

目次

基于时间序列分解的京津冀区域PM_{2.5}和O₃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,肖成德,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,胡敏韵,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,婁红,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,周瑞娟 (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)

溱沔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,洪学莹 (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,王璞 (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霞,董燕,张露尹,王荣耀 (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昊,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NO₃-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,杨佩佳,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,董霖红,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,王雨茜,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地质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N₂O排放及氮素转化的影响研究进展刘一戈,杨安琪,陈舒欣,牛奕奕,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,刘宝瑛,黄伟,冯志华 (3078)

聚乙烯微塑料对盐渍化土壤微生物群落的影响王志超,李哲,李嘉辰,屈忠义,胡文煊,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,景文慧,杨启武,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)

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^{1,2}, 张晖², 吴霞², 钟鸣², 段桂兰³, 董霁红¹, 张培培², 樊洪明^{2*}

(1. 中国矿业大学环境与测绘学院, 徐州 221116; 2. 山东省煤田地质局物探测量队, 济南 250104; 3. 中国科学院生态环境研究中心, 北京 100085)

摘要:以黄河流域山东段近河道煤矿区土壤为研究对象, 采用地累积污染指数法和改进内梅罗污染指数法对土壤重金属污染特征进行评估, 利用绝对主成分-多元线性回归模型(APCS-MLR)定量解析了土壤重金属污染来源, 并结合 ArcGIS 中克里金空间差值法分析土壤 Hg 和 Cd 空间分布, 进一步验证了模型源解析结果的准确性. 结果表明, 土壤 Cu、Zn、Pb、Cr、Cd、Ni、As 和 Hg 实测含量均超出了正常场地, 其中, 土壤 Hg 和 Cd 超出了土壤元素背景值. Hg 的变异系数(CV)均高于 0.500, 空间异质性明显, 且与其他重金属相关性极低, 存在相同污染来源的可能性很小. 地累积污染指数和改进内梅罗污染指数结果显示, 土壤重金属总体处于偏中度污染, 其中, 土壤 Hg 污染程度最高, 最大值处于偏重度污染程度, Cu、Cd 和 As 存在局部污染情况, 处于轻度污染程度, 土壤重金属污染与煤矿区开采活动、修复整治和工程施工等密切相关. 研究区土壤重金属两大污染源分别为成土母质和工矿业交通的复合源(已知源 1)、大气沉降和煤炭生产的复合源(已知源 2), 其贡献率分别为 76.705% 和 16.171%; 通过克里金空间差值模拟的 Hg 和 Cd 含量分布证明了 APCS-MLR 模型的解析结果较为可信. 研究可为黄河流域山东段煤矿区土壤重金属污染精准防治和改良、保障粮食和农产品安全, 以及提高生态环境质量提供科学依据.

关键词:土壤重金属; 污染特征; 绝对主成分-多元线性回归模型(APCS-MLR); 源解析; 克里金空间差值

中图分类号: X53 文献标识码: A 文章编号: 0250-3301(2024)05-2952-10 DOI: 10.13227/j.hjxx.202306029

Pollution Characteristics and Source Analysis of Soil Heavy Metal in Coal Mine Area near the Yellow River in Shandong

DAI Wen-ting^{1,2}, ZHANG Hui², WU Xia², ZHONG Ming², DUAN Gui-lan³, DONG Ji-hong¹, ZHANG Pei-pei², FAN Hong-ming^{2*}

(1. School of Environment and Spatial Informatics, China University of Mining and Technology, Xuzhou 221116, China; 2. Geophysical Prospecting and Surveying Team of Shandong Bureau of Coal Geological, Jinan 250104, China; 3. Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China)

Abstract: To explore the pollution characteristics and source of soil heavy metal in a coal mine area near the Yellow River in Shandong, the geo-accumulation index method and improved Nemerow pollution index method were used to evaluate the pollution characteristics of soil heavy metal. The absolute principal component-multiple linear regression model (APCS-MLR) was used to quantitatively analyze the source of soil heavy metal, and the spatial distribution of Hg and Cd were analyzed using the Kriging spatial difference method in ArcGIS. The result accuracy of the APCS-MLR model was further verified. The results showed that: The measured contents of soil heavy metal Cu, Zn, Pb, Cr, Cd, Ni, As, and Hg all exceeded the normal site, among which, Hg and Cd exceeded the background values of soil elements in Shandong. The coefficient of variation (CV) of Hg was higher than 0.500, indicating significant spatial heterogeneity. Moreover, the correlation between Hg and other heavy metals was generally low, and the possibility of the same pollution source was small. The results of the geo-accumulation index and improved Nemerow pollution index showed that the overall soil heavy metal pollution was at a moderate level, among which the Hg pollution level was the highest, and its maximum value was at a slanted-heavy pollution level; Cu, Cd, and As in soil caused local pollution, which were at a slanted-light pollution level. Soil heavy metal pollution was closely related to mining activities, rehabilitation, and engineering construction in the coal mine area. The two major pollution sources of soil heavy metal in the research area were the compound source of the parent material and industrial and mining transportation sources (known source 1) and the compound source of atmospheric sedimentation and coal production (known source 2), the contribution rates of which were 76.705% and 16.171%, respectively. The results of the APCS-MLR model were shown to be reliable by analyzing the content distribution of Hg and Cd using the Kriging space difference mode. This research can provide scientific basis for the precise control and improvement of soil heavy metal pollution, ensuring the safety of food and agricultural products and improving the quality of the ecological environment in the coal mine area in the Shandong section of the Yellow River Basin.

Key words: soil heavy metal; pollution characteristics; absolute principal component score-multiple linear regression receptor model (APCS-MLR); source analysis; Kriging space difference

黄河流域是我国重要的生态屏障, 同时也是我国煤炭资源开采规模最大的地区, 煤炭年产量约占全国总产量的 70%, 在我国能源安全供给保障中占有“压舱石”的地位^[1,2]. 目前, 我国 14 座大型煤炭生产基地有 9 座分布在黄河流域. 煤炭资源开采保障了黄河流域乃至全国的基础能源供应和社会经济发展, 但也不可避免地对地质生态环境产生严重影

响, 诱发植被损毁、景观破碎、生物多样性锐减和土壤重金属污染等一系列生态环境问题^[3-6]. 煤矿区

收稿日期: 2023-06-05; 修订日期: 2023-08-14

基金项目: 山东省煤田地质局重点科研专项(鲁煤地科字(2022)14号); 国家自然科学基金项目(52061135111)

作者简介: 戴文婷(1991-), 女, 博士研究生, 工程师, 主要研究方向为土壤污染监测、评价和修复等, E-mail: daiwenting422@cumt.edu.cn

* 通信作者, E-mail: 1138577622@qq.com

土壤污染状况不容乐观,特别是以重金属为重要污染源的土壤污染已成为显著影响土壤健康的重要因素之一,并严重威胁粮食安全和人体健康^[7-10],土壤重金属污染问题越来越受到社会各界的关注^[11-14]。典型的土壤重金属(包括类重金属)有:铜(Cu)、锌(Zn)、铅(Pb)、铬(Cr)、镉(Cd)、镍(Ni)、砷(As)和汞(Hg)等,以上重金属具有极强的神经毒性、远距离迁移性和难降解性^[15,16],可通过食物链迁移富集,在更大的时空尺度上危害生态环境和威胁人体健康^[9,17]。开展土壤重金属污染评价与明确重金属污染来源是有效防治土壤污染、保障粮食安全的重要前提。2016年,国务院印发了《土壤污染防治行动计划》(国发[2016]31号),表明国家对土壤污染治理修复工作的高度重视^[11]。在构建国家土壤健康-粮食安全发展新格局和推动实现煤矿区生态环境质量提升的大背景下,开展黄河流域煤矿区土壤重金属污染评价与溯源识别工作,既可为精准防治煤矿区土壤污染提供科学参考,也可为推动煤矿区土壤改良和培育健康土壤、生态环境质量提升提供理论依据,具有重要的现实意义。

