

目次

基于时间序列分解的京津冀区域PM _{2.5} 和O ₃ 空间分布特征	姚青, 丁净, 杨旭, 蔡子颖, 韩素芹 (2487)
基于随机森林的北京城区臭氧敏感性分析	周红, 王鸣, 柴文轩, 赵昕 (2497)
基于随机森林模型的四川盆地臭氧污染预测	杨晓彤, 康平, 王安怡, 臧增亮, 刘浪 (2507)
海口市臭氧浓度统计预报模型的构建与效果评估	符传博, 林建兴, 唐家翔, 丹利 (2516)
京津冀地区2015~2020年臭氧浓度时空分布特征及其健康效益评估	高冉, 李琴, 车飞, 张艳平, 祖永刚, 刘芬 (2525)
2022年北京市城区PM _{2.5} 水溶性离子含量及其变化特征	陈圆圆, 崔迪, 赵泽熙, 常森, 景宽, 沈秀娥, 刘保献 (2537)
郑州市冬春季PM _{2.5} 中金属元素污染特征、来源及健康风险评估	陶杰, 闫慧姣, 徐艺斐, 荆海涛 (2548)
淄博市供暖前后PM _{2.5} 中多环芳烃及其衍生物污染特征、来源及健康风险	孙港立, 吴丽萍, 徐勃, 高玉宗, 赵雪艳, 姬亚芹, 杨文 (2558)
西安市采暖季过渡期高时间分辨率细颗粒物组分特征及来源解析	李萌津, 张勇, 张倩, 田杰, 李丽, 刘卉昆, 冉伟康, 王启元 (2571)
天津冬季两个典型污染过程高浓度无机气溶胶成因及来源分析	卢苗苗, 韩素芹, 刘可欣, 唐晓, 孔磊, 丁净, 樊文雁, 王自发 (2581)
基于空间尺度效应的山东省PM _{2.5} 浓度时空变化及空间分异地理探测	徐勇, 韦梦新, 邹滨, 郭振东, 李沈鑫 (2596)
我国典型化工行业VOCs排放特征及其对臭氧生成潜势	武婷, 崔焱文, 肖威德, 翟增秀, 韩萌 (2613)
廊坊秋季大气污染过程中VOCs二次气溶胶生成潜势及来源分析	张敬巧, 刘铮, 丁文文, 朱瑶, 曹婷, 凌德印, 王淑兰, 王宏亮 (2622)
景观格局对河流水质影响的尺度效应Meta分析	王玉仓, 杜晶晶, 张禹, 吴昊, 胡敏敏, 陈丁江 (2631)
白洋淀夏季汛期入淀河流水体溶解性有机物的光谱特征及来源	孟佳靖, 宴红, 陈哲, 周石磊, 底怡玲, 武辰彬, 王晨光, 张家丰, 崔建升 (2640)
北京市丰台区永定河以东浅层地下水水化学演变规律及成因分析	胡昱欣, 周瑞静, 宋炜, 杨全合, 王鑫茹 (2651)
庐庐断裂带(安徽段)浅层地下水水化学特征、控制因素及水质评价	刘海, 魏伟, 宋阳, 徐洁, 管政亭, 黄健敏, 赵国红 (2665)
农药施用对兴凯湖水中农药残留的影响及其风险评价	王蔚青, 徐雄, 刘权震, 林利华, 吕婧, 王东红 (2678)
黄河兰州段河岸带土壤中微生物与耐药基因的赋存特征	韦程宸, 魏枫沂, 夏慧, 黄魁 (2686)
基于多源数据的巢湖蓝藻水华时空分布及驱动因素分析	金晓龙, 邓学良, 戴睿, 徐倩倩, 吴月, 范裕祥 (2694)
再生水构建水环境中沉水植物附着细菌群落特征	贺赞, 李雪梅, 李宏权, 魏琳琳, 姜春晖, 姜大伟, 李魁晚 (2707)
水位波动和植被恢复对三峡水库消落带土壤原核微生物群落结构的交互影响	梅渝, 黄平, 王鹏, 朱凯 (2715)
银川市典型湖泊沉积物细菌群落结构及其对重金属的响应关系	蒙俊杰, 刘双羽, 邱小琼, 周娟娟 (2727)
热水解时间对污泥厌氧消化系统微生物群落结构影响分析	张含, 张涵, 王佳伟, 高金华, 文洋, 李相昆, 任征然 (2741)
市政污水中吗啡来源辨析	邵雪婷, 赵悦彤, 蒋冰, 裴伟, 李彦莹, 谭冬芹, 王德高 (2748)
滦河流域生态环境动态遥感评价	李艳翠, 袁金国, 刘博涵, 郭豪 (2757)
黄河流域生态系统服务价值时空演化及影响因素	王奕洪, 孙学堂 (2767)
基于贝叶斯网络的生态系统服务权衡协同关系强度及其空间格局优化:以汾河流域为例	蔡进, 危小建, 江平, 梁玉琦 (2780)
贵州高原典型喀斯特县域生境质量时空演变及定量归因	李月, 冯霞, 吴路华, 罗光杰, 罗红芬 (2793)
2000~2021年黄土高原生态分区NEP时空变化及其驱动因子	周怡婷, 严俊霞, 刘菊, 王瑛 (2806)
基于SSP-RCP情景的黄土高原土地变化模拟及草原碳储量	崔伟, 董燕, 张露尹, 王荣臻 (2817)
京津冀城市群建设用地扩张多情景模拟及其对生态系统碳储量的影响	武爱彬, 陈辅国, 赵艳霞, 秦彦杰, 刘欣, 郭小平 (2828)
西南岩溶区土地利用变化对团聚体稳定性及其有机碳的影响	江可, 贾亚男, 杨琰, 陈坚淇, 禹朴家 (2840)
不同土地利用方式下土壤有机质分子组成变化的整合分析	黄世威, 赵一锴, 朱馨雨, 刘贺雷, 刘姣姣, 陈稍, 陈佳永, 张阿凤 (2848)
基于改进麻雀搜索算法优化BP神经网络的土壤有机质空间分布预测	胡志瑞, 赵万伏, 宋根先, 王芳, 林妍敏 (2859)
不同有机物料施用对菜地磷累积和转化的影响	孙凯, 崔玉涛, 李顺晋, 魏冰丽, 王媛, 杨宏博, 王孝忠, 张伟 (2871)
集约化柑橘种植抑制土壤磷循环微生物活性	周连吴, 曾全超, 梅唐英泽, 汪明霞, 谭文峰 (2881)
控释掺混肥对麦玉米轮作体系作物产量和温室气体排放的影响	高玮, 王学霞, 谢建治, 陈延华, 倪小会, 王甲辰, 董艳芳, 李子双, 曹兵 (2891)
生物炭对黄绵土中NO ₃ -N运移过程影响及模拟	白一茹, 刘旭, 张钰涵, 张睿媛, 马艳, 王幼奇 (2905)
中国农田土壤重金属污染分析与评价	杨雳, 白宗旭, 薄文浩, 林静, 杨俱佳, 陈涛 (2913)
城市土壤和地表灰尘重金属污染研究进展与展望	王晓雨, 刘恩峰, 杨祥梦, 王碧莲, 林锦阔, 颜梦霞, 毕世杰 (2926)
场地重金属污染土壤固化及MICP技术研究进展	陈玥如, 高文艳, 陈虹任, 薛生国, 吴川 (2939)
黄河流域山东段近河道煤矿区土壤重金属污染特征及源解析	戴文婷, 张晖, 吴霞, 钟鸣, 段桂兰, 董霁红, 张培培, 樊洪明 (2952)
拒马河流域河流沉积物与土壤重金属含量及风险评价	韩双宝, 袁磊, 张秋霞, 郑焰, 李甫成 (2962)
银川市黄河滩区土壤重金属污染特征、生态风险评估及来源解析	于路加, 马海军, 王翠平 (2971)
基于源导向和蒙特卡罗模型的广东省某城市土壤重金属健康风险评估	陈莲, 邹子航, 张培珍, 王雨菡, 王振江, 林森, 唐翠明, 罗国庆, 钟建武, 李智毅, 王圆 (2983)
西南典型碳酸盐岩高地背景区农田重金属化学形态、影响因素及回归模型	唐瑞玲, 徐进力, 刘彬, 杜雪苗, 顾雪, 于林松, 毕婧 (2995)
贵州省水田土壤-水稻Hg含量特征与安全种植区划	韦美溜, 周浪, 黄燕玲, 庞瑞, 王佛鹏, 宋波 (3005)
柠檬酸辅助甜高粱对南方典型母质土壤的镉修复效应	刘梦宇, 罗绪锋, 辜娇峰, 易轩韬, 周航, 曾鹏, 廖柏寒 (3016)
改性酒糟生物炭对紫色土壤镉形态及水稻吸收镉的影响	肖乃川, 王子芳, 杨文娜, 谢永红, 代文才, 高明 (3027)
生物炭对四环素和铜复合污染土壤生菜生长及污染物累积的影响	郑晨格, 裴欢欢, 张亚珊, 李嘉欣, 刘奋武, 乔星星, 秦俊梅 (3037)
基于Meta分析的蚯蚓堆肥对堆肥质量和重金属的影响效应	姜继韶, 侯睿, 崔慧林, 闫广轩, 刘栋 (3047)
微塑料对土壤N ₂ O排放及氮素转化的影响研究进展	刘一戈, 杨安琪, 陈舒欣, 牛英奕, 卢瑛, 李博 (3059)
土地利用对洱海罗时江小流域土壤微塑料污染的影响	戴柳云, 侯磊, 王化, 符立松, 王艳霞, 李晓琳, 王万宾, 梁启斌 (3069)
养殖海湾淤泥质海岸沉积物微塑料污染特征	宋可心, 贺金成, 李昌文, 解思琦, 刘宝堃, 黄伟, 冯志华 (3078)
聚乙烷微塑料对盐渍化土壤微生物群落的影响	王志超, 李哲, 李嘉晨, 屈忠义, 杨文煊, 李卫平 (3088)
鄱阳湖候鸟栖息地微塑料表面细菌群落结构特征与生态风险预测	俞锦丽, 赵俊凯, 罗思琦, 朱颖婷, 张文慧, 胡启武, 刘淑丽 (3098)
粤闽浙沿海重点城市道路交通节能减排路径	徐艺诺, 翁大维, 王硕, 胡喜生, 王占永, 张园园, 张兰怡 (3107)
电动重卡替代柴油重卡的全生命周期碳减排效益分析	徐圆圆, 龚德鸿, 黄正光, 杨浪 (3119)

