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Comprehensive Earth Critical Zone Observation and Terrestrial Surface Flux Monitoring Provide Strong Scientific Support for Ecological Protection and Regional Sustainable Development on the Loess Plateau of China

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Comprehensive Earth Critical Zone Observation and Terrestrial Surface Flux Monitoring Provide Strong Scientific Support for Ecological Protection and Regional Sustainable Development on the Loess Plateau of China

Abstract

Since the foundation of Chinese Loess Plateau Research and Observation Station for Earth Critical Zone and Terrestrial Surface Flux (CLP-CZO), CLP-CZO has been committing itself to serving the frontier critical zone science and regional or national policy needs. During the past decades, the research station has made several important advancements, including loess stratigraphy, paleo-environment evolution, ecosystem processes and services, soil and water conservation and policy advices for the Chinese Loess Plateau and the Yellow River. For its excellent research and policy services, the research station has been awarded two times of China National Natural Science Award and one time of Outstanding Scientific and Technological Achievement Award of the Chinese Academy of Sciences. Up to now, the research station has published more than 300 peer-reviewed high quality papers. The significant science and policy advisory achievements include: (1) high quality and comprehensive loess and paleo-monsoon research, which has uncovered the internal relationships between loess-paleosol stratigraphy and paleo-climate and paleo-environment evolution and built the original theory of Paleo-monsoon Controlled Environment Evolution, and which has made the Chinese Quaternary paleo-climate research leading the world; (2) systematic research of land use patterns, ecosystem processes and services of the Chinese Loess Plateau, which has uncovered the interactive mechanisms of land use patterns and ecosystem processes and services in the area and put forward the parameter system and framework of the critical zone classification of the Chinese Loess Plateau for sustainable development; (3) systematic research of multiscale soil and water processes and conservation and its responses to large vegetation and engineering rehabilitation measures on the Chinese Loess Plateau, which has uncovered the complex relationships between soil moisture and regional climate, soil and vegetation and quantitatively evaluated the environment benefits and tradeoffs of large vegetation and engineering rehabilitation measures; (4) continuously providing advisory reports to the central government, the state council, state leaders and local government departments, which has provided strong science support for the decision-makers for the ecological rehabilitation and sustainable economic and social development of the Chinese loess Plateau and the Yellow River.

Keywords

loess deposits; climate and environment evolution; ecological processes; soil and water conservation; human-land relationships; ecosystem service; policy advice; comprehensive observation and research

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rehabilitation and civil engineering measures for soil and water conservation and its eco-environmental effects on the Chinese Loess Plateau. He has made innovative research in the paired watersheds observation of afforestation vs natural regrowth of grasses, valley reshaping and damming vs natural landforms. He published more than 40 papers in peer-reviewed journals and received many funding from National Natural Science Foundation of China, Ministry of Science and Technology of China, and CAS.E-mail:jinzhao@ieecas.cn

地球关键带与地表通量综合观测研究为黄土高原生态保护和可持续发展提供有力的科技支撑

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摘要 中国科学院黄土高原地球关键带与地表通量野外观测研究站（以下简称“黄土高原关键带站”）立足黄土高原，面向黄河中游，开展季风区地球关键带和地表通量的长期定位观测和数据积累，在科学上为世界地球关键带科学作出突出贡献，在服务国家需求上为黄河流域生态保护和高质量发展等国家战略提供有力的科技支撑。黄土高原关键带站提出了黄土关键带形成演化的“季风控制论”，重建了地质历史时期黄土高原植被、温度和降水的变化，查明了黄土关键带形成演化的气候背景；重建了过去500年温度、降水等气候要素序列，揭示了黄土高原干旱、高温等极端气候事件发生的诱因及特点；系统开展了黄土高原生态系统过程与服务研究，揭示了黄土高原关键带土地利用格局与生态过程的作用机理，阐明了不同生态系统服务的形成与相互作用机制，提出了面向可持续发展的黄土高原关键带类型划分的指标体系和方法框架；深入开展了黄土高原多尺度水土过程及其对重大生态工程的响应研究，阐明了黄土高原和黄河流域过去60年径流输沙和水沙关系的时空尺度特征与驱动机制，揭示了土壤水分与区域气候、土壤和植被的相互关系，定量评估了黄土高原生物和工程治理措施的环境效应；为黄土高原综合治理、生态保护和经济社会可持续发展提供决策咨询。

关键词 黄土沉积，气候环境演变，生态过程，水土过程，人地关系，生态系统服务，咨询建议，综合观测研究

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黄土高原西起日月山，东至太行山，南靠秦岭，北抵阴山，是黄河泥沙的主要来源地，也是我国重要的能源重化工基地和北方地区的生态屏障。作为世界上最具特色的地貌单元之一，黄土高原具有独特的地

