的侵占会导致稀树草原生态系统的牲畜承载能力下降[42]。纳米比亚和南非的生态学家和农民对成本效益高的，减少灌木侵占的措施进行了广泛的研究，这些措施包括空中喷药、使用重型机械和手工清除[43]。在潮湿的稀树草原上，火烧是刺激新草生长的一个重要措施[43]。

1.1.2 澳大利亚稀树草原 澳大利亚稀树草原主要集中分布在澳大利亚北部地区，以桉树（*Eucalyptus robusta*）为主，形成一个开放的上层树冠（<50%的覆盖率），各种一年生和多年生的C_4草在下层占主导地位[19-20]。放牧是澳大利亚大部分地区最主要的土地使用方式[44]。牛的引入已经导致澳大利亚稀树草原发生了相当大的变化[45]，直接影响包括优先采食适口好的植物物种、降低了竞争力较强植物的覆盖率和增加了土壤干扰[28-29]，间接影响包括因地面覆盖物减少而导致的动物群落变化[46]。在澳大利亚昆士兰州东北部的研究表明，在高度干扰的稀树草原生态系统中去除牛群，在恢复的前10年里，本地草和外来草的物种丰富度均增加，适口性较差的物种减少，适口性较好的物种增加[47]。火是澳大利亚稀树草原功能最重要的驱动因素，稀树草原火格局的改变会影响树和草的平衡[48]。火的发生频率或强度的减少会促进树的生长和扩展，极大地改变稀树草原的生态系

统结构,增加木质部分的碳储存;火的发生频率或强度的增加有利于草的生长,因为它抑制了树的生长和扩展[49]。澳大利亚北部土著土地和海洋管理联盟有限公司(North Australian Indigenous Land and Sea Management Alliance,NAILSMA)建立了西阿纳姆土地消减火灾(West Arnhem Land Fire Abatement,WALFA)项目,让土著土地所有者参与进来,利用现代技术重新引入传统火灾管理,方法是增加早期旱季火灾的发生率,以减少旱季后期大型高强度火灾的范围,火灾管理可以减少30%的燃烧面积,每年减少约0.6×10^6 t CO_2当量的排放[50]。在澳大利亚西北部皮尔巴拉地区,有数十万hm^2的土地被已有的和新出现的铁矿作业所干扰[51]。研究发现,接种固氮蓝藻对矿区修复中使用的土壤基质的生物结皮覆盖率和土壤有机碳水平有积极和快速的影响[52],通过本地*Microcoleus*和*Nostoc*属的蓝藻预处理种子,对用于矿区修复的一些物种有益,不会抑制植物的建立[53]。杂草入侵是澳大利亚热带稀树草原的一个主要威胁,因为入侵会改变火灾格局,养分循环和稀树草原植被结构[54-55]。非洲多年生植物圭亚那须芒草(*Andropogon gayanus*)是澳大利亚的热带稀树草原的主要入侵种,目前主要使用除草剂(草甘膦)、焚烧和砍伐来控制成熟的圭亚那须芒草,残留的除草剂可以减少圭亚那须芒草现有土壤种子库的繁殖,可以与季节性砍伐和/或焚烧相结合,然后在出苗后施用草甘膦以杀死已建立的植株[56]。白蚁是热带土壤结构和功能的关键媒介,研究表明,白蚁介导的过程可以在澳大利亚稀树草原退化的土壤中启动和维持,从而改善土壤结构和关键的生态系统功能,可以将促进白蚁活动的技术纳入热带土壤恢复管理中[57]。

1.1.3 南美洲稀树草原 在南美洲,稀树草原大部分在巴西、哥伦比亚、委内瑞拉和玻利维亚[58]。巴西稀树草原被称为塞拉多(Cerrado),集中分布在巴西中部高原[21-22]。塞拉多是全球生物多样性热点,拥有约13000种植物,其中34%为特有物种[22,59-61]。由于农业和畜牧业活动的影响,塞拉多已成为巴西最受威胁的生物群系之一[23]。近40年来,其总面积的约一半已转化为牧场、农田和造林地[62-63]。由于全球对木材产品的需求不断增加,在巴西的塞拉多稀树草原,外来的桉树和松树(*Pinus*)的植树造林活动不断增加[64],再加上对火的抑制,导致塞拉多草原生物多样性的丧失[30]。在巴西东南部的植树造林后的稀树草原上,被动恢复(松树砍伐后的自然再生)和本地树木种植(松树砍伐后高密度种植的本地树苗)都恢复了上层植被结构、丰富度和组成。在松树砍伐后,稀树草原恢复将需要通过计划火烧或机械疏伐来控制木本植物的侵袭,并种植稀树草原半灌木和草本植物[30]。非洲入侵草是塞拉多草原的主要威胁之一[27],这类草除了能占据广泛的塞拉多草原区外[65-66],还可能改变火格局[67-68],降低本地木本植物幼苗的存活[69],从而进一步取代本地物种[70]。巴西中部地区的本地灌木*Lepidaploa aurea*通过化感作用对入侵草的生长产生负面影响,有助于控制正在恢复中的塞拉多草原地区的非洲C_4草*Urochloa deumbens*的入侵[71];锄草和草甘膦可以成功地控制*U. deumbens*的入侵,但草甘膦会损害本地物种,锄草对本地植物群落更有利,火烧作为一种补充技术是有效的,通过破坏*U. deumben*s的种子库,使得本地物种成功定居[72]。直接播种是恢复塞拉多草原植被的一种理想的技术,然而,树苗很难克服杂草的竞争,在实施直接播种时,选择不仅能适应水分胁迫环境,而且种子较大、幼苗具有大而深的根系的物种[73],在早期的恢复阶段,通过一年生作物来提供遮荫[74],快速生长的物种防止土壤侵蚀和改变微生境条件,多年生草类重新建立草本层,而树木和多年生的灌木则在恢复过程的后期为恢复稀树草原的结构做出贡献[75]。使用覆盖作物是提高巴西东北部塞拉多土壤生物质量的一个重要工具[76]。废弃的牧场需要采取干预措施,防止木本植物的侵袭,重新引入本地草本植物和灌木[77]。矿产开发也是导致巴西稀树草原退化的一个重要因素,研究表明,在暴露的砾石矿表面,种植塞拉多草原原生植物,通常会被入侵的草类所取代,种植笔花豆属(*Stylosanthes*)植物,能有效地抑制入侵植物[78]。在巴西稀树草原恢复中,尽管需要控制入侵的草,但表土置换有利于许多本地草本和木本物种的繁殖,特别是随表土转移的根部碎片的活性芽库,使得大量的灌木和树木从根部重新生长,表土置换是采矿、城市化以及公路、铁路、管道和渠道建设活动后的一种成功的植物替代手段[79]。研究显示,自然再生的方法需要40多年的恢复才能达到35%的植被覆盖,植树造林需要15年才能达到80%的植被覆盖,使用表土置换+植树或在采矿基质中加入污水污泥,实现了植被覆盖的最快发展(2.5~5.0年),植被覆盖高达80%~95%[80]。

1.2 温带草原恢复研究和实践现状

温带草原是地球上最大的生物群落之一。欧亚大陆草原、北美大陆草原和南美草原是最重要的温带草原,南

非则是非洲温带草原的主要分布地。由于城市化、放牧和农业的影响,温带草原已经严重退化,导致生态系统服务的丧失,草原的承载能力下降,本地植物和动物的栖息地减少[81],这些生态系统中的70%在1950年之前就已经被改变或退化[82]。

1.2.1 欧亚大陆草原　欧亚大陆草原是世界上最大的草原(steppe)地带[83],从中国、蒙古国和西伯利亚南部,跨越哈萨克斯坦、西伯利亚西南部、俄罗斯的欧洲部分、乌克兰和匈牙利,到安纳托利亚、罗马尼亚、斯洛伐克,以及奥地利和西班牙的外围草原[84]。几千年来,欧亚草原主要的生物群落受到人类活动的高度影响、干扰和改变,主要破坏性威胁是将草原转化为耕地、过度放牧、采矿、石油和天然气开发、城市侵占和植树造林,这些威胁的严重程度在不同地区有所不同,例如,在俄罗斯,最严重的威胁是将草地转化为农业用地,但在蒙古国,是过度放牧、采矿和油田开采[83]。分布于中国北方的草原总面积约3×10^8 hm^2[85],由于长期过度放牧和草地开垦为农田,大约90%的草地都有不同程度的退化,其中严重退化草地占60%以上[86]。

