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综　述
REVIEW

气候变化与土壤侵蚀相互作用研究进展【封面文章】

郁科科[1,2]，李爱珍[1]，刘利鹏[1]，张　超[1]，蓝江湖[3*]

1. 宝鸡文理学院　地理与环境学院，宝鸡　721013
2. 陕西省灾害监测与机理模拟重点实验室，宝鸡　721013
3. 中国科学院地球环境研究所　黄土与第四纪地质国家重点实验室，西安　710061

摘　要：气候变化和土壤侵蚀是当前全球变化研究重点关注的两个自然过程，二者之间的相互作用是地表过程的重要研究内容之一。本文从土壤侵蚀对气候变化的响应、碳循环过程对土壤侵蚀的反馈两个方面综述了气候变化与土壤侵蚀相互作用研究进展。分析认为：理想的地质载体是深刻理解地质历史时期土壤侵蚀对气候变化响应特征的关键；土壤侵蚀预测模型的适用条件和范围以及降雨侵蚀力估算方法缺乏标准化是造成土壤侵蚀量估算结果存在差异的主要因素；侵蚀作用下土壤有机碳矿化的生物学过程与机制是科学评估土壤侵蚀是碳源或碳汇的关键环节。建议未来在以下三个方向开展工作：（1）以湖泊沉积物为地质载体研究历史时期气候变化与土壤侵蚀有着巨大发展和应用潜力，建议利用 AMS ^{14}C、^{137}Cs 和 ^{210}Pb 等多种定年手段，使用环境指示意义明确的代用指标，建立近千年高分辨率流域气候与侵蚀序列，研究十年至百年尺度气候变化与土壤侵蚀之间的关系；（2）流域版水蚀预报模型（WEPP）可能更适合小流域预测研究，在其实践应用过程中除规范标准小区的坡度和坡长之外，还应通过长期观测和试验确定不同气候区侵蚀性降雨阈值以计算降雨侵蚀力；（3）可以尝试采用定量稳定同位素探针技术（qSIP）研究微生物对土壤有机碳库的分解和转化的驱动机制，因为 qSIP 不仅能量化土壤微生物的生长速率，还能同步测定土壤有机碳的矿化速率。

关键词：气候变化；土壤侵蚀；相互作用

Interaction between climate change and soil erosion: a review【Cover】

YU Keke[1,2], LI Aizhen[1], LIU Lipeng[1], ZHANG Chao[1], LAN Jianghu[3*]

1. College of Geography and Environment, Baoji University of Arts and Sciences, Baoji 721013, China
2. Shaanxi Key Laboratory of Disasters Monitoring & Mechanism Simulation, Baoji 721013, China
3. State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an 710061, China

Abstract: ***Background, aim, and scope*** Soil erosion processes accompanied by hydrological and biochemical cycles document the flows and transformations of material, energy, and information from an erosion source to

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通信作者：蓝江湖，E-mail：lanjh@ieecas.cn
Corresponding Author: LAN Jianghu, E-mail: lanjh@ieecas.cn
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a deposition sink, which are vital for ecological and economic environments in catchments at various scales. Climate (reported hereon are precipitation) is usually considered the main factor controlling soil erosion intensity at the long-historical stage. Therefore, the interaction or relationship between climate change and soil erosion is an important topic in the study of earth surface processes. Here, we summarize the historical background of the study of the interaction between climate change and soil erosion. Major opinions and other recent advances, up to the present, are also reviewed. We then examine recent progress and recommend future research based on current knowledge and technical feasibility. ***Materials and methods*** We compiled publications that addressed the interaction between climate change and soil erosion, covering geological archives, model-dependent evaluations, and carbon cycle-soil erosion feedback processes. ***Results*** The results are as follows: (1) an ideal geological archive may be the key to understanding the response characteristics of soil erosion to climate change in historical periods; (2) the applicable conditions and scope of soil erosion prediction models and the lack of standardization for rainfall erosivity estimation methods are the main factors that cause differences in soil erosion estimates; (3) soil erosion plays an important role in shaping modern landforms and physically impacts the carbon process due to soil particle movement. ***Discussion*** (1) Lacustrine sediment, as a collector of past climatic and environmental changes, can not only record long-term, continuous, high-resolution, undisturbed information on regional rainfall, vegetation cover, and human disturbances but also provide information about soil erosion processes. Thus, it has a significant advantage in reconstructing soil erosion history. (2) It is critical to choose an independent index for soil calculation models because the factors that affect soil erosion are interrelated and interact with each other. Before applying soil erosion prediction models in practice, however, the observed data must be used to validate the model and calibrate its parameters. In addition, the size of the experimental field plots must parallel those of the unit plot (i.e., with a steepness of 9° and a slope length of 22.13 m) when constructing a steepness or slope length model. Otherwise, the results cannot be compared to other results. (3) Microorganisms have a critical role in controlling terrestrial C fluxes as they promote the release of C to the atmosphere through their catabolic activities. Both the dynamics of soil microorganisms and the mineralization rate of soil organic carbon during the post-erosion period are crucial to accurately define the role of soil erosion as a net carbon sink or atmospheric source. ***Conclusions*** (1) These models have the potential to be developed for and applied to lake sediments to create a geological archive, thus enabling the connection between climate change and soil erosion in historical periods to be studied. (2) The soil erosion model is premised upon a top-level design and user-oriented construction, which enable its applicability. Multidisciplinary cooperation, long-term adherence, and new technology updates are also necessary for maintaining the vitality of the models. (3) The biological process and mechanism of soil organic carbon mineralization are the keys to scientifically evaluating soil erosion as a carbon sink or atmospheric source. ***Recommendations and perspectives*** Research in the field of climate change and soil erosion interactions is likely to take many new directions in the coming years, refining our understanding of long-standing earth surface process across various fields. Here, we outline a few selected research areas that may provide new insights into both the current situation and future. (1) We recommend using AMS ^{14}C, ^{137}Cs, and ^{210}Pb to reconstruct the history of soil erosion intensity and climate change during the last millennium as a basis for studying the relationship between soil erosion intensity and climate change on decadal to centennial timescales. In addition, the environmental significance of proxies in lake sediments must be clarified. (2) Long-term high-quality experiments and monitoring provide an important basis for establishing soil erosion models. For the watershed version of the WEPP model, the slope and length of the unit plot should be normalized, and the erosivity of rainfall in different regions should be calculated using the erosive daily rainfall threshold determined via long-term observations and experiments. (3) Quantitative stable isotope probing (qSIP) can be used to study

