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矿山生态修复及其固碳潜力研究进展

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摘　要: 作为全球最大的碳"储库"之一,矿山在全球碳循环中的作用备受关注.研究旨在通过系统梳理和深入分析矿山生态修复在固碳增汇和"碳中和"中的作用和机制,以及固碳潜力评估方法,为制订以生态恢复和固碳为目的矿山生态修复措施提供科学依据,从而为加快实现"双碳"目标助力.研究建立了矿山生态系统碳循环的概念模型;以矿山生态修复原理为基础,梳理并讨论了包括地形地貌重塑、土壤重构和植被重建的3大修复措施及其固碳机制,以及实施的注意事项;总结了固碳潜力评估模型和方法.下一步研究应在可持续发展的基础上不断优化修复措施并提高固碳评估的准确性,延长矿山生态修复效益维持时间,促成矿山生态系统固碳能力的可持续发展.

关键词: 矿山;生态修复;碳中和;土壤重构;植被重建;水文地质.

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Advances in Mines Ecological Restoration and Carbon Sequestration Potential

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Abstract: As one of the largest carbon "reservoirs" in the world, the role of mines in the global carbon cycle has attracted much attention. In this study it aims to systematically sort out and deeply analyze the roles and mechanisms of mine ecological restoration in carbon sequestration and carbon neutrality. At the same time, it concludes the methods for assessing carbon sequestration potentials, to provide a scientific basis for formulating mine ecological restoration measures aimed at ecological restoration and carbon sequestration, and help to accelerate the achievement of the "dual-carbon" goal. In this study establishes a conceptual model of the carbon cycle in the mining ecosystem. Based on the principles of mine ecological restoration, it discusses three major restoration measures, including topographic and geomorphic remodeling, soil reconstruction and revegetation, and their carbon sequestration mechanisms, as well as the keys in their implementation. Besides, this study summarizes the carbon sequestration potential assessment model and method. The next step of the study should be to optimize the restoration measures and improve the

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accuracy of carbon sequestration assessment based on sustainable development, to prolong the maintenance time of the ecological benefits of mine restoration and contribute to the sustainable development of carbon sequestration capacity of mine ecosystems.

Key words: mine; ecological restoration; carbon neutrality; soil reconstruction; revegetation; hydrogeology.

在人类发展的进程中,工业化极大提高了人类生产生活的速度,但同时机器运作燃烧大量化石燃料排放的温室气体也导致了全球变暖(Liu *et al.*, 2024).为应对气候变化带给人类的严峻挑战,包括我国在内,全球已有178个缔约方签署了旨在应对全球气候变化的《巴黎协定》.我国还于2020年9月明确提出2030年"碳达峰"与2060年"碳中和"(简称"双碳")的目标,应对气候变化由此成为国家战略.目前国内外已投入大量资金和人力研究碳捕获和碳吸收的途径和技术,并在设置严格排放标准的同时优化经济产业结构,以减少碳排放.

矿山生态系统在全球碳循环中扮演着重要角色,也是全球最大的碳"储库"之一(Wang *et al.*, 2023).矿山开发在给人类社会带来巨大经济效益的同时,给生态系统和其他资源造成的破坏作用和损失也不容小觑.矿山开发不仅会造成地表景观破坏、水土流失、水污染和土壤质量下降等生态环境和资源问题(张明天等, 2021),还会降低地层稳定性,从而诱发滑坡、泥石流甚至地震等地质灾害(蒋文翠等, 2022).与这些"显性"和广为人知的负面影响相比,矿山开发将矿山生态系统从"碳汇"转为"碳源",这一变化则是"隐蔽"的和鲜为人知的.该转变进一步加剧了全球变暖趋势,也给实现"碳中和"带来更大挑战.随着新型修复理念的提出和遥感技术的发展,矿山生态修复模式不断更新,矿山生态修复工程的目标也由系统生态平衡,转向生态恢复和固碳增汇兼顾(张涛等, 2020;李聪聪等, 2021; Yang *et al.*, 2022; 魏中凯, 2023).此外,各国也在逐步将矿山生态修复列入法律法规中,完善政策保障(Borges *et al.*, 2019; Purtill *et al.*, 2022).

全球范围内矿山数量庞大且分布广泛.如果这些矿山的生态系统得到恢复,它们增加的固碳量将是惊人的(郭媛媛等, 2022).矿山生态修复的固碳潜力问题,国内外已经开展过一些研究工作(McKenna *et al.*, 2020; de Almeida Valente *et al.*, 2022; Chen *et al.*, 2023; Bao *et al.*, 2024),其中,生态系统模型能够通过模拟不同环境变量下的碳循环和碳收支量实现固碳潜力评估,但评估方法尚缺乏系统归纳总结.

本文基于国内外研究成果,对矿山生态系统的碳循环、修复原理和措施、固碳潜力评估模型和方法等进行总结,为科学制订以生态恢复和固碳增汇为目标的矿山生态修复措施提供依据,也为科学评估矿山生态修复在"碳中和"中的贡献提供参考.

1　碳中和与矿山生态系统

"碳中和"是指在一段时间内包括化石燃料燃烧等造成的碳排放量等于地球生态系统吸收以及固存的碳,实现途径主要为碳减排和碳增汇(方精云, 2021).其中,碳捕集、利用和封存是一系列依靠人工技术实现碳处理的方法,可达到减排增汇的效果,但在现阶段收效甚微且成本高、稳定性差(卞正富等, 2022),不在本文讨论之列.当下,碳减排主要依靠节约能源、调整能源结构、提高能源利用效率、发展低碳和清洁能源进而减少碳排放.碳增汇主要通过陆地生态系统和海洋生态系统植物的光合作用以及大气和生态系统之间的碳循环实现碳吸收(方精云, 2021),其中陆地生态系统更易被人类进行建设和管理.碳增汇实际就是固碳,即增加除大气外的碳库的碳储量.固碳过程包括植物和土壤与大气之间的碳交换以及植物和土壤之间的内部碳循环,该过程通过化学和生物反应转化物质并输送能量,将大气和土壤中各种形式的碳稳固地存储于生态系统中.

矿山生态修复工程属于"碳中和"的碳增汇途径.基于前人研究(杨博宇和白中科, 2021; 贾国栋等, 2022;陈浮等, 2023; 严格, 2023; Hayman, 2024)识别得到矿山生态系统碳循环概念模型(图1).太阳辐射作为地球生态系统元素循环的驱动力,为地面植物和土壤提供水、热、能量,促使草木发生光合作用,吸收大气中二氧化碳的同时释放氧气.植物内部进行物质转移,将养分输送至各个器官促进地上和地下生物量增加.动植物残体、植被凋落物和根系分泌物等经土壤中的微生物分解形成土壤有机碳.土壤有机碳含量决定土壤肥力(赵姣等, 2023),通过形成土壤团聚体转化为不易分解的碳固存于地下(刘亚龙等, 2023).土壤呼吸作用(Chen *et al.*, 2021)和土壤无机碳的挥发(Pietrzykowski and Daniels, 2014)是矿山生态系统碳