在中国,自20世纪80年代国内草原大面积退化以来,草原工作者开展了大量天然草地恢复治理工作[87]。通过实施退牧还草、退耕还草、草原生态保护和修复等工程,以及草原生态保护补助奖励等政策,草原生态系统质量有所改善,草原生态功能逐步恢复。2011-2018年,全国草原植被综合盖度从51%提高到55.7%,重点天然草原牲畜超载率从28%下降到10.2%[88]。通常情况下,围封禁牧被认为是恢复退化草原生态系统植被和土壤的一种有效和经济的方法[89-91]。在中国北方草地,围封禁牧增加了植被的高度[92-93]、覆盖率[94-95]和生物量[96-97],但对于植物多样性和土壤条件的影响有正面的[93,98-99]、负面的[100-101]和中性的[102-103]。不同的生物物理条件(植物群落、土壤质地、气候等)可能导致对围封禁牧的不同反应,围封禁牧对草原的影响也在很大程度上随不同的生态系统而变化[104-105]。春季休牧[106-110]和秋季休牧对退化草原的植被生物量、盖度、高度、多样性[111-113]以及土壤理化性质、土壤酶活性等都有积极作用[114-116]。划区轮牧是将草原划分为几个轮牧小区,一个生长季内牲畜在草地不同的放牧小区之间轮替利用草原[87,117],可以提高牧草产量和质量、增加牲畜体重和改善土壤理化性质[118-119]。浅耕和松耙能够促进群落向原生植被演替,从而加速退化草地的恢复[120]。浅耕通过人为改变地表状况,改善植物的生长微环境[121-122],显著提高了退化草原植被盖度、高度、地上生物量、多样性[123-124],对土壤理化特征以及微生物活性的改善具有良好的促进作用[125-126],浅耕主要适宜于以羊草(*Leymus chinensis*)为主的根茎型禾草典型草原、草甸草原及低洼地和略有碱斑的草甸草原[127],松耙更适宜于相对干旱的大针茅(*Stipa grandis*)和冷蒿(*Artemisia frigida*)建群的草地[106,128]。补播是在不破坏或少破坏草地原有植被的情况下,通过撒播将种子播种在退化草地上[87,127],补播时一般要结合浅耕、灌溉、施肥等辅助恢复措施[106],在内蒙古的撂荒地和沙地灌丛草场、陕西典型梁原草场、新疆荒漠草场实施的补播,增产幅度在58.4%~392.0%[127],最近的研究表明,免耕补播物种与退化草原土壤应具中性或正反馈作用,补播应遵循"禾大豆小"空斑原则,补播后草原宜适度利用保持亚顶级群落状态[129]。草地施肥是改善土壤养分状况、提高牧草产量和质量的一项重要措施,一般情况下,施肥可以提高牧草产量70%~80%[127],但是,长期施用化肥会导致优势草种减少和土壤理化性状恶化[130-131],生物有机肥能够通过活性微生物菌群改善土壤状况,可以防止草地板结退化,对施肥当年植物群落多样性和地上生物量及品质具有积极作用[132]。Meta分析表明,中国湿润地区、温性草原和中度退化草原恢复效果相对较好,生物多样性的恢复速度快于生态系统服务[133]。

有关哈萨克斯坦、蒙古国退化草原恢复的研究和实践的报道相对较少,至今还没有任何经验,或者只是在这个方向上进行了初步尝试[43]。东欧平原的南部,一些国家的研究者们通过采用当地混合植物种子播种和植物材料转移等复垦方法[134-137],成功实施了大尺度草原恢复项目,加速了退化草地的次生演替,增加了生物多样性[135,138]。在俄罗斯,20世纪90年代以来,农业用地的弃耕,被看作是一种积极的土地转型,潜在地促进了退化草原的恢复,改善了土壤质量以及碳封存,增加了生物多样性[139-142]。

1.2.2 北美大陆草原　北美大陆草原从加拿大南部经美国延伸到墨西哥北部。在加拿大,大约70%的原生草原已经消失,主要是由于农业发展和石油及天然气开发[143]。自20世纪40年代末以来,美国永久草地面积一直在下降。1948-2002年,由于城市和郊区的发展、农业用地和木本植被的侵占,美国草地面积占土地面积的百分

比从60%下降到了44%[144]。雅诺斯生物圈保护区位于墨西哥奇瓦瓦州的西北角，该保护区于2009年由墨西哥联邦政府建立，主要是为了保护广阔的原生奇瓦瓦荒漠草原。由于管理不善和持续的工厂化农业扩张，使得奇瓦瓦荒漠草原成为墨西哥最受威胁的生态系统之一[43,145-148]。

在加拿大，政府机构、野生动物管理人员、土地所有者、土著居民以及其他利益相关者做了大量的草原恢复工作。例如，为了保护混合草原(mixed-grass prairie)，建立了草原国家公园，在公园内，通过重新引进平原野牛群(plains bison)并保持在一个可持续的水平、种植银色鼠尾草(*Artemisia cana*)、割草或放牧以及重新种植本地物种、实施计划火烧等措施，不仅使得草原得以恢复，而且提升了野生动物栖息地的质量[143]。在加拿大萨斯喀彻温省中部的艾伯特王子国家公园，通过与当地土地所有者、土著社区和其他利益相关者合作，加强对自由放养平原野牛的管理；通过增加植被覆盖率至90%和减少入侵物种至25%来恢复两个砾石坑；对野牛进行监测，为计划火烧提供信息；试行分流式围栏设计，以防止野牛离开公园；使用计划火烧来恢复混合羊茅(*Festuca ovina*)草原[149]。在雷丁山国家公园，采用计划火烧、翻耕土壤和入侵植物控制方法来恢复羊茅草原，恢复了40 hm^2的羊茅草原[149]。加拿大沃特顿湖国家公园是在山麓公园生态区内保护山麓羊茅草原的唯一的国家公园。由于植物入侵、历史基础设施建设、游憩开发和农业改造，导致阿尔伯塔的原生羊茅草原一直在大幅下降，只有不到35%的羊茅草原未被破坏。在该区域内，通过控制入侵植物、采集并种植本地植物种子以及计划火烧来引入本地植物、减少乔灌木的侵占，增加了野生动物的栖息地[150-151]。

在美国，随着草原和相关栖息地的消失，联邦政府在过去的25～30年里一直在推动建立原生草原，并分担成本，以重新获得与永久草原相关的许多生态服务。1985年通过的《农业法案》(Farm Bill)授权建立了“保护区项目”(Conservation Reserve Program，CRP)，加快了美国草地的恢复。CRP是一个向农业生产者提供的自愿项目，帮助他们利用环境敏感的土地种植长期的资源保护植物，如本地草种，以改善野生动植物栖息地，控制土壤侵蚀，并改善水质。25年来，通过CRP项目的实施，使得超过1295万 hm^2的土地得到恢复。通过连续的《农业法案》授权，美国农业部的其他项目也得到了批准，如野生动植物栖息地奖励项目(Wildlife Habitat Incentives Program，WHIP)、湿地保护项目(Wetlands Reserve Program，WRP)、环境质量奖励项目(Environmental Quality Incentives Program，EQIP)和保护安全项目(Conservation Security Program，CSP)。这些项目鼓励土地所有者种植本地草种，并为其提供成本分担援助。此外，美国鱼类和野生动植物服务项目(Fish and Wildlife Service Program)“野生动植物伙伴”(Partners for Wildlife)，通过给自愿参与的土地所有者提供技术和财政支持，让土地所有者继续拥有和管理他们的土地，在满足他们需求的同时，改善野生动植物的生存条件，从而实现退化草地恢复[152]。

目前，在墨西哥联邦国家自然保护区委员会的拨款和私人资金的资助下，新里昂自治大学(Universidad Autónoma de Nuevo León)、BMI野生动物协会(IMC Vida Silvestre Asociación)和墨西哥国立自治大学生态学研究所(Instituto de Ecologia, Universidad National Autónoma de México)开展了大量的恢复工作，采用的恢复措施取决于当地合作伙伴，许多做法仍处于试验阶段，例如，通过气辊、轮廓线和关键线、约曼犁等进行土壤恢复；灌木被机械地移除，以阻止扩张，移除的灌木为合作伙伴提供柴火；在树木迁移地区种植本地多年生草种，收集种子，随后播种；在合作伙伴的牧场上建造石笼网，以阻止沿溪流形成的沟壑，并可增加土壤湿度，以利于草本植物的生长。项目合作伙伴于2011年启动了可持续畜牧业项目，目的是学习和教授改进的畜牧业技术。在圣佩德罗的一个放牧团体，在许多恢复项目试验中发挥着作用，许多私人牧场主已经开始以个人身份合作[145]。

1.2.3　南美草原　南美草原称潘帕斯草原，主体部分在阿根廷。潘帕斯草原曾经覆盖了阿根廷布宜诺斯艾利斯省的大部分地区以及恩特雷罗斯、圣菲、科尔多瓦、拉潘帕和圣路易斯省的部分地区[153]。自20世纪初以来，潘帕斯草原被迅速转化为耕地和管理牧场，影响了景观结构和土地利用模式，降低了生物多样性[153-154]，生物入侵较为严重[155]。阿根廷国立南方大学和布宜诺斯艾利斯大学的植物学家、生态学家和保护生物学家一直在开展研究项目，旨在恢复原有的潘帕斯草原生态系统[155]。例如，在阿根廷山地潘帕斯草原上，通过去除野马，草原显示出良好的恢复能力，物种多样性和均匀度升高，多年生草的数量增多，地上生物量增大，外来物种的比例降低[156]。在经过多年耕作和放牧的草原上，外来物种在群落中起主导作用，会阻碍本土植物群落的恢复，可通过清除外来

植物和播种本地草来实现恢复[157−158];通过先去除适口性较差植物的地上部分以及浅层土壤,然后播种适口性较好植物的种子,使得适口性较好的植物成功建植[159]。同时,注重提升人们对退化草原恢复的重要性的认识,通过一个包括研究、娱乐和教育内容的积极计划,可以减少目前潘帕斯草原的退化过程,并恢复原始景观[155]。