西南岩溶区土地利用变化对团聚体稳定性及其有机碳的影响

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摘要: 土壤团聚体稳定性与团聚体有机碳的关系及其对土地利用变化的响应研究, 对西南岩溶区估算土壤碳汇潜力、改善石漠化问题和土地利用管理有重要意义. 为探究西南岩溶区土地利用方式变化对土壤团聚体组分、稳定性及团聚体有机碳含量的影响, 选取次生林、柚子林、水田、花椒林和旱地这5种典型土地利用方式下0~30 cm的土壤为研究对象, 分析了不同土地利用方式下土壤团聚体组分及其有机碳含量的变化规律, 揭示了土壤团聚体组分与团聚体有机碳含量之间的关系, 探讨了土地利用方式变化后土壤团聚体对有机碳含量变化的贡献. 结果表明, 次生林、柚子林和水田表层(0~15 cm)土壤中大团聚体的含量分别为63.32%、52.38%和47.77%, 显著高于旱地(23.70%), 下层(15~30 cm)土壤趋势相同; 次生林、柚子林和水田土壤团聚体的几何平均直径(GMD)和平均质量直径(MWD)显著高于旱地. 表层土壤中, 次生林和水田的有机碳含量显著高于其他土地利用方式, 下层土壤中, 只有水田的有机碳含量显著高于其他. 各土地利用方式下, 团聚体有机碳含量均表现为: 大团聚体>微团聚体>粉黏粒. 大团聚体对土壤有机碳含量的增加具有积极作用, 而粉黏粒组分则有消极作用. 相关性分析表明, 土壤大团聚体含量与GMD、MWD及土壤团聚体有机碳含量均呈显著正相关. 土壤大团聚体含量的增加有利于提高土壤团聚体的稳定性和储存土壤有机碳, 适度发展林业和水田耕作有利于提高西南岩溶区土壤的固碳潜力.

关键词: 土地利用变化; 土壤团聚体; 土壤有机碳(SOC); 稳定性; 岩溶区

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Effects of Land Use Change on Soil Aggregate Stability and Soil Aggregate Organic Carbon in Karst Area of Southwest China

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Abstract: Investigating the relationship of soil aggregate stability with the organic carbon in the aggregate and its response to land use change is conducive to the estimation of soil carbon sink potential, improvement of rocky desertification, and rational land use in karst areas of Southwest China. In order to explore the effects of land use change on the composition and stability of soil aggregate stability as well as the content of aggregate organic carbon, the soil (0-30 cm) of five land use types (secondary forest, pomelo forest, paddy field, pepper forest, and dry land) was selected as the research object. The characteristics and correlation of soil aggregate components and organic carbon under different land use patterns were obtained, and the contribution of soil aggregates to the change in organic carbon after land use change was calculated. The results showed that the macroaggregates in the surface soil (0-15 cm) of the secondary forest, pomelo forest, and paddy field were 63.32%, 52.38%, and 47.77%, respectively, which were significantly higher than that of dry land (23.70%), as was also seen in the lower layer (15-30 cm). The geometric mean diameter (GMD) and mean weight diameter (MWD) of soil aggregates in the secondary forest, pomelo forest, and paddy field were significantly higher than those in dry land. In the surface soil, the organic carbon of the secondary forest and paddy field was significantly higher than that of other land use patterns. By contrast, in the lower soil layer, only the organic carbon of the paddy field was significantly higher than that of the others. Under different land use patterns, the organic carbon content of aggregates followed the same order of macroaggregates > microaggregates > silt and clay, indicating that macroaggregates allowed soil organic carbon to accumulate, whereas silt and clay did the opposite. According to correlation analysis, the content of soil macroaggregates was significantly positively correlated with GMD, MWD, and soil aggregate organic carbon, suggesting that the increase in soil macroaggregates could improve the stability of soil aggregates and store more soil organic carbon. Further, as land use change may have significantly affected the soil aggregate, moderate development of forestry and paddy cultivation is suggested to improve the soil carbon sequestration potential in the karst area of Southwest China.