近年来,国内外学者在煤矿区土壤重金属污染评价和溯源识别方面做了大量的研究工作,研究方法已形成一定范式。目前,传统的污染评价方法有地累积指数法、单因子污染指数法、内梅罗污染指数法和污染负荷指数法等,利用评价方法并结合潜在生态风险指数法和健康风险模型可开展土壤重金属分布特征、污染程度、生态风险和人体健康风险评价等研究工作^[18-20]。土壤重金属源解析一般包括污染源识别过程和不同来源贡献率定量解析,应用较多的源解析方法和模型有:多元统计分析、地统计分析、化学质量平衡模型法、UNMIX模型、绝对主成分-多元线性回归模型(absolute principal component score-multiple linear regression receptor model, APCS-MLR)和正定矩阵因子分解法(positive matrix factorization, PMF)等^[21-24]。其中,APCS-MLR模型不用事先了解污染源个数,以污染物为研究对象,操作方法简单^[25,26],该模型既能定性分析污染物来源,又能定量计算污染物对受体的贡献率,得到广泛应用。

山东省作为黄河流域重要的下游生态廊道,生态功能突出且矿产资源禀赋优势明显。本文以黄河流域山东段近河道煤矿区为研究对象,在分析测定土壤重金属(Cu、Zn、Pb、Cr、Cd、Ni、As和Hg)含量的基础上,采用地累积污染指数法和改进内梅罗综合污染指数法评价土壤重金属污染特征,选用APCS-MLR模型定量分析土壤重金属污染来源和贡

献率,运用克里金空间插值法分析和模拟研究区土壤中Hg和Cd空间分布特征,结合实地调研情况进一步补充验证模型源解析结果,以期为黄河流域山东段煤矿区土壤重金属污染精准防治和改良、保障粮食和农产品安全,以及提高生态环境质量提供科学依据。

1 材料与方法

1.1 研究区概况

黄河流域山东段位于黄河下游、山东省西北部,全长628 km,呈SW-NE走向,流经山东省9个地市^[27],是黄河流域重要的下游生态廊道。地处暖温带半湿润季风气候区,冬季北风盛行,夏季以东南风为主、降雨集中在7~9月,年降雨量大于480 mm,年平均温度在11.7~14.2℃之间。地势较为平坦,87.6%为平原洼地区,属于鲁西平原、鲁北平原和黄河三角洲冲积平原;12.4%为低山丘陵区,主要分布在东平、长清、历城和章丘等县(区),属于泰山山区余脉。区域最高点位于济南长清区,最低点位于东营入海口。研究区为黄河流域山东段济南市和德州市境内近黄河河道的3个煤矿区(煤矿Z、煤矿J和煤矿Q),研究区北部有其他煤矿开采区、锅炉厂和工程建设场地等分布,煤矿生产和工程建设等活动频繁。煤矿Z位于济南市长清区及德州市齐河县,面积约191.410 km²,矿井设计生产能力为90×10⁴ t·a⁻¹,设计服务年限为42.8 a;煤矿J位于济南市济阳县,面积约49.380 km²,矿井设计生产能力为45×10⁴ t·a⁻¹,2019年底停产;煤矿Q位于德州市齐河县,面积约为49.450 km²,矿井核定生产能力为75×10⁴ t·a⁻¹。

1.2 样品采集与处理

2023年3月,在研究区开展土壤样品采集工作。根据研究区地形、地貌及土地利用现状等情况,并充分考虑道路可达性、采样点布置均匀性和距离黄河河道远近等,结合遥感影像图、奥维地图和手持GPS进行煤矿区样点布设,采用蛇形布点法在每个煤矿区布设11个样点。同时,选取研究区附近、煤矿区范围以外和自然条件相近的场地作为正常场地,采用蛇形布点法在正常场地布设11个样点,共计布设44个样点,3个煤矿区和正常场地采样点布设情况见图1。土壤样品采用五点混合采样法采取30 cm以上的表层土壤,用四分法保留1.5 kg左右装入采样袋,采样过程中利用GPS进行定位,记录采样点编号、经纬度、采样点土地利用方式和周边环境等信息。

将所有土壤样品运回实验室后,经自然风干,

去除土壤样品中石砾、植物根系和残叶等非土壤物质,用研钵研碎磨匀,并过100目筛,制好的样品标好编号后,密封保存备用,防止交叉污染.土壤pH值、重金属含量等理化指标测定在中国科学院生态环境研究中心完成.土壤pH值采用1:5土水比土壤浸提法进行测定;采用王水提取、ICP-MS法测定土壤样品中Cu、Zn、Pb、Cr、Cd和Ni含量,先经

混酸(HNO₃-HF-HClO₄)消解后,采用电感耦合等离子体质谱仪进行测定,6种重金属检出限依次为0.200、2.000、2.000、0.400、0.020和1.000 μg·g⁻¹.土壤样品中As和Hg含量采用冷原子-测汞仪进行测定,两类重金属检出限依次为0.200和0.005 μg·g⁻¹.样品测定质量通过国家标准土壤样品、空白样和平行双样进行控制.

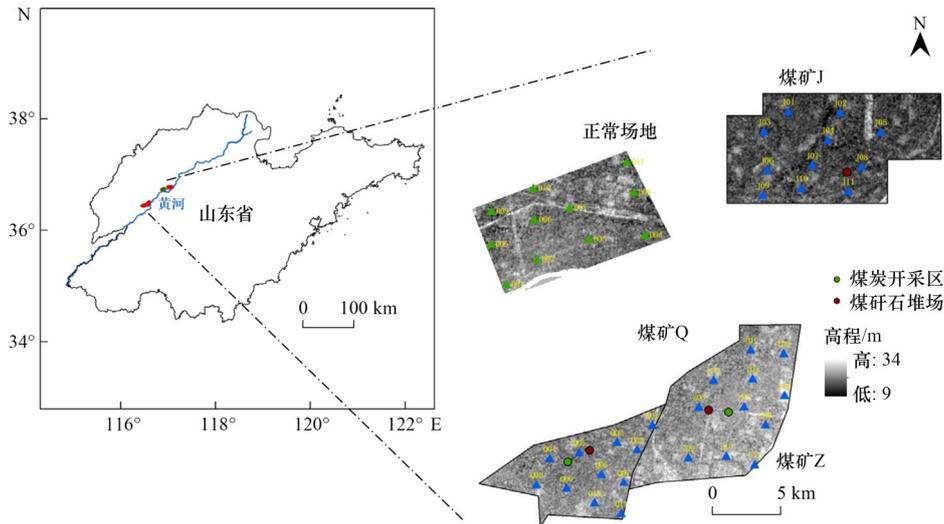


图1 研究区及样点布设示意

Fig. 1 Layout of the research area and sample sites

1.3 研究方法

1.3.1 地累积污染指数法

地累积污染指数(I_{geo})用于定量评价沉积物和土壤重金属污染程度,该指数考虑了成岩作用对背景值的影响和人类活动对重金属的影响^[28],计算公式如下:

$$I_{geo} = \log_2 \left(\frac{C_i}{kS_i} \right) \quad (1)$$

式中, C_i 表示元素*i*的实测含量($\text{mg} \cdot \text{kg}^{-1}$); S_i 表示山东省土壤元素*i*的环境背景值($\text{mg} \cdot \text{kg}^{-1}$); k 表示修正造岩运动引起的背景值波动而设定的系数(一般 $k=1.5$).

1.3.2 改进内梅罗污染指数法

传统内梅罗污染指数过度突出污染指数最大的污染物对生态环境的影响,未考虑各污染因子的权重,评价结果不够精确^[29,30].基于地累积污染指数法对传统内梅罗污染指数进行改进,改进内梅罗污染指数(I_{IN})计算公式如下^[31]:

$$I_{IN} = \sqrt{\frac{1}{2} \left[(I_{geo\max})^2 + (I_{geo\text{ave}})^2 \right]} \quad (2)$$

式中, $I_{geo\max}$ 和 $I_{geo\text{ave}}$ 分别为 I_{geo} 的最大值和平均值($\text{mg} \cdot \text{kg}^{-1}$).