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质背景、深厚的黄土沉积、多样的地貌景观和悠久的文化历史，是中华文明的重要发祥地。长期以来，黄土高原特殊的地理区位和资源禀赋在中国经济社会版图中占有不可替代的地位。黄土高原深受东亚季风影响，降雨变率大，且以暴雨形式为主，加之长期不合理的人为扰动和易于侵蚀的黄土土质，使得黄土高原生态环境异常脆弱、自然灾害频发，是对气候变化和人类活动极为敏感的地区。

新中国成立以来，党和政府高度重视黄土高原的生态治理工作，取得了举世瞩目的成就。尤其是退耕还林（草）工程实施20年来，黄土高原生态条件得到明显提升：植被覆盖度显著增加，实现了由黄到绿的转变；水土流失得到有效控制，入黄泥沙显著减少；乡村增收渠道有所拓展，“三生”（生产、生活、生态）空间趋于优化。然而，黄土高原脆弱的生态环境仍未根本改变，水资源短缺、人地关系协调困难、民生保障十分薄弱、绿色发展面临巨大挑战等新问题又接踵而来，从而导致新、老问题交织、叠加发生。

当前，黄土高原传统的水文-生态-人地过程正在发生深刻变化，传统的研究方法已不足以解答新时代黄土高原面临的系列新现象和新问题。地球关键带与地表通量是21世纪地球科学的前沿领域，强调多学科交叉、多尺度耦合和整体性研究，可为新时代黄土高原可持续发展提供理论支撑和技术保障。

黄土高原关键带站以黄土高原为整体，以地球关键带和地表通量观测为核心，进行长期的数据观测和积累，形成系统性和整体性的观测、研究、示范和服务平台，在科学上为世界地球关键带科学作出突出贡献，在服务国家需求上为黄河流域生态保护和高质量发展、乡村振兴、“美丽中国”建设等提供有力的科技支撑。

1 黄土关键带的结构与形成演化

（1）系统开展黄土高原风尘序列研究，提出黄土关键带形成演化的“季风控制论”。近几十年以来，基于黄土高原典型的黄土-古土壤序列（即核心组成部分，图1），持续开展了黄土关键带的结构特征和形成演化研究，揭示出独一无二的黄土关键带地形与东亚古季风变迁关系密切[1-3]，并且受到南、北半球冰量变化和高、低纬度气候快速变化的影响[4-7]。通过对风成黄土-红黏土记录的深入研究，提出晚新生代以来不同时间尺度亚洲季风-干旱环境变迁与青藏高原生长和全球环境变化联系的动力学模型[8-10]，指出黄土关键带的形成是亚洲季风-干旱环境系统长期演变的结果，是全球典型的季风区地球关键带，这对地球系统科学发展有重要意义。相关研究在*Science*、*Nature*及其子刊等重要杂志发表SCI论文200余篇，被SCI引用过万次，出版编辑专著1部，获国家自然科学奖二等奖2项，省部级一等奖4项，获何梁何利基金、陈嘉庚地球科学奖各1项，以及国际奖2项，团队部分成员获美国科学院院士和美国地球物理协会Fellow称号等荣誉。

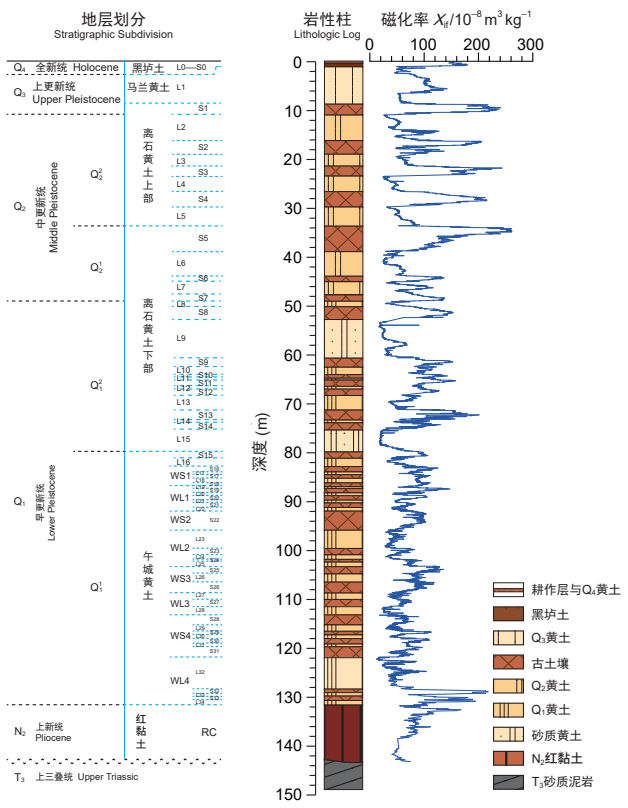

图1 洛川黄土-古土壤沉积地层特征及磁化率曲线[1,2]