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the driving mechanism of microorganism decomposition and transformation into the soil organic carbon pool, because it can not only quantify the growth rate of soil microorganisms, but also simultaneously measure the mineralization rate of soil organic carbon.

Key words: climate change; soil erosion; interaction

地球表层系统是一个多要素相互作用的综合体，各要素之间的相互作用、相互关系以及地表综合体的时空变化规律是地表过程研究重点关注的问题（丁永建等，2013）。一些关键地表过程的变化可以直接或间接改变地球表层系统的物质循环和能量流动格局，从而导致气候要素（温度和降水等）发生变化。例如：土壤侵蚀是陆地生态系统中重要的自然地质现象（地表流水是地球表面最常见的地质营力，本文讨论的土壤侵蚀仅指因降水和径流冲刷引起的水力侵蚀），能够驱动土壤碳库（陆地生态系统最大的碳库，碳素的贮存形式以有机碳为主）（Minasny et al.，2017；Alidoust et al.，2018；卫晓锋等，2022）发生变化，影响全球碳平衡和碳循环格局，导致全球气候变化（Batjes，2014）。土壤侵蚀可导致土壤表层有机碳组分、含量以及分布格局发生显著变化（张雪等，2012；Kirkels et al.，2014；Zhang et al.，2014；杜兰兰等，2016；Doetterl et al.，2016；Yue et al.，2016；肖胜生等，2017；Wang et al.，2020），土壤侵蚀过程引起土壤有机碳发生迁移并加速土壤有机碳原位矿化和异地矿化等（Lal，2003；Zhang et al.，2014；Yue et al.，2016）。据研究，全球每年因土壤侵蚀而被矿化成 CO_2 或 CH_4 进入大气的有机碳高达 0.8—1.2 Gt（Lal，2004），而大气中 CO_2 浓度的增加直接或间接导致气候变化（Piao et al.，2013；Stockmann et al.，2013；Skliris et al.，2016；Minasny et al.，2017；董曹沂等，2022）。

另一方面，全球碳循环格局变化和大气 CO_2 浓度上升导致的全球气候变暖正在改变或调整全球降水格局，从而产生水分分配和频率异常现象。例如：气候持续变暖将导致中纬度大部分陆地和湿润的热带降水强度增强和频率增加（秦大河和 Thomas Stocker，2014），北半球高纬度地区降水量增加以及极地和高山地区强降水事件更加频繁（苏勃等，2019）。这些降水格局的调整和变化导致的气候异常现象，对全球地表径流、土壤侵蚀以及水土保持产生潜在影响。例如：有研究认为在气候变暖背景下，极端降水事件频率和强度的增加会加剧土壤侵蚀（IPCC，2013，2018；Piao et al.，2019）。土壤侵蚀强度和范围变化也会对土壤碳库和全球碳循环格局产生重要影响，从而驱动气候变化。这种具有“牵一发而动全身”效应的关键地表过程研究也是国际社会关注的重点内容。因此，研究与陆地生态系统碳循环密切相关的地表过程不仅是预测未来大气 CO_2 浓度的重要前提，也是认识和理解地球各圈层间的相互作用等科学问题的基础（宋冰和牛书丽，2016）；尤其是与气候变化紧密关联的关键地表过程以及圈层间物质循环与能量交换成为地表过程研究的重要内容和难点之一（丁永建等，2013）。