1.2.4 非洲温带草原 非洲温带草原主要分布在南非、莱索托和斯威士兰的内陆高原上,在较为温暖的地区以 C_4 植物为主,在较为凉爽的高海拔地区,C_3 植物占优势地位[43]。南非大片的草原,特别是中等降水量地区的草原,已经被改造成了耕地[160−161]。在山区降水量较高的地区,陡峭的山坡使农作物种植变得困难,所以在草原上有很大比例的人工造林。此外,南非40%的矿产资源分布于温带草原地区。由于以上这些人类活动或者城市扩张,使得30%~32%的草原被改造[43,160]。研究表明,在南非半干旱地区,相较于原生草原,5~90年的土地耕作导致土壤C和N含量损失了10%~73%[162−163]。对南非老耕地的次生演替研究发现,在停止耕种后,会形成以苞茅属(*Hyparrhenia*)植物为主的草原,这种草原大多具有较低的物种丰富度,只有少数其他物种能够建立或生存[164]。来自南非、德国、美国的高校和科研机构开展了退化草原恢复研究。发现了许多成功且经济的恢复措施,包括重新播种本土物种形成次生草原[165]。然而,成功地重新播种,取决于当时的天气条件、杂草控制、苗床准备和有助于种子发芽和建立的预处理[166]。传统的犁地和撒播方法对建立后期演替植物群落和控制遗留杂草及入侵植物最为有效[167]。研究发现,在次生草原,土壤有机碳的恢复是缓慢的,即使在次生草原建立30年后,土壤有机碳的恢复也主要限于0~5 cm土层[168],在耕地转变为草原的过程中,只有大团聚体的数量得到了恢复,而它们的保护能力明显没有恢复,因此不足以完全固定土壤有机质[169],土壤中的微生物组成已被集约化耕作严重破坏,真菌与细菌比率的完全自然恢复在几十年的时间尺度上是不可行的[170]。与美国高草草原相比,在耕地转变为草原过程中,南非高地草原土壤碳、氮储量的恢复更快,归因于恢复初期更大的土壤有机碳饱和亏缺,再加上高质量根系的发展,促进了土壤微生物生物量和团聚体结构的恢复,同时气候条件限制了非洲高地草原的土壤有机质分解[171−172]。

2 世界退化草原恢复研究和实践评述和展望

2.1 退化草原恢复研究和实践需要更多的关注

在许多国家和国际可持续发展政策中,对草原的关注度一直比较低,例如《可持续发展目标》和《生物多样性公约》[173]。2019年3月1日,联合国大会宣布2021−2030年为联合国生态系统恢复的10年,旨在大规模恢复退化的生态系统,以应对气候危机、加强粮食安全、保证供水和保护生物多样性[174]。联合国生态系统恢复10年(2021−2030年)将草原、灌丛和稀树草原加入他们的重点生态系统中[173]。在可持续发展政策中适当关注草原及其提供的生态系统服务,对于恢复退化的草原至关重要。联合国生态系统恢复10年(2021−2030年)和《生物多样性公约》为2020年后全球生物多样性框架提供了一个机会,为保护、可持续管理和恢复草原提供了目标,并防止了在天然草原上植树等破坏性做法[15,173,175]。生态补偿作为环境政策工具在退化草原恢复中发挥着重要作用,在未来的退化草原恢复实践中,还需要国家和政府制定新的政策来促进和资助草原恢复。

相比较而言,退化草原恢复研究和实践在科学文献、媒体以及保护机构中得到的关注程度也低于森林和淡水生境[7,63,176]。大多数以恢复为目的的研究集中在森林、河流和湿地,而草原恢复的出版物不到森林或河流的一半;此外,只有1/3的关于草原恢复的研究是开放性的,相比之下,海洋生境、泥炭地和其他地区的研究开放率较高;在高引用率的出版物中,关于草原恢复的研究落后于海洋和城市生境的研究[7]。鉴于草原的生态学意义,需要更多的研究,增加开放性出版物的比例,以促进这些发现在实践中的应用。

2.2 需要设置更加合理的退化草原恢复目标

早期的退化草原恢复多数以恢复原生植被的盖度、生物多样性为目标[13,177−179],尤其是在欧美国家的案例中,研究者认为生物多样性如果能够恢复的话,那么其他诸如生产力,目标物种,土壤养分等功能都能随之恢复,这种思想一直主导着当前生态恢复理论与实践[180]。将土壤碳库作为恢复目标的研究也比较多[181−183],其余恢复目标,如生产力,昆虫群落,土壤微生物,土壤氮库,目标物种,植物群落结构,土壤性质,土壤种子库,土壤湿度,饲用牧草等都相对较少[180,184]。近年来,生态恢复开始注重生态系统功能的研究[185−187],例如土壤形成、硝化作用、碳固持

或分解,都可以作为恢复项目的目标[188-191]。因为生态系统退化和全球变化不仅影响生态系统的生物组成,而且影响生态系统功能[192]。

在退化草原恢复实践中,设置退化草原恢复目标还需要考虑当地的限制条件和利益相关者的需求[193]。生态恢复的一个基本原则是确定一个适当的参照生态系统来指导项目目标,并为监测和评估提供参考依据。参照生态系统可以是实际的样点(包含了退化前当地的本土植物、动物和其他生物群系),也可以是从参照样点、野外观测指标、历史和预测数据中综合得出的概念模型[194]。退化草原恢复不仅包括恢复生态系统的完整性,还需满足个人、社会和经济价值,这种生态和社会效益的结合可以改善社会－生态系统的复原力。在设置退化草原恢复目标时,可以通过对退化和恢复草原的潜在生态系统服务权衡的标准化评估和共同认识来平衡利益相关者的需求[173]。

2.3　退化草原恢复评估和监测的方法需要提高

为了满足全球退化草原的恢复需求,需要开发更好的方法来评估和监测恢复效果。最近,Bardgett 等[173]提出采用标准化的"五步法"来评估退化草原状况和退化草地恢复方案的效益(包括恢复方案对草地生态系统服务的影响以及不同利益相关者群体从退化草原恢复中获得的收益)。第 1 步,评估多个利益相关者群体对不同生态系统服务的需求和相对优先权;第 2 步,确定普通的生态系统服务指标(适用于所有利益相关者);第 3 步,确定特殊的生态系统服务指标(适用于一部分利益相关者);第 4 步,评估草原退化状况并确定恢复方案;第 5 步,通过参与式方法选择和实施恢复战略。即对整个社区来说,最佳解决方案可以通过对利益相关群体加权的方式进行估算,或者通过评估哪些修复方案能使群体间的冲突最小化来选择。

草原恢复研究中,应该提高碳固持和分解的测定分析频率,应该包括监测特定的动物群体,它们是生态系统过程的驱动力,如分解、授粉或种子传播[185]。退化草原土壤的修复对草原的可持续发展至关重要。在以前的草原生态恢复研究案例中土壤微生物关注较少,随着土壤微生物研究技术的发展,近些年关注较多[171,195-196]。但是土壤微生物系统较为复杂,而且其恢复目标难以把握,在生态恢复中可以作为参考指标,况且其与土壤养分紧密相关,一般与土壤养分一起作为整体考虑[180]。

2.4　退化草原恢复后管理需要重视

混合草种播种是大规模恢复草原的一个重要手段。然而,由此产生的植被通常具有较低的生物多样性,而且高密度的杂草种子在土壤种子库中不断积累,甚至在恢复的几年后也是如此。因此,修复后的管理是必要的,以抑制地上和地下的杂草。研究者们建议在规划修复项目时,就设计好草原修复地的长期管理,以确保管理计划在生态学上和经济上是可行的,并用土壤种子库的分析来补充对植被发展的监测,从而评估长期的恢复是否成功[197]。

草原是干扰驱动的生态系统,适度干扰有助于维持草原生物多样性。恢复后的草原生态系统可能包含新的物种组成以及新的环境条件,并包括了过去土地使用的遗留问题(氮沉积、杂草入侵等),需要持续的干扰管理来维持播种目标物种的覆盖率和减少杂草[197]。由于物种组成、土地使用遗留问题、杂草入侵或其他因素的不同,参照样地的管理并不一定适合于修复后的草原,修复后的草原需要采取不同的管理措施以实现恢复目标[7]。

2.5　全球变化背景下退化草原恢复面临的问题和挑战

CO_2增加、气温上升、降水强度和频率的变化等气候事件对草原生态系统有着强烈的影响。例如,由于大气中的CO_2浓度升高、气候变暖和更潮湿的条件,美洲、澳大利亚和非洲的天然草场正因木本植物的侵袭而退化[198];强烈和频繁的干旱与过度放牧相结合,加剧了亚洲中部草原的沙漠化和退化[199]。在草原恢复过程中,这些变化的气候条件可能会导致恢复过程中出现意想不到的结果,包括在降水量增加的半湿润草原上出现更多的树[200],以及在降水量减少的干旱草原恢复过程中出现更多的荒漠化[201]。草原上的禾草、杂类草和灌木都对气候变化很敏感,因此,应根据气候变化预测结果和植物物种丧失风险,对草原恢复方案的长期可行性进行评估[202]。在退化草地恢复研究中,需要采用具有较高的基因和物种多样性的混合种子组合,这将在环境中形成斑块,可能是应对预期气候变化的最佳策略[13]。

参考文献 References:

[1] Bai Y F, Huang J H, Zheng S X, *et al*. Drivers and regulating mechanisms of grassland and desert ecosystem services. Chinese Journal of Plant Ecology, 2014, 38(2): 93-102.
白永飞, 黄建辉, 郑淑霞, 等. 草地和荒漠生态系统服务功能的形成与调控机制. 植物生态学报, 2014, 38(2): 93-102.

[2] Finn J A, Kirwan L, Connolly J, *et al*. Ecosystem function enhanced by combining four functional types of plant species in intensively managed grassland mixtures: A 3-year continental-scale field experiment. Journal of Applied Ecology, 2013, 50(2): 365-375.

[3] Fang J Y, Bai Y F, Li L H, *et al*. Scientific basis and practical ways for sustainable development of China's pasture regions. Chinese Science Bulletin, 2016, 61(2): 155-164.
方精云, 白永飞, 李凌浩, 等. 我国草原牧区可持续发展的科学基础与实践. 科学通报, 2016, 61(2): 155-164.