（2）重建黄土高原植被、温度和降水变化，查明了黄土关键带形成演化的气候背景。重建黄土-红黏土序列中C4植被多次扩张历史，提出了东亚C4植被扩张的季风控制新假说[11]；证实黄土高原C4/C3生态变化响应季风降水，明确了黄土-古土壤的有机碳同位素可以指示黄土高原过去生态系统演化[12]；提出C4植被可作为非森林生境的一个判断标准，为恢复黄土高原塬面生态变化历史提供了新的思路[13]。利用黄土-古土壤序列中碳酸盐碳同位素变化，探讨了降水-植被耦合关系对轨道参数、极地冰盖和/或二氧化碳胁迫的不同响应[14]。定量重建了黄土高原古降水和古温度变化（图2），指出南、北半球低纬夏季太阳辐射梯度驱动亚洲季风的新机制[15]，揭示了陆地植被对古温度变化的重要调控作用[16]，相关成果发表在*Science*和*Nature Communications*。

2 黄土高原生态系统过程与服务

（1）揭示了黄土高原关键带土地利用格局与生态过程的作用机理。将尺度-格局-过程相结合，综合分析了土地利用格局与生态过程的多尺度作用机理。在坡面尺度，系统研究了土地利用格局对土壤水分、养分和侵蚀，植被水分利用，水文-生物化学过程，以及土壤微生物和土壤动物等生态过程的作用机理；建立了坡面生态水文过程模型；提出了坡面合理的土地利用结构。在小流域尺度，分析了植被恢复格局和景观变化对水土生态过程空间异质性的影响。将坡面和小流域尺度植被恢复对水文过程影响的工作扩展到流域尺度，揭示了黄土高原生态恢复的流域水沙效应，阐明了过去60年黄河径流输沙和水沙关系的时空尺度特征与驱动机制（图3）[17]。部分研究成果获2005年度国家自然科学奖二等奖。

（2）揭示了黄土高原关键带不同生态系统服务形成与相互作用机理。生态系统过程与服务的关系是生态系统服务评估的科学基础，关系认识不清会影响评

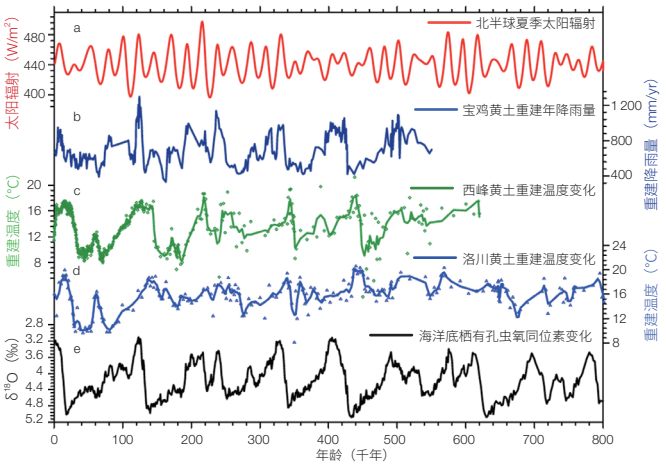

图2 黄土高原古温度、古降水变化及其与太阳辐射和冰量变化对比

（a）北半球夏季太阳辐射；（b）^{10}Be重建的降水变化[15]；（c）西峰黄土重建温度变化[16]；（d）洛川黄土重建的温度变化[16]；（e）深海氧同位素反映的全球冰量变化（LR04曲线）