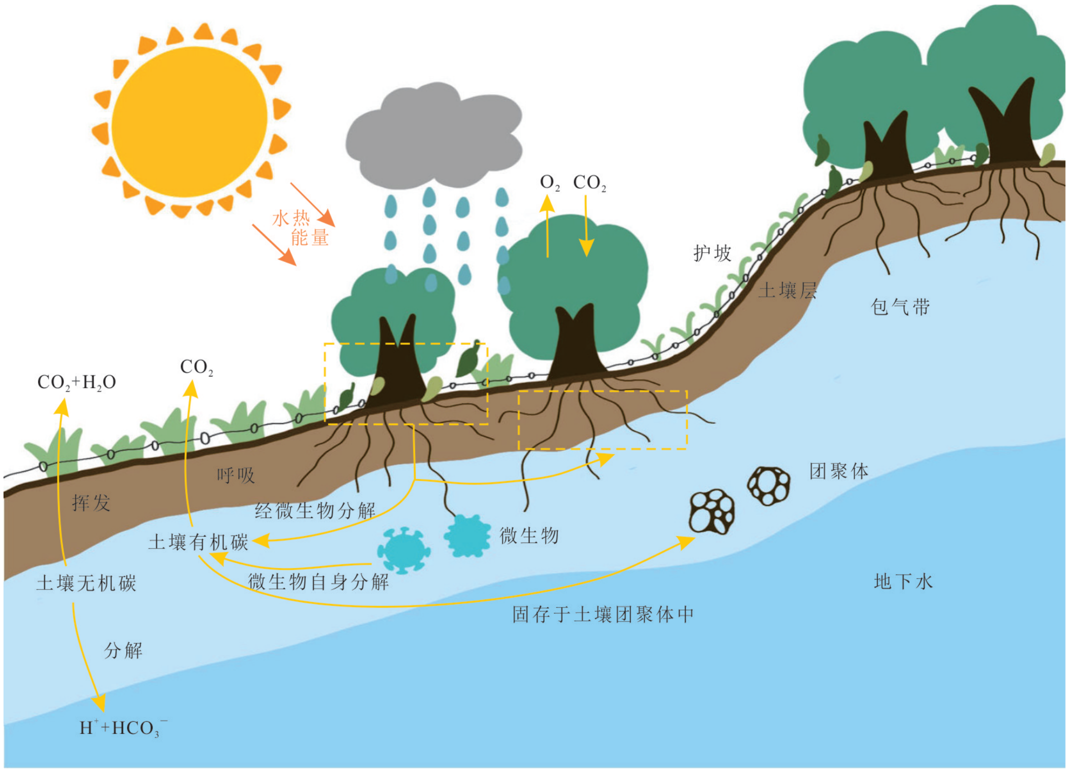

图1 矿山生态系统碳循环示意图

Fig. 1 Schematic diagram of the carbon cycle in mining ecosystem

排放的主要途径.与此同时,土壤无机碳分解为氢离子和重碳酸根离子进入地下水中继续循环.在岩溶环境中,陆地水生植物截留碳酸盐岩产生的大量无机碳形成稳定的有机碳(周婷等,2024).

历史遗留矿山的原生植被和土壤在矿产开发时被破坏,固碳途径也因此被迫中断.开发时在地表形成的陡峭矿坑壁在大气降水和地表径流的侵蚀作用下产生严重的水土流失,使大量已被矿山土壤吸收和固定的碳流失,影响碳平衡和养分循环过程(das Chagas *et al*., 2024).矿山生态修复工程一方面通过恢复植被使其固碳途径得以重建,另一方面通过修坡固坡和植被重建使水土流失和碳流失减少,最终使矿山生态系统的固碳功能得以恢复甚至提升.矿山生态系统实际上就是受到人为影响的天然生态系统,其碳循环步骤与天然生态系统大体相同,但经历扰动和修复后,地形、土壤结构和植被类型均已发生改变,其影响下碳循环的变化主要体现在固碳速率和时效上(Ramos *et al*., 2022; Yuan *et al*., 2022; Zhang *et al*., 2023).因此,在理清矿山生态系统碳循环的基础上,需要从矿山生态修复原理出发,进一步梳理探究修复措施及固碳潜力评价.

2 矿山生态修复原理

矿山生态修复主要基于恢复生态学原理,借助物理、化学、生物等技术手段,将采矿导致的自然生态失衡恢复至稳定的良性循环(李聪聪等,2021;艾婷和李志伟,2023).从固碳增汇角度看,生态修复将使已开发矿山土壤和植被的碳储备和碳吸收功能得到恢复甚至优于开发前的水平(严格,2023).生态地质层理论(王佟等,2022)指出,修复生态地质层及其构建材料的选用是矿山生态修复的关键.综上所述,矿山生态修复应以区域生态系统为研究区,以生态平衡为目的,以可持续发展为原则,全面考虑地质、水文等条件进行生态环境复原或再造.矿山生态修复途径有地貌重塑、土壤重构、植被重建、景观重现、生物多样性重组与保护5种(白中科等,2018).当前的研究主要集中于土壤改良、土壤剖面重建和植被种类选择等(Shao *et al*., 2023),未来的研究则会更加注重矿山生态修复与固碳、气候变化和生物多样性等的关系方面.矿山生态功能的恢复是一个长期的过程(Eldridge *et al*., 2022),复垦土壤的固碳潜力与复垦年限有关,因此后期抚育是矿山生态系统长期高效固碳增汇的重要保障.

3　矿山生态修复措施

矿山类型多样、数量庞大且分布广泛，生态修复工程应以固碳机制为基础，根据废弃矿山类型、地貌特征、气候、地质条件等因地制宜地制订实施方案．根据修复区生态结构的稳定程度和采矿工程的扰动情况，选择不同程度的自然修复与人工修复相结合（雷少刚等，2022）．不同矿山类型修复重点不同，能源矿山等应排查地质隐患并进行安全工程治理，金属矿山应注重环境污染治理与长期环境监测．目前主要修复措施包括地形地貌重塑、土壤重构和植被重建（图 2）．

3.1　地形地貌重塑

地形地貌重塑是长期生态修复的基础（Hancock *et al.*，2020），主要通过改变地表形态控制土壤侵蚀作用和土壤呼吸作用．坡度越缓，降水对地表的侵蚀作用越弱，水土流失伴随的固碳损失越小．地形坡度升高和降雨增强均可造成土壤二氧化碳通量下降，土壤有机碳的流失是其重要诱因（李如剑等，2016）．基于矿山生态系统固碳机制，地形地貌通过对局部气候的改变（Gong *et al.*，2016）影响土壤呼吸作用速率和土壤有机碳含量，其中主要考虑海拔和坡向（Kobler *et al.*，2019），其次是坡长和坡度．陡坡、阴坡、短坡和高海拔有利于土壤有机碳的固定，发挥增汇作用（胡振琪等，2023）．地形通过改变气象条件间接改变植被碳吸收，具体表现在北坡太阳辐射较南坡低，使植被生长发育较弱（王楠楠等，2024）．因此，地形地貌重塑设计方案需要综合考虑多种条件．目前已有主要针对地质安全、水土保持的地形地貌重塑思路与方法，并且在实际工程中有显著修复效果（赵欣等，2023），常见措施包括分级削坡、挖方回填、建设截洪沟或排水沟等（罗明等，2019；李丽等，2022）．

3.2　土壤重构

矿山开采对土壤的破坏主要包括挖损、塌陷和压占 3 种，它们会改变土壤和地层的原有结构和土壤生态环境．土壤重构通过物理、化学和生物作用改良土壤质量并重建土壤剖面，是土地复垦和矿山生态修复的关键（胡振琪，2022），也可直接或间接提高矿山生态修复的碳汇．

目前，土壤质量改良有物理、化学和生物 3 个途径（Pietrzykowski and Daniels，2014；Li *et al.*，2023）．物理改良通过浮石等无机材料改善土壤排水功能和一些物理性能．化学改良通过石灰中和土壤中过量的酸（占幼鸿，2018），通过添加高剂量泥污提高土壤团聚体稳定性和固碳能力（Ojeda *et al.*，2015），通过粉煤灰、磷酸盐材料和有机材料等固定金属或降低有毒物质的浓度，以及提高土壤肥力（赵鹏等，2023）．生物改良主要依靠动物、植物和微生物改善土壤理化性质（da Silva *et al.*，2022；Misebo *et al.*，2022），同时也可以富集、移除或代谢土壤中的有毒物质（Muñoz-Rojas *et al.*，2018；王绪旺和蒋应军，2020）．土壤剖面重构主要依靠物理手段将已遭受污染的土壤进行隔断，或设计剖面结构后回填，如在“土层生态位”和“土壤关键层”理念的指导下（胡振琪，2019），通过“分层剥离、交错回填”优化剖面结构．以上各种土壤重构方法为植被重建提供适宜的土壤环境，创造植被健康生长条件．土壤有机碳含量随修复时间的推移显著增加，植被更长的存活时长和修复时间有利于土壤的固碳增汇（闫美芳等，2019）．

在土壤重构对碳汇的直接影响方面，土壤有机碳含量与粒径、孔隙度和含水量正相关，与容重和 pH 负相关（Yuan *et al.*，2017），并且土壤团聚体的形成增强固碳能力．除此之外，微生物在加速碳循环的同时，其残体成为有机碳可直接增加土壤碳汇（Wang *et al.*，2024）．在时间维度上，土壤有机碳在植被重建后的前 30 年内逐步上升后趋于稳定（Zhang *et al.*，2018；Zhu *et al.*，2024）．随着时间推移，有机物的累积和微生物等的共同作用，导致重构土壤的 pH 降低，也会影响植被生长和土壤固碳速率（Yuan *et al.*，2017）．