[4] Li X L. Mechanisms underlying the dwarf phenotype of *Leymus chinensis* induced by long-term overgrazing. Beijing: Chinese Academy of Agricultural Sciences, 2016.
李西良. 羊草对长期过度放牧的矮小化响应与作用机理. 北京: 中国农业科学院, 2016.

[5] Bakker J P, Berendse F. Constraints in the restoration of ecological diversity in grassland and heathland communities. Trends in Ecology & Evolution, 1999, 14(2): 63-68.

[6] Steffen W, Richardson K, Rockstrom J, *et al*. Planetary boundaries: Guiding human development on a changing planet. Science, 2015, 347(6223): 1-10.

[7] Torok P, Brudvig L A, Kollmann J, *et al*. The present and future of grassland restoration. Restoration Ecology, 2021, 29(S1): e13378.

[8] Walther G R, Roques A, Hulme P E, *et al*. Alien species in a warmer world: Risks and opportunities. Trends in Ecology & Evolution, 2009, 24(12): 686-693.

[9] Wang D L, Wang L, Xin X P, *et al*. Systematic restoration for degraded grasslands: Concept, mechanisms and approaches. Scientia Agricultura Sinica, 2020, 53(13): 2532-2540.
王德利, 王岭, 辛晓平, 等. 退化草地的系统性恢复: 概念, 机制与途径. 中国农业科学, 2020, 53(13): 2532-2540.

[10] Jones H P, Jones P C, Barbier E B, *et al*. Restoration and repair of earth's damaged ecosystems. Proceedings of the Royal Society B-Biological Sciences, 2018, 285(1873): 1-8.

[11] Hampe A, Petit R J. Conserving biodiversity under climate change: The rear edge matters. Ecology Letters, 2005, 8(5): 461-467.

[12] Thomas C D, Cameron A, Green R E, *et al*. Extinction risk from climate change. Nature, 2004, 427(6970): 145-148.

[13] Wilsey B. Restoration in the face of changing climate: Importance of persistence, priority effects and species diversity. Restoration Ecology, 2020, 29(S1): 1-25.

[14] Wesche K, Ambarl D, Kamp J, *et al*. The Palaearctic steppe biome: A new synthesis. Biodiversity and Conservation, 2016, 25(12): 2197-2231.

[15] Dudley N, Eufemia L, Fleckenstein M, *et al*. Grasslands and savannahs in the UN decade on ecosystem restoration. Restoration Ecology, 2020, 28(6): 1313-1317.

[16] Werner P A. Savanna ecology and management: Australian perspectives and intercontinental comparisons. Oxford: Blackwell Scientific Publications, 1991.

[17] O'Connor T G. Long-term response of an herbaceous sward to reduced grazing pressure and rainfall variability in a semi-arid South African savanna. African Journal of Range & Forage Science, 2015, 32(4): 261-270.

[18] Van Oudtshoorn F. Veld management: Principles and practices. Queenswood: Briza Publications, 2015.

[19] Chen X, Hutley L B, Eamus D. Carbon balance of a tropical savanna of northern Australia. Oecologia, 2003, 137(3): 405-416.

[20] Williams R J, Myers B A, Muller W J, *et al*. Leaf phenology of woody species in a North Australian tropical savanna. Ecology, 1997, 78(8): 2542-2558.

[21] Tibcherani M, Aranda R, Mello R L. Time to go home: The temporal threshold in the regeneration of the ant community in the Brazilian savanna. Applied Soil Ecology, 2020, 150: 1-9.

[22] Ratter J A, Ribeiro J F, Bridgewater S. The Brazilian Cerrado vegetation and threats to its biodiversity. Annals of Botany, 1997, 80(3): 223-230.

[23] Da Silva J M C, Bates J M. Biogeographic patterns and conservation in the South American Cerrado: A tropical Savanna hotspot. Bioscience, 2002, 52(3): 225-233.

[24] Mcculloch M, Fallon S, Wyndham T, *et al*. Coral record of increased sediment flux to the inner Great Barrier Reef since European settlement. Nature, 2003, 421(6924): 727－730.

[25] Peel M, Peel J, Manaka L. Grasses of the Kruger National Park and surrounding Bushveld. African Journal of Range & Forage Science, 2015, 32(3): 231－232.

[26] Ditomaso J M, Masters R A, Peterson V F. Rangeland invasive plant management. Rangelands, 2010, 32(1): 43－47.

[27] Pivello V R, Shida C N, Meirelles S T. Alien grasses in Brazilian savannas: A threat to the biodiversity. Biodiversity & Conservation, 1999, 8(9): 1281－1294.

[28] Orr D M, O'reagain P J. Managing for rainfall variability: Impacts of grazing strategies on perennial grass dynamics in a dry tropical savanna. Rangeland Journal, 2011, 33(2): 209－220.

[29] Whittaker S R J. The irreversible cattle-driven transformation of a seasonally flooded Australian savanna. Journal of Biogeography, 2003, 30(5): 783－802.

[30] Haddad T M, Pilon N, Durigan G, *et al*. Restoration of the Brazilian savanna after pine silviculture: Pine clearcutting is effective but not enough. Forest Ecology and Management, 2021, 491: 1－13.

[31] Reynolds C, Venter N, Cowie B W, *et al*. Mapping the socio-ecological impacts of invasive plants in South Africa: Are poorer households with high ecosystem service use most at risk? Ecosystem Services, 2020, 42: 1－10.

[32] Ren H, Joon D, Peng S L. Ecosystem of savanna in Africa. Journal of Tropical and Subtropical Botany, 2002, 10(10): 381－390.
任海, Joon D, 彭少麟. 非洲稀树草原生态系统概况. 热带亚热带植物学报, 2002, 10(10): 381－390.

[33] Strathie L W, Mcconnachie A J, Retief E. Initiation of biological control against *Parthenium hysterophorus* L. (Asteraceae) in South Africa. African Entomology, 2011, 19(2): 378－392.

[34] Belgeri A, Navie S C, Vivian-Smith G, *et al*. Early recovery signs of an Australian grassland following the management of *Parthenium hysterophorus* L. Flora, 2014, 209(10): 587－596.

[35] Dhileepan K, Strathie L. *Parthenium hysterophorus* L. (Asteraceae)//Muniappan R, Reddy G V P, Raman A. Biological control of tropical weeds using arthropods. Cambs: Cambridge University Press, 2009: 274－318.

[36] Cowie B W, Venter N, Witkowski E T F, *et al*. Implications of elevated carbon dioxide on the susceptibility of the globally invasive weed, *Parthenium hysterophorus*, to glyphosate herbicide. Pest Management Science, 2020, 76(7): 2324－2332.

[37] Cowie B W, Witkowski E T F, Byrne M J, *et al*. Physiological response of *Parthenium hysterophorus* to defoliation by the leaf-feeding beetle *Zygogramma bicolorata*. Biological Control, 2018, 117: 35－42.

[38] Terblanche C, Nanni I, Kaplan H, *et al*. An approach to the development of a national strategy for controlling invasive alien plant species: The case of *Parthenium hysterophorus* in South Africa. Bothalia, 2016, 46(1): 1－11.

[39] Tessema Z K, De Boer W F, Prins H H T. Changes in grass plant populations and temporal soil seed bank dynamics in a semi-arid African savanna: Implications for restoration. Journal of Environmental Management, 2016, 182: 166－175.

[40] Kgosikoma O E, Mogotsi K. Understanding the causes of bush encroachment in Africa: The key to effective management of savanna grasslands. Tropical Grasslands-Forrajes Tropicales, 2013, 1(2): 215－219.

[41] Van Auken O W. Causes and consequences of woody plant encroachment into western North American grasslands. Journal of Environmental Management, 2009, 90(10): 2931－2942.

[42] Ward D. Do we understand the causes of bush encroachment in African savannas? African Journal of Range & Forage Science, 2005, 22(2): 101－105.

[43] Squires V, Dengler J, Feng H, *et al*. Grasslands of the world: Diversity, management and conservation. Boca Raton: Chemical Rubber Company Press, 2018.

[44] Woinarski J C Z. The illusion of nature: Perception and the reality of natural landscapes, as illustrated by vertebrate fauna in the Northern Territory, Australia. Ecological Management & Restoration, 2014, 15(1): 30－33.

[45] Fisher D O, Johnson C N, Lawes M J, *et al*. The current decline of tropical marsupials in Australia: Is history repeating? Global Ecology and Biogeography, 2014, 23(2): 181－190.

[46] Kutt A S, Woinarski J C Z. The effects of grazing and fire on vegetation and the vertebrate assemblage in a tropical savanna woodland in north-eastern Australia. Journal of Tropical Ecology, 2007, 23: 95－106.

[47] Kemp J E, Kutt A S. Vegetation change 10 years after cattle removal in a savanna landscape. Rangeland Journal, 2020, 42(2): 73－84.

[48] Beringer J, Hutley L B, Tapper N J, *et al*. Savanna fires and their impact on net ecosystem productivity in North Australia.

Global Change Biology, 2007, 13(5): 990-1004.

[49] D'odorico P, Laio F, Ridolfi L. A probabilistic analysis of fire-induced tree-grass coexistence in savannas. American Naturalist, 2006, 167(3): 79-87.

[50] Russell-Smith J, Cook G D, Cooke P M, *et al*. Managing fire regimes in north Australian savannas: Applying Aboriginal approaches to contemporary global problems. Frontiers in Ecology and the Environment, 2013, 11: 55-63.