Key words: land use change; soil aggregates; soil organic carbon (SOC); stability; karst area

土壤是地球关键带的重要组成, 是人类赖以生存和发展所需最基本的自然资源之一^[1], 研究人类活动对土壤的影响及其响应是地球系统科学在岩溶地区的重要应用^[2]. IPCC关于气候变化与土地的特别报告指出, 土地利用的方式和强度显著影响土壤碳汇^[3]. 土壤团聚体是土壤的重要组成和基本单元, 是维持土壤生产力和土壤结构稳定的关键^[4]. 土壤团聚体对土壤有机碳(soil organic carbon, SOC)有物理保

护作用并能影响土壤有机碳的固存, 因而对估算土壤碳汇有重要意义^[5,6].

土地利用方式变化导致土壤结构的变化^[7], 显

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著影响土壤团聚体粒径的分布和稳定性, 土壤结构与 SOC 之间的关系是研究土壤碳的关键^[8]. 近年来, 有研究表明土地利用方式变化导致土壤中粉黏粒的含量降低^[9], 在黄土高原的研究发现团聚体的稳定性随着大团聚体含量的变化而改变^[10], 一些研究发现大团聚体对土地利用变化响应更为敏感, 其中的有机碳也更易流失^[11,12]. 此外, 有研究指出大团聚体的含量与 SOC 含量呈极显著正相关, 且土壤团聚体的稳定性随着 SOC 含量升高而提高^[13], 但也有学者认为团聚体含量与 SOC 含量之间没有显著相关性^[14]. 由于区域性限制和人类活动干扰, 以上结论普遍存在一定局限性甚至是矛盾.

我国西南地区岩溶区域分布广泛, 地质背景特殊, 石漠化问题严重, SOC 流失显著, 土壤质量明显退化^[2,15]. 我国通过实施大规模的自然封育和退耕还林工程, 石漠化问题显著好转, 植被的恢复提高了土壤质量和固碳的潜力^[16~18]. 与此同时, 西南地区积极发展花椒、柚子等经济作物的种植, 土地利用方式日渐多样. 然而, 西南岩溶地区土地利用方式变化后土壤团聚体的变化规律及其与 SOC 之间的关系尚不明确, 此前的研究多聚焦于全土而较少涉及团聚体, 对水田这类存在干湿交替现象的特殊土地利用方式的研究也较为少见^[19]. 此外, 全球变化背景下, 频繁的暴雨等加剧了土壤侵蚀, 土壤结构

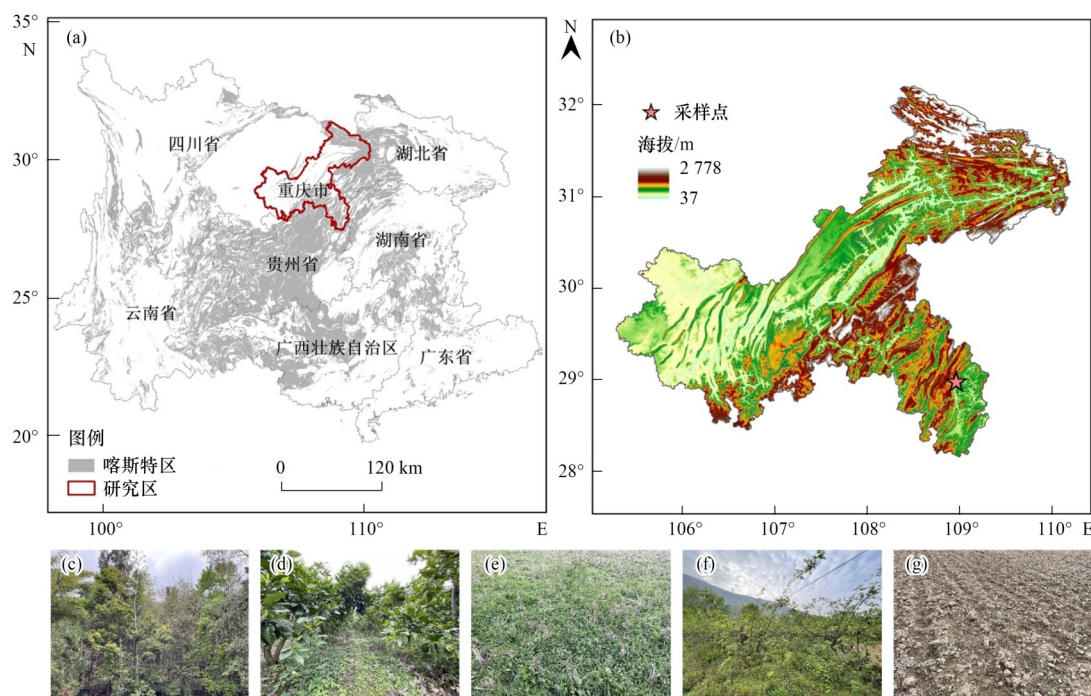
更易退化, 威胁土壤健康与粮食安全, 对土地利用管理提出了挑战, 亟需土壤团聚体稳定性及其有机碳含量的相关研究.

鉴于此, 以我国西南岩溶地区典型的石漠化区域重庆市酉阳龙潭槽谷为例, 采用空间代替时间的方法, 选取 5 种具有代表性的土地利用方式(次生林、柚子林、水田、花椒林和旱地)下 0~30 cm 土层的土壤, 测定土壤团聚体组分及团聚体有机碳含量, 分析并揭示土地利用方式变化对土壤团聚体组分、稳定性及有机碳的影响及其相关性, 探讨土壤团聚体在土壤碳循环过程中的作用, 以期西南岩溶区土地利用管理、石漠化治理和“双碳”目标的实现提供理论依据.

1 材料与方法

1.1 研究区概况

龙潭槽谷位于重庆市酉阳土家族苗族自治县(图 1), 地处武陵山区, 属于背斜型岩溶低位槽谷, 海拔高 350~380 m, 基岩由寒武系和奥陶系白云岩构成. 县域属亚热带季风气候区, 年均温约 15℃, 年均降水量约 1 300 mm, 属石漠化重点治理区域. 研究区土壤为石灰土, 植被类型为亚热带常绿阔叶林. 研究区内主要的土地利用方式为旱地、水田和经济林等.