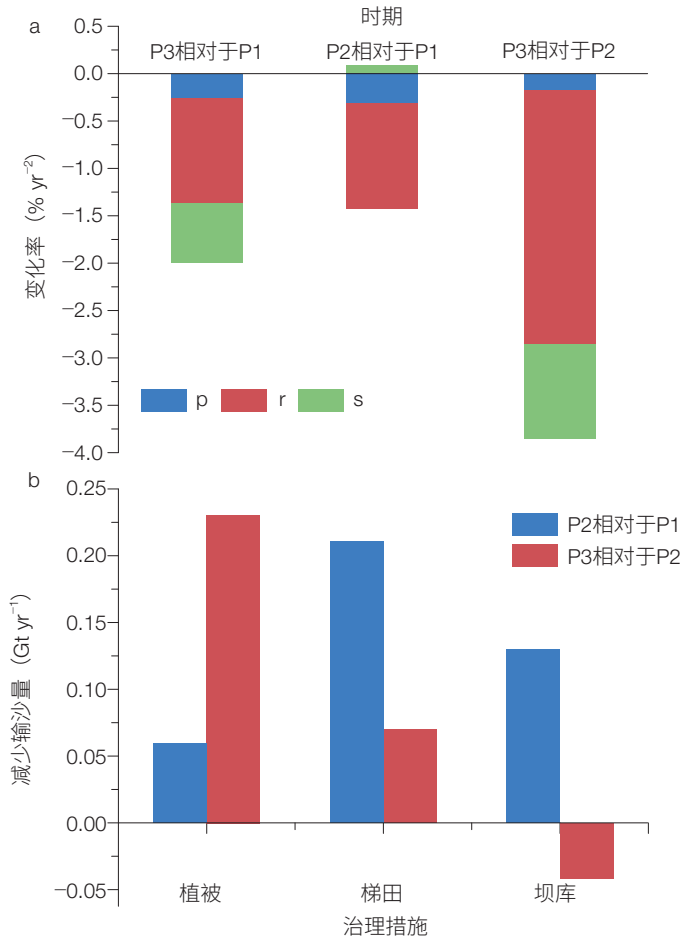

图3 近60年黄河泥沙减少归因分析[17]

（a）不同时间段降雨（p）、产水量（r）和泥沙含量（s）对黄河泥沙量减少的贡献率；（b）植被、梯田和坝库在不同时间段减少的泥沙量；P1，1951—1979年；P2，1980—1999年；P3，2000—2010年

估的科学性和可靠性。针对该问题，提出了关联生态系统过程与服务的模型框架，建立了黄土高原不同尺度生态系统结构-过程-服务同步观测体系。从样地、小流域不同尺度揭示了水源涵养、土壤保持、固碳功能的形成机理。建立了不同尺度生态系统服务权衡分析方法，阐明了不同生态系统服务相互作用机制，明确了不同生态系统服务恢复过程及其权衡关系特征。构建了黄土高原自然-社会经济复合系统水资源可持续利用定量耦合分析框架，综合考虑植被生长耗水和社会经济用水，基于碳水权衡关系计算了不同情景下的黄土高原植被恢复的水资源区域承载力（图 4）[18]。研发了具有生态系统服务定量识别、物质量与价值量评估、土地利用/覆被和管理情景模拟、优化决策等功能的区域生态系统服务综合评估与优化模型系统（SAORES）。该成果有效连接生态系统过程与服务，深化了生态系统服务机理认识，建立了生态系统服务综合评估系统。研究成果获 2016 年度中国科学院杰出科技成就奖、何梁何利“科学与技术进步奖-地球科学奖”、中华环境优秀奖和欧洲地球科学联合会洪堡奖章等荣誉。

（3）提出了面向可持续发展的黄土高原关键带类型划分指标体系和方法框架。面向关键带可持续性的科技需求，将生态系统服务科学与地球关键带科学需求相整合，提出：① 关键带的生态系统服务应该作为核心科学议题纳入研究体系；② 加强与管理决策相关的时间尺度下的深度耦合研究，包括结构-过程-功能-服务的耦合及多学科的交叉与集成；③ 将景观多功能性的研究和关键带研究相结合，区域关键带空间异质性和类型学的研究可以作为推进上述研究的重要途径。基于生态系统服务，提出了面向可持续发展的关键带类型划分的指标体系和方法框架，将黄土高原地区划分为 8 类关键带系统（图 5）[19]，对于关键带空间格局的认识、不同关键带之间相互作用及优化关键带观测网络布局具有重要意义[19]。

3 黄土高原多尺度水土过程及生物和工程治理措施的环境效应

（1）重建黄土高原过去 500 年温度、降水等气候要素序列，分析了气候变化的时空特征、规律及可能驱动机制。基于广泛分布于黄土高原及周边地区

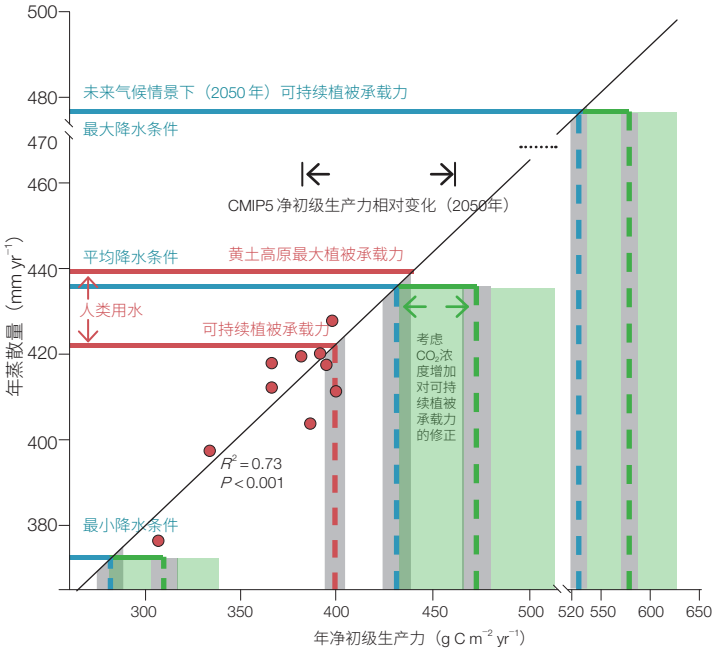

图 4　基于固碳产水权衡关系的黄土高原植被承载力阈值[18]