1.3.3 绝对因子得分-多元线性回归模型

绝对因子得分-多元线性回归(APCS-MLR)模型是在主成分分析得到绝对主成分因子得分的基础上,分别以绝对主成分因子得分和各土壤重金属含量作为自变量和因变量进行多元线性回归分析,再利用回归系数获取不同污染源的贡献率,计算步骤和公式如下^[32,33].

首先,对原始数据进行标准化:

$$Z_{ij} = \frac{C_{ij} - \bar{C}_j}{\sigma_j} \quad (3)$$

式中, Z_{ij} 表示标准化值; C_{ij} 表示元素*j*在第*i*个样品中的含量($\text{mg} \cdot \text{kg}^{-1}$); \bar{C}_j 和 σ_j 分别表示元素*j*的含量平均值和标准差($\text{mg} \cdot \text{kg}^{-1}$).

引入0含量因子,计算绝对主成分因子得分APCS_k:

$$Z_{0j} = \frac{0 - \bar{C}_j}{\sigma_j} = -\frac{\bar{C}_j}{\sigma_j} \quad (4)$$

$$\text{APCS}_k = Z_{ik} - (Z_{0j})_j \quad (5)$$

以APCS_k为自变量,各土壤重金属含量为因变量,进行多元线性回归分析,再利用回归系数计算各污染源对土壤重金属的贡献率,计算公式如下:

$$C_j = b_{0j} + \sum_{k=0}^p (b_{kj} \times \text{APCS}_k) \quad (6)$$

式中, C_j 表示重金属 j 的含量($\text{mg}\cdot\text{kg}^{-1}$); b_{0j} 表示重金属 j 多元回归常数项; p 表示因子个数; b_{kj} 表示源 k 对重金属 j 的回归系数; $b_{kj}\times\text{APCS}_k$ 表示源 p 对 C_j 的贡献率。

在APCS-MLR模型中, 贡献率计算过程可能出现负值, 影响源解析结果的准确性。为解决该问题, 将采用绝对值计算污染源的贡献率^[34], 已知污染源的贡献率计算公式如下:

$$\text{PC} = \frac{|b_{kj} \times \text{APCS}_k|}{|b_{0j}| + \sum_{j=1}^n |b_{kj} \times \text{APCS}_k|} \times 100\% \quad (7)$$

未知污染源的贡献率计算公式如下:

$$\text{PC} = \frac{|b_{kj}|}{|b_{0j}| + \sum_{j=1}^n |b_{kj} \times \text{APCS}_k|} \times 100\% \quad (8)$$

1.4 数据分析

采用Microsoft Excel 2022对土壤重金属进行数据统计分析, SPSS 27.0进行相关性分析、因子分析和线性回归分析, ArcGIS 10.2进行土壤样点布设、地统计学分析、空间插值分析和图件绘制、编辑等。

2 结果与讨论

2.1 土壤重金属统计分析

2.1.1 描述性统计分析

研究区土壤理化指标描述性统计分析结果见表1。研究区3个煤矿区土壤pH平均值均大于8.400, 为碱性土壤。与山东省土壤元素背景值^[35]对比, 3个煤矿区土壤Cd和Hg含量平均值均超出了背景值, Cr含量平均值未超过背景值, Cu、Zn、Pb、Ni和As

均存在局部样点含量超出了背景值; 与正常场地土壤重金属含量平均值对比, 3个煤矿区土壤8种重金属含量平均值均超出了正常场地; 初步明确3个煤矿区土壤8种重金属存在不同程度的污染。在土壤重金属监测领域, 变异系数(coefficient of variation, CV)在一定程度上能够反映人类活动对土壤重金属的影响程度^[36], 变异水平根据CV可以划分为低变异($\text{CV} \leq 0.300$)、中等变异($0.300 < \text{CV} \leq 0.500$)、高变异($0.500 < \text{CV} \leq 1.000$)和极高变异($\text{CV} > 1.000$)^[37]。除个别情况外, 3个煤矿区土壤Cu、Zn、Pb、Cr、Cd、Ni和As的变异系数均小于0.300, 属于低变异, 在空间上有较好的同质性, 受人为因素影响较小; Hg的变异系数分别为0.853、1.265和0.997, 均大于0.500, 属于高变异和极高变异, 在空间上有明显的异质性, 受人类活动影响很大^[38]。

2.1.2 相关性分析

相关性分析用于定量评价土壤重金属之间内在联系的强弱程度, 具有高度正相关的土壤重金属可能拥有共同或相似的污染源^[39,40]。运用SPSS 27.0对研究区土壤重金属进行皮尔逊(Pearson)相关性分析, 结果如表2所示。研究区除土壤Cd和Hg, 其他6种重金属之间的相关系数均大于0.800(除Zn和Pb的相关系数为0.758), 存在显著正相关关系, 表明这6种重金属具有相似的来源或富集、迁移等地球化学行为; 土壤Cd与其他7种重金属的相关系数在0.367~0.635之间, 存在中度或低度相关关系, 说明Cd与其他7种重金属可能存在相同来源, 且Cd可能存在复合来源; 除土壤Cd和Cr, 土壤Hg与其他5种重金属的相关系数均为负值且 $|r| < 0.300$, 存在极

表1 研究区土壤理化指标描述性统计

Table 1 Descriptive statistics of physicochemical indexes in the research area

项目	指标	pH值	Cu	Zn	Pb	Cr	Cd	Ni	As	Hg
煤矿Z	最大值/ $\text{mg}\cdot\text{kg}^{-1}$	8.890	25.810	76.146	24.306	42.113	0.185	32.571	15.014	0.131
	最小值/ $\text{mg}\cdot\text{kg}^{-1}$	8.420	12.650	48.638	11.493	28.935	0.085	18.000	8.747	0.012
	平均值/ $\text{mg}\cdot\text{kg}^{-1}$	8.670	20.132	66.059	18.376	36.186	0.141	26.387	12.534	0.039
	标准差/ $\text{mg}\cdot\text{kg}^{-1}$	0.147	3.662	7.254	3.560	4.048	0.025	3.944	1.911	0.034
	变异系数	0.017	0.182	0.110	0.194	0.112	0.179	0.149	0.152	0.853
煤矿J	最大值/ $\text{mg}\cdot\text{kg}^{-1}$	8.890	30.368	75.608	33.666	45.523	0.227	33.067	17.602	0.424
	最小值/ $\text{mg}\cdot\text{kg}^{-1}$	7.763	11.886	45.202	12.709	31.064	0.090	18.306	8.498	0.014
	平均值/ $\text{mg}\cdot\text{kg}^{-1}$	8.450	17.007	55.143	16.570	34.427	0.139	22.543	10.917	0.092
	标准差/ $\text{mg}\cdot\text{kg}^{-1}$	0.326	4.673	7.758	5.642	4.108	0.046	3.802	2.293	0.117
	变异系数	0.039	0.275	0.141	0.341	0.119	0.330	0.169	0.210	1.265
煤矿Q	最大值/ $\text{mg}\cdot\text{kg}^{-1}$	9.500	18.238	55.323	21.069	38.497	0.164	23.427	10.598	0.241
	最小值/ $\text{mg}\cdot\text{kg}^{-1}$	7.967	9.097	35.156	11.484	24.213	0.104	14.056	6.012	0.019
	平均值/ $\text{mg}\cdot\text{kg}^{-1}$	8.692	13.741	45.155	15.669	31.737	0.131	19.332	8.444	0.062
	标准差/ $\text{mg}\cdot\text{kg}^{-1}$	0.373	2.789	5.801	2.786	4.148	0.019	2.919	1.394	0.062
	变异系数	0.043	0.203	0.128	0.178	0.131	0.147	0.151	0.165	0.997
参考值	土壤元素背景值/ $\text{mg}\cdot\text{kg}^{-1}$	7.700	24.000	63.500	25.800	66.000	0.084	25.800	9.300	0.019
	正常场地/ $\text{mg}\cdot\text{kg}^{-1}$	8.732	12.500	44.083	14.312	31.301	0.073	18.942	8.071	0.018

低的负相关关系,说明Hg与这5种重金属存在相同来源的可能性极小^[37,41].