(a) 西南岩溶区, (b) 研究区, (c) 次生林, (d) 柚子林, (e) 水田, (f) 花椒林, (g) 旱地

图 1 研究区概况及采样点示意

Fig. 1 Map of study area and sampling sites

1.2 样本采集

土壤样品于 2022 年 4 月采自重庆市酉阳土家族

苗族自治县泔溪镇泉孔村(29°00' N, 108°57' E). 按空间代替时间的原则, 根据高程、坡度、土壤母质

相似的原则选取西南地区具有代表性的5种土地利用方式作为处理：次生林[图1(c)]、柚子林[图1(d)]、水田[图1(e)]、花椒林[图1(f)]和旱地[图1(g)]，两种耕地自1950s开始种植，两种经济林为石漠化治理所植并已持续利用10a以上，次生林为响应退耕还林政策所植，生长年限已超过20a，主要以青冈(*Quercus glauca* Thunb.)、刺槐(*Robinia pseudoacacia*)和女贞(*Ligustrum lucidum*)为主。在每种土地利用方式下，选取了4个1m×1m独立的重复样方，为保证土样的独立性并避免数据的假重复，各样方之间的间距均大于20m^[20]。在每个样方随机选取3个取样点，使用环刀分两层(0~15cm和15~30cm)采集土壤样品，将土样用铝盒小心装好编号并转移至实验室。土壤样品在去除石块、植物根系和凋落物后自然阴干备用。

1.3 实验方法

土壤团聚体的分布采用湿筛法^[21]测定。称取50g阴干的土样，置于1L去离子水中充分浸泡至饱和，将饱和土样转移至套筛(孔径分别为0.25mm和0.053mm)中，在保证水面没过土样的前提下来回振荡筛动至少100次，收集各粒径土样后使用烘箱50℃烘干至恒重，称量得到不同粒径大小的团聚体质量，计算各粒径团聚体在原土样中所占的比例。参考《美国农业部土粒分级标准》并依据Tisdall等^[22]的观点，将粒径>0.25mm的团聚体组分记为大团聚体，0.053~0.25mm的记为微团聚体，<0.053mm的记为粉黏粒组分。

土壤及各土壤团聚体有机碳含量均采用重铬酸钾-外加热法^[23]测定。

使用几何平均直径(geometric mean diameter, GMD)和平均质量直径(mean weight diameter, MWD)来衡量土壤团聚体的稳定性^[24]，具体计算步骤见公式(1)和公式(2)。

$$\text{GMD} = \exp \left[\frac{\sum_{i=1}^n \omega_i \ln \bar{x}_i}{\sum_{i=1}^n \omega_i} \right] \quad (1)$$

$$\text{MWD} = \frac{\sum_{i=1}^n (\bar{x}_i \cdot \omega_i)}{\sum_{i=1}^n \omega_i} \quad (2)$$

式中， ω_i 为所属第*i*个团聚体组分质量占全土质量之比， $\bar{x}_i$ 为该粒径团聚体的平均直径。

不同粒径团聚体对土地利用变化后全土有机碳含量贡献的计算见公式(3)。

$$\Delta C = (C_A \cdot w_A) - (C_B \cdot w_B) \quad (3)$$

式中，*C*和*w*分别为所处粒径的有机碳含量和团聚体含量。

1.4 数据处理分析

采用Excel 2021整理实验数据，使用IBM SPSS Statistics 16.0进行数据的单因素方差分析(One-way ANOVA)，并通过最小显著性差异法(LSD法)检验数据差异的显著性($P < 0.05$)，利用R 4.2.3做相关性分析并可视化结果，采用Origin Pro 2022绘制图表。

2 结果与分析

2.1 不同土地利用方式下土壤团聚体分布差异

土地利用方式对土壤团聚体在全土中的分布具有显著影响(图2)。在0~15cm土层中，5种土地利用方式下土壤大团聚体含量的大小关系依次为：次生林(63.32%)>柚子林(52.38%)≈水田(47.77%)>花椒林(32.55%)>旱地(23.70%)。在15~30cm土层中，次生林、柚子林和水田中土壤大团聚体含量显著高于花椒林和旱地。整体上看，同一土地利用方式下，表层0~15cm土壤大团聚体含量高于下层15~30cm土壤。

同一土地利用方式下，大团聚体、微团聚体以及粉黏粒3个组分具有良好的分异性(图2)。其中，次生林和柚子林的大团聚体含量在土壤表层和下层均显著高于微团聚体和粉黏粒，花椒林和旱地土壤中微团聚体含量最大且显著高于大团聚体和粉黏粒的含量。

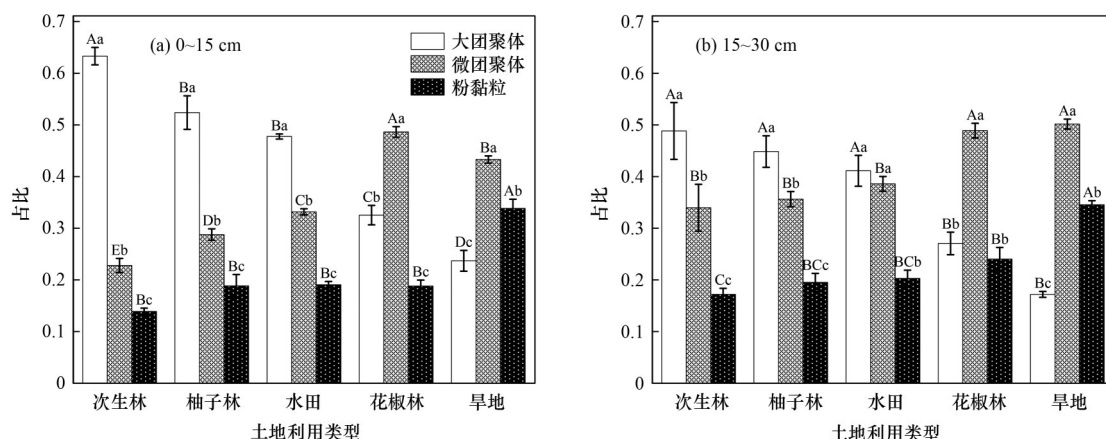
2.2 不同土地利用方式下土壤团聚体稳定性的差异

如图3(a)所示，次生林表层和下层土壤的GMD值均显著大于其余4种土地利用方式，柚子林和水田的GMD值显著大于花椒林和旱地。旱地下层土壤的GMD值显著小于其他4种土地利用方式。各土地利用方式表层土壤的GMD值均显著大于下层土壤。从两层土壤的平均值来看，次生林、柚子林、水田、花椒林和旱地下土壤团聚体GMD值分别为0.60、0.45、0.39、0.25和0.15mm。

如图3(b)所示，次生林、柚子林和水田土壤表层和下层的MWD值均显著大于其余3种土地利用方式，旱地土壤的MWD值显著小于其他4种土地利用方式。从两层土壤的平均值来看，次生林、柚子林、水田、花椒林和旱地下土壤团聚体MWD值分别为1.52、1.33、1.23、0.86和0.61mm。

2.3 不同土地利用方式土壤团聚体和全土的SOC差异

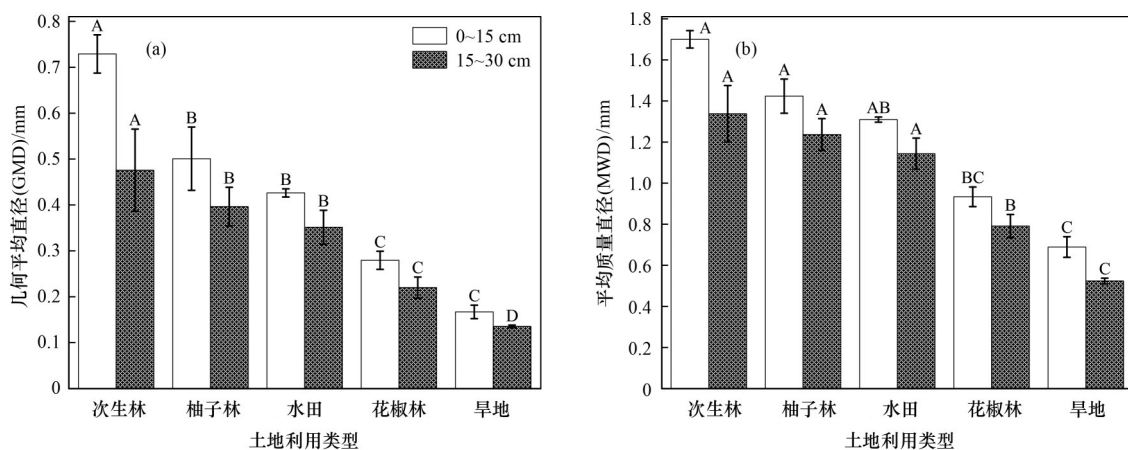
如图4所示，各土地利用方式下表层0~15cm SOC含量大于下层土壤(15~30cm)。表层土壤中，水田和次生林各团聚体和全土SOC含量均显著高于