截至目前，已通过实地调查与野外监测（Yue et al.，2016；Wang et al.，2020）、模型估算（Azari et al.，2016；董立俊等，2019）以及地质记录（Yu et al.，2017；Liu et al.，2018；Jenny et al.，2019；Wang et al.，2021a；Wang et al.，2022）等途径和方法对气候变化与土壤侵蚀之间的响应关系与反馈机制开展相关研究。本文将从历史时期和未来土壤侵蚀对气候变化的响应、土壤侵蚀对碳循环影响等三个方面综述气候变化与土壤侵蚀相互作用研究进展，并对未来研究方向进行展望，以期为今后相关研究提供一些建议和参考。

1　土壤侵蚀对气候变化的响应

1.1　地质记录

深刻理解和掌握过去变化规律有利于把握和预测未来，地质历史时期气候变化对土壤侵蚀的影响也是人类社会关注的焦点问题。在全球气候侵蚀带中，半湿润气候侵蚀亚带和半干旱气候侵蚀亚带是水力侵蚀最强烈的地区之一（吴发启和朱首军，2016）。黄土高原东西横跨半湿润和半干旱两个气候区，是全球水力侵蚀的重灾区。目前发现最早关于土壤侵蚀对气候变化响应模式的研究文献，也是前人对黄土高原强侵蚀期与气候期的对应关系做出的经验推断，如强侵蚀期发生在

气候暖湿期（刘东生，1985）、气候干湿过渡期（唐克丽等，1991）以及气候干旱期（景可和李凤新，1993）。这些认识和观点需要理想的地质档案记录进行佐证。淤地坝坝库沉积和湖泊沉积物是仅有的两种记录流域土壤侵蚀信息的地质载体，其中淤地坝是黄土高原地区所特有的一种地质记录。中国学者以淤地坝坝库沉积为地质载体，采用 ^{137}Cs 示踪技术在黄土高原开展小流域土壤侵蚀量、沉积速率和泥沙来源等相关研究工作（张信宝等，2007；Long et al.，2008；Zhang et al.，2009a；Wang et al.，2016；Wei et al.，2017；Zhao et al.，2017；王夏青等，2019；Wang et al.，2019；Wang et al.，2021a；Wang et al.，2022）。在这些研究成果中，仅王夏青等（2019）、Wang et al.（2021a）与 Wang et al.（2022）讨论了黄土高原小流域土壤侵蚀对气候变化的响应模式，认为黄土高原小流域土壤侵蚀量与 ENSO 有关：El Niño 次年和 La Niña 年黄土高原小流域侵蚀产沙频率和产沙量均较高，归因于东亚季风增强而带来较多的强降水事件。这为理解黄土高原小流域土壤侵蚀强度变化的气候动力学机制提供了新的线索。但是，淤地坝坝库沉积仅记录洪水沉积而无背景沉积，且集中性强降雨的雨量不能代表年总降雨量，因此需要结合现代器测降水数据进行分析。另外，淤地坝形成或修建时间以及沉积物指标的局限性，也不足以反演流域气候变化历史，尤其是较长时间序列的气候变化。

相较之下，湖泊沉积物作为流域物质的“储存库”，具有连续性好、代用指标丰富、蕴含信息量大、分辨率高等特点，不仅能重建较为理想的气候演变序列，还能详细记录流域土壤侵蚀信息（Arnaud et al.，2016；Yu et al.，2017；Liu et al.，2018；Huang et al.，2021；张欢等，2021）。湖泊沉积物记录着流域气候变化与地表过程，大气降水到达地面后形成的地表径流对流域地表产生侵蚀作用，侵蚀后的陆源碎屑物质被地表径流搬运入湖形成连续沉积（图 1a）。湖泊沉积物的某些代用指标能够指示流域侵蚀状况。例如：磁化率升高指示流域内侵蚀和径流搬运能力增强，间接指示流域降水量增多；磁化率降低指示流域内侵蚀和径流搬运能力减弱，间接指示流域降水量减少（谢海超等，2017；谭金凤等，2018；马学志等，2019；Zhang et al.，2019a；Guo et al.，2022）。湖泊沉积物中 Si 元素来自外源碎屑物质（Cuven et al.，2010；Kylander et al.，2011），高含量反映沉积时地表径流的侵蚀和搬运动力较强（Yu et al.，2017；张欢等，2021）。湖泊沉积物粒度的粗细直接反映沉积时水动力的大小，通常在降水量较多的湿润年份，地表径流侵蚀和搬运能力增强，较多的粗颗粒被搬运入湖，沉积物粒度偏粗；降水量较少的干旱年份，地表径流侵蚀和搬运能力减弱，较多的细颗粒物质入湖沉积，沉积物粒度偏细（Chen et al.，2004）。但不同成因或类型的湖泊沉积物磁化率和粒度指标的环境指示意义也存在差别。例如：昆特依盐湖沉积物低频磁化率记录的是成盐期（曾方明和向树元，2017）；卡拉库里冰川湖磁化率高（低）值指示冰川前进（退缩）（Liu et al.，2014）；更尕海（Qiang et al.，2014）粒度 ＞63 μm 组分指示沙尘暴活动；卡拉库里冰川湖沉积物粒度变粗指示冰川前进，粒度变细指示冰川后退（Liu et al.，2014）。湖泊沉积物指标的环境指示意义往往具有多解性，对湖泊沉积物代用指标的解释不能一概而论，应充分考虑各种影响因素，并结合其他指标进行综合辨识。除上述指标以外，黏土矿物绿泥石和伊利石指示干旱寒冷的气候环境（这些地区通常以物理风化为主），因此在这些地区的湖泊沉积物中，强物理侵蚀也会将绿泥石和伊利石等黏土矿物输入到湖泊中。例如：青藏高原北部黑海湖泊沉积物中的绿泥石和伊利石含量升高指示流域物理侵蚀增强（邸迎伟，2013）。