综上所述，良好的土壤重构成分和结构可提升植被重建效果和土壤直接碳汇，而修复持续时间对矿山有机碳积累具有较大贡献．

3.3　植被重建

植被重建通过乔木、灌木和草本植物等多种类型分区域组合种植，确保物种多样性，建立一个稳定的生态系统，同时尽可能达到最大碳汇量．其兼具调节气候（Peng *et al.*，2014）、保持水土和固碳增汇（Cheng *et al.*，2024；He *et al.*，2024；Yue *et al.*，2024）等多重生态效益，是矿山生态修复工程中实现碳汇的最主要部分．

作为植被重建的第一步也是最重要的步骤，植被筛选以适应修复区生态环境为标准（Zhang *et al.*，2022），即优先选择固碳增汇效果更好的植

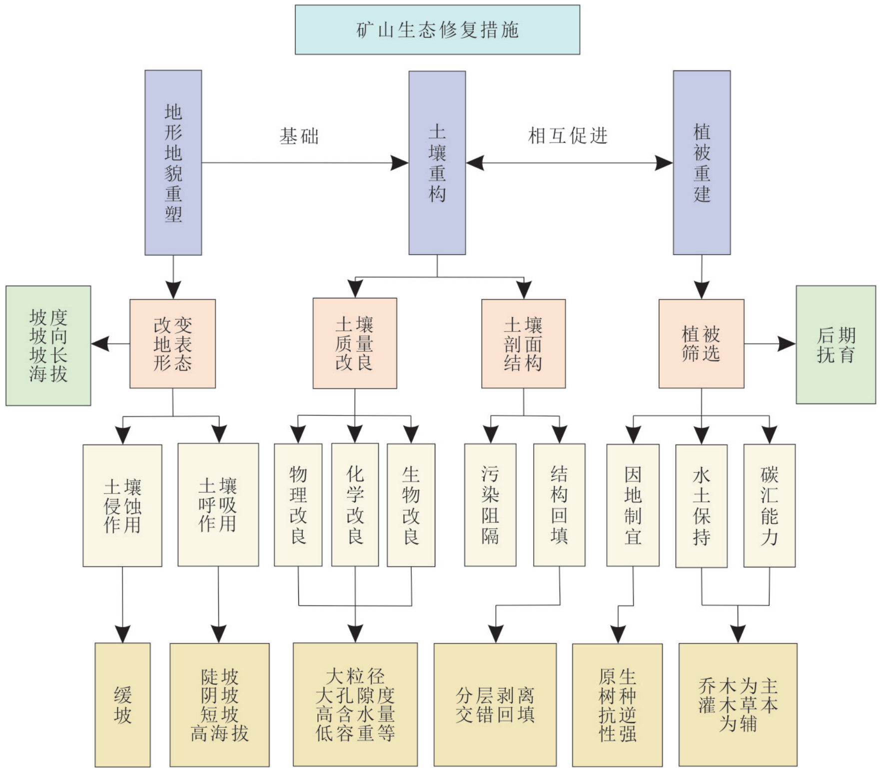

图 2　矿山生态修复流程

Fig.2　Flow chart of mine ecological restoration measures

被.甚至有研究显示,无论施何种肥料,先锋物种的树木生长情况均更好,证明植被选择的重要性(de Almeida Valente *et al*., 2019).合理的植被组合对土壤理化性质可产生正面影响(Zhu *et al*., 2024),使土壤有机碳显著增加(de Aguiar Santiago *et al*., 2022).与此同时,高有机质土壤对植被生长产生一定促进作用,矿山生态修复实现了土壤与植被系统的良性循环.苏军德(2018)经过对甘肃省矿山修复区林分的含碳量进行测定,其碳密度及碳储量结果表现为乔木>灌木>草本植物.侯瑞萍等(2022)对长江经济带林地进行碳储、碳汇量研究,结果表明乔木林是区域碳汇主体,且对土壤有机碳积累贡献最大.因此,植被重建以乔木为主,适当的灌木和草本植物搭配减小坡体承重,以达到更好的水土保持效果,同时降低矿山生态修复成本.朱新雨(2023)总结了目前植被选择的研究结果,优先选择如与根瘤菌、弗兰克氏菌和蓝藻等共生的固氮能力强的植物,以及如狗牙根、沙棘和夹竹桃等抗逆性强的先锋植物.这些优质植被可使矿山生态修复产生更好的生态效益.蒋云清等(2023)研究藏东南生态修复工程时,提出在高海拔地区生态恢复难度大,应选择更易成活的植被种类从而提高定植成功率.在大尺度上,碳汇效果较好的造林树种基本遵循气候分区分布(Xu *et al*., 2023),我国亦如此(表 1).

在植物生长过程中,由于不同植被与土壤之间的物质和能量传递具有时空差异,引入植被的时间也会对修复工程的固碳效果产生影响(Zhu *et al*., 2024).多样化物种混合播种,对气候变化的适应性及抗干扰能力更强(Aguirre-Gutiérrez *et al*., 2023),并且不同凋落物成分与掉落时间使土壤保持固碳效率(陈遐林, 2003),形成更丰富的微生物群落(Eldridge *et al*., 2022).年龄的增长可导致森林的固碳能力下降,阶段性采伐等措施则可以优化森林年龄结构从而逆转下降趋势(Shang *et al*., 2023; Leng *et al*., 2024; Yu *et al*., 2024).因此,植被重建应在因地制宜的基础上选择抗逆性强和碳汇能力强的多植被组合,植被筛选可参考矿山开采前当地的植被,并且重视植被长期演替和抚育工作.

地形地貌重塑是土壤重构的基础,后者又与植被重建相互促进.地形地貌重塑恢复矿山受损坡面,在实施工程时需要考虑各项指标的影响以及工程难度,为后续工作打下基础;土壤重构通过物化生 3 种途径改良土壤质量并重建土壤剖面,良好的土壤状态可促进植被生长并保持高效固碳能力;植

表1　我国部分地区碳汇优势树种

Table 1 The dominant tree species for carbon sinks in some regions of China

地区	气候特点	研究区	研究区气候条件	碳汇优势树种
华北	夏季高温多雨 冬季寒冷干燥	山西	年均温10 ℃ 年均降水量530 mm	桦木、落叶松、栎林等(陈遐林, 2003)
华南	夏季高温多雨 冬季温和少雨	广东	年均温20 ℃ 年均降水量1 600 mm	灰木莲、厚荚相思、马尾松等(林玮等, 2020)
东北	四季分明 雨热同期	辽宁	年均温7 ℃ 年均降水量750 mm	银中杨、油松、水曲柳等(于佳等, 2015)
西北	气候空间分异大 年、日温差大	陕西	年均温12 ℃ 年均降水量670 mm	华山松、铁杉、冷杉、桦木等(岳程瑜, 2023)
西南	气候空间分异大	云南	年均温17 ℃ 年均降水量1 000 mm	乔松、黄杉、枫杨等(梁瑄等, 2023)

被筛选作为植被重建工作的重点,综合考虑因地制宜、水土保持和碳汇能力3个因素,新修复区的树种选择可参考气候及地理环境相似地区.总体来说,矿山生态修复可提高生态系统质量与稳定性,促进碳的积累与固定.

4　矿山生态系统固碳潜力

矿山生态系统的固碳潜力评估将区域碳循环量化,可为工程的植被筛选、方案设计和调整等提供参考,以达到最大碳储量和最佳固碳效果.由矿山生态系统碳循环概念模型(图1)可知,从大气中捕获的碳主要储存于植被和土壤中,因此固碳潜力评估涉及林草和土壤固碳两部分(图3).

4.1　林草固碳潜力

应用较为广泛的林草固碳潜力评估方法分为正向和反向两类.正向法应用样地清查法实地测量、采样、实验、计算获得实际数据,工作量繁重但数据精准.这类方法的误差主要来自于采样过程.反向法基于遥感数据和模型推演,评估陆地生态系统的碳收支和"碳中和"贡献.

目前最常见的固碳潜力评估思路首先通过样地清查法和遥感反演法获得修复区森林的生物量.样地清查法由胸径、树木高度等实测数据通过林木材积公式计算林草蓄积量,推算生物量的方法包括生物量转换因子法和生物量转换因子连续函数法(岳程瑜, 2023).具体碳计量参数和树种异速生长方程可参考《造林项目碳汇计量与监测指南》.生物转换因子法中仅考虑了胸径、树高等指标,而实际上生物量与蓄积量的关系还受到林龄等因素的影响(Tian *et al.*, 2024).生物量转换因子连续函数法进一步基于统计学和机器学习,利用大量数据源将恒定的转换因子建立林龄等关系函数,以便更加准确地估算森林生物量(方精云等, 2002).建立不同树种生长率和树木胸径的单木胸径年生长率模型,可补充由于树高较难测量等问题导致缺失的数据,提高数据准确性(季文旭等, 2024).遥感反演法的数据包括太阳光辐射、微波和激光雷达3种来源,估算通过经验模型、物理模型、机理模型和综合模型四种方法建立与生物量的关系,各有其优劣和适用范围(岳程瑜, 2023).除此之外,遥感数据也可直接估算碳储量.融合无人机和遥感获得的矿山激光雷达数据和高光谱数据直接建立乔灌草3种碳储量估算模型,可较大程度提高使用独立数据的精度,在地形复杂区具有一定优势(唐佳佳等, 2023).