不同大写字母表示不同土地利用方式下土壤团聚体粒径大小的差异显著 ($P < 0.05$); 不同小写字母表示同一种土地利用方式下土壤团聚体粒径组分的差异显著 ($P < 0.05$)

图2 不同土地利用方式下土壤团聚体分布差异

Fig. 2 Differences in particle size distribution of soil aggregates under different land use patterns



不同大写字母表示不同土地利用方式下土壤团聚体稳定性GMD和MWD的显著差异 ($P < 0.05$)

图3 不同土地利用方式下土壤团聚体几何平均直径(GMD)和平均质量直径(MWD)的特征

Fig. 3 Characteristics of geometric mean diameter (GMD) and mean weight diameter (MWD) under different land use patterns

其他3种土地利用方式. 而在下层土壤中, 除水田各团聚体和全土SOC含量显著高于其余4种土地利用方式外, 其余4种土地利用方式之间各团聚体和全土SOC含量均无显著差异.

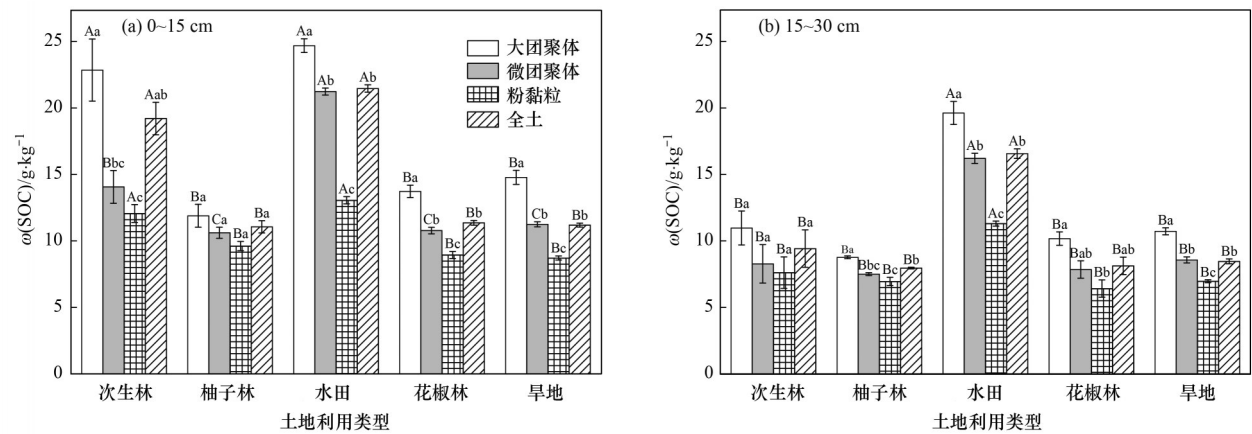
不同粒径团聚体之间, 表层0~15 cm和下层15~30 cm全土SOC含量均与微团聚体持平或略高于微团聚体(图4). 表层土壤中, 除柚子林外, 其余4种土地利用方式团聚体SOC含量均呈现出大团聚体>微团聚体>粉黏粒的变化趋势, 柚子林各团聚体及全土的SOC含量无显著差异. 下层土壤中, 柚子林、水田、花椒林和旱地的SOC含量均表现为: 大团聚体>微团聚体>粉黏粒, 次生林团聚体及全土的SOC含量无显著差异.

2.4 土地利用方式变化后各团聚体对全土SOC含量的贡献

当旱地转变为次生林和水田后表层(0~15 cm)SOC含量分别上升了 $8.06 \text{ g} \cdot \text{kg}^{-1}$ 和 $10.12 \text{ g} \cdot \text{kg}^{-1}$, 较早

地增幅达71.95%和90.34%(表1). 转变为柚子林后下降了 $0.14 \text{ g} \cdot \text{kg}^{-1}$, 转变为花椒林后上升了 $0.18 \text{ g} \cdot \text{kg}^{-1}$. 下层土壤(15~30 cm)中, 旱地转变为水田后SOC含量上升了 $8.11 \text{ g} \cdot \text{kg}^{-1}$, 较早地增幅达53.73%, 在转变为次生林后只增加了 $0.96 \text{ g} \cdot \text{kg}^{-1}$, 而在转变为柚子林和花椒林后分别下降了 $0.50 \text{ g} \cdot \text{kg}^{-1}$ 和 $0.34 \text{ g} \cdot \text{kg}^{-1}$.

土地利用方式变化后不同粒径团聚体对全土SOC含量的贡献存在明显差异(表1). 当旱地转变为其他4种土地利用方式后, 两个土层的大团聚体均对SOC的增加有积极作用, 尤其是在次生林、柚子林和水田中; 在表层0~15 cm土壤中, 当旱地转变为水田和花椒林时, 微团聚体对全土SOC的含量的增加有积极作用, 而在下层15~30 cm土壤中, 只有旱地转变为水田时, 微团聚体对全土SOC的含量的增加有积极作用, 其他情况下, 微团聚体和粉黏粒在土地利用方式变化后对SOC含量的增加有消极作用.



不同大写字母表示不同土地利用方式下土壤有机碳(SOC)含量的显著差异($P < 0.05$);不同小写字母表示同一土地利用方式下不同粒径及全土的土壤有机碳(SOC)含量的显著差异($P < 0.05$)

图4 不同土地利用方式下全土和土壤团聚体SOC的含量

Fig. 4 SOC content of bulk soil and soil aggregates under different land use patterns

表1 土地利用方式改变后不同粒径团聚体对全土SOC增加的作用¹⁾/ $\text{g} \cdot \text{kg}^{-1}$

Table 1 Effect of different particle size aggregates on the increase in SOC after land use change/ $\text{g} \cdot \text{kg}^{-1}$

土层深度/cm	土地利用类变化	全土有机碳变化	ΔC		
			大团聚体	微团聚体	粉黏粒
0 ~ 15	旱地→次生林	8.06	10.97	-1.67	-1.27
	旱地→柚子林	-0.14	2.73	-1.83	-1.14
	旱地→水田	10.12	8.29	2.17	-0.46
	旱地→花椒林	0.18	0.97	0.37	-1.27
15 ~ 30	旱地→次生林	0.96	3.51	-1.49	-1.10
	旱地→柚子林	-0.50	2.09	-1.63	-1.05
	旱地→水田	8.11	6.23	1.96	-0.11
	旱地→花椒林	-0.34	0.91	-0.46	-0.87

1) ΔC 表示土地利用方式改变后,不同粒径团聚体对全土中SOC变化的作用

2.5 土壤团聚体稳定性指标与SOC含量的相关性

由图5可知,大团聚体含量与微团聚体及粉黏粒的含量均呈极显著负相关($P < 0.001$),与GMD和MWD呈极显著正相关($P < 0.001$);微团聚体含量与粉黏粒的含量呈极显著正相关($P < 0.001$),与GMD和MWD呈极显著负相关($P < 0.001$);粉黏粒含量与GMD和MWD呈极显著负相关($P < 0.001$). GMD和MWD呈极显著正相关($P < 0.001$).