另一方面，也可根据湖泊沉积速率（图 1b，斜率越大说明沉积速率越快）的快慢来判断流域侵蚀程度的强弱：沉积速率越高指示流域侵蚀作用越强。根据 AMS ^{14}C 年代学计算的湖泊沉积速率变化已成功应用到全新世（11.5 ka BP）土壤侵蚀与气候环境变化的关系研究中（Simonneau et al.，2013；Liu et al.，2018；Jenny et al.，2019；Zhang et al.，2019b；张欢等，2021；Zhang et al，2022）。例如：Jenny et al.（2019）基于全球 632 个湖泊的 ^{14}C 年龄数据，运用广义加性模型来估算全新世以来全球尺度土壤侵蚀与湖泊沉积速率变化，发现湖泊沉积速率在早全新世（12.0—8.0 ka BP）气候增暖背景下处于较低水平，4.0 ka BP 以来呈上升趋势；但在区域尺度上湖泊沉积速率的变化

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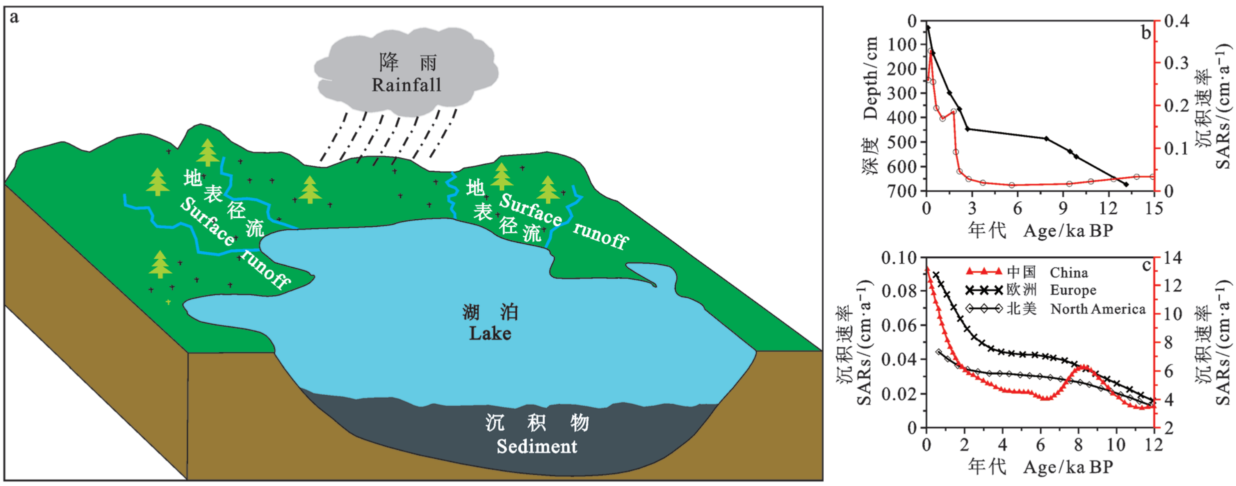
趋势和幅度存在差异，例如中国和欧洲地区的湖泊沉积速率在 4.0 ka BP 以后显著上升，北美地区的湖泊沉积速率则在全新世末期才呈现明显上升趋势，而中国的湖泊沉积速率在早全新世出现一个次级峰值段，明显高于北美和欧洲（图 1c）。需要注意的是，土壤侵蚀和气候变化是地球系统十年至百年尺度上的变化过程（张兰生等，2017），而全新世主要讨论的是百年至千年尺度上的全球变化。这就需要科学合理地选择定年手段，建立高分辨率湖泊沉积年代序列，还需筛选明确指示流域侵蚀强弱变化的湖泊沉积物代用指标，才能重建可靠的土壤侵蚀序列与气候变化历史。



a：湖泊沉积与流域侵蚀过程（根据 Xu et al.（2013）修改）；b：某湖 ^{14}C 年代模型及其沉积速率变化（Jenny et al.（2019））；c：欧洲和北美（Jenny et al.（2019））以及中国（Zhang et al.（2022））湖泊沉积速率变化趋势。

a: the process of lake deposition and watershed erosion (modified after Xu et al. (2013)); b: example for one site of sediment accumulation rate (SARs) derived from ^{14}C-dates (Jenny et al. (2019)); c: the SARs trends during Holocene in Europe and North America (Jenny et al. (2019)) and China (Zhang et al. (2022)).