2.2 土壤重金属污染特征分析

2.2.1 地累积污染指数评价

研究区土壤重金属地累积污染指数 I_{geo} 评价结果如图2所示,土壤重金属实测含量对比山东省土壤元素背景值的 I_{geo} 平均值由大到小依次为: $Hg > Cd > As > Ni > Zn > Cu > Pb > Cr$, 土壤Hg污染程度最为严重.结合图2(a)可以看出, Hg污染程度较为多样,各污染等级均有样点分布,其最大值处于偏重度污染状态,这与Hg存在明显空间异质性的特点吻合;土壤Cd的 I_{geo} 平均值小于0,但其最大值处于轻度污染状态;所有样点中土壤Cu、Zn、Pb、Cr、Ni和As的 I_{geo} 均小于0,表现为无污染.土壤重金属实测含量对比正常场地的 I_{geo} 平均值由大到小依次为: $Hg > Cd > Cu > As > Zn > Ni > Pb > Cr$, 同样,土壤Hg污染程度最为严重,结合图2(b)可以看出,其最大值处于偏重度污染和重度污染的临界状态;土壤Cu、Cd和As的 I_{geo} 平均值均小于0,但均存在局部样点处于污染状态,其中Cd实测含量的最大值处于偏重度污染状态;所有样点中土壤Zn、Pb、Cr和Ni的 I_{geo} 均小于0,表现为无污染.总体而言,研究区土壤Hg污染相对严重,且污染范围较广;Cu、Cd和As呈现局部污染情况,可能存在点源污染.

2.2.2 改进内梅罗污染指数评价

研究区土壤重金属改进内梅罗污染指数 I_{in} 评价结果如图3所示,土壤重金属实测含量对比山东省

土壤元素背景值的 I_{in} 值介于0.541~3.901之间,平均值为1.340,处于偏中度污染程度[图3(a)].其中,煤矿Z、J和Q中污染最为严重的样点分别为Z01、J09和Q01,处于中度污染、偏重度污染状态.样点Z01为小麦地,旁边是煤矿区平整修复场地,煤矸石充填修复、重型货车运输过程中产生煤灰粉尘等均会导致周边土壤重金属富集^[42];样点J09为煤矿区复垦后农用地,已有研究表明煤矿区复垦土壤重金属普遍存在富集现象^[43];样点Q01旁边为土建工程场地,受工地建设和大型工程车辆行驶等影响较大.土壤重金属实测含量对比正常场地的 I_{in} 值介于0.289~3.986之间,平均值为1.065,处于偏中度污染程度[图3(b)],同样的,煤矿Z、J和Q中污染最为严重的样点分别为Z01、J09和Q01,处于中度污染、偏重度污染状态.总体而言,对比山东省土壤元素背景值和正常场地,研究区土壤重金属总体均处于偏中度污染程度,局部样点存在中度污染和偏重度污染状态,这与煤矿区开采活动、修复整治和工程施工等密切相关.

2.3 土壤重金属来源解析

2.3.1 APCS-MLR模型源解析

利用SPSS 27.0软件对研究区土壤重金属含量进行KMO和巴特利特球形度检验,结果分别为0.787和 < 0.001 ,表明可进一步对其进行主成分分析.结合相关性分析结果,提取初始特征值大于1.000的因子作为主成分因子,将2个主成分因子标准化后进行正交旋转,旋转后的累计贡献率为92.876%,分析结果如表3和表4所示.

表2 研究区土壤重金属相关性系数¹⁾

Table 2 Correlation coefficients of soil heavy metal in the research area

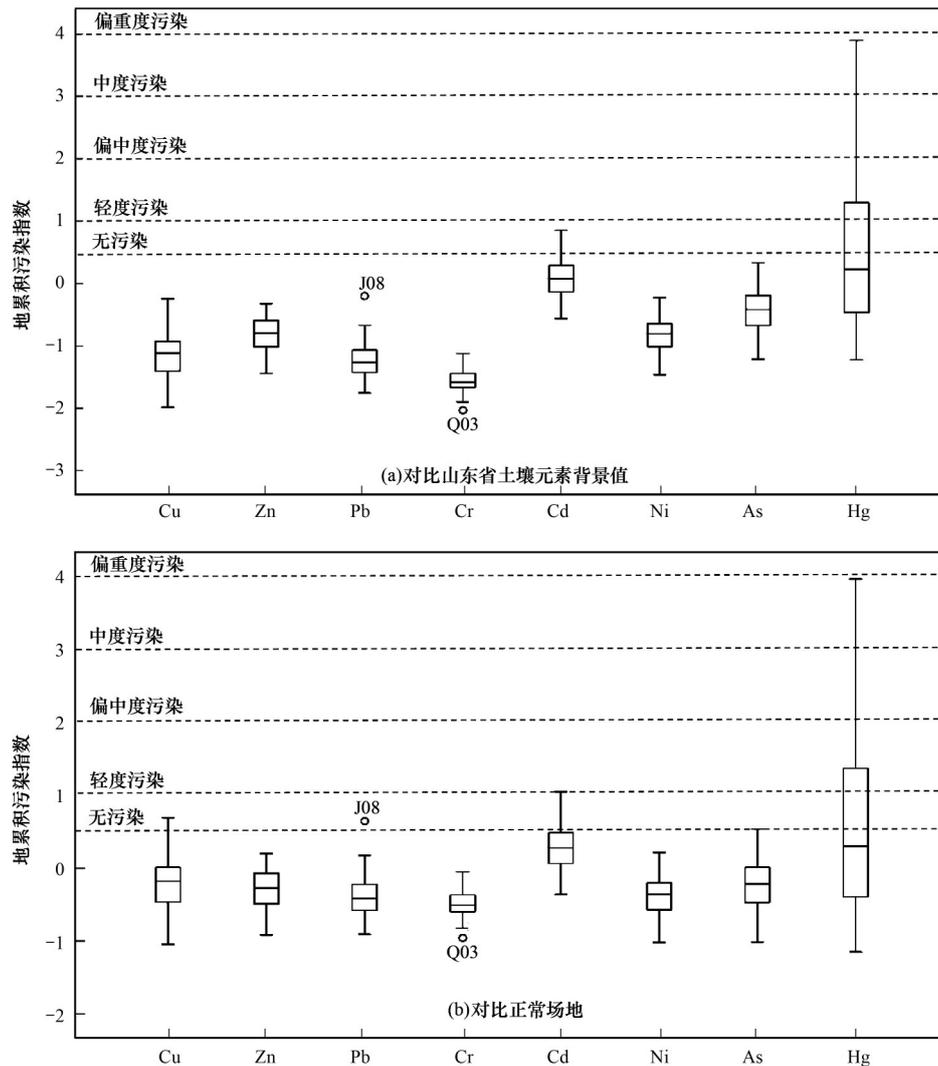
	Cu	Zn	Pb	Cr	Cd	Ni	As	Hg
Cu	1							
Zn	0.942**	1						
Pb	0.899**	0.758**	1					
Cr	0.911**	0.850**	0.871**	1				
Cd	0.484**	0.416*	0.614**	0.635**	1			
Ni	0.979**	0.969**	0.851**	0.923**	0.486**	1		
As	0.976**	0.959**	0.855**	0.882**	0.488**	0.969**	1	
Hg	-0.173	-0.131	-0.235	0.087	0.367*	-0.114	-0.174	1

1)**表示在0.01水平(双侧)上显著相关,*表示在0.05水平(双侧)上显著相关

第一主因子(FAC1)方差贡献率为76.705%,除土壤Hg外,其他7种重金属的旋转载荷均较高;第二主因子(FAC2)方差贡献率为16.171%,土壤Cd和Hg旋转载荷较高,分别为0.541和0.970,初步说明土壤Cu、Zn、Pb、Cr、Ni和As主要受到第一主因子影响,Cd受第一主因子和第二主因子共同影响,

Hg主要受第二主因子影响.利用APCS-MLR分析结果显示,8种重金属拟合度 R^2 分别为0.978、0.887、0.839、0.928、0.753、0.963、0.957和0.870,均在0.750以上.计算研究区土壤重金属主因子的贡献率,结果如图4所示.