[51] Erickson T E, Munoz-Rojas M, Kildisheva O A, *et al*. Benefits of adopting seed-based technologies for rehabilitation in the mining sector: A Pilbara perspective. Australian Journal of Botany, 2017, 65(8): 646-660.

[52] Munoz-Rojas M, Roman J R, Roncero-Ramos B, *et al*. Cyanobacteria inoculation enhances carbon sequestration in soil substrates used in dryland restoration. Science of the Total Environment, 2018, 636: 1149-1154.

[53] Munoz-Rojas M, Chilton A, Liyanage G S, *et al*. Effects of indigenous soil cyanobacteria on seed germination and seedling growth of arid species used in restoration. Plant and Soil, 2018, 429(1/2): 91-100.

[54] Setterfield S A, Rossiter-Rachor N A, Hutley L B, *et al*. Turning up the heat: The impacts of *Andropogon gayanus* (gamba grass) invasion on fire behaviour in northern Australian savannas. Diversity and Distributions, 2010, 16(5): 854-861.

[55] Rossiter-Rachor N A, Setterfield S A, Douglas M M, *et al*. Invasive *Andropogon gayanus* (gamba grass) is an ecosystem transformer of nitrogen relations in Australian savanna. Ecological Applications, 2009, 19(6): 1546-1560.

[56] Luck L, Bellairs S M, Rossiter-Rachor N A. Residual herbicide treatments reduce *Andropogon gayanus* (gamba grass) recruitment for mine site restoration in northern Australia. Ecological Management & Restoration, 2019, 20(3): 214-221.

[57] Dawes T Z. Reestablishment of ecological functioning by mulching and termite invasion in a degraded soil in an Australian savanna. Soil Biology & Biochemistry, 2010, 42(10): 1825-1834.

[58] Cochrane T T, Azevedo L G D, Thomas D, *et al*. Land use and productive potential of American savannas//Tothill J C, Mott J C. Ecology and management of the world's savannas. Canberra: Australian Academy of Science, 1985: 114-124.

[59] Castro A A J F, Martins F R, Tamashiro J Y, *et al*. How rich is the flora of Brazilian cerrados. Annals of the Missouri Botanical Garden, 1999, 86(1): 192-224.

[60] Kier G, Mutke J, Dinerstein E, *et al*. Global patterns of plant diversity and floristic knowledge. Journal of Biogeography, 2005, 32(7): 1107-1116.

[61] Myers N, Mittermeier R A, Mittermeier C G, *et al*. Biodiversity hotspots for conservation priorities. Nature, 2000, 403(6772): 853-858.

[62] Beuchle R, Grecchi R C, Shimabukuro Y E, *et al*. Land cover changes in the Brazilian Cerrado and Caatinga biomes from 1990 to 2010 based on a systematic remote sensing sampling approach. Applied Geography, 2015, 58: 116-127.

[63] Overbeck G E, Velez-Martin E, Scarano F R, *et al*. Conservation in Brazil needs to include non-forest ecosystems. Diversity and Distributions, 2015, 21(12): 1455-1460.

[64] Fernandes G W, Coelho M S, Machado R B, *et al*. Afforestation of savannas: An impending ecological disaster. Natureza & Conservacao, 2016, 14(2): 146-151.

[65] Durigan G, De Siqueira M F, Franco G A D C. Threats to the cerrado remnants of the state of Sao Paulo, Brazil. Scientia Agricola, 2007, 64(4): 355-363.

[66] Klink C A, Machado R B. Conservation of the Brazilian Cerrado. Conservation Biology, 2005, 19(3): 707-713.

[67] Gorgone-Barbosa E, Pivello V R, Bautista S, *et al*. How can an invasive grass affect fire behavior in a tropical savanna? A community and individual plant level approach. Biological Invasions, 2015, 17(1): 423-431.

[68] Hoffmann W A, Jaconis S, Mckinley K L, *et al*. Fuels or microclimate? Understanding the drivers of fire feedbacks at savanna-forest boundaries. Austral Ecology, 2012, 37(6): 634-643.

[69] Hoffmann W A, Haridasan M. The invasive grass, *Melinis minutiflora*, inhibits tree regeneration in a Neotropical savanna. Austral Ecology, 2008, 33(1): 29-36.

[70] Damasceno G, Souza L, Pivello V R, *et al*. Impact of invasive grasses on Cerrado under natural regeneration. Biological Invasions, 2018, 20(12): 3621-3629.

[71] Lopes P G, Caldas Oliveira S C, Salles K A, *et al*. Allelopathy of a native shrub can help control invasive grasses at sites under ecological restoration in a Neotropical savanna. Plant Ecology & Diversity, 2018, 11(4): 527-538.

[72] Assis G B, Pilon N A L, Siqueira M F, *et al*. Effectiveness and costs of invasive species control using different techniques to restore cerrado grasslands. Restoration Ecology, 2021, 29(S1): 1-33.

[73] Passaretti R A, Pilon N A L, Durigan G. Weed control, large seeds and deep roots: Drivers of success in direct seeding for

savanna restoration. Applied Vegetation Science, 2020, 23(3): 406－416.

[**74**] Silva R R P, Vieira D L M. Direct seeding of 16 Brazilian savanna trees: Responses to seed burial, mulching and an invasive grass. Applied Vegetation Science, 2017, 20(3): 410－421.

[**75**] Coutinho A G, Alves M, Sampaio A B, *et al*. Effects of initial functional-group composition on assembly trajectory in savanna restoration. Applied Vegetation Science, 2019, 22(1): 61－70.

[**76**] Do Nascimento Amorim S P, Boechat C L, Luz Duarte L D S, *et al*. Grasses and legumes as cover crops affect microbial attributes in oxisoil in the Cerrado (savannah environment) in the Northeast region. Revista Caatinga, 2020, 33(1): 31－42.

[**77**] Cava M G B, Pilon N A L, Ribeiro M C, *et al*. Abandoned pastures cannot spontaneously recover the attributes of old-growth savannas. Journal of Applied Ecology, 2018, 55(3): 1164－1172.

[**78**] Starr C R, Correa R S, Filgueiras T D, *et al*. Plant colonization in a gravel mine revegetated with *Stylosanthes* spp. in a Neotropical savanna. Landscape and Ecological Engineering, 2013, 9(1): 189－201.

[**79**] Ferreira M C, Walter B M T, Vieira D L M. Topsoil translocation for Brazilian savanna restoration: Propagation of herbs, shrubs, and trees. Restoration Ecology, 2015, 23(6): 723－728.

[**80**] Correa R S, Do Carmo Balduino A P, Viana Teza C T, *et al*. Vegetation cover development resulting from different restoration approaches of exploited mines. Floresta E Ambiente, 2018, 25(4): 1－9.

[**81**] Humphries T, Florentine S K, Dowling K, *et al*. Weed management for landscape scale restoration of global temperate grasslands. Land Degradation & Development, 2021, 32(3): 1090－1102.

[**82**] Hassan R, Scholes R, Ash N. Ecosystems and human well-being: Current state and trends (Vol. 1). Washington, D. C.: Island Press, 2005.

[**83**] Hurka H, Friesen N, Bernhardt K G, *et al*. The Eurasian steppe belt: Status quo, origin and evolutionary history. Turczaninowia, 2019, 22(3): 5－71.

[**84**] Werger M, Staalduinen M. Eurasian steppes. Ecological problems and livelihoods in a changing world. Dordrecht: Springer, 2012.

[**85**] Li B. The rangeland degradation in North China and its preventive strategy. Scientia Agricultura Sinica, 1997, 30(6): 2－10.
李博. 中国北方草地退化及其防治对策. 中国农业科学, 1997, 30(6): 2－10.

[**86**] Bai Y F, Zhao Y J, Wang Y, *et al*. Assessment of ecosystem services and ecological regionalization of grasslands support establishment of ecological security barriers in Northern China. Bulletin of Chinese Academy of Sciences, 2020, 35(6): 675－689.
白永飞, 赵玉金, 王扬, 等. 中国北方草地生态系统服务评估和功能区划助力生态安全屏障建设. 中国科学院院刊, 2020, 35(6): 675－689.

[**87**] Pan Q M, Xue J G, Tao J, *et al*. Current status of grassland degradation and measures for grassland restoration in northern China. Chinese Science Bulletin, 2018, 63(17): 1642－1650.
潘庆民, 薛建国, 陶金, 等. 中国北方草原退化现状与恢复技术. 科学通报, 2018, 63(17): 1642－1650.

[**88**] National Development and Reform Commission, Ministry of Natural Resources of China. Master plan of major projects for the protection and restoration of important national ecosystems (2021－2035). https://www.ndrc.gov.cn/xxgk/zcfb/tz/202006/P020200611354032680531.pdf, 2020-06-03.
国家发展改革委, 自然资源部. 全国重要生态系统保护和修复重大工程总体规划(2021－2035年). https://www.ndrc.gov.cn/xxgk/zcfb/tz/202006/P020200611354032680531.pdf, 2020-06-03.

[**89**] Liu Y, Pan Q, Liu H, *et al*. Plant responses following grazing removal at different stocking rates in an Inner Mongolia grassland ecosystem. Plant and Soil, 2011, 340(1/2): 199－213.

[**90**] Sun J, Ma B, Lu X. Grazing enhances soil nutrient effects: Trade-offs between aboveground and belowground biomass in alpine grasslands of the Tibetan Plateau. Land Degradation & Development, 2018, 29(2): 337－348.

[**91**] Zhang Y, Zhao W. Vegetation and soil property response of short-time fencing in temperate desert of the Hexi Corridor, northwestern China. Catena, 2015, 133: 43－51.