图 1　流域侵蚀与湖泊沉积记录示意图

Fig. 1　Schematic diagram of watershed erosion and lake sediment records

1.2　未来气候变化情景下的模拟与预测研究

目前多数基于全球气候变暖背景下的降雨量变化趋势仍存在不确定性，原因是降雨量变化趋势不具有全球同步性，而是存在区域性差异。例如：在全球尺度上，过去百年北美和南美东部、亚洲中部和北部降水显著增加，而地中海、非洲南部、亚洲南部部分地区降水有所减少（秦大河等，2007）；在区域尺度上，中国东部季风区出现“南涝北旱”，而西北干旱区降水却呈增加趋势（丁一汇和王会军，2016）。因此未来气候变化背景下，区域降水量变化趋势和幅度的差异与不确定性必然导致土壤侵蚀量和径流量的变化趋势存在一定的不可预见性。

为了解未来气候变化情景下的土壤侵蚀量和径流量变化，研究人员根据管理用户需求先后研发了多种土壤侵蚀模型，如何对这些模型结果进行基准评价并量化模型的不确定性是当前全球变化研究的重点内容之一。80 多年来，随着土壤侵蚀理论的逐渐成熟，通用土壤流失方程（universal soil loss equation，USLE）、水蚀预报模型（water erosion prediction project，WEPP）等几个代表性模型应运而生。全球气候模式（GCM）是目前预测未来气候变化及其影响研究的最可行方法，具体方法和步骤是：先建立多年实测气象数据与大尺度气象因子的统计关系，然后进行数据回算以检验统计关系，再将 GCM 输出的大尺度预测气象数据通过降尺度到研究区域，最后将降尺度数据输入经参数率定后的模型以进行模拟结果输出。国内外学者利用土壤侵蚀模型在全球范围内开展了较多的模拟预测研究，结果显示未来气候变化情景下，土壤侵蚀量和输沙量的变化趋势并不一致。例如：在未来降水增多的情景下，中国（Zhang et al.，2009b；范兰和张光辉，2010；李志等，

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2010；Zhang et al.，2010；董立俊等，2019）、泰国（Plangoen et al.，2013）、印度（Gupta and Kumar，2017）、伊朗北部（Azari et al.，2016）和巴西（Anache et al.，2018）的土壤侵蚀量和输沙量均有所增加，北爱尔兰却在减少（Mullan et al.，2012），而德国 East Saxony 地区先增加后减少（Routschek et al.，2014）；甚至有研究显示：摩洛哥地区（Simonneaux et al.，2015）和埃塞俄比亚（Tsegaye and Bharti，2022）未来降水量减少而产沙量却在增加。上述土壤侵蚀和径流产沙的模拟预测结果之所以存在差异，除了与全球降水变化的不同步性和区域差异性有关之外，还可能主要受以下两个因素影响：一是各土壤侵蚀预测模型都有一定的适用条件和范围。如 USLE 为坡面模型，仅预报坡面细沟和细沟间侵蚀，预测短时间尺度上的土壤流失量误差较大，不能反映土壤流失量的空间差异等，且参数需要根据当地观测结果进行率定。倘若存在对土壤侵蚀量影响更直接的指标，则应建立其与降雨侵蚀力指标 EI_{30} 的转换关系，以实现结果的可比性（谢云和岳天雨，2018）。二是降雨侵蚀力取决于降雨量和降雨强度两个因素，而模型是根据雨量来估算降雨侵蚀力，这可能导致不同气候区的降雨侵蚀力估算结果出现不同程度的误差。例如中国年均降雨量大于 1000 mm 的地区，年均侵蚀力相对误差平均值约 16%；而在年均降雨量小于 500 mm 的地区，年均侵蚀力相对误差平均值高达 42%（章文波和付金生，2003）。因为降水丰沛的南方地区侵蚀力取决于降雨量，而在西北干旱区侵蚀力则取决于降雨强度（陈世发，2016）。因此，通过长期的野外观测、控制实验和试验数据、科学合理选择模型并优化模型参数等以提高模型预测结果的准确性是未来相关研究的主要挑战之一。