由生物量和含碳系数相乘得到过往年份碳储量,应用假设法、模型模拟法和定性分析法建立蓄积量与林龄的关系并进行数据验证,进而预测未来某时的碳储量,碳储量变化量即该时间段的碳汇.未来某一时间段内的碳汇量即固碳潜力,当树龄达到过熟林上限时,森林蓄积量和生物量碳储量达到峰值,此时固碳潜力也达到最大值,一般树木种植20～200年达到饱和(刘迎春等, 2019).其中,含碳系数通常取0.50.基于森林资源清查数据,使用Richards方程可拟合大多数树种的生长过程,但碳汇潜力估算中假设预测年限内无森林大片砍伐等情况发生,这与实际情况产生误差(付晓等, 2022).利用Logistic生长方程拟合慢生树种蓄积量和林龄的关系,也可得到较好的拟合效果(李思慧等, 2024).张景路等(2023)基于4个常用生长方程研究新疆天山地区云杉的碳汇潜力估测,考虑林龄、树高、胸径等指标构建蓄积量模型,对比选择Schum-

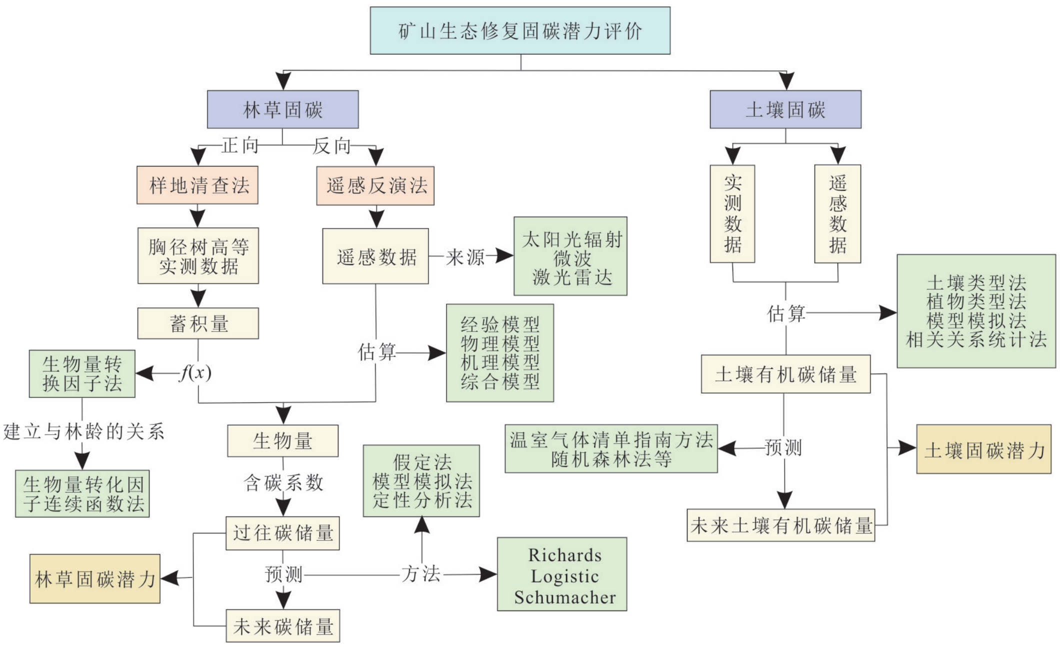

图 3 矿山生态修复固碳潜力评估方法框架

Fig.3 Framework diagram of the methodology for evaluating the carbon sequestration potential of mine ecological restoration

acher方程误差绝对值最小，而Logistic、Gompertz和Mitscherlich的曲线形态相对偏差较大．由此可见，不同地域和不同树种的生长速度匹配不同方程的生长曲线，评估时选择多种模型并进行数据验证可提高固碳潜力评估结果的精准度．

4.2 土壤固碳潜力

土壤固碳潜力评估思路与林草类似，即首先基于以实际测样或遥感数据估算获得已知年份的土壤有机碳储量，常用的估算方法包括土壤类型法、植被类型法、模型模拟法和相关关系统计法等，随后建立模型预测土壤碳汇．基于模型数据的推演和预测，可使用算法进行宏观范围的分析和计算．该方法的评估的误差来源于数据集和模型的准确性，可通过结合多个数据集和分析方法减小误差（Xia *et al.*，2024）．

胡国铮等（2023）采用IPCC（intergovernmen-tal panel on climate change），联合国政府间气候变化专门委员会的温室气体清单指南方法，引入生态管理和草地退化的变化因子，通过目标年与基线年的土壤有机碳储量变化率，估算并预测了2001年至2030年我国大尺度范围草地生态管理下的土壤碳汇．沈佳丽等（2023）应用随机森林法构建不同土层深度的土壤有机碳预测模型，其和罗薇等（2018）同样强调在评估过程中应重点关注深层土壤，因为30 cm以下的土壤占土壤碳库50％以上．此外，蔡亚楠等（2024）提出目前土壤有机碳的含义辨析问题，土壤有机碳是目前最常用的固碳指标，但实际情况中只有难分解的土壤有机碳会留在土壤中被固存下来，因此提出以碱提取液测定的土壤稳定性碳作为碳汇指标，更具有实际意义．土壤碳库储存地球上80％的碳，其固碳潜力具有重要意义，因此长期的土壤固碳增汇监测以及精准的模型预估是矿山生态修复碳中和贡献评估的基础．

综上所述，矿山固碳潜力评估方法根据实际采样测量难度和数据量等进行选择．后续研究应进一步优化评估模型和参数调整等，以提高评估结果的准确性．

5 结论与展望

5.1 结论

以生态恢复和固碳为目的的矿山生态修复工程近年来在国内外受到重视．矿山生态系统的固碳依靠大气、植被和土壤之间的碳循环．理清其运行机制有助于修复措施的优化，以及固碳潜力和“碳中和”贡献的评估．作为矿山生态修复工程的基础，地形地貌重塑在减少水土流失的同时还能减少碳流失，从而增加碳储存．基于地形对土壤碳交换的影响去设计和优化坡型，有助于矿山在修复后产生

更好的碳汇效果.作为全球最大的碳“储库”,土壤的固碳潜力取决于其成分和结构.矿山土壤重构一般也从这两方面恢复被损坏的土壤,且以重建植被为重构目标.作为最重要的大气二氧化碳清除手段,植树造林同样也是以固碳为目的的矿山生态修复工程的核心任务.在矿山植被重建中,因地制宜(主要考虑气候和土壤)地选择碳汇优势物种对提高矿山的碳汇能力至关重要.如果植被类型选择得当,重建植被的固碳潜力可显著大于原生矿山植被.另外,由于土壤和植被在碳循环中彼此耦连,关系密切,土壤重构在固碳方面和植被重建往往相辅相成且相互影响.

固碳潜力评估为掌控矿山“碳中和”进度提供定量数据.矿山生态系统固碳涉及林草固碳和土壤固碳两方面,其评估思路大体相同,即通过已知年份碳储量创建模型预测碳汇.目前林草碳储量评估方法有样地清查法和遥感反演法,固碳潜力预测模型包括Richards、Logistic和Schumacher等;土壤碳储量评估方法有土壤类型法、植被类型法等,应用温室气体清单指南方法和随机森林法等进行土壤固碳潜力预测.每种方法由于考虑因素和数据来源不同,适用于不同情况的评估.样地清查法和土壤有机碳实验的工作量大但数据精确,遥感分析范围大但数据误差也大.不同估算方法和模型对修复区的气候条件和树种等数据的要求不同.长期监测和多种模型相互验证至关重要.