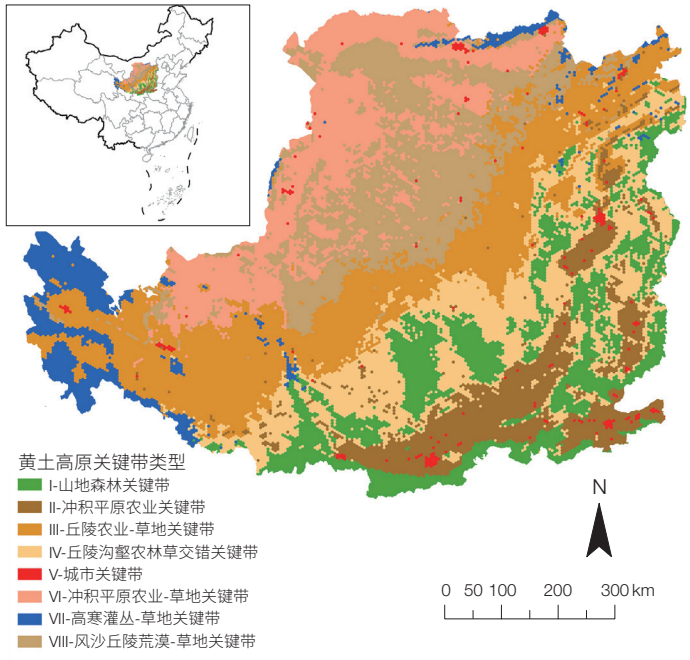

图 5　基于生态系统 - 过程 - 服务作用机理的黄土高原关键带分类[19]

的树木年轮资料，通过树轮宽度、密度和稳定同位素等多种指标的提取，精确建立年表，重建了黄土高原过去 500 年来不同时空尺度的温度、降水、干旱指数（PDSI）等气候要素序列，弥补了器测记录过短和高分辨率气候代用序列缺乏的不足，为研究东亚季风区气候环境演化、气候模拟和预测提供了大量高分辨率基础科学数据，成果获 2011 年陕西省科学技术奖二等奖。研究发现：① 近 400 年黄土高原北部及我国北方环境敏感带降水年际不相关，但在年代际尺度上变化基本同步。黄土高原的这种干湿变化受亚洲夏季风强度变化、亚印太交汇区海温变化和太阳活动等因素共同影响。② 黄土高原及周边地区的树木年轮均记录了 20 世纪 20 年代后期发生在中国北方大部分地区的严重干旱事件。干旱事件的发生不仅与季风降水减少有关，还受同期高温气候影响，近几十年黄土高原各地均表现出不同程度干旱化趋势。③ 基于黄土高原北部贺兰山和内蒙古白音敖包树轮降水重建结果，对两地未来 20 年降水进行了预测[20]；截至 2019 年，预测结果已较好得到现代观测记录的验证。④ 综合黄土高原西部 10 个地点树轮资料，重建了一条反映过去 448 年亚洲夏季风强度变化的降水序列。重建序列再现了许多由弱/强亚洲夏季风引发的已知历史极端气候事件。历史上严重旱灾和蝗灾均与弱季风时期相关联，特别发现在过去 448 年中前所未有的、最为强烈和显著的持续 80 多年的亚洲夏季风降水下降趋势。模拟结果揭示人类活动排放的硫酸盐气溶胶增加是导致这一降水下降趋势的主要原因（图 6）[21]。

（2）研究了季风区黄土关键带多尺度土壤水文过程的时空分异规律，分析其对重大生态工程的响应过程和机制。研究了季风区黄土关键带多尺度土壤水文过程的时空变化规律及其与气候、植被、土壤、地形、重大生态工程等的相互关系。研究发现：① 在坡面尺度，微地形、坡长和次降雨对坡面 0—40 cm 深度的土壤水分状况具有显著影响，对 40—500 cm 深度的