2 碳循环对土壤侵蚀的反馈

土壤侵蚀是土壤碳库的重要驱动因素，对土壤碳库的封存和流失有着显著的影响和作用（Yue et al.，2016）。土壤侵蚀主要通过以下两个方面影响碳循环格局：一是影响土壤与大气间的碳通量，二是改变生态系统内部土壤有机碳的分布格局。如图 2 所示：在垂直方向上，土壤侵蚀过程中土壤与大气之间的 CO_2 交换有三个途径和方式：（1）侵蚀土壤中大气 CO_2 替换通量（F3）（图 2a）；（2）埋藏的碳被分解而进入大气的碳源（F4）（图 2b）；（3）运输过程中碳分解产生的大气 CO_2 源（F5）（图 2c）。若 F3−(F4+F5) 为正值，表示土壤侵蚀是碳汇，若为负值则是碳源（*Fv*）（图 2d）。因此，土壤侵蚀表现为碳源或碳汇取决于土壤侵蚀引起的土壤与大气之间的净碳收支，而这部分碳通量取决于土壤侵蚀过程中暴露出的土壤有机碳有多少被矿化成气体。目前，尽管土壤侵蚀引起的土壤有机碳矿化有较多的定量估算值，但由于不同学者的估算缺乏一致性和标准化，以及对关键区域甚至全球尺度上的生物地理学格局及其对有机碳矿化调控机制的理解还不够深入和全面等原因，致使估算结果存在明显差异。例如：Lal（2004）估算在全球尺度上，每年因侵蚀而被矿化成气体进入大气的有机碳高达 0.8—1.2 Gt；Jacinthe and Lal（2001）认为有近 20%—30% 的土壤有机碳在侵蚀过程中被微生物矿化而进入大气；而 Polyakov and Lal（2008）通过模拟实验发现，约有 15% 的有机碳因土壤侵蚀而被矿化进入大气；但也有学者认为土壤侵蚀过程中被矿化释放到大气中的有机碳可以忽略不计（Smith et al.，2001）。

另一方面，在全球碳收支总量平衡的情况下，侵蚀引起的土壤有机碳侧向迁移直接影响土壤有机碳垂向迁移量（土壤与大气之间的碳通量）的准确估算，因此侵蚀作用下土壤有机碳的侧向迁移通量在全球碳收支平衡中也具有重要作用（Van Oost et al.，2007；Van Oost et al.，2012；Hoffmann et al.，2013）。在全球尺度上，Van Oost et al.（2007）指出全球每年约 4.7—6.1 Gt 的土壤有机碳因侵蚀而发生侧向迁移，这与 Lal（2004）估算的 0.4—0.6 Gt 土壤有机碳侧向迁移通量存在明显差别。土壤有机碳侧向迁移通量难以精准估算，主要是由于小流域尺度上土壤侵蚀流失的碳通量难以直接监测和测算（Boyer et al.，2006），因为流域水体通过光合作用和呼吸作用等生物地球化学过程所释放的 CO_2 难以准确测定（Marx et al.，2017）。通常认为，土壤侵蚀引起的土壤有机碳的侧向迁移对陆地碳源汇的贡献大小取决于土壤有机碳的迁移路径和最后沉积地点（Yue et al.，2016）。如果被侵蚀搬运至沉积区的土壤碳的周转周期小于原生态系统土壤碳的周转周期，则加剧土壤有机碳的矿化和释放，反之则有利于土壤有机碳的封存和积累（Van Oost et al.，2007；Yue et al.，2016）。

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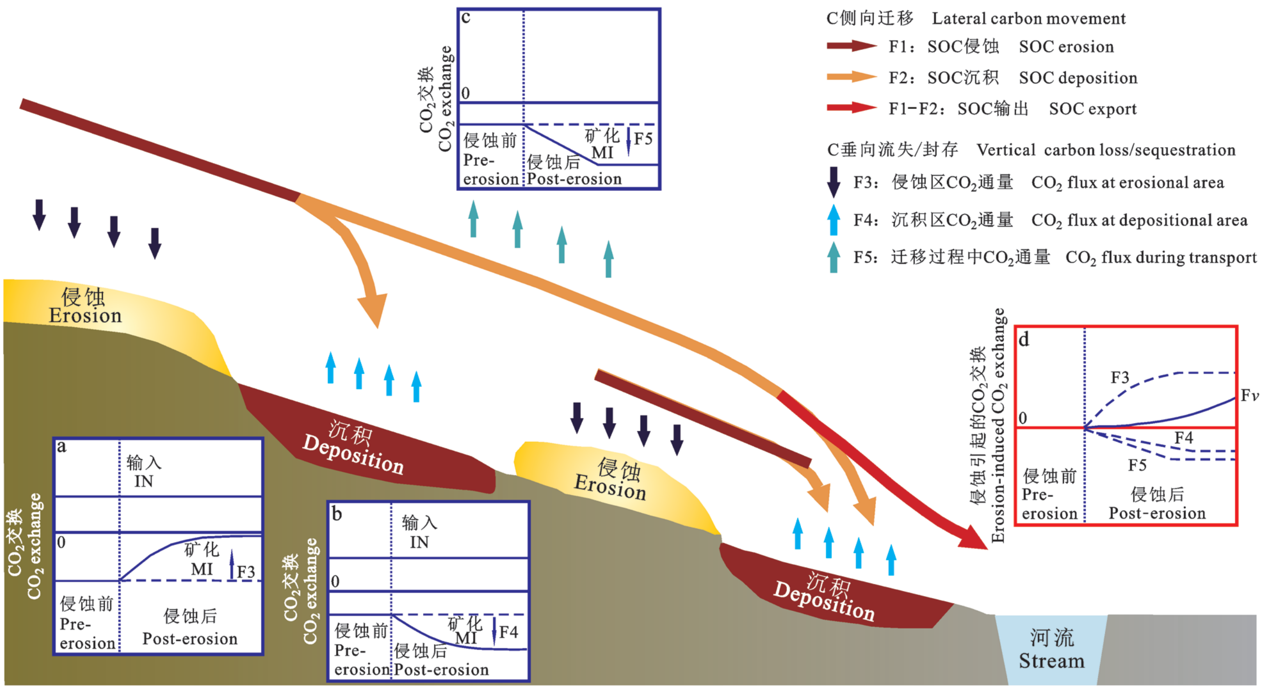