大团聚体、微团聚体、粉黏粒及全土中SOC含量互为极显著正相关($P < 0.001$),GMD和MWD与全土有机碳含量均呈极显著正相关($P < 0.001$).

大团聚体含量与各团聚体以及全土的SOC含量呈显著正相关,其中,与全土以及粉黏粒SOC含量极显著正相关($P < 0.001$).微团聚体含量与粉黏粒和全土的有机碳的含量呈极显著负相关($P < 0.001$).

3 讨论

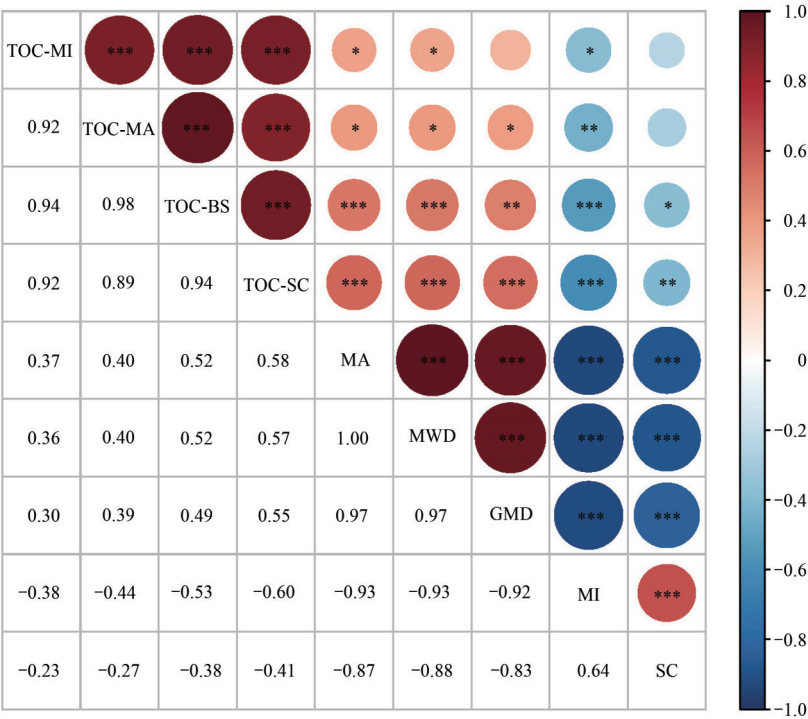
3.1 土地利用方式变化对土壤团聚体组分与稳定性的影响

土壤团聚体可以体现土壤结构的优劣^[25],大团

聚体含量反映了土壤结构的稳定,是维持土壤生态系统服务功能的保障^[26,27].本研究中,次生林土壤中大团聚体的含量为5种处理最高的一种,说明西南岩溶区的造林活动可以有效提高大团聚体的含量,这与An等^[28]和Bai等^[29]在我国黄土高原和亚热带地区关于造林活动可以改善土壤结构的研究结论一致,表明适度发展林业可以提升西南岩溶区的土壤质量.

岩溶区土壤团聚体的稳定性随土地利用方式改变而变化^[30].本研究发现水田大团聚体含量为47.77%,而旱地仅为23.70%,表明旱地周期性的机械耕作会破坏大团聚体并产生更多的粉黏粒^[31],水田耕作则促进了土壤大团聚体的形成^[32].研究区内水稻单季种植,旱地双季种植,水田耕作强度更低,稻田休耕有利于土壤大团聚体的形成,从而显著增加土壤团聚体的稳定性^[33],维持和保护了土壤结构的稳定,与Zhao等^[34]关于耕作强度与土壤团聚体粒径组分的关系的研究结论相一致,即耕作强度和田间管理措施对土壤结构有较大影响.

本研究中,水田的大团聚体含量和GMD、



MA、MI 和 SC 分别为大团聚体、微团聚体和粉粒和黏粒在全土中所占的比例,GMD 为几何平均直径,MWD 为平均质量直径,TOC-MA、TOC-MI、TOC-SC 和 TOC-BS 分别为大团聚体、微团聚体、粉粒和黏粒以及全土中土壤有机碳(SOC)含量;数值大小表示相关性指数,正值表示正相关,负值表示负相关;*,**和***分别表示在 $P < 0.05$ 、 $P < 0.01$ 和 $P < 0.001$ 水平上显著相关

图5 土壤团聚体稳定性指标与有机碳含量的相关性

Fig. 5 Correlations between soil aggregate stability indices and SOC content

MWD 均显著高于旱地,通过走访农户得知,水田使用复合肥和粪水配施.在中国南方地区,长期采用化肥和有机肥配施显著提高了农田土壤团聚体的稳定性^[35-37].

3.2 不同土地利用方式下团聚体有机碳含量的变化及其对全土有机碳含量的贡献

通过相关性分析发现,大团聚体含量与全土有机碳含量呈极显著正相关,而微团聚体和粉黏粒含量与全土的有机碳含量均呈显著负相关.表明植被恢复可以促进有机碳从微团聚体向大团聚体转移^[38,39],大团聚体可以储存更多的土壤有机质^[40].有机碳的储存过程与团聚体的粒径大小密切相关^[41],大团聚体中的颗粒有机碳和矿物结合有机碳在 SOC 的积累中发挥作用^[42],石灰土中富含的钙离子可以链接团聚体表面和 SOC^[43].由此可见,岩溶地区土壤中大团聚体是 SOC 储存过程中最积极的参与者,提高土壤大团聚体的含量有利于土壤碳汇潜力的提升.

本研究中,GMD 和 MWD 与全土中有机碳的含量显著正相关,这与邓华等^[44]的研究结果一致,即 SOC 的含量随团聚体稳定性的增加而增加.然而本研究发现,虽然表层土壤中水田和次生林各团聚体以及全土的有机碳含量均显著高于其他土地利用方式,但下层土壤中只有水田的 SOC 含量显著高于其他,说明水田土壤中碳的储存过程与其他土地利用方式

不同^[45].水田在耕作过程中向土壤输送了有机肥和秸秆等有机质,长期的水稻种植可以物理保护土壤中的活性有机碳以提高土壤的生物活性^[31,33],更高的微生物活性有助于残留的微生物通过附着团聚体以固定 SOC^[46],促进土壤中有机碳含量增加;稻田特有的水耕熟化机制会导致土壤中生成固相的 Fe(II) 矿物,这类含铁矿物及其络合物能够吸附有机碳,从而提高 SOC 含量^[15];水田相较于旱地耕作对土壤扰动更少,比翻耕处理下的旱地 SOC 含量高^[47].由此可见,岩溶区水田相较于旱地能储存更多 SOC.