5.2　展望

矿山生态修复是“碳中和”和生态文明建设进程中的重要一环.矿山在开发时受到的扰动较大,在修复后影响其碳汇潜力的不确定因素也较多.在后续的矿山生态修复工程中应加强多种固碳方式的综合运用并注重工程方案的优化,从而提高修复效率和增强碳汇效果.此外,还需加强森林防火,保护生态修复成果.在固碳潜力研究中需要关注时间效应,通过优化树龄结构及加强抚育等长期修复效果,使修复后的矿山生态系统在可持续发展的基础上发挥更大的固碳潜力——以遏制地质灾害隐患为基础,以恢复自然生态平衡为目标,逐步形成矿山生态系统的良性循环.期待在未来加强探索矿山生态修复新技术和固碳潜力评估新方法,进一步推进以生态恢复和固碳为目的的矿山修复工程,加快推动实现“双碳”目标.

References

Aguirre-Gutiérrez, J., Stevens, N., Berenguer, E., 2023. Valuing the Functionality of Tropical Ecosystems beyond Carbon. *Trends in Ecology & Evolution*, 38(12): 1109−1111. https://doi.org/10.1016/j.tree.2023.08.012

Ai, T., Li, Z.W., 2023. Practice and Exploration of Mine Ecological Restoration and Reconstruction from the Perspective of Multidisciplinary Integration. *China Coal*, 49(Suppl.1): 29−35 (in Chinese with English abstract).

Bai, Z.K., Zhou, W., Wang, J.M., et al., 2018. Rethink on Ecosystem Restoration and Rehabilitation of Mining Areas. *China Land Science*, 32(11): 1−9 (in Chinese with English abstract).

Bao, Y.L., Meng, X.T., Liu, H.J., et al., 2024. Assessing the Improvement Potentials of Climate Model Partitioning and Time-Variant Feature Extraction for Soil Organic Carbon Prediction. *Catena*, 241: 108014. https://doi.org/10.1016/j.catena.2024.108014

Bian, Z.F., Yu, H.C., Han, X.T., 2022. Solutions to Mine Ecological Restoration under the Context of Carbon. *Journal of China Coal Society*, 47(1): 449−459 (in Chinese with English abstract).

Borges, S.R., Santos, R.S., Oliveira, D.M.S., et al., 2019. Practices for Rehabilitating Bauxite-Mined Areas and an Integrative Approach to Monitor Soil Quality. *Land Degradation & Development*, 30(7): 866−877. https://doi.org/10.1002/ldr.3273

Cai, Y.N., Ju, Z.S., Huang, Q., et al., 2024. Analysis on the Contents and Methods of Soil Organic Varbon Dink. *Acta Ecologica Sinica*, 44(2): 602−611 (in Chinese with English abstract).

Chen, F., Zhu, Y.F., Ma, J., et al., 2023. Mechanism, Potential and Regulation of Carbon Sequestration and Sink Enhancement in Ecological Restoration of Mining Areas in the Loess Plateau. *Coal Science and Technology*, 51(1): 502−513 (in Chinese with English abstract).

Chen, M., Chen, X.Y., Hu, Z.Y., et al., 2021. Contribution of Root Respiration to Total Soil Respiration during Non-Growing Season in Mine Reclaimed Soil with Different Covering-Soil Thicknesses. *International Journal of Coal Science & Technology*, 8(5): 1130−1137. https://doi.org/10.1007/s40789-020-00402-4

Chen, X.L., 2003. Carbon Sink Functions of Major Forest Types in North China (Dissertation). Beijing Forestry University, Beijing (in Chinese with English abstract).

Chen, X.L., Taylor, A.R., Reich, P.B., et al., 2023. Tree Diversity Increases Decadal Forest Soil Carbon and Nitrogen Accrual. *Nature*, 618: 94−101. https://doi.org/

10.1038/s41586-023-05941-9

Cheng, K., Yang, H.T., Tao, S.L., et al., 2024. Carbon Storage through China's Planted Forest Expansion. *Nature Communications*, 15(1): 4106. https://doi.org/10.1038/s41467-024-48546-0

da Silva, G.O.A., Southam, G., Gagen, E.J., 2022. Accelerating Soil Aggregate Formation: A Review on Microbial Processes as the Critical Step in a Post-Mining Rehabilitation Context. *Soil Research*, 61(3): 209—223. https://doi.org/10.1071/sr22092

das Chagas, H.S., Guedes, R.S., Gastauer, M., et al., 2024. Plant Growth and Metabolism of Exotic and Native Crotalaria Species for Mine Land Rehabilitation in the Amazon. *Journal of Forestry Research*, 35(1): 143—154. https://doi.org/10.1007/s11676-023-01676-5

de Aguiar Santiago, F.L., Silva, A.O., Carneiro, M.A.C., et al., 2022. Revegetation of Mined Areas Influences the Physiological Profile of Bacterial Communities and Improves the Biochemical Functions of Soil. *Pedobiologia*, 90: 150793. https://doi.org/10.1016/j.pedobi.2022.150793

de Almeida Valente, F.D., de Castro, M.F., Filho, J.F.L., et al., 2022. Native Multispecies and Fast-Growing Forest Root Biomass Increase C and N Stocks in a Reclaimed Bauxite Mining Area. *Environmental Monitoring and Assessment*, 195(1): 129. https://doi.org/10.1007/s10661-022-10720-6

de Almeida Valente, F.D., de Castro, M.F., Torres, C.M.M.E., et al., 2019. Growth, Biomass and Carbon Stocks in Forest Cover Planted in an Area of Bauxite Mining in Rehabilitation. *Revista Brasileira de Ciência Do Solo*, 43. https://doi.org/10.1590/18069657rbcs20180212

Eldridge, D.J., Oliver, I., Powell, J.R., et al., 2022. Temporal Dynamics in Biotic and Functional Recovery Following Mining. *Journal of Applied Ecology*, 59(6): 1632—1643. https://doi.org/10.1111/1365-2664.14172

Fang, J.Y., 2021. Ecological Perspectives of Carbon Neutrality. *Chinese Journal of Plant Ecology*, 45(11): 1173—1176 (in Chinese with English abstract).

Fang, J.Y., Chen, A.P., Zhao, S.Q., et al., 2002. Estimation of Forest Biomass in China: Some Notes on Fang et al. *Science* (Science, 2001, 291: 2320—2322). *Journal of Plant Ecology*, 26(2): 243—249 (in Chinese with English abstract).

Fu, X., Zhang, Y.X., Wang, X.J., 2022. Prediction of Forest Biomass Carbon Pool and Carbon Sink Potential in China before 2060. *Scientia Silvae Sinicae*, 58(2): 32—41 (in Chinese with English abstract).

Gong, X.Y., Giese, M., Dittert, K., et al., 2016. Topographic Influences on Shoot Litter and Root Decomposition in Semiarid Hilly Grasslands. *Geoderma*, 282: 112—119. https://doi.org/10.1016/j.geoderma.2016.07.017

Guo, Y.Y., Yu, B.Y., Peng, S.P., 2022. Coal Green Transformation and Mine Ecological Restoration Are the Backbone of Moving towards Carbon Neutrality. *Environmental Protection*, 50(13): 35—37 (in Chinese with English abstract).

Hancock, G.R., Martín Duque, J.F., Willgoose, G.R., 2020. Mining Rehabilitation-Using Geomorphology to Engineer Ecologically Sustainable Landscapes for Highly Disturbed Lands. *Ecological Engineering*, 155: 105836. https://doi.org/10.1016/j.ecoleng.2020.105836

Hayman, G., 2024. Forestation Is Not an Easy Fix. *Science*, 383(6685): 833—834. https://doi.org/10.1126/science.adn7026

He, T.H., Ding, W.X., Cheng, X.L., et al., 2024. Meta-Analysis Shows the Impacts of Ecological Restoration on Greenhouse Gas Emissions. *Nature Communications*, 15(1): 2668. https://doi.org/10.1038/s41467-024-46991-5

Hou, R.P., Xia, C.Z., Chen, J., et al., 2022. Carbon Storage and Carbon Sink of Forest Land and Other Biomass in the Yangtze River Economic Belt. *Acta Ecologica Sinica*, 42(23): 9483—9498 (in Chinese with English abstract).

Hu, G.Z., Hasbagan, G., Li, M.J., et al., 2023. Study on the Simulation of Soil Carbon Sink in Grassland Ecological Management in China: Based on IPCC Inventory Method. *Climate Change Research*, 19(3): 371—380 (in Chinese with English abstract).

Hu, Z.Q., 2019. Re-Exploration of Land Reclamation Science. *China Land Science*, 33(5): 1—8 (in Chinese with English abstract).

Hu, Z.Q., 2022. Theory and Method of Soil Reconstruction of Reclaimed Mined Land. *Journal of China Coal Society*, 47(7): 2499—2515 (in Chinese with English abstract).