a、b 和 c 分别表示碳输入、侵蚀前和侵蚀后有机碳矿化，正值代表碳汇；d 表示侵蚀前后有机碳输入－矿化差值引起的 CO_2 额外通量；F1 表示侵蚀土壤中流失的有机碳，F2 表示侵蚀土壤碳沉积，F3 表示侵蚀土壤中大气 CO_2 替换通量，F4 表示因埋藏碳分解而进入大气的碳源，F5 表示在运输过程中碳分解产生的大气 CO_2 源，*Fv* 是 F3、F4 和 F5 的综合结果。

a, b, and c demonstrate carbon input (IN) and carbon mineralization (MI) pre-erosion and post-erosion, positive value represents carbon sink; d shows the extra CO_2 flux induced by erosion in terms of the difference of (IN−MI) pre- and post-erosion; F1 is the removal of carbon from eroded soils; F2 is the deposition of eroded soil carbon; F3 is the dynamic replacement of atmospheric CO_2 in eroded soils; F4 is the carbon source to the atmosphere due to the decomposition of buried carbon; F5 is the CO_2 source to the atmosphere from the decomposition of carbon during transport; *Fv* is the integrated results of F3, F4, and F5.

图 2　土壤侵蚀过程中碳素侧向和垂向碳通量分量的示意图（根据 Yue et al.（2016）重绘）

Fig. 2　Schematic of lateral and vertical carbon flux components due to soil erosion (redrawn according to Yue et al. (2016))

土壤碳库储量以及稳定性与土壤微生物活性紧密相关（Lehmann and Kleber，2015；Ma et al.，2018；Ma et al.，2020；Ni et al.，2020；Wang et al.，2021b），土壤微生物常被喻为有机质中碳与养分元素循环的“转化器”，是控制有机碳周转的重要因子（Schmidt et al.，2011；Li et al.，2018；Li et al.，2019）。不同来源有机碳的矿化速率受土壤微生物量、胞外酶活性等因素影响（Jian et al.，2016；Pold et al.，2017），且深层土壤中含有较多难降解的惰性土壤有机碳，导致矿化速率降低（Jiang et al.，2017）。与此同时，土壤有机质的类型、土壤环境条件（如通气状况、水热状况）等均对土壤微生物活动产生影响，导致土壤有机质矿化速率和产物也存在差异（李天杰等，2004）。迄今为止，土壤侵蚀对大气 CO_2 而言究竟表现为碳源还是碳汇仍存在争议。土壤学家认为土壤侵蚀作为碳源（Lal，2004，2005；Lal and Pimentel，2008；Doetterl et al.，2016），而沉积学家认为土壤侵蚀作为碳汇对有机碳的存储有重要贡献（Renwick et al.，2004；Van Oost et al.，2007；Van Oost et al.，2012；Kirkels et al.，2014）。争议的关键在于侵蚀作用下土壤有机碳在运输或迁移过程中土壤微生物对土壤有机碳的分解和矿化作用是否被高度重视或充分考虑。研究表明，土壤微生物量的大小影响土壤有机碳矿化激发效应的强弱（Li et al.，2018）。因此，全面深入理解侵蚀作用下土壤有机碳矿化的生物学过程与机制、如何精准估算土壤有机碳的矿化速率以及侧向迁移通量是科学评估土壤侵蚀是碳源或碳汇的核心与关键。