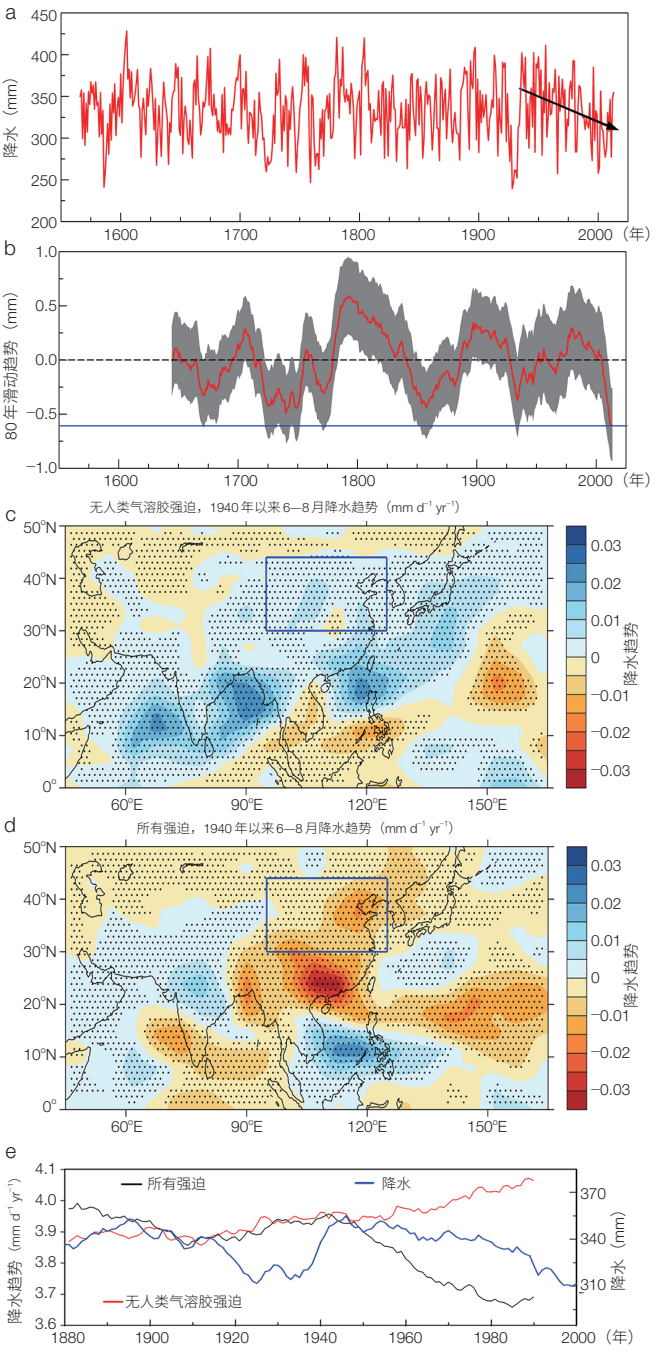

图 6　利用树轮重建的黄土高原西部过去 448 年降水变化历史，发现近 80 年来季风降水的减少主要归因于人类活动排放的硫酸盐气溶胶的增加[21]。

（a）黄土高原西部上年 7 月到当年 6 月降水量（P_{JJ}）重建的过去 4 个世纪降雨量变化（红色曲线），斜黑线表示 1934—2013 年 80 年间降雨量下降趋势；（b）黄土高原西部上年 7 月到当年 6 月降水量（P_{JJ}）重建降水量的 80 年滑动趋势（红线），灰色区域表示 95% 的置信区间，蓝色水平线表示 80 年降水量的最大降幅约为 0.62 mm/ 年；（c）和（d）耦合气候模式模拟的 1940 年以来北方夏季降水趋势；（e）中国北方地区降雨量与降水趋势模拟的比较，黑、红线分别表示气候模式模拟的中国北方地区降变化 21 年滑动平均值，蓝线表示重建降雨量的 21 年滑动平均值

土壤水分影响不明显；② *在流域尺度*，年平均土壤储水量变化在0—1.5 m深度与降雨强高度相关，流域内超过90%的采样点均形成了土壤干层，气象、地形和土地利用对土壤干层的形成、时空分布格局具有至关重要的控制作用；③ *在500 km样带尺度*，0—5 m土壤储水量从东南向西北逐渐递减，半干旱区比半湿润区低320 mm，半干旱区土壤储水量和有效储水量主要受土壤性质的影响，而半湿润区则受土壤、海拔和纬度的综合制约；④ *在区域尺度*，针对黄土高原人工植被建设和气候变化导致的土壤干层问题，提出了量化土壤干层的新指标（QI），有效避免了传统指标单位的不一致性问题，并揭示了整个黄土高原QI的空间分异特征及影响因素；⑤ *其他量化指标*，量化了退耕还林（草）和治沟造地工程对小流域土壤水资源储量、通量的影响，明确了重大生态工程对小流域水资源的影响幅度及环境效应；通过时间稳定性和突变点诊断分析，证实了根系吸水是深层土壤水分减小的根本原因，退耕还林（草）工程对坡面土壤水分格局具有显著影响[22, 23]（图7）。