Hu, Z.Q., Li, Y.Y., Li, G.S., et al., 2023. Opportunities and Challenges of Land Reclamation and Ecological Restoration in Mining Areas under Carbon Neutral Target. *Coal Science and Technology*, 51(1): 474—483 (in Chinese with English abstract).

Ji, W.X., Feng, Z.K., Zhang, H.Y., et al., 2024. Assessment of Carbon Sink Potential of Arboreal Forests Based on DBH Growth Rate Model for Standing Trees. *Journal of Agricultural Science and Technology*, 26(1): 99—109 (in Chinese with English abstract).

Jia, G.D., Zhang, L.Q., Yu, X.X., 2022. Carbon Sequestration Mechanism, Realization Way and Carbon Neutralization

Strategy of Ecological Restoration. *Bulletin of Soil and Water Conservation*, 42(5): 393－397(in Chinese with English abstract).

Jiang, W.C., Yang, J.Q., Peng, E.R., et al., 2022. Research Progress of Mine Ecological Restoration. *Mining Research and Development*, 42(4): 127－132(in Chinese with English abstract).

Jiang, Y.Q., Wang, G.Y., Huang, M.Y., et al., 2023. Effects of Different Ecological Restoration Measures on Reconstruction of Slope Vegetation in Southeastern Xizang Autonomous Region. *Bulletin of Soil and Water Conservation*, 43(5):187－194(in Chinese with English abstract).

Kobler, J., Zehetgruber, B., Dirnböck, T., et al., 2019. Effects of Aspect and Altitude on Carbon Cycling Processes in a Temperate Mountain Forest Catchment. *Landscape Ecology*, 34(2): 325－340. https://doi.org/10.1007/s10980-019-00769-z

Lei, S.G., Bian, Z.F., Yang, Y.J., 2022. Discussion on the Guided Restoration for Mine Ecosystem. *Journal of China Coal Society*, 47(2): 915－921(in Chinese with English abstract).

Leng, Y., Li, W., Ciais, P., et al., 2024. Forest Aging Limits Future Carbon Sink in China. *One Earth*, 7(5):822－834. https://doi.org/10.1016/j.oneear.2024.04.011

Li, C.C., Wang, T., Wang, H., et al., 2021. Monitoring Technology and Method of Ecological Environment Rehabilitation and Treatment in Jvhugeng Mining Area. *Journal of China Coal Society*, 46(5): 1451－1462(in Chinese with English abstract).

Li, L., Yang, J.Z., Chen, D., et al., 2022. Remote Sensing Survey on the Distribution and Ecological Restoration of Abandoned Open-Pit Mines in the Jiangsu Section of the Yangtze River Economic Zone. *Hydrogeology & Engineering Geology*, 49(1): 183－190(in Chinese with English abstract).

Li, R.J., Zhang, Y.J., Zhao, M., et al., 2016. Simulation on the Effects of Slope and Rainfall on Soil CO_2 Flux and SOC Loss. *Acta Scientiae Circumstantiae*, 36(4): 1336－1342 (in Chinese with English abstract).

Li, S.H., Zhu, T.S., Wei, C.X., et al., 2024. Forest Carbon Storage Calculation and Carbon Sink Potential Prediction in Beijing. *Environmental Science and Management*, 49(1):22－27(in Chinese with English abstract).

Li, W.Y., Zhang, J.F., Song, S.S., et al., 2023. Combination of Artificial Zeolite and Microbial Fertilizer to Improve Mining Soils in an Arid Area of Inner Mongolia, China. *Journal of Arid Land*, 15(9): 1067－1083. https://doi.org/10.1007/s40333-023-0028-1

Liang, X., Li, C.B., 2023. Analysis of Current Situation and Potential of Forest Carbon Sink in Yunnan Province. *Chinese Agricultural Science Bulletin*, 39(30):47－53(in Chinese with English abstract).

Lin, W., Bai, Q.S., Chen, X.M., et al., 2020. Construction of the Carbon Sink Capacity Evaluation System of Main Afforestation Tree Species in South China and Selection of the Fine Carbon Sink Species. *Journal of Southwest Forestry University* (*Natural Sciences*), 40(1):28－37(in Chinese with English abstract).

Liu, Y.C., Gao, X.L., Fu, C., et al., 2019. Estimation of Carbon Sequestration Potential of Forest Biomass in China Based on National Forest Resources Inventory. *Acta Ecologica Sinica*, 39(11): 4002－4010(in Chinese with English abstract).

Liu, Y.L., Wang, P., Wang, J.K., 2023. Formation and Stability Mechanism of Soil Aggregates: Progress and Prospect. *Acta Pedologica Sinica*, 60(3):627－643(in Chinese with English abstract).

Liu, Z., Deng, Z., Davis, S.J., et al., 2024. Global Carbon Emissions in 2023. *Nature Reviews Earth & Environment*, 5(4): 253－254. https://doi.org/10.1038/s43017-024-00532-2

Luo, M., Zhou, Y., Ju, Z.S., et al., 2019. Technological Model and Benefit Pre-Evaluation of Eco-Environmental Rehabilitation Engineering of Typical Mines in the Nanling Area of Northern Guangdong Province under the Pilot Framework of the Eco-Restoration of Mountains-Rivers-Forests-Farmlands-Lakes-Grasslands. *Acta Ecologica Sinica*, 39(23): 8911－8919(in Chinese with English abstract).

Luo, W., Zhang, H.H., Chen, J.J., et al., 2018. Storage and Spatial Distribution of Soil Organic Carbon in Guangdong Province, China. *Ecology and Environmental Sciences*, 27(9): 1593－1601(in Chinese with English abstract).

McKenna, P.B., Lechner, A.M., Phinn, S., et al., 2020. Remote Sensing of Mine Site Rehabilitation for Ecological Outcomes: A Global Systematic Review. *Remote Sensing*, 12(21):3535. https://doi.org/10.3390/rs12213535

Misebo, A.M., Pietrzykowski, M., Woś, B., 2022. Soil Carbon Sequestration in Novel Ecosystems at Post-Mine Sites: A New Insight into the Determination of Key Factors in the Restoration of Terrestrial Ecosystems. *Forests*, 13(1): 63. https://doi.org/10.3390/f13010063

Muñoz-Rojas, M., Román, J.R., Roncero-Ramos, B., et al., 2018. Cyanobacteria Inoculation Enhances Carbon Sequestration in Soil Substrates Used in Dryland Restoration. *Science of the Total Environment*, 636:1149－1154. https://doi.org/10.1016/j.scitotenv.2018.04.265

Ojeda, G., Ortiz, O., Medina, C.R., et al., 2015. Carbon Sequestration in a Limestone Quarry Mine Soil Amended with Sewage Sludge. *Soil Use and Management*, 31(2): 270－278.https://doi.org/10.1111/sum.12179

Peng, S.S., Piao, S.L., Zeng, Z.Z., et al., 2014. Afforestation in China Cools Local Land Surface Temperature. *Proceedings of the National Academy of Sciences of the United States of America*, 111(8): 2915－2919. https://doi.org/10.1073/pnas.1315126111

Pietrzykowski, M., Daniels, W.L., 2014. Estimation of Carbon Sequestration by Pine (Pinus *Sylvestris* L.) Ecosystems Developed on Reforested Post-Mining Sites in Poland on Differing Mine Soil Substrates. *Ecological Engineering*, 73: 209－218. https://doi. org/10.1016/j. ecoleng.2014.09.058

Purtill, J., Gagen, E.J., Hamilton, B., 2022. A Brief History of Mine Rehabilitation Reforms in Queensland. *Environmental and Planning Law Journal*, 39(1): 64－78. https://doi.org/10.3316/agispt.20221010075611

Ramos, S.J., Gastauer, M., Martins, G.C., et al., 2022. Changes in Soil Properties during Iron Mining and in Rehabilitating Minelands in the Eastern Amazon. *Environmental Monitoring and Assessment*, 194(4):256.https://doi.org/10.1007/s10661-022-09892-y

Shang, R., Chen, J.M., Xu, M., et al., 2023. China's Current Forest Age Structure will Lead to Weakened Carbon Sinks in the near Future. *The Innovation*, 4(6): 100515. https://doi.org/10.1016/j.xinn.2023.100515

Shao, Y., Xu, Q.X., Wei, X., 2023. Progress of Mine Land Reclamation and Ecological Restoration Research Based on Bibliometric Analysis. *Sustainability*, 15(13): 10458. https://doi.org/10.3390/su151310458

Shen, J.L., Chen, S.C., Hu, B.F., et al., 2023. Prediction and Mapping Soil Organic Carbon in Jianghan Plain by Machine Learning. *Journal of Agricultural Resources and Environment*, 40(3): 644－650(in Chinese with English abstract).