3　结论与展望

3.1　十至百年尺度上高分辨率湖泊沉积与流域侵蚀研究

以湖泊沉积物为地质载体开展土壤侵蚀研究有着巨大发展和应用潜力，利用湖泊沉积物进行

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土壤侵蚀研究也是一个新的研究领域。例如：Yu et al.（2017）利用湖泊沉积物粒度和元素等多指标研究黄土高原高山小流域土壤侵蚀对气候变化的响应程度，结果表明干旱气候环境下植被覆盖度较低，集中性强降水过程对流域土壤侵蚀程度较强，且十年/数十年尺度干旱时段内的洪水事件对流域土壤侵蚀尤为强烈。但需注意的是，湖泊沉积物指标的环境指示意义往往具有多解性，在不同的湖泊研究中应充分考虑各种影响因素，并结合其他指标进行综合辨识。过去千年是衔接地质记录与仪器观测资料的重要时段，过去千年气候更是当代与未来气候变化的背景，对理解气候系统在十年至百年尺度上的变化机理、预估增暖情景下的降水异常格局等有独特价值（PAGES，2014）。^{137}Cs（半衰期 30.17 a）和 ^{210}Pb（半衰期 22.23 a）放射性同位素可以建立过去几十年至两百年时间长度的高分辨率湖泊沉积序列。因此，建议在不同气候区以湖泊沉积物为研究对象，采用 AMS ^{14}C、^{137}Cs 和 ^{210}Pb 等多种定年手段，并筛选和澄清代用指标的环境指示意义，建立近千年高分辨率湖泊沉积与流域侵蚀序列，研究十年至百年尺度气候变化与土壤侵蚀之间的关系。

3.2 基于长期野外观测试验的土壤侵蚀模型应用选择与参数优化

USLE 和 WEPP 是在长期观测和试验数据的基础上建立的土壤侵蚀模型。小流域是土壤侵蚀的基本空间单元，WEPP 模型不仅能够克服 USLE 模型的缺陷，而且已具有坡面版、流域版和网格版三个版本，因此选择流域版 WEPP 模型更具科学性。在参数选择和计算时，一是应以标准小区规定的坡度（9%）和坡长（22.13 m）标准来建立坡度和坡长因子公式，应用时需要注意标准小区是计算标准而非建设标准；二是虽然侵蚀性降雨标准有 12 mm（谢云等，2000；张鹏等，2014）和 9.7 mm（Xie et al.，2016），但是 12 mm 的标准可能仅适用于黄土高原地区。因此在计算具体降雨侵蚀力时，建议在考虑不同气候区降雨侵蚀力决定因素（降雨量或降雨强度）的基础上，通过长期野外观测和试验确定侵蚀性降雨标准，由此计算的降雨侵蚀力和土壤侵蚀量则更加准确。

3.3 侵蚀后土壤碳素矿化的微生物学过程机制与定量化研究

土壤有机碳库变化是导致陆地生态系统碳循环估算存在不确定性的重要原因。土壤中的微生物量与土壤有机碳库库容大小密切相关，微生物残体也是土壤有机碳的主要来源（Karhu et al.，2014；Paul，2016；Kögel-Knabnerjk，2017；Liang et al.，2017；Liang et al.，2019；Ma et al.，2018；Ma et al.，2020；Ni et al.，2020；Gao et al.，2021；Yang et al.，2022），对稳定土壤碳库有着重要贡献。土壤微生物及胞外酶在土壤有机碳库周转与矿化过程中起着主导和协调作用，是土壤碳生物地球化学循环的周转环节，决定着土壤有机碳库的分解与蓄积（温学发等，2019；Yang et al.，2021）。一方面，土壤侵蚀通过改变土壤微生物群落结构与分布格局来影响土壤有机碳的矿化过程，最终影响土壤向大气释放的 CO_2 通量；另一方面，土壤侵蚀通过改变土壤团聚体中微生物活动来影响土壤有机碳的周转与封存。因此，深刻理解和认识土壤有机碳矿化的微生物过程和机制，以及测定与其紧密关联的土壤有机碳矿化速率对准确判断土壤侵蚀过程是大气的碳源或碳汇至关重要。

稳定同位素探针技术（stable isotope probing，SIP）虽然能够在复杂的环境中分析微米尺度下微生物的生理特性，并以此获取参与土壤物质转化的功能微生物信息，但只能定性指示哪些微生物参与某个特定的物质循环过程，不能量化这些微生物对物质循环的贡献。定量稳定同位素探针技术（quantitative stable isotope probing，qSIP）是在传统 SIP 的基础上，结合实时定量聚合酶链反应（polymerase chain reaction，PCR）和高通量测序技术，利用模型计算每个微生物同化同位素的量，进而量化微生物参与的特定生态学过程（Hungate et al.，2015；Koch et al.，2018）。例如 Wang et al.（2021b）利用 qSIP 技术不仅量化了土壤微生物的生长速率，而且同步测量了土壤有机碳的矿化速率。因此，可以小流域为研究基本单位采集土壤，利用 qSIP 技术系统测量土壤有机碳的矿化速率，建立区域甚至全球数据库对土壤侵蚀的碳源或碳汇作用进行精准评估。

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