本研究发现花椒林土壤中大团聚体的含量显著低于另外 2 种林地和水田,GMD 和 MWD 值反映出花椒林土壤的稳定性已经遭到破坏,SOC 的含量也较低.花椒为岩溶区重要的经济作物,种植历史长,土地利用强度大,真菌等微生物的分泌物抑制了团聚体的形成^[48],土壤碳的矿化量增加,降低了 SOC 的稳定性^[49,50],目前当地花椒产量明显降低,土壤质量下降显著,因此西南岩溶区的花椒种植需要加强田间管理以确保种植效率和土壤健康.

4 结论

(1)西南岩溶区土地利用方式变化对土壤团聚体粒径分布及稳定性影响显著.旱地转变为林地和水田的过程显著提高了土壤大团聚体的含量和团聚

体稳定性, 适度发展林业可以优化西南岩溶区的土壤结构。

(2) 表层土壤中, 次生林和水田的有机碳含量显著高于其他土地利用方式, 下层土壤中, 只有水田的有机碳含量显著高于其他。综合考虑, 水田耕作有利于西南岩溶区粮食安全的保证和 SOC 的储存。

(3) 根据相关性分析, 大团聚体含量与土壤各组分有机碳含量呈显著正相关, 微团聚体、粉黏粒与土壤各组分有机碳含量呈显著负相关, 土壤大团聚体对 SOC 的储存有积极作用, 保护土壤大团聚体有利于提高西南岩溶区土壤碳汇潜力。