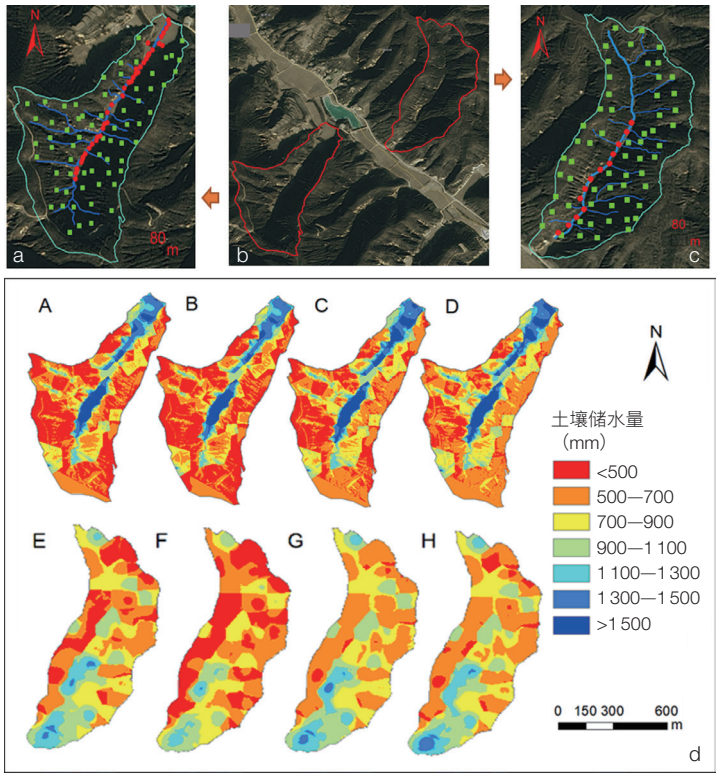

图7 黄土关键带对比流域土壤水分观测的样点分布及土壤储水量季节动态分布[22]

（a）—（c）土壤水分观测的样点分布，其中治理（a）和未治理流域（b）的样点数分别为89和72，监测深度为5 m；（d）土壤储水量的季节动态分布图；A，春季治理流域；B，夏季治理流域；C，秋季治理流域；D，冬季治理流域；E，春季未治理流域；F，夏季未治理流域；G，秋季未治理流域；H，冬季未治理流域

*（3）研究了黄土高原生物和工程治理的环境效应，阐明了小流域水土过程的响应规律和机制。*① *在固沟保塬方面*，定量研究了董志塬过去50年土地利用变化规律及典型沟道侵蚀演变特征，指出了黄土垂直节理是黄土塬区溯源侵蚀和侵蚀灾变的物质结构基础，总结了黄土垂直节理的形成机制、影响因素、分布规律和形态特征，提出了垂直节理发育、扩张和退化的水力耦合数学模型；② *在退耕还林（草）方面*，以退耕还林和还草对比小流域为研究对象，揭示了其水文生态效应的差异，阐明了退耕还林和还草小流域碳氮循环、能量平衡、水分补给和降雨-产流的内在机制，明确了黄土高原长时间的退耕还林，将可能彻底抑制地表径流的产生[24]；③ *在沟道治理工程方面*，指出了黄土高原由于长期的植被恢复，淤地坝建设面临无沙可淤和空坝的问题，定量评估了治沟造地对流域地形地貌、关键带过程和地表通量的影响，揭示了治沟造地流域地下水抬升的规律和盐碱化发生的机制（图8），发现盐碱化主要发生在流域上游而不是下游，主要由上游狭窄的沟道特征、较高的原始地形、高的地下水位和黄土的碱性性质共同导致[25]。

4 黄土高原综合治理与高质量发展对策

黄土高原关键带站持续为黄土高原综合治理、生态保护和经济社会可持续发展提供决策咨询。在国家西部大开发战略刚启动时，黄土高原关键带站学术带头人安芷生院士对后期国家西部大开发战略的实施和黄土高原的生态治理起到了重要作用；2002年，提出

黄土高原的植被重建必须遵循植被的地带性规律和非地带性特征，其中“遵循自然规律，因地制宜，宜林则林，宜草则草”被国务院《退耕还林条例》采纳；2018 年，提出了新时代黄土高原生态环境综合治理“26 字”方略，即“塬区固沟保塬，坡面退耕还林草，沟道拦蓄整地，沙区固沙还灌草”。