Su, J.D., 2018. A Study on Vegetation Carbon Storage in Ecological Restoration Area of Abandoned Mines. *Bulletin of Soil and Water Conservation*, 38(5):234－237(in Chinese with English abstract).

Tang, J.J., Dong, J., Yang, Y.J., et al., 2023. Inversion of Aboveground Carbon Stock of Vegetation in Mine Ecological Restoration Area by Combining LiDAR and Hyperspectral Data. *Metal Mine*, (1):65－72(in Chinese with English abstract).

Tian, H.L., Zhu, J.H., Lei, X.D., et al., 2024. Models Considering the Theoretical Stand Age will Underestimate the Future Forest Carbon Sequestration Potential. *Forest Ecology and Management*, 562:121982.https://doi.org/10.1016/j.foreco.2024.121982

Wang, C.Q., Kuzyakov, Y., 2024. Rhizosphere Engineering for Soil Carbon Sequestration. *Trends in Plant Science*, 29(4): 447－468. https://doi. org/10.1016/j.tplants.2023.09.015

Wang, N.N., Liu, Y.L., Yin F., et al., 2024. Estimation and Analysis of Ecosystem Carbon Sinks with Topographic Correction. *Geomatics and Information Science of Wuhan University* (in press) (in Chinese with English abstract).

Wang, S., Roland, B., Adhikari, K., et al., 2023. Spatial-Temporal Variations and Driving Factors of Soil Organic Carbon in Forest Ecosystems of Northeast China. *Forest Ecosystems*, 10: 100101. https://doi. org/10.1016/j.fecs.2023.100101

Wang, T., Liu, F., Zhao, X., et al., 2022. Theory of Ecological Geological Layer and Its Application in Mine Environment Remediation. *Journal of China Coal Society*, 47(10):3759－3773(in Chinese with English abstract).

Wang, X.W., Jiang, Y.J., 2020. Impact of Iron Tailings on Soil Environment and Ecological Restoration and Degradation Measures. *Mining and Metallurgy*, 29(6): 94－98(in Chinese with English abstract).

Wei, Z.K., 2023. Study on Current Situation and Development Trend of Ecological Restoration and Treatment of Abandoned Open-Pit Mines. *China Energy and Environmental Protection*, 45(1):45－51(in Chinese with English abstract).

Xia, X.S., Ren, P.Y., Wang, X.H., et al., 2024. The Carbon Budget of China: 1980—2021. *Science Bulletin*, 69(1): 114－124.https://doi.org/10.1016/j.scib.2023.11.016

Xu, H., Yue, C., Zhang, Y., et al., 2023. Forestation at the Right Time with the Right Species can Generate Persistent Carbon Benefits in China. *Proceedings of the National Academy of Sciences of the United States of America*, 120(41): e1989979176. https://doi. org/10.1073/pnas.2304988120

Yan, G., 2023. Carbon Effects of Ecological Restoration in the Land Space of Quarry-Type Abandoned Mines (Dissertation). Jiangxi Agricultural University, Nanchang(in Chinese with English abstract).

Yan, M.F., Wang, L., Hao, C.Z., et al., 2019. Effects of Ecological Restoration on Soil Organic Carbon in Post-Mining Lands. *Acta Ecologica Sinica*, 39(5):1838－1845 (in Chinese with English abstract).

Yang, B. Y., Bai, Z. K., 2021. Research Advances and Emission Reduction Measures in Carbon Source and Sink of Land Ecosystems in Coal Mining Area under the Carbon Neutrality. *China Mining Magazine*, 30(5): 1－9(in Chinese with English abstract).

Yang, B.Y., Bai, Z.K., Fu, S., et al., 2022. Division of Carbon Sink Functional Areas and Path to Carbon Neutrality in Coal Mines. *International Journal of Coal Science & Technology*, 9(1): 48. https://doi. org/10.1007/s40789-022-00507-y

Yu, J., Chen, H.W., Yan, H.W., 2015. Study on Carbon Sink Functions of Garden Plants in Urban Areas of Shenyang, Liaoning. *Journal of Central South University of Forestry & Technology*, 35(8): 94－97(in Chinese with English abstract).

Yu, Z., Liu, S. R., Li, H. K., et al., 2024. Author Correction: Maximizing Carbon Sequestration Potential in Chinese Forests through Optimal Management. *Nature Communications*, 15: 4020. https://doi. org/10.1038/s41467-024-48054-1

Yuan, Y., Zhao, Y. F., Gao, Y., et al., 2022. The Effect of Tree Species on Soil Organic Carbon Recovery in a Restoration Project Is Associated with Vegetation Biomass: Evidence from the Pingshuo Mine Reclaimed Ecosystem, North China. *Land Degradation & Development*, 33 (18):3870－3881. https://doi.org/10.1002/ldr.4429

Yuan, Y., Zhao, Z. Q., Zhang, P. F., et al., 2017. Soil Organic Carbon and Nitrogen Pools in Reclaimed Mine Soils under Forest and Cropland Ecosystems in the Loess Plateau, China. *Ecological Engineering*, 102: 137－144. https://doi.org/10.1016/j.ecoleng.2017.01.028

Yue, C. Y., 2023. Study on Estimating Forest Carbon Stock and Its Carbon Sink Potential in Shaanxi Province (Dissertation). Northwest Agriculture and Forestry University, Yangling(in Chinese with English abstract).

Yue, X., Zhou, H., Cao, Y., et al., 2024. Large Potential of Strengthening the Land Carbon Sink in China through Anthropogenic Interventions. *Science Bulletin*, 69(16): 2622－2631. https://doi.org/10.1016/j.scib.2024.05.037

Zhan, Y. H., 2018. Introduction to the Ecological Restoration of Non-Ferrous Metal Mine Wasteland. *Mining and Metallurgy*, 27(2):96－100(in Chinese with English abstract).

Zhang, G.Q., Zhang, P., Cao, Y., 2018. Ecosystem Carbon and Nitrogen Storage Following Farmland Afforestation with Black Locust (Robinia Pseudoacacia) on the Loess Plateau, China. *Journal of Forestry Research*, 29(3):761－771. https://doi.org/10.1007/s11676-017-0479-3

Zhang, J.L., Zhang, H.F., Gao, J., et al., 2023. Estimation of Carbon Sequestration Potential of Picea Schrenkiana Based on Stand Growth Model. *Jiangsu Journal of Agricultural Sciences*, 39(6): 1332－1340(in Chinese with English abstract).

Zhang, M.T., Hou, K.P., Wang, Y., et al., 2021. Study on Ecological Restoration and Landscape Reconstruction of Jinning Phosphate Mine Dump. *Mining and Metallurgy*, 30(5):11－17(in Chinese with English abstract).

Zhang, P.P., Liu, G.W., Yu, Y., 2023. Ecological Stoichiometry of Soil Carbon, Nitrogen and Phosphorus in Reclaimed Farmland in Coal Mining Subsidence Area. *Journal of Soil Science and Plant Nutrition*, 23(2): 2498－2511. https://doi.org/10.1007/s42729-023-01207-5

Zhang, T., Liao, C.J., Jiang, L.L., et al., 2020. Case Project of Ecological Restoration of a Nonferrous Metal Mine in Guangxi. *China Mining Magazine*, 29(1): 62－67(in Chinese with English abstract).

Zhang, X.J., Wang, G.Q., Xue, B.L., et al., 2022. Changes in Vegetation Cover and Its Influencing Factors in the Inner Mongolia Reach of the Yellow River Basin from 2001 to 2018. *Environmental Research*, 215: 114253. https://doi.org/10.1016/j.envres.2022.114253

Zhao, J., Ma, J., Zhu, Y.F., et al., 2023. Effects of Vegetation Types on Carbon Cycle Functional Genes in Reclaimed Soil from Open Pit Mines in the Loess Plateau. *Environmental Science*, 44(6): 3386－3395(in Chinese with English abstract).

Zhao, P., Shi, X. P., Shang, Q., et al., 2023. The Research Progress on Soil Amelioration in Mine Reclamation Land. *Journal of Agricultural Resources and Environment*, 40(1):1－14(in Chinese with English abstract).