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CONTENTS

Spatial Distribution Characteristics of PM _{2.5} and O ₃ in Beijing-Tianjin-Hebei Region Based on Time Series Decomposition	YAO Qing, DING Jing, YANG Xu, <i>et al.</i>	(2487)
Ozone Sensitivity Analysis in Urban Beijing Based on Random Forest	ZHOU Hong, WANG Ming, CHAI Wen-xuan, <i>et al.</i>	(2497)
Prediction of Ozone Pollution in Sichuan Basin Based on Random Forest Model	YANG Xiao-tong, KANG Ping, WANG An-yi, <i>et al.</i>	(2507)
Establishment and Effective Evaluation of Haikou Ozone Concentration Statistical Prediction Model	FU Chuan-bo, LIN Jian-xing, TANG Jia-xiang, <i>et al.</i>	(2516)
Spatial and Temporal Distribution Characteristics of Ozone Concentration and Health Benefit Assessment in the Beijing-Tianjin-Hebei Region from 2015 to 2020	GAO Ran, LI Qin, CHE Fei, <i>et al.</i>	(2525)
Water-soluble Inorganic Ion Content of PM _{2.5} and Its Change Characteristics in Urban Area of Beijing in 2022	CHEN Yuan-yuan, CUI Di, ZHAO Ze-xi, <i>et al.</i>	(2537)
Pollution Characteristics, Source, and Health Risk Assessment of Metal Elements in PM _{2.5} Between Winter and Spring in Zhengzhou	TAO Jie, YAN Hui-jiao, XU Yi-fei, <i>et al.</i>	(2548)
Characteristics, Sources Apportionment, and Health Risks of PM _{2.5} -bound PAHs and Their Derivatives Before and After Heating in Zibo City	SUN Gang-li, WU Li-ping, XU Bo, <i>et al.</i>	(2558)
Components Characteristic and Source Apportionment of Fine Particulate Matter in Transition Period of Heating Season in Xi'an with High Time Resolution	LI Meng-jin, ZHANG Yong, ZHANG Qian, <i>et al.</i>	(2571)
Source and Cause Analysis of High Concentration of Inorganic Aerosol During Two Typical Pollution Processes in Winter over Tianjin	LU Miao-miao, HAN Su-qin, LIU Ke-xin, <i>et al.</i>	(2581)
Spatial-temporal Variation and Spatial Differentiation Geographic Detection of PM _{2.5} Concentration in the Shandong Province Based on Spatial Scale Effect	XU Yong, WEI Meng-xin, ZOU Bin, <i>et al.</i>	(2596)
Characteristics of VOCs Emissions and Ozone Formation Potential for Typical Chemicals Industry Sources in China	WU Ting, CUI Huan-wen, XIAO Xian-de, <i>et al.</i>	(2613)
Formation Potential of Secondary Organic Aerosols and Sources of Volatile Organic Compounds During an Air Pollution Episode in Autumn, Langfang	ZHANG Jing-qiao, LIU Zheng, DING Wen-wen, <i>et al.</i>	(2622)
Scale Effects of Landscape Pattern on Impacts of River Water Quality: A Meta-analysis	WANG Yu-cang, DU Jing-jing, ZHANG Yu, <i>et al.</i>	(2631)
Spectral Characteristics and Sources of Dissolved Organic Matter in Inflow Rivers of Baiyangdian Lake Water in Summer Flood Season	MENG Jia-jing, DOU Hong, CHEN Zhe, <i>et al.</i>	(2640)
Analysis on Hydrochemical Evolution of Shallow Groundwater East of Yongding River in Fengtai District, Beijing	HU Yu-xin, ZHOU Rui-jing, SONG Wei, <i>et al.</i>	(2651)
Hydrochemical Characteristics, Controlling Factors and Water Quality Evaluation of Shallow Groundwater in Tan-Lu Fault Zone (Anhui Section)	LIU Hai, WEI Wei, SONG Yang, <i>et al.</i>	(2665)
Effects of Pesticides Use on Pesticides Residues and Its Environmental Risk Assessment in Xingkai Lake (China)	WANG Wei-qing, XU Xiong, LIU Quan-zhen, <i>et al.</i>	(2678)
Characteristics of Microorganisms and Antibiotic Resistance Genes of the Riparian Soil in the Lanzhou Section of the Yellow River	WEI Cheng-chen, WEI Feng-yi, XIA Hui, <i>et al.</i>	(2686)
Analysis of the Spatiotemporal Distribution of Algal Blooms and Its Driving Factors in Chaohu Lake Based on Multi-source Datasets	JIN Xiao-long, DENG Xue-liang, DAI Rui, <i>et al.</i>	(2694)
Characteristics of Epiphytic Bacterial Community on Submerged Macrophytes in Water Environment Supplemented with Reclaimed Water	HE Yun, LI Xue-mei, LI Hong-quan, <i>et al.</i>	(2707)
Effects of Water Level Fluctuations and Vegetation Restoration on Soil Prokaryotic Microbial Community Structure in the Riparian Zone of the Three Gorges Reservoir	MEI Yu, HUANG Ping, WANG Peng, <i>et al.</i>	(2715)
Bacterial Community Structure of Typical Lake Sediments in Yinchuan City and Its Response to Heavy Metals	MENG Jun-jie, LIU Shuang-yu, QIU Xiao-cong, <i>et al.</i>	(2727)
Effect of Thermal Hydrolysis Pretreatment Time on Microbial Community Structure in Sludge Anaerobic Digestion System	ZHANG Han, ZHANG Han, WANG Jia-wei, <i>et al.</i>	(2741)
Source Apportionment of Morphine in Wastewater	SHAO Xue-ting, ZHAO Yue-tong, JIANG Bing, <i>et al.</i>	(2748)
Ecological Environment Dynamical Evaluation of Hutuo River Basin Using Remote Sensing	LI Yan-cui, YUAN Jin-guo, LIU Bo-han, <i>et al.</i>	(2757)
Spatiotemporal Evolution and Influencing Factors of Ecosystem Service Value in the Yellow River Basin	WANG Yi-qi, SUN Xue-ying	(2767)
Ecosystem Service Trade-off Synergy Strength and Spatial Pattern Optimization Based on Bayesian Network: A Case Study of the Fenhe River Basin	CAI Jin, WEI Xiao-jian, JIANG Ping, <i>et al.</i>	(2780)
Spatial-temporal Evolution and Quantitative Attribution of Habitat Quality in Typical Karst Counties of Guizhou Plateau	LI Yue, FENG Xia, WU Lu-hua, <i>et al.</i>	(2793)
Spatio-temporal Variation in NEP in Ecological Zoning on the Loess Plateau and Its Driving Factors from 2000 to 2021	ZHOU Yi-ting, YAN Jun-xia, LIU Ju, <i>et al.</i>	(2806)
Land Change Simulation and Grassland Carbon Storage in the Loess Plateau Based on SSP-RCP Scenarios	CUI Xie, DONG Yan, ZHANG Lu-yin, <i>et al.</i>	(2817)
Multi-scenario Simulation of Construction Land Expansion and Its Impact on Ecosystem Carbon Storage in Beijing-Tianjin-Hebei Urban Agglomeration	WU Ai-bin, CHEN Fu-guo, ZHAO Yan-xia, <i>et al.</i>	(2828)
Effects of Land Use Change on Soil Aggregate Stability and Soil Aggregate Organic Carbon in Karst Area of Southwest China	JIANG Ke, JIA Ya-nan, YANG Yan, <i>et al.</i>	(2840)
Integrated Analysis of Soil Organic Matter Molecular Composition Changes Under Different Land Uses	HUANG Shi-wei, ZHAO Yi-kai, ZHU Xin-yu, <i>et al.</i>	(2848)
Prediction Spatial Distribution of Soil Organic Matter Based on Improved BP Neural Network with Optimized Sparrow Search Algorithm	HU Zhi-rui, ZHAO Wan-fu, SONG Yin-xian, <i>et al.</i>	(2859)
Effects of Application of Different Organic Materials on Phosphorus Accumulation and Transformation in Vegetable Fields	SUN Kai, CUI Yu-tao, LI Shun-jin, <i>et al.</i>	(2871)
Intensive Citrus Cultivation Suppresses Soil Phosphorus Cycling Microbial Activity	ZHOU Lian-hao, ZENG Quan-chao, MEI Tang-ying-ze, <i>et al.</i>	(2881)
Effects of Controlled-release Blended Fertilizer on Crop Yield and Greenhouse Gas Emissions in Wheat-maize Rotation System	GAO Wei, WANG Xue-xia, XIE Jian-zhi, <i>et al.</i>	(2891)
Effect of Biochar on NO ₃ ⁻ -N Transport in Loessial Soil and Its Simulation	BAI Yi-ru, LIU Xu, ZHANG Yu-han, <i>et al.</i>	(2905)
Analysis and Evaluation of Heavy Metal Pollution in Farmland Soil in China: A Meta-analysis	YANG Li, BAI Zong-xu, BO Wen-hao, <i>et al.</i>	(2913)
Critical Review on Heavy Metal Contamination in Urban Soil and Surface Dust	WANG Xiao-yu, LIU En-feng, YANG Xiang-meng, <i>et al.</i>	(2926)
Research Progress on Solidification and MICP Remediation of Soils in Heavy Metal Contaminated Site	CHEN Yue-ru, GAO Wen-yan, CHEN Hong-ren, <i>et al.</i>	(2939)
Pollution Characteristics and Source Analysis of Soil Heavy Metal in Coal Mine Area near the Yellow River in Shandong	DAI Wen-ting, ZHANG Hui, WU Xia, <i>et al.</i>	(2952)
Heavy Metal Content and Risk Assessment of Sediments and Soils in the Juma River Basin	HAN Shuang-bao, YUAN Lei, ZHANG Qiu-xia, <i>et al.</i>	(2962)
Characteristics, Ecological Risk Assessment, and Source Apportionment of Soil Heavy Metals in the Yellow River Floodplain of Yinchuan City	YU Lu-jia, MA Hai-jun, WANG Cui-ping	(2971)
Health Risk Assessment of Heavy Metals in Soils of a City in Guangdong Province Based on Source Oriented and Monte Carlo Models	CHEN Lian, ZOU Zi-hang, ZHANG Pei-zhen, <i>et al.</i>	(2983)
Chemical Speciation, Influencing Factors, and Regression Model of Heavy Metals in Farmland of Typical Carbonate Area with High Geological Background, Southwest China	TANG Rui-ling, XU Jin-li, LIU Bin, <i>et al.</i>	(2995)
Hg Content Characteristics and Safe Planting Zoning of Paddy Soil and Rice in Guizhou Province	WEI Mei-liu, ZHOU Lang, HUANG Yan-ling, <i>et al.</i>	(3005)
Cadmium Phytoremediation Effect of Sweet Sorghum Assisted with Citric Acid on Typical Parent Soil in Southern China	LIU Meng-yu, LUO Xu-feng, GU Jiao-feng, <i>et al.</i>	(3016)
Effects of Modified Distillers' Grains Biochar on Cadmium Forms in Purple Soil and Cadmium Uptake by Rice	XIAO Nai-chuan, WANG Zi-fang, YANG Wen-na, <i>et al.</i>	(3027)
Effects of Biochar on Growth and Pollutant Accumulation of Lettuce in Soil Co-contaminated with Tetracycline and Copper	ZHENG Chen-ge, PEI Huan-huan, ZHANG Ya-shan, <i>et al.</i>	(3037)
Effects of Vermicomposting on Compost Quality and Heavy Metals: A Meta-analysis	JIANG Ji-shao, HOU Rui, CUI Hui-lin, <i>et al.</i>	(3047)
Advances in the Effects of Microplastics on Soil N ₂ O Emissions and Nitrogen Transformation	LIU Yi-ge, YANG An-qi, CHEN Shu-xin, <i>et al.</i>	(3059)
Effects of Land Use Patterns on Soil Microplastic Pollution in the Luoshijiang Sub-watershed of Erhai Lake Basin	DAI Liu-yun, HOU Lei, WANG Hua, <i>et al.</i>	(3069)
Characteristics of Microplastic Pollution in Sediment of Silty Coast in Culture Bay	SONG Ke-xin, HE Jin-cheng, LI Chang-wen, <i>et al.</i>	(3078)
Effect of Polyethylene Microplastics on the Microbial Community of Saline Soils	WANG Zhi-chao, LI Zhe, LI Jia-chen, <i>et al.</i>	(3088)
Characterization of Microplastic Surface Bacterial Community Structure and Prediction of Ecological Risk in Poyang Lake, China	YU Jin-li, ZHAO Jun-kai, LUO Si-qi, <i>et al.</i>	(3098)
Energy-saving and Emission Reduction Path for Road Traffic in Key Coastal Cities of Guangdong, Fujian and Zhejiang	XU Yi-nuo, WENG Da-wei, WANG Shuo, <i>et al.</i>	(3107)
Life Cycle Carbon Reduction Benefits of Electric Heavy-duty Truck to Replace Diesel Heavy-duty Truck	XU Yuan-yuan, GONG De-hong, HUANG Zheng-guang, <i>et al.</i>	(3119)