[**92**] Tao L B, Yu S, Wang G H, *et al*. Effects of enclosure on characteristics and stability of vegetation community of desert steppe in sandy area of Eastern Ningxia. Chinese Journal of Grassland, 2018, 40(2): 67－74.
陶利波, 于双, 王国会, 等. 封育对宁夏东部风沙区荒漠草原植物群落特征及其稳定性的影响. 中国草地学报, 2018, 40(2): 67－74.

[**93**] Wu J B, Wang X D. Effect of enclosure ages on community characters and biomass of the degraded alpine steppe at the Northern

Tibet. Acta Agrestia Sinica, 2017, 25(2): 261－266.
吴建波，王小丹．围封年限对藏北退化高寒草原植物群落特征和生物量的影响．草地学报，2017，25(2)：261－266.

[94] Xiao J Y, Pu X P, Xu C L. Effects of grazing prohibition on restoration of degraded grassland. Pratacultural Science, 2015, 32(1): 138－145.
肖金玉，蒲小鹏，徐长林．禁牧对退化草地恢复的作用．草业科学，2015，32(1)：138－145.

[95] Zheng C L, Cao Z L, Wang X, *et al*. Effects of enclosure on vegetations recovery in desertified grassland in Hulunbeir. Science of Soil and Water Conservation, 2005, 3(3): 78－81.
郑翠玲，曹子龙，王贤，等．围栏封育在呼伦贝尔沙化草地植被恢复中的作用．中国水土保持科学，2005，3(3)：78－81.

[96] Hu Y F, Peng J J, Yuan S, *et al*. Influence of ecological restoration on vegetation and soil microbiological properties in alpine-cold semi-humid desertified land. Ecological Engineering, 2016, 94: 88－94.

[97] Yang L N, Baoyin T. Study on biomass of *Leymus chinensis* community after different improving measures. Chinese Journal of Grassland, 2010, 32(1): 86－91.
杨丽娜，宝音陶格涛．不同改良措施下羊草群落生物量的研究．中国草地学报，2010，32(1)：86－91.

[98] Kalhoro S A, Xu X, Ding K, *et al*. The effects of different land uses on soil hydraulic properties in the Loess Plateau, Northern China. Land Degradation & Development, 2018, 29(11): 3907－3916.

[99] Shan G L, Chu X H, Tian Q S, *et al*. Research on the dynamic changes of soil properties of typical steppe in the restoring process. Acta Prataculturae Sinica, 2012, 21(4): 1－9.
单贵莲，初晓辉，田青松，等．典型草原恢复演替过程中土壤性状动态变化研究．草业学报，2012，21(4)：1－9.

[100] Shi X M, Li X G, Li C T, *et al*. Grazing exclusion decreases soil organic C storage at an alpine grassland of the Qinghai－Tibetan Plateau. Ecological Engineering, 2013, 57: 183－187.

[101] Wang X, Yang X, Wang L, *et al*. A six-year grazing exclusion changed plant species diversity of a *Stipa breviflora* desert steppe community, northern China. PeerJ, 2018, 6(6): 1－18.

[102] Wang Y, Sun Y, Wang Z, *et al*. Grazing management options for restoration of alpine grasslands on the Qinghai－Tibet Plateau. Ecosphere, 2018, 9(11): 1－17.

[103] Yuan Z Q, Epstein H, Li G Y. Grazing exclusion did not affect soil properties in alpine meadows in the Tibetan permafrost region. Ecological Engineering, 2020, 147(23): 1－8.

[104] Deng L, Kim D G, Peng C, *et al*. Controls of soil and aggregate-associated organic carbon variations following natural vegetation restoration on the Loess Plateau in China. Land Degradation & Development, 2018, 29(11): 3974－3984.

[105] Tai X, Epstein H E, Li B. Effects of grazing exclusion on spring and autumn pastures in arid regions of China: Insights from field surveys and landsat images. Agriculture Ecosystems & Environment, 2021, 310: 1－11.

[106] Bai Y F, Pan Q M, Xing Q. Fundamental theories and technologies for optimizing the production functions and ecological functions in grassland ecosystems. Chinese Science Bulletin, 2016, 61(2): 201－212.
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．科学通报，2016，61(2)：201－212.

[107] Li Q F, Zhao G, Zheng M A, *et al*. Delay grazing a practical approach to grassland environment protection and sustainable animal production in grassland of Northern China. Acta Agrestia Sinica, 2005(S1): 53－56, 66.
李青丰，赵钢，郑蒙安，等．春季休牧对草原和家畜生产力的影响．草地学报，2005(S1)：53－56，66.

[108] Ma Y S, Li S X, Wang Y L, *et al*. Effect of rest-grazing in the greenup period on degraded vegetation in alpine meadow. Acta Agrestia Sinica, 2017, 25(2): 290－295.
马玉寿，李世雄，王彦龙，等．返青期休牧对退化高寒草甸植被的影响．草地学报，2017，25(2)：290－295.

[109] Zhao G, Cao Z L, Li Q F. A freliminary study of the effects of deferred spring grazing on the pasture vegetation. Acta Agrestia Sinica, 2003(2): 183－188.
赵钢，曹子龙，李青丰．春季禁牧对内蒙古草原植被的影响．草地学报，2003(2)：183－188.

[110] Zhu L B, Zeng Z H, Zhao B P, *et al*. Effect of spring rest-grazing on steppe vegetation. Acta Agrestia Sinica, 2008(3): 278－282.
朱立博，曾昭海，赵宝平，等．春季休牧对草地植被的影响．草地学报，2008(3)：278－282.

[111] Gu W R. Effects of seasonal delaying grazing on vegetation and soil under different grazing intensities. Urumqi: Xinjiang Agricultural University, 2013.
古伟容．不同放牧强度下季节性休牧对草地植被及土壤的影响．乌鲁木齐：新疆农业大学，2013.

[112] Tao J S. Study on the effection about plant community characteristics among different time of rest-grazing on *Leymus chinensis*

pasture. Lanzhou: Gansu Agricultural University, 2009.
陶金山. 不同休牧时期对羊草草原群落特征影响的研究. 兰州: 甘肃农业大学, 2009.

[113] Zhang G R, Li W Q, Zhang F W, *et al*. Responses of key ecological attributes to multi-path restoration measures of degraded alpine meadows. Acta Ecologica Sinica, 2020, 40(18): 6293-6303.
张光茹, 李文清, 张法伟, 等. 退化高寒草甸关键生态属性对多途径恢复措施的响应特征. 生态学报, 2020, 40(18): 6293-6303.

[114] Bai G, Bao Y, Du G, *et al*. Arbuscular mycorrhizal fungi associated with vegetation and soil parameters under rest grazing management in a desert steppe ecosystem. Mycorrhiza, 2013, 23(4): 289-301.

[115] Li G, Wang M J, Zhang F C, *et al*. Effects of grazing rest in different seasons on soil properties of *Calamagrostis angustifolia* meadow in the Sanjiang plain. Heilongjiang Animal Science and Veterinary Medicine, 2013(1): 77-80.
李钢, 王明君, 张风承, 等. 不同季节休牧对三江平原小叶章草甸土壤性状的影响. 黑龙江畜牧兽医, 2013(1): 77-80.

[116] Li Y J, Song X L, Xiu W M, *et al*. Effects of spring rest grazing on organic carbon storage in *Leymus chinensis* steppe in Inner Mongolia, China. Journal of Agro-Environment Science, 2013, 32(11): 2221-2230.
李玉洁, 宋晓龙, 修伟明, 等. 春季休牧对内蒙古羊草草原有机碳储量的影响. 农业环境科学学报, 2013, 32(11): 2221-2230.

[117] Zhang Z Q, Jiang M D, Feng T J. An integrated analysis of rotational grazing and continuous grazing experiments in arid and semi-arid grasslands in northern China. Pratacultural Science, 2020, 37(11): 2366-2373.
张智起, 姜明栋, 冯天骄. 划区轮牧还是连续放牧?—基于中国北方干旱半干旱草地放牧试验的整合分析. 草业科学, 2020, 37(11): 2366-2373.

[118] Ren J Z. Grazing, the basic form of grassland ecosystem and its transformation. Journal of Natural Resources, 2012, 27(8): 1259-1275.
任继周. 放牧, 草原生态系统存在的基本方式—兼论放牧的转型. 自然资源学报, 2012, 27(8): 1259-1275.

[119] Wei Z J, Wu R T, Dabu X, *et al*. The influence of different grazing systems on soil physical and chemical properties in desert steppe. Grassland of China, 2005(5): 6-10.
卫智军, 乌日图, 达布希拉图, 等. 荒漠草原不同放牧制度对土壤理化性质的影响. 中国草地, 2005(5): 6-10.

[120] Baoyin T, Li F Y. Can shallow plowing and harrowing facilitate restoration of *Leymus chinensis* grassland? Results from a 24-year monitoring program. Rangeland Ecology & Management, 2009, 62(4): 314-320.

[121] Baoyin T, Liu M L. The study on biomass composition dynamics of community in degenerated steppe of *Leymus chinensis* after shallow ploughing. Journal of Natural Resources, 2003(5): 544-551.
宝音陶格涛, 刘美玲. 退化羊草草原在浅耕翻处理后植物群落生物量组成动态研究. 自然资源学报, 2003(5): 544-551.

[122] Zong N, Shi P L, Jiang J, *et al*. Effects of shallow plowing on soil and plant community of degraded alpine meadow in Tibetan plateau. Pratacultural Science, 2014, 31(1): 8-14.
宗宁, 石培礼, 蒋婧, 等. 浅耕对西藏高原退化草甸土壤和植物群落特征的影响. 草业科学, 2014, 31(1): 8-14.