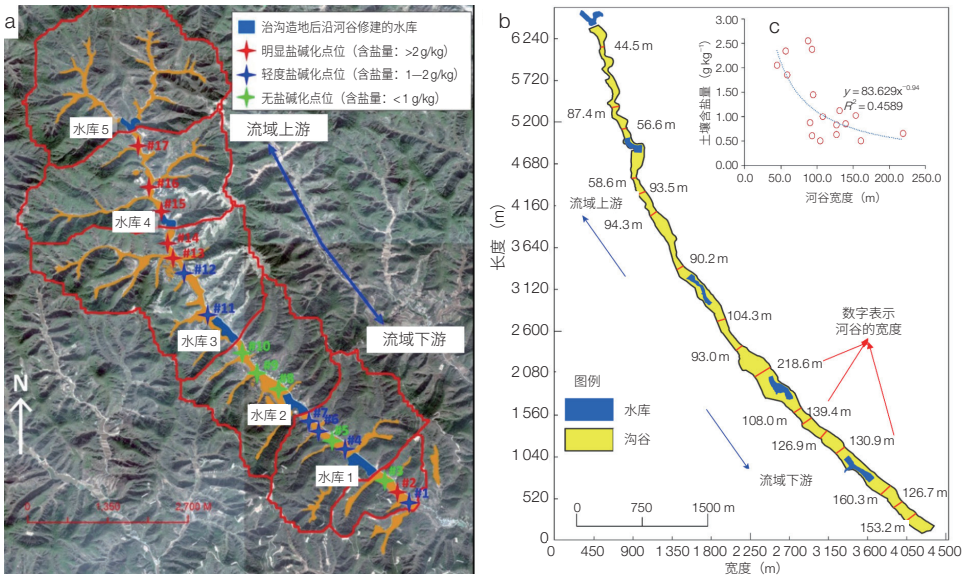

图 8　治沟造地流域盐碱化空间分布与流域地形的关系 [25]

（a）治沟造地流域盐碱化的空间分布特征，上游出现了明显的盐碱化；（b）治沟造地流域沟道宽度的空间分布特征，上游沟道变得越来越狭窄；（c）沟道宽度与土壤含盐量的相关关系，沟道越窄，盐碱化越严重

黄土高原关键带站学术带头人傅伯杰院士于 2018 年和 2019 年就黄土高原淤地坝以及退耕还林（草）提出相关建议，指出应跟随国家政策，加强生态补偿，充分发挥农民积极性和国家及地方政府整体引导效应，关注退耕还林（草）工程的综合效应，建立退耕还林（草）工程长效机制。

图 9　新时代黄土高原生态环境综合治理“26 字”方略

5 结语

近 10 年来，黄土高原关键带站围绕地球关键带与地表通量研究的学科前沿，以黄土高原和黄河流域国家重大需求为导向，在黄土关键带的结构与形成演化、生态系统过程与服务、重大生态工程的水土环境效应和黄土高原综合治理与高质量发展对策方面取得了一系列公益性、原创性成果，解决了国家在黄土高原生态保护和人地关系协调发展中急需解决的部分重大科技问题，为区域经济与社会可持续发展提供了重要的科技支撑，在国内外产生了重要影响。黄土高原关键带站的长期定位观测和数据积累，能够为世界地球关键带科学作出重要贡献，为黄河流域生态保护和高质量发展等提供持续和有力的科技支撑。

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Comprehensive Earth Critical Zone Observation and Terrestrial Surface Flux Monitoring Provide Strong Scientific Support for Ecological Protection and Regional Sustainable Development on the Loess Plateau of China

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Abstract Since the foundation of Chinese Loess Plateau Research and Observation Station for Earth Critical Zone and Terrestrial Surface Flux (CLP-CZO), CLP-CZO has been committing itself to serving the frontier critical zone science and regional or national policy needs. During the past decades, the research station has made several important advancements, including loess stratigraphy, paleo-environment evolution, ecosystem processes and services, soil and water conservation and policy advices for the Chinese Loess Plateau and the Yellow River. For its excellent research and policy services, the research station has been awarded two times of China National Natural Science Award and one time of Outstanding Scientific and Technological Achievement Award of the Chinese Academy of Sciences. Up to now, the research station has published more than 300 peer-reviewed high quality papers. The significant science and policy advisory achievements include: (1) high quality and comprehensive loess and paleo-monsoon research, which has uncovered the internal relationships between loess-paleosol stratigraphy and paleo-climate and paleo-environment evolution and built the original theory of Paleo-monsoon Controlled Environment Evolution, and which has made the Chinese Quaternary paleo-climate research leading the world; (2) systematic research of land use patterns, ecosystem processes and services of the Chinese Loess Plateau, which has uncovered the interactive mechanisms of land use patterns and ecosystem processes and services in the area and put forward the parameter system and framework of the critical zone classification of the Chinese Loess Plateau for sustainable development; (3) systematic research of multiscale soil and water processes and conservation and its responses to large vegetation and engineering rehabilitation measures on the Chinese Loess Plateau, which has uncovered the complex relationships between soil moisture and regional climate, soil and vegetation and quantitatively evaluated the environment benefits and tradeoffs of large vegetation and engineering rehabilitation measures; (4) continuously providing advisory reports to the central government, the state council, state leaders and local government departments, which has provided strong science support for the decision-makers for the ecological rehabilitation and sustainable economic and social development of the Chinese loess Plateau and the Yellow River.

Keywords loess deposits, climate and environment evolution, ecological processes, soil and water conservation, human-land relationships, ecosystem service, policy advice, comprehensive observation and research

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