已知源1对土壤Cu、Zn、Pb、Cd、Ni和As的



空心圆表示异常值, J08 样点处 Pb 地累积污染指数和 Q03 样点处 Cr 地累积污染指数异常

图 2 研究区土壤重金属地累积污染指数箱线图

Fig. 2 Boxplot of the geo-accumulation index of soil heavy metal in the research area

贡献率分别为 98.347%、68.744%、86.697%、45.439%、72.911% 和 85.636%，说明已知源 1 对这 6 种重金属含量贡献占主导作用，结合相关性分析结果，除土壤 Cd 外，其他 5 种重金属之间基本都呈现高度正相关，可能存在相同来源；土壤 Cd 与其他 5 种重金属存在高度或低度相关关系，说明 Cd 与这 5 种重金属可能存在相同来源，且 Cd 可能存在复合来源，已知源贡献率和相关性分析结果吻合。土壤 Cu、Zn、Pb、Cd、Ni 和 As 的 CV 值均小于 0.300 (除煤矿 J 中 Cd 的 CV 值为 0.330)，且均未超过山东省土壤元素背景值，研究区土壤 pH 值在 7.763~9.500 之间，属于碱性土壤，土壤碱化后会降低 Cu 和 Zn 等金属阳离子的溶解性，表明其受自然因素影响较大。另外，土壤 Cu、Zn 和 Pb 是交通活动的标志元素，且 Cd 常以伴生元素存在于多种矿产中，我国多数煤矿含有丰富的 Cd。土壤样点均布设在农田及其周边，部分土壤样点布设于交通道路两侧，研究区内煤矿

资源开采需要大量运煤车，大型货车出入频繁，伴随运输过程煤渣掉落、车辆尾气排放、引擎及轮胎磨损等导致 Cu、Zn、Pb 和 Cd 等元素在土壤中富集。因此，推断已知源 1 可以代表成土母质和工矿业交通的复合源。已知源 2 对土壤 Hg 和 Cd 的贡献率分别为 52.382% 和 22.057%，Hg 的 CV 值较高，空间异质性明显，Hg 和 Cd 与其他重金属的相关性不高，且均呈现不同程度的污染，说明这 2 种重金属受人类活动影响较大。相关研究发现，采煤、洗煤和燃煤等以煤炭为主的工业活动会增加土壤中 Hg 的富集^[44]。Hg 具有易挥发性和长距离迁徙性，进入大气界面发生扩散，经大气干湿沉降累积在土壤表层，形成面源污染，这就是 Hg 含量空间异质性明显、污染范围广的主要原因^[45]。工矿企业和工业“三废”排放会增加 Cd 富集，特别是矿石精炼^[46]。因此，推断已知源 2 可以代表大气沉降和煤炭生产的复合源。综合土壤重金属成分矩阵和来源

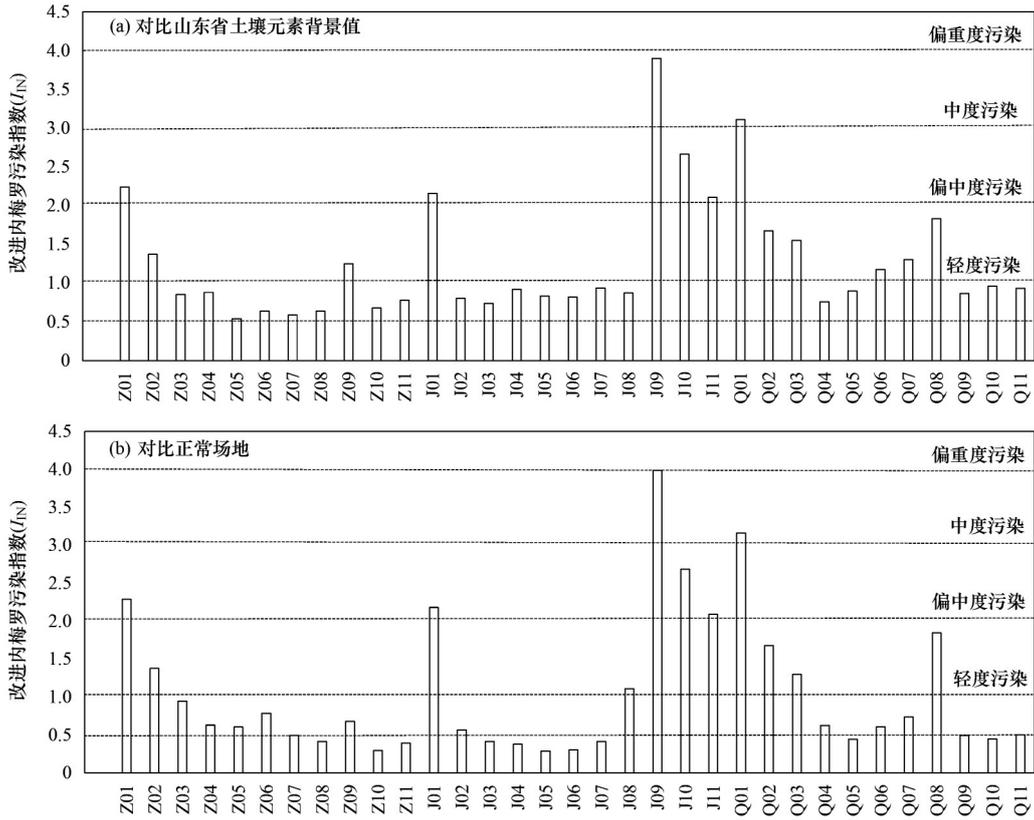


图3 研究区土壤重金属改进内梅罗综合污染评价结果

Fig. 3 Results of improved Nemerow pollution index of soil heavy metal in the research area

表3 研究区主成分总方差解释

Table 3 Interpretation of total variance of principal components in the research area

因子	初始特征值			提取载荷平方和			旋转载荷平方和		
	总计	方差/%	累计/%	总计	方差/%	累计/%	总计	方差/%	累计/%
1	6.198	77.473	77.473	6.198	77.473	77.473	6.136	76.705	76.705
2	1.232	15.403	92.876	1.232	15.403	92.876	1.294	16.171	92.876
3	0.354	4.424	97.299						
4	0.097	1.212	98.512						
5	0.086	1.081	99.592						
6	0.016	0.204	99.797						
7	0.011	0.134	99.931						
8	0.006	0.069	100.000						

表4 研究区土壤重金属成分矩阵

Table 4 Soil heavy metal composition matrix in the research area

土壤重金属	主成分分析矩阵		旋转后成分矩阵	
	FAC1	FAC2	FAC1	FAC2
Cu	0.974	-0.142	0.983	-0.033
Zn	0.961	-0.081	0.964	0.026
Pb	0.941	-0.124	0.949	-0.018
Cr	0.959	0.132	0.938	0.238
Cd	0.772	0.458	0.716	0.541
Ni	0.985	-0.063	0.986	0.047
As	0.976	-0.124	0.984	-0.014
Hg	0.037	0.972	-0.072	0.970

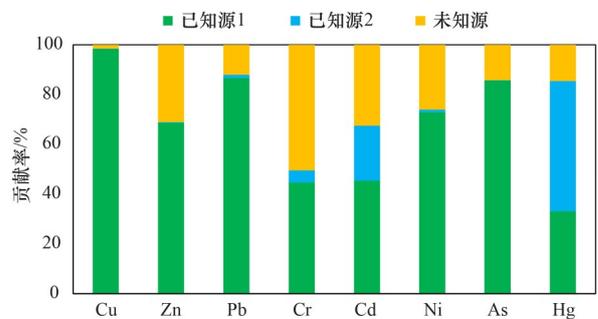


图4 各因子对土壤重金属含量分布的贡献率

Fig. 4 Contribution rate of each factor to the distribution of soil heavy metal content