Zhao, X., Wang, T., Li, C.C., et al., 2023. Construction and Restoration Technology of Terrain Remodeling Layer in the Restoration of Ecological Geological Layer in Open-Pit Mining Areas. *Coal Geology & Exploration*, 51(7): 113－122(in Chinese with English abstract).

Zhou, T., Wang, X.F., Xiao, Z.L., et al., 2024. Analysis of the Main Characteristics and Influencing Factors of CO_2 Emissions from Inland Waters in China. *Science China: Earth Science*, 54(6):2065－2085(in Chinese).

Zhu, X. Y., 2023. Vegetation Reconstruction Method of Lingquan Open-Pit Mine Based on Vegetation Classification and Establishment Type (Dissertation). China University of Mining and Technology, Xuzhou(in Chinese with English abstract).

Zhu, Y.F., Wang, L.P., Ma, J., et al., 2024. Assessment of Carbon Sequestration Potential of Mining Areas under Ecological Restoration in China. *Science of the Total Environment*, 921:171179. https://doi.org/10.1016/j.scitotenv.2024.171179

中文参考文献

艾婷,李志伟,2023.多专业融合视角下矿山生态修复重建实践探索.中国煤炭,49(增刊1):29-35.
白中科,周伟,王金满,等,2018.再论矿区生态系统恢复重建.中国土地科学,32(11):1-9.
卞正富,于昊辰,韩晓彤,2022.碳中和目标背景下矿山生态修复的路径选择.煤炭学报,47(1):449-459.
蔡亚楠,鞠正山,黄勤,等,2024.土壤有机碳汇内涵与核算方法辨析.生态学报,44(2):602-611.
陈浮,朱燕峰,马静,等,2023.黄土高原矿区生态修复固碳机制与增汇潜力及调控.煤炭科学技术,51(1):502-513.
陈遐林,2003.华北主要森林类型的碳汇功能研究(博士学位论文).北京:北京林业大学.
方精云,2021.碳中和的生态学透视.植物生态学报,45(11):1173-1176.
方精云,陈安平,赵淑清,等,2002.中国森林生物量的估算:对Fang等Science一文(Science,2001,291:2320-2322)的若干说明.植物生态学报,26(2):243-249.
付晓,张煜星,王雪军,2022.2060年前我国森林生物量碳库及碳汇潜力预测.林业科学,58(2):32-41.
郭媛媛,于宝源,彭苏萍,2022.煤炭绿色转型与矿山生态修复是迈向碳中和的中坚.环境保护,50(13):35-37.
侯瑞萍,夏朝宗,陈健,等,2022.长江经济带林地和其他生物质碳储量及碳汇量研究.生态学报,42(23):9483-9498.
胡国铮,干珠扎布,李铭杰,等,2023.中国草地生态管理的土壤碳汇模拟研究:基于IPCC清单方法.气候变化研究进展,19(3):371-380.
胡振琪,2019.再论土地复垦学.中国土地科学,33(5):1-8.
胡振琪,2022.矿山复垦土壤重构的理论与方法.煤炭学报,47(7):2499-2515.
胡振琪,理源源,李根生,等,2023.碳中和目标下矿区土地复垦与生态修复的机遇与挑战.煤炭科学技术,51(1):474-483.
季文旭,冯仲科,张瀚月,等,2024.基于立木胸径生长率模型的乔木林碳汇潜力评估.中国农业科技导报,26(1):99-109.
贾国栋,张龙齐,余新晓,2022.生态修复的固碳机制、实现途径及碳中和对策.水土保持通报,42(5):393-397.
蒋文翠,杨继清,彭尔瑞,等,2022.矿山生态修复研究进展.矿业研究与开发,42(4):127-132.
蒋云清,王国严,黄梦月,等,2023.不同生态修复措施对藏东南工程边坡植被重建的作用.水土保持通报,43(5):187-194.
雷少刚,卞正富,杨永均,2022.论引导型矿山生态修复.煤炭学报,47(2):915-921.
李聪聪,王佟,王辉,等,2021.木里煤田聚乎更矿区生态环境修复监测技术与方法.煤炭学报,46(5):1451-1462.
李丽,杨金中,陈栋,等,2022.长江经济带江苏段废弃露天矿山分布与生态修复遥感调查研究.水文地质工程地质,49(1):183-190.
李如剑,张彦军,赵慢,等,2016.坡度和降雨影响土壤CO_2通量和有机碳流失的模拟研究.环境科学学报,36(4):1336-1342.
李思慧,朱天姝,魏朝晌,等,2024.北京市森林碳储量核算与碳汇潜力预测研究.环境科学与管理,49(1):22-27.
梁瑄,李春波,2023.云南省森林碳汇现状与潜力分析.中国农学通报,39(30):47-53.
林玮,白青松,陈雪梅,等,2020.华南主要造林树种碳汇能力评价体系构建及优良碳汇树种筛选.西南林业大学学报(自然科学),40(1):28-37.
刘亚龙,王萍,汪景宽,2023.土壤团聚体的形成和稳定机制:研究进展与展望.土壤学报,60(3):627-643.
刘迎春,高显连,付超,等,2019.基于森林资源清查数据估算中国森林生物量固碳潜力.生态学报,39(11):4002-4010.
罗明,周妍,鞠正山,等,2019.粤北南岭典型矿山生态修复工程技术模式与效益预评估:基于广东省山水林田湖草生态保护修复试点框架.生态学报,39(23):8911-8919.
罗薇,张会化,陈俊坚,等,2018.广东省土壤有机碳储量及分布特征.生态环境学报,27(9):1593-1601.
沈佳丽,陈颂超,胡碧峰,等,2023.基于机器学习的江汉平原土壤有机碳预测及制图.农业资源与环境学报,40(3):644-650.
苏军德,2018.矿山废弃地生态修复区植被碳库研究.水土保持通报,38(5):234-237.
唐佳佳,董婧,杨永均,等,2023.联合LiDAR和高光谱数据反演矿山生态修复区植被地上碳储量.金属矿山,(1):65-72.
王楠楠,刘耀林,尹峰,等,2024.顾及地形校正的生态系统碳汇估算与分析.武汉大学学报(信息科学版)(待刊).
王佟,刘峰,赵欣,等,2022.生态地质层理论及其在矿山环境治理修复中的应用.煤炭学报,47(10):3759-3773.
王绪旺,蒋应军,2020.铁尾矿路用对土壤环境的影响及生态修复降解措施.矿冶,29(6):94-98.
魏中凯,2023.废弃露天矿山生态修复治理现状及发展趋势研究.能源与环保,45(1):45-51.
严格,2023.采石类废弃矿山国土空间生态修复碳效应研究(博士学位论文).南昌:江西农业大学.
闫美芳,王璐,郝存忠,等,2019.煤矿废弃地生态修复的土壤有机碳效应.生态学报,39(5):1838-1845.

杨博宇,白中科,2021.碳中和背景下煤矿区土地生态系统碳源/汇研究进展及其减排对策.中国矿业,30(5):1－9.

于佳,陈宏伟,闫红伟,2015.沈阳市常用园林植物碳汇功能研究.中南林业科技大学学报,35(8):94－97.

岳程瑜,2023.陕西省森林碳储量及其碳汇潜力估算研究(硕士学位论文).杨凌:西北农林科技大学.

占幼鸿,2018.浅谈有色金属矿业废弃地的生态恢复.矿冶,27(2):96－100.

张景路,张绘芳,高健,等,2023.基于林分生长模型的天山云杉碳汇潜力估测.江苏农业学报,39(6):1332－1340.

张明天,侯克鹏,王亚,等,2021.晋宁磷矿排土场生态修复与景观再造研究.矿冶,30(5):11－17.

张涛,廖长君,蒋林伶,等,2020.广西某有色金属矿山生态修复工程实例.中国矿业,29(1):62－67.

赵姣,马静,朱燕峰,等,2023.植被类型对黄土高原露采矿山复垦土壤碳循环功能基因的影响.环境科学,44(6):3386－3395.

赵鹏,史兴萍,尚卿,等,2023.矿区复垦地土壤改良研究进展.农业资源与环境学报,40(1):1－14.

赵欣,王佟,李聪聪,等,2023.露天矿区生态地质层修复中地形重塑层的构建技术及应用.煤田地质与勘探,51(7):113－122.

周婷,王晓锋,肖作林,等,2024.中国内陆水体CO_2排放的主要特征及影响因素分析.中国科学:地球科学,54(6):2065－2085.

朱新雨,2023.基于植被分类和立地类型划分的灵泉露天矿植被重建方法(硕士学位论文).徐州:中国矿业大学.