[123] Qu W J, Song N P, Chen L, *et al*. Responses of two types of desertification grasslands in desert steppe to shallow ploughing. Research of Soil and Water Conservation, 2014, 21(1): 85-89, 94.
曲文杰, 宋乃平, 陈林, 等. 荒漠草原两种沙化草地对浅耕翻的响应. 水土保持研究, 2014, 21(1): 85-89, 94.

[124] Zhang H S, Shao X Q, Liu G H, *et al*. Effects of enclosing and shallow ploughing as improvement technologies on the vegetation restoration of degraded *Leymus chinensis* (Trin.) Tzvel. meadow grassland. Acta Agrestia Sinica, 2010, 18(3): 339-344, 351.
张洪生, 邵新庆, 刘贵河, 等. 围封、浅耕翻改良技术对退化羊草草地植被恢复的影响. 草地学报, 2010, 18(3): 339-344, 351.

[125] Shao Y Q, Liu Z L, Jia Z B, *et al*. Effect of different control measures on the soil cultured microorganisms flora in degraded grassland. Chinese Journal of Grassland, 2011, 33(5): 77-81.
邵玉琴, 刘钟龄, 贾志斌, 等. 不同治理措施对退化草原土壤可培养微生物区系的影响. 中国草地学报, 2011, 33(5): 77-81.

[126] Sun G, Wu N, Luo P. Characteristics of soil nitrogen and carbon of pastures under different management in Northwestern Sichuan. Acta Phytoecologica Sinica, 2005(2): 304-310.
孙庚, 吴宁, 罗鹏. 不同管理措施对川西北草地土壤氮和碳特征的影响. 植物生态学报, 2005(2): 304-310.

[127] Ma Z G, Wang Y Q. Rangeland improvement and sustainable utilization in Northern China. Hohhot: Inner Mongolia

University Press, 2013.
马志广, 王育青. 中国北方草原改良与可持续利用. 呼和浩特: 内蒙古大学出版社, 2013.

[128] Chen M. Technology of improvement of degraded grassland in Northern China. China Animal Husbandry Bulletin, 1999(6): 29.
陈敏. 北方退化草地改良技术. 中国牧业通讯, 1999(6): 29.

[129] Zhang Y J, Zhou J Q, Yang G W, *et al*. Theory and application of no-tillage reseeding in degraded grasslands. Chinese Science Bulletin, 2020, 65(16): 1546−1555.
张英俊, 周冀琼, 杨高文, 等. 退化草原植被免耕补播修复理论与实践. 科学通报, 2020, 65(16): 1546−1555.

[130] Liu H J, Chen Y W, Sun G F, *et al*. Effects of different organic-inorganic fertilizer combination ratios on rice yield and nutrient loss with surface runoff. Chinese Journal of Ecology, 2017, 36(2): 405−412.
刘红江, 陈虞雯, 孙国峰, 等. 有机肥−无机肥不同配施比例对水稻产量和农田养分流失的影响. 生态学杂志, 2017, 36(2): 405−412.

[131] Yang Q, Wang W, Zeng H. Effects of nitrogen addition on the plant diversity and biomass of degraded grasslands of Nei Mongol, China. Acta Phytoecologica Sinica, 2018, 42(4): 430−441.
杨倩, 王娓, 曾辉. 氮添加对内蒙古退化草地植物群落多样性和生物量的影响. 植物生态学报, 2018, 42(4): 430−441.

[132] Song J X, Lei X, Ye M Q, *et al*. Effects of bioorganic fertilizer on community diversity and production performance of degraded grassland. Acta Agrestia Sinica, 2019, 27(5): 1355−1363.
宋君祥, 雷雄, 叶明清, 等. 生物有机肥对川西北退化草地群落结构和生产性能的影响. 草地学报, 2019, 27(5): 1355−1363.

[133] Jiang X, Ma J X. The impact of different factors on the outcomes of grassland ecological restoration to in China: A Meta-analysis. Acta Prataculturae Sinica, 2021, 30(2): 14−31.
蒋翔, 马建霞. 我国草地生态恢复对不同因素响应的Meta分析. 草业学报, 2021, 30(2): 14−31.

[134] Albert A J, Kelemen A, Valko O, *et al*. Secondary succession in sandy old-fields: A promising example of spontaneous grassland recovery. Applied Vegetation Science, 2014, 17(2): 214−224.

[135] Prach K, Fajmon K, Jongepierova I, *et al*. Landscape context in colonization of restored dry grasslands by target species. Applied Vegetation Science, 2015, 18(2): 181−189.

[136] Ruprecht E. Successfully recovered grassland: A promising example from Romanian old-fields. Restoration Ecology, 2006, 14(3): 473−480.

[137] Toeroek P, Vida E, Deak B, *et al*. Grassland restoration on former croplands in Europe: An assessment of applicability of techniques and costs. Biodiversity and Conservation, 2011, 20(11): 2311−2332.

[138] Lengyel S, Varga K, Kosztyi B, *et al*. Grassland restoration to conserve landscape-level biodiversity: A synthesis of early results from a large-scale project. Applied Vegetation Science, 2012, 15(2): 264−276.

[139] Baumann M, Kamp J, Poetzschner F, *et al*. Declining human pressure and opportunities for rewilding in the steppes of Eurasia. Diversity and Distributions, 2020, 26(9): 1058−1070.

[140] Kamp J, Urazaliev R, Donald P F, *et al*. Post-Soviet agricultural change predicts future declines after recent recovery in Eurasian steppe bird populations. Biological Conservation, 2011, 144(11): 2607−2614.

[141] Kurganova I, De Gerenyu V L, Kuzyakov Y. Large-scale carbon sequestration in post-agrogenic ecosystems in Russia and Kazakhstan. Catena, 2015, 133: 461−466.

[142] Pazur R, Prishchepov A V, Myachina K, *et al*. Restoring steppe landscapes: Patterns, drivers and implications in Russia's steppes. Landscape Ecology, 2021, 36(2): 407−425.

[143] Parks Canada Agency. Parks Canada's conservation and restoration program: Recovering species at risk in Grasslands National Park 2018. https://www.pc.gc.ca/en/agence-agency/bib-lib/rapports-reports/core-2018/pra-terr/pra3, 2018-06-07.

[144] Wedin W F, Fales S, Berry W. Grassland quietness and strength for a new American agriculture. Madison: American Society of Agronomy, 2009.

[145] Hruska T, Toledo D, Sierra-Corona R, *et al*. Social-ecological dynamics of change and restoration attempts in the Chihuahuan desert grasslands of Janos Biosphere Reserve, Mexico. Plant Ecology, 2017, 218(1): 67−80.

[146] List R, Pacheco J, Ponce E, *et al*. The Janos Biosphere Reserve Northern Mexico. International Journal of Wilderness, 2010, 16(2): 35−41.

[147] Ponce-Guevara E, Davidson A, Sierra-Corona R, *et al*. Interactive effects of black-tailed prairie dogs and cattle on shrub encroachment in a desert grassland ecosystem. PLoS One, 2016, 11(5): 1−11.

[**148**] Sierra-Corona R, Davidson A, Fredrickson E L, *et al*. Black-tailed prairie dogs, cattle, and the conservation of North America's arid grasslands. PLoS One, 2015, 10(3): 1−15.

[**149**] Parks Canada Agency. A natural priority−A report on Parks Canada's conservation and restoration program. https://www.pc.gc.ca/en/agence-agency/bib-lib/rapports-reports/core-2018, 2019-05-02.

[**150**] Parks Canada Agency. Parks Canada's conservation and restoration program: Restoring grasslands in Waterton Lakes National Park. https://www.pc.gc.ca/en/agence-agency/bib-lib/rapports-reports/core-2018/ouest-west/ouest-west4, 2018-08-28.

[**151**] Parks Canada Agency. Waterton Lakes National Park of Canada draft management plan, 2021. https://www.pc.gc.ca/en/pn-np/ab/waterton/info/index/participation/ebauche-plan, 2021-09-27.

[**152**] Miller C F. The evolving understanding of grassland restoration seeding protocols. Ecological Restoration, 2013, 31(2): 127−129.

[**153**] Medan D, Torretta J P, Hodara K, *et al*. Effects of agriculture expansion and intensification on the vertebrate and invertebrate diversity in the pampas of Argentina. Biodiversity and Conservation, 2011, 20(13): 3077−3100.

[**154**] Viglizzo E F, Lertora F, Pordomingo A J, *et al*. Ecological lessons and applications from one century of low external-input farming in the pampas of Argentina. Agriculture Ecosystems & Environment, 2001, 83(1/2): 65−81.

[**155**] Villamil C B. Grassland restoration in the Pampas region//Leadlay E. Building a sustainable future: The role of botanic gardens. Proceedings of the 3rd Global Botanic Gardens Congress, Wuhan, China, 16−20 April, 2007. Richmond: Botanic Gardens Conservation International, 2007.

[**156**] Villalobos A, Zalba S M. Continuous feral horse grazing and grazing exclusion in mountain pampean grasslands in Argentina. Acta Oecologica-International Journal of Ecology, 2010, 36(5): 514−519.

[**157**] Tognetti P M, Chaneton E J. Invasive exotic grasses and seed arrival limit native species establishment in an old-field grassland succession. Biological Invasions, 2012, 14(12): 2531−2544.

[**158**] Tognetti P M, Chaneton E J, Omacini M, *et al*. Exotic vs. native plant dominance over 20 years of old-field succession on set-aside farmland in Argentina. Biological Conservation, 2010, 143(11): 2494−2503.