贡献率分析可知，土壤 Cu、Zn、Pb、Ni 和 As 主要受自然因素影响，Cd 受自然因素和矿业运输、生

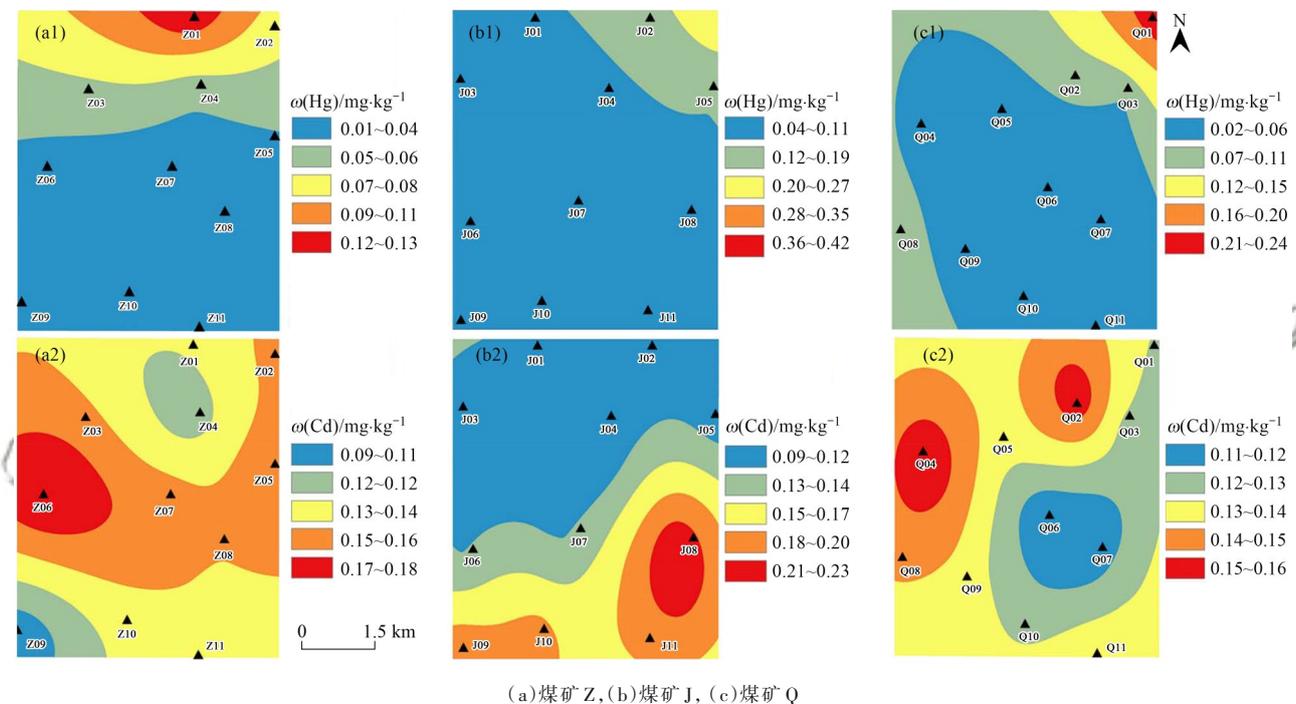
产等活动共同影响，Hg 主要受大气沉降和煤炭生产等矿业活动影响。

由于 APCS-MLR 是基于主成分分析提取特征值大于 1 的成分进行解析, 未包含 7.124% 的未知源. 根据表 3 主成分总方差解释可知, 未知源分别来自 6 个成分, 方差贡献率分别为 4.424%、1.212%、1.081%、0.204%、0.134% 和 0.069%, 这部分未知源数据则可能来自多种污染源的混合源^[38].

2.3.2 基于克里金空间插值的 Hg、Cd 空间特征分析

根据前文分析结果可知, 研究区土壤 Hg 和 Cd 污染较为严重, 同时, 为了验证 APCS-MLR 模型源解析结果的准确性, 采用克里金空间插值法生成煤矿 Z、J 和 Q 土壤 Hg 和 Cd 含量的空间分布情况, 进一步根据实地调查情况对模型源解析结果进行补充验证, 图 5 为煤矿 Z、J 和 Q 的土壤 Hg 和 Cd 空间分

布. 3 个煤矿土壤 Hg 空间分布特征明显且保持一致, 均由南向北呈递增趋势. 研究区北部有煤矿区分布, 煤矿生产活动频繁, 且地处季风气候, 冬季北风盛行, 夏季以东南风为主且降雨集中, 因此, 北风对 Hg 在大气界面扩散起了关键作用. Hg 随北风从污染源由北向南扩散和沉降, 富集在土壤表层, 进一步验证了 APCS-MLR 模型解析的 Hg 来源于煤炭生产活动和大气沉降. 3 个煤矿土壤 Cd 空间分布特征明显, 均由某一个或两个污染点源向周边扩散, 经实地调查, Cd 含量较高的污染点源与煤炭开采区、煤矸石堆场及工程建设场地基本吻合, 进一步验证了 APCS-MLR 模型解析的 Cd 来源于工矿企业和工业“三废”. 因此, APCS-MLR 模型源解析结果较为可信.



(a) 煤矿 Z, (b) 煤矿 J, (c) 煤矿 Q

图 5 研究区土壤 Hg 和 Cd 空间分布

Fig. 5 Spatial distribution of heavy metal in soils of the research area

3 结论

(1) 研究区土壤 8 种重金属实测含量均超出了正常场地, 其中, 土壤 Hg 和 Cd 超出了土壤元素背景值. 土壤 Hg 的 CV 值均高于 0.500, 属于高变异和极高变异, 空间异质性明显, 受人类活动影响很大; 其他 7 种重金属 CV 值较低, 在空间上有较好的同质性. 土壤 Hg 和 Cd 与其他重金属的相关性较低, 存在相同污染来源的可能性很小.

(2) 研究区土壤 Hg 污染相对严重, 最大值处于偏重度污染程度, 且污染范围较广; Cu、Cd 和 As 存在局部污染情况, 处于轻度污染程度. 研究区土

壤重金属总体处于偏中度污染, 与土壤元素背景值、正常场地对比, I_n 平均值分别为 1.340 和 1.065; 样点 Z01、J09 和 Q01 污染最为严重, 处于中度污染、偏重度污染状态, 这与煤矿区开采活动、修复整治和工程施工等密切相关.

(3) 利用 APCS-MLR 模型解析出研究区 2 个土壤重金属已知源, 分别为成土母质和工矿业交通的复合源、大气沉降和煤炭生产的复合源, 其贡献率分别为 76.705% 和 16.171%; Cu、Zn、Pb、Ni 和 As 主要受自然因素影响, Cd 受自然因素和矿业运输、生产等活动共同影响, Hg 主要受大气沉降和煤炭生产等矿业活动影响. 通过克里金空间差值模拟的土壤

Hg 和 Cd 含量分布证明了 APCS-MLR 模型的解析结果较为可信, APCS-MLR 模型和 ArcGIS 空间分析相结合能够更为全面地解析土壤重金属来源。

参考文献:

- [1] 卞正富, 于昊辰, 雷少刚, 等. 黄河流域煤炭资源开发战略研判与生态修复策略思考[J]. 煤炭学报, 2021, **46**(5): 1378-1391.
Bian Z F, Yu H C, Lei S G, *et al.* Strategic consideration of exploitation on coal resources and its ecological restoration in the Yellow River Basin, China [J]. Journal of China Coal Society, 2021, **46**(5): 1378-1391.
- [2] 申艳军, 杨博涵, 王双明, 等. 黄河几字弯区煤炭基地地质灾害与生态环境典型特征[J]. 煤田地质与勘探, 2022, **50**(6): 104-117.
Shen Y J, Yang B H, Wang S M, *et al.* Typical characteristics of geological hazards and ecological environment of coal base in the bends area of the Yellow River [J]. Coal Geology & Exploration, 2022, **50**(6): 104-117.
- [3] Zeng Y F, Pang Z Z, Wu Q, *et al.* Study of water-controlled and environmentally friendly coal mining models in an ecologically fragile area of Northwest China [J]. Mine Water and the Environment, 2022, **41**(3): 802-816.
- [4] 宁岳伟, 刘勇, 张红, 等. 煤矿矿区复垦植被类型对土壤微生物功能基因和酶活的影响[J]. 环境科学, 2022, **43**(9): 4647-4654.
Ning Y W, Liu Y, Zhang H, *et al.* Effects of different vegetation types on soil microbial functional genes and enzyme activities in reclaimed coal mine [J]. Environmental Science, 2022, **43**(9): 4647-4654.
- [5] Nie X R, Hu Z Q, Zhu Q, *et al.* Research on temporal and spatial resolution and the driving forces of ecological environment quality in coal mining areas considering topographic correction [J]. Remote Sensing, 2021, **13**(14), doi: 10.3390/rs13142815.
- [6] 赵家印, 杨地, 杨湘智, 等. 云南省某煤矿开采遗址周边农用地土壤重金属污染评价及源解析研究[J]. 生态与农村环境学报, 2022, **38**(11): 1473-1481.
Zhao J Y, Yang D, Yang X Z, *et al.* Pollution assessment and source identification of heavy metals in farmland soils around a coal mine area in Yunnan Province [J]. Journal of Ecology and Rural Environment, 2022, **38**(11): 1473-1481.
- [7] Liu Q Y, Wu Y H, Zhao W H, *et al.* Soil environmental criteria in six representative developed countries: soil management targets, and human health and ecological risk assessment [J]. Critical Reviews in Environmental Science and Technology, 2023, **53**(5): 577-600.
- [8] 安永龙, 殷秀兰, 李文娟, 等. 张家口市万全区某种植区土壤重金属污染评价与来源分析[J]. 环境科学, 2023, **44**(6): 3544-3561.
An Y L, Yin X L, Li W J, *et al.* Evaluation and source analysis of soil heavy metal pollution in a planting area in Wanquan District, Zhangjiakou City [J]. Environmental Science, 2023, **44**(6): 3544-3561.
- [9] 欧灵芝, 胡鸣明, 安德章, 等. 高砷煤矿周围旱作土壤重金属污染特征及农作物健康风险评估[J]. 农业资源与环境学报, 2023, **40**(1): 25-35.
Ou L Z, Hu M M, An D Z, *et al.* Characteristics and health risk assessment of heavy metals in dryland soil and crops around a coal mine with high levels of arsenic [J]. Journal of Agricultural Resources and Environment, 2023, **40**(1): 25-35.
- [10] Liu J W, Kang H, Tao W D, *et al.* A spatial distribution - principal component analysis (SD-PCA) model to assess pollution of heavy metals in soil [J]. Science of the Total Environment, 2022, **859**, doi: 10.1016/j.scitotenv.2022.160112.
- [11] 张旺, 高珍冉, 邵粤鹰, 等. 基于 APCS-MLR 受体模型的贵州喀斯特矿区水田土壤重金属源解析[J]. 农业工程学报, 2022, **38**(3): 212-219.
Zhang W, Gao Z R, Tai Y Y, *et al.* Source analysis of the heavy metals in paddy field soils in Karst mining areas of Guizhou using APCS-MLR receptor model [J]. Transactions of the Chinese Society of Agricultural Engineering, 2022, **38**(3): 212-219.
- [12] Muneeb A, Ahmad I, Hameed M, *et al.* Status of soil and water pollution at the largest coal mining area of Punjab, Pakistan [J]. Fresenius Environmental Bulletin, 2021, **30**(1): 441-447.
- [13] Rajendran S, Priya T A K, Khoo K S, *et al.* A critical review on various remediation approaches for heavy metal contaminants removal from contaminated soils [J]. Chemosphere, 2021, **287**, doi: 10.1016/j.chemosphere.2021.132369.
- [14] 李军, 李旭, 高世刚, 等. 基于 APCS-MLR 和 PMF 模型的燃煤电厂周边土壤潜在有毒元素(PTEs)污染特征与来源解析[J]. 环境科学, 2023, **44**(10): 5689-5703.
Li J, Li X, Gao S G, *et al.* Contamination characteristics and source apportionment of potentially toxic elements in soil around the coal-fired power plant based on APCS-MLR and PMF models [J]. Environmental Science, 2023, **44**(10): 5689-5703.
- [15] Guo Y Q, Chen B, Li Y X, *et al.* The co-benefits of clean air and low-carbon policies on heavy metal emission reductions from coal-fired power plants in China [J]. Resources, Conservation and Recycling, 2022, **181**, doi: 10.1016/j.resconrec.2022.106258.
- [16] 王树民, 顾永正, 杨建兴, 等. 1000MW 近零排放燃煤机组重金属排放及分布特征[J]. 中国环境科学, 2022, **42**(5): 2060-2069.
Wang S M, Gu Y Z, Yang J X, *et al.* Emissions and distribution characteristics of heavy metal in 1000MW near-zero emission coal-fired units [J]. China Environmental Science, 2022, **42**(5): 2060-2069.
- [17] 郭斌, 白昊睿, 张波, 等. 基于 RF 和连续小波变换的露天煤矿土壤镉含量高光谱遥感反演[J]. 农业工程学报, 2022, **38**(10): 138-147.
Guo B, Bai H R, Zhang B, *et al.* Inversion of soil zinc contents using hyperspectral remote sensing based on random forest and continuous wavelet transform in an opencast coal mine [J]. Transactions of the Chinese Society of Agricultural Engineering, 2022, **38**(10): 138-147.
- [18] Linnik V G, Minkina T M, Bauer T V, *et al.* Geochemical assessment and spatial analysis of heavy metals pollution around coal-fired power station [J]. Environmental Geochemistry and Health, 2020, **42**(12): 4087-4100.
- [19] Aguilera A, Bautista F, Gutiérrez-Ruiz M, *et al.* Correction to: Heavy metal pollution of street dust in the largest city of Mexico, sources and health risk assessment [J]. Environmental Monitoring and Assessment, 2021, **193**(8), doi: 10.1007/s10661-021-09344-z.
- [20] 刘柱光, 方樟, 丁小凡. 燃煤电厂贮灰场土壤重金属污染及健康风险评估[J]. 生态环境学报, 2021, **30**(9): 1916-1922.
Liu Z G, Fang Z, Ding X F. Heavy metal pollution and health risk assessment of soil in ash yard of coal-fired power plant [J]. Ecology and Environmental Sciences, 2021, **30**(9): 1916-1922.
- [21] 洪涛, 孔祥胜, 岳祥飞. 滇东南峰丛洼地土壤重金属含量、来源及潜在生态风险评估[J]. 环境科学, 2019, **40**(10): 4620-4627.
Hong T, Kong X S, Yue X F. Concentration characteristics, source analysis, and potential ecological risk assessment of heavy metals in a peak-cluster depression area, southeast of Yunnan Province [J]. Environmental Science, 2019, **40**(10): 4620-4627.
- [22] 闫晓露, 郑欢, 赵炬杭, 等. 辽东湾北部河口区土壤重金属污染源识别及健康风险评估[J]. 环境科学学报, 2020, **40**(8): 3028-3039.
Yan X L, Zheng H, Zhao X H, *et al.* Source identification and health risk assessment of soil heavy metal in the estuary of Northern Liaodong Bay, China [J]. Acta Scientiae Circumstantiae, 2020, **40**(8): 3028-3039.
- [23] Zhang W H, Yan Y, Yu R L, *et al.* The sources-specific health

- risk assessment combined with APCS/MLR model for heavy metals in tea garden soils from south Fujian Province, China [J]. CATENA, 2021, **203**, doi: 10.1016/j.catena.2021.105306.
- [24] 王成, 赵艳萍, 谢鸣捷. 苏南典型工农业交错区土壤铅富集特征及源解析——基于 PCA-PMF 方法[J]. 中国环境科学, 2021, **41**(1): 279-287.
- Wang C, Zhao Y P, Xie M J. Characteristics of lead enrichment in the soil from a typical peri-urban agricultural area of the southern Jiangsu and source apportionment based on the PCA-PMF method [J]. China Environmental Science, 2021, **41**(1): 279-287.
- [25] Ma J, Shen Z J, Wang S L, *et al.* Source apportionment of heavy metals in soils around a coal gangue heap with the APCS-MLR and PMF receptor models in Chongqing, southwest China [J]. Journal of Mountain Science, 2023, **20**(4): 1061-1073.
- [26] Ma J W, Lanwang K, Liao S Y, *et al.* Source apportionment and model applicability of heavy metal pollution in farmland soil based on three receptor models[J]. Toxics, 2023, **11**(3), doi: 10.3390/toxics11030265.
- [27] 刘金花, 丛中笑, 王治军. 基于三生空间转型的生态环境效应多尺度研究——以黄河流域山东段为例[J]. 中国环境科学, 2023, **43**(5): 2519-2530.
- Liu J H, Cong Z X, Wang Z J. Ecological effects of production-living-ecological space transformation at multi-scales: a case study on the Shandong Section of the Yellow River Basin [J]. China Environmental Science, 2023, **43**(5): 2519-2530.
- [28] 李嘉蕊. 基于土壤-作物-人体系统的耕地重金属污染评价和健康风险评估[D]. 杭州: 浙江大学, 2019.
- Li J R. Heavy metal pollution assessment and health risk assessment of cultivated land based on soil-crop-human system [D]. Hangzhou: Zhejiang University, 2019.
- [29] 王紫媛, 刘星月, 王伟超, 等. 典型滇池湿地公园的水质评价与污染源分析[J]. 灌溉排水学报, 2022, **41**(S1): 90-96.
- Wang Z Y, Liu X Y, Wang W C, *et al.* Water quality evaluation and pollution source analysis of typical lake wetland parks around Dianchi Lake [J]. Journal of Irrigation and Drainage, 2022, **41**(S1): 90-96.
- [30] 刘娅君, 李彩霞, 梅楠, 等. 三峡库区稻田土壤重金属污染特征及风险评价[J]. 环境科学, 2023, **44**(6): 3520-3530.
- Liu Y J, Li C X, Mei N, *et al.* Characteristics and risk evaluation of heavy metal contamination in paddy soils in the Three Gorges Reservoir Area [J]. Environmental Science, 2023, **44**(6): 3520-3530.
- [31] Liu L L, Liu Q Y, Ma J, *et al.* Heavy metal(loid)s in the topsoil of urban parks in Beijing, China: Concentrations, potential sources, and risk assessment[J]. Environmental Pollution, 2020, **260**, doi: 10.1016/j.envpol.2020.114083.
- [32] Thurston G D, Spengler J D. A quantitative assessment of source contributions to inhalable particulate matter pollution in metropolitan Boston [J]. Atmospheric Environment (1967), 1985, **19**(1): 9-25.
- [33] 张海霞, 蔡昂祖, 赵海萍, 等. 基于 PMF 和 APCS-MLR 模型的工业城市大气降尘金属源解析及综合污染评价[J]. 环境工程学报, 2022, **16**(11): 3816-3827.
- Zhang H X, Cai A Z, Zhao H P, *et al.* Source apportionment of metals in atmospheric deposition of a typical industrial city based on PMF and APCS-MLR and comprehensive pollution assessment [J]. Chinese Journal of Environmental Engineering, 2022, **16**(11): 3816-3827.
- [34] Chen Z, Zhou Q P, Lv J S, *et al.* Assessment of groundwater quality using APCS-MLR model: a case study in the pilot promoter region of Yangtze River Delta Integration Demonstration Zone, China [J]. Water, 2023, **15**(2), doi: 10.3390/w15020225.
- [35] 中国环境监测总站. 中国土壤元素背景值[M]. 北京: 中国环境科学出版社, 1990.
- [36] 罗豪杰, 潘俊, 陈小霞, 等. 基于 Monte-Carlo 模拟的湖南省典型工厂周边农田土壤重金属区域潜在生态风险特征及来源解析[J]. 环境科学, 2024, **45**(2): 1038-1048.
- Luo H J, Pan J, Chen X X, *et al.* Potential ecological risk characteristics and source apportionment of heavy metals in farmland soils around typical factories in Hunan Province based on Monte-Carlo Simulation [J]. Environmental Science, 2024, **45**(2): 1038-1048.
- [37] 刘楠, 唐莹影, 陈盟, 等. 基于 APCS-MLR 和 PMF 的铅锌矿流域土壤重金属来源解析[J]. 中国环境科学, 2023, **43**(3): 1267-1276.
- Liu N, Tang Y Y, Chen M, *et al.* Source apportionment of soil heavy metals in lead-zinc area based on APCS-MLR and PMF [J]. China Environmental Science, 2023, **43**(3): 1267-1276.
- [38] Karim Z, Qureshi B A, Mumtaz M, *et al.* Heavy metal content in urban soils as an indicator of anthropogenic and natural influences on landscape of Karachi—a multivariate spatio-temporal analysis [J]. Ecological Indicators, 2014, **42**: 20-31.
- [39] 孟利, 左锐, 王金生, 等. 基于 PCA-APCS-MLR 的地下水污染源定量解析研究[J]. 中国环境科学, 2017, **37**(10): 3773-3786.
- Meng L, Zuo R, Wang J S, *et al.* Quantitative source apportionment of groundwater pollution based on PCA-APCS-MLR [J]. China Environmental Science, 2017, **37**(10): 3773-3786.
- [40] 张丽平. 基于地理国情数据的城市土地利用变化及其地表降雨径流影响分析[D]. 济南: 山东建筑大学, 2022.
- Zhang L P. Analysis of urban land use change and its impact on surface rainfall runoff based on geographical conditions data [D]. Jinan: Shandong Jianzhu University, 2022.
- [41] 柴磊, 王新, 马良, 等. 基于 PMF 模型的兰州耕地土壤重金属来源解析[J]. 中国环境科学, 2020, **40**(9): 3919-3929.
- Chai L, Wang X, Ma L, *et al.* Sources appointment of heavy metals in cultivated soils of Lanzhou based on PMF models [J]. China Environmental Science, 2020, **40**(9): 3919-3929.
- [42] 朱慧萍, 方凤满, 林跃胜, 等. 荻港镇某水泥厂周边不同介质中重金属含量、来源及潜在生态风险分析[J]. 环境化学, 2017, **36**(12): 2711-2718.
- Zhu H P, Fang F M, Lin Y S, *et al.* Distribution, source apportionment and potential ecological risk assessment of heavy metals in different environmental media around a cement factory in Digang town [J]. Environmental Chemistry, 2017, **36**(12): 2711-2718.
- [43] 谭敏. 典型高潜水位煤矿区重金属时空分布特征及复垦适宜性研究[D]. 徐州: 中国矿业大学, 2021.
- Tan M. Heavy metals spatial and temporal distribution characteristics and reclamation suitability in typical coal mining areas with high groundwater level [D]. Xuzhou: China University of Mining and Technology, 2021.
- [44] 刘娣, 苏超, 张红, 等. 典型煤炭产业聚集区土壤重金属污染特征与风险评价[J]. 生态环境学报, 2022, **31**(2): 391-399.
- Liu D, Su C, Zhang H, *et al.* Pollution characteristics and risk assessment of heavy metal pollution in a typical coal-based industrial cluster zone [J]. Ecology and Environmental Sciences, 2022, **31**(2): 391-399.
- [45] 卫晓锋, 孙紫坚, 陈自然, 等. 基于成土母质的矿产资源基地土壤重金属生态风险评价与来源解析[J]. 环境科学, 2023, **44**(6): 3585-3599.
- Wei X F, Sun Z J, Chen Z R, *et al.* Ecological risk assessment and source apportionment of heavy metals in mineral resource base based on soil parent materials [J]. Environmental Science, 2023, **44**(6): 3585-3599.
- [46] 高越, 吕童, 张蕴凯, 等. PMF 和 RF 模型联用的土壤重金属污染源解析与污染评价: 以西北某典型工业园区为例[J]. 环境科学, 2023, **44**(6): 3488-3499.
- Gao Y, Lv T, Zhang Y K, *et al.* Source apportionment and pollution assessment of soil heavy metal pollution using PMF and RF model: a case study of a typical industrial park in Northwest China [J]. Environmental Science, 2023, **44**(6): 3488-3499.

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)
Spatial-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-hua, <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)