[**159**] Puthod G, Loydi A, Garcia A, *et al*. Enhancement of palatable perennial grasses by disturbance and seed addition in degraded native grasslands of the dry pampas in Central Argentina. Arid Land Research and Management, 2020, 34(4): 445−459.

[**160**] Fairbanks D, Thompson M W, Vink D E, *et al*. The South African land-cover characteristics database: A synopsis of the landscape. South African Journal of Science, 2000, 96(2): 69−82.

[**161**] Mucina L, Rutherford M C. The vegetation of South Africa, Lesotho and Swaziland. Pretoria: South African National Biodiversity Institute, 2006.

[**162**] Dupreez C C, Dutoit M E. Effect of cultivation on the nitrogen fertility of selected agro-ecosystems in South Africa. Fertilizer Research, 1995, 42(1/2/3): 27−32.

[**163**] Lobe I, Amelung W, Du Preez C C. Losses of carbon and nitrogen with prolonged arable cropping from sandy soils of the South African Highveld. European Journal of Soil Science, 2001, 52(1): 93−101.

[**164**] Bredenkamp G J, Brown L R. A reappraisal of Acocks' Bankenveld: Origin and diversity of vegetation types. South African Journal of Botany, 2003, 69(1): 7−26.

[**165**] Taljaard D J. The evaluation of different technologies to restore old cultivated lands. Potchefstroom: North West University, 2008.

[**166**] Hessing M B, Johnson C D. Early secondary succession following restoration and reseeding treatments in Northern Arizona. Journal of Range Management, 1982, 35(5): 667−669.

[**167**] Van Oudtshoorn F, Brown L, Kellner K. The effect of reseeding methods on secondary succession during cropland restoration in the Highveld region of South Africa. African Journal of Range & Forage Science, 2011, 28(1): 1−8.

[**168**] Preger A C, Koesters R, Du Preez C C, *et al*. Carbon sequestration in secondary pasture soils: A chronosequence study in the South African Highveld. European Journal of Soil Science, 2010, 61(4): 551−562.

[**169**] Koesters R, Preger A C, Du Preez C C, *et al*. Re-aggregation dynamics of degraded cropland soils with prolonged secondary pasture management in the South African Highveld. Geoderma, 2013, 192: 173−181.

[**170**] Lauer F, Koesters R, Du Preez C C, *et al*. Microbial residues as indicators of soil restoration in South African secondary pastures. Soil Biology & Biochemistry, 2011, 43(4): 787−794.

[**171**] Baer S G, Bach E M, Meyer C K, *et al*. Belowground ecosystem recovery during grassland restoration: South African highveld compared to US tallgrass prairie. Ecosystems, 2015,18(3): 390−403.

[172] Scott D A, Bach E M, Du Preez C C, *et al*. Mechanisms influencing physically sequestered soil carbon in temperate restored grasslands in South Africa and North America. Biogeochemistry, 2021, 156(1): 131－143.

[173] Bardgett R D, Bullock J M, Lavorel S, *et al*. Combatting global grassland degradation. Nature Reviews Earth & Environment, 2021, 2(10): 720－735.

[174] Ding H M. UN General Assembly announces UN Decade of Ecosystem Restoration resolution. http://www.greentimes.com/green/news/gjhz/wsdt/content/2019-03/14/content_415721.htm, 2019-03-14.
丁洪美. 联合国大会宣布"联合国生态系统恢复十年"决议. http://www.greentimes.com/green/news/gjhz/wsdt/content/2019-03/14/content_415721.htm, 2019-03-14.

[175] Buisson E, Fidelis A, Overbeck G E, *et al*. A research agenda for the restoration of tropical and subtropical grasslands and savannas. Restoration Ecology, 2021, 29(S1): e13292.

[176] Temperton V M, Buchmann N, Buisson E, *et al*. Step back from the forest and step up to the Bonn challenge: How a broad ecological perspective can promote successful landscape restoration. Restoration Ecology, 2019, 27(4): 705－719.

[177] Baer S G, Adams T, Scott D A, *et al*. Soil heterogeneity increases plant diversity after 20 years of manipulation during grassland restoration. Ecological Applications, 2020, 30(1): 1－15.

[178] Leahy M J, Buback S, Maginel C. Twenty years of tallgrass prairie reconstruction and restoration at Pawnee Prairie Natural Area, Missouri. Natural Areas Journal, 2020, 40(1): 62－71.

[179] Stover H J, Henry H A L. Legacy effects of soil homogenization on tallgrass prairie restoration: Toward resolved understanding of the relationship between soil heterogeneity and plant species diversity. Restoration Ecology, 2020, 28(1): 93－103.

[180] Shang Z H, Dong S K, Zhou H K, *et al*. Synthesis-review for research cases of grassland ecological restoration: Years, effect and method. Acta Ecologica Sinica, 2017, 37(24): 8148－8160.
尚占环, 董世魁, 周华坤, 等. 退化草地生态恢复研究案例综合分析: 年限、效果和方法. 生态学报, 2017, 37(24): 8148－8160.

[181] He N, Wu L, Wang Y, *et al*. Changes in carbon and nitrogen in soil particle-size fractions along a grassland restoration chronosequence in northern China. Geoderma, 2009, 150(3/4): 302－308.

[182] Liu W, Wei J, Cheng J, *et al*. Profile distribution of soil inorganic carbon along a chronosequence of grassland restoration on a 22-year scale in the Chinese Loess Plateau. Catena, 2014, 121: 321－329.

[183] Wu X, Li Z, Fu B, *et al*. Restoration of ecosystem carbon and nitrogen storage and microbial biomass after grazing exclusion in semi-arid grasslands of Inner Mongolia. Ecological Engineering, 2014, 73: 395－403.

[184] Jiang S J, Feng T J, Liu G H, *et al*. A bibliometric analysis of the application of grassland ecological restoration technology. Pratacultural Science, 2020, 37(4): 685－702.
蒋胜竞, 冯天骄, 刘国华, 等. 草地生态修复技术应用的文献计量分析. 草业科学, 2020, 37(4): 685－702.

[185] Kollmann J, Meyer S T, Bateman R, *et al*. Integrating ecosystem functions into restoration ecology recent advances and future directions. Restoration Ecology, 2016, 24(6): 722－730.

[186] Wright J, Symstad A, Bullock J M, *et al*. Restoring biodiversity and ecosystem function: Will an integrated approach improve results? //Naeem E B S, Bunker D E, Hector A, *et al*. Biodiversity, ecosystem functioning and human wellbeing. New York: Oxford University Press, 2009: 167－177.

[187] Young T P, Petersen D A, Clary J J. The ecology of restoration: Historical links, emerging issues and unexplored realms. Ecology Letters, 2005, 8(6): 662－673.

[188] Van Andel J, Aronson J. Restoration ecology: The new frontier 2nd edition. Oxford: Blackwell Publishing, 2012.

[189] Majer J D. Animals in the restoration process-progressing the trends. Restoration Ecology, 2009, 17(3): 315－319.

[190] Ruiz-Jaen M C, Aide T M. Restoration success: How is it being measured? Restoration Ecology, 2005, 13(3): 569－577.

[191] Society for Ecological Restoration International Science, Policy Working Group. The SER International Primer on Ecological Restoration. https://cdn.ymaws.com/www.ser.org/resource/resmgr/custompages/publications/SER_Primer/ser_primer.pdf, 2004.

[192] Choi Y D, Temperton V M, Allen E B, *et al*. Ecological restoration for future sustainability in a changing environment. Ecoscience, 2008, 15(1): 53－64.

[193] Ehrenfeld J G. Defining the limits of restoration: The need for realistic goals. Restoration Ecology, 2000, 8(1): 2－9.

[194] Walden E, Lindborg R. Facing the future for grassland restoration—What about the farmers? Journal of Environmental

Management, 2018, 227: 305－312.

[**195**] Wang S K, Zuo X A, Zhao X Y, *et al*. Responses of soil fungal community to the sandy grassland restoration in Horqin Sandy Land, northern China. Environmental Monitoring and Assessment, 2016, 188(21): 1－13.

[**196**] Yuan J, Ouyang Z, Zheng H, *et al*. Effects of different grassland restoration approaches on soil properties in the southeastern Horqin sandy land, northern China. Applied Soil Ecology, 2012, 61(S1): 34－39.

[**197**] Valko O, Deak B, Torok P, *et al*. Dynamics in vegetation and seed bank composition highlight the importance of post-restoration management in sown grasslands. Restoration Ecology, 2021, 29(S1): e13192.

[**198**] Archer S R, Andersen E M, Predick K I, *et al*. Woody plant encroachment: Causes and consequences//Briske D D. Rangeland Systems: Processes, Management and Challenges. New York: Springer, 2017: 25－84.

[**199**] Zhang G L, Biradar C M, Xiao X M, *et al*. Exacerbated grassland degradation and desertification in Central Asia during 2000－2014. Ecological Applications, 2018, 28(2): 442－456.

[**200**] Briggs J M, Knapp A K, Blair J M, *et al*. An ecosystem in transition. Causes and consequences of the conversion of mesic grassland to shrubland. Bioscience, 2005, 55(3): 243－254.

[**201**] Peters D P C, Yao J, Sala O E, *et al*. Directional climate change and potential reversal of desertification in arid and semiarid ecosystems. Global Change Biology, 2012, 18(1): 151－163.

[**202**] Kane K, Debinski D M, Anderson C, *et al*. Using regional climate projections to guide grassland community restoration in the face of climate change. Frontiers in Plant Science, 2017, 8: 1－11.