

目次

疫情期间人为源减排对城市大气氧化性的影响朱剑蓝, 秦墨梅, 朱嫣红, 胡建林 (617)

不同天气形势对南京地区双高污染的输送及潜在源区分析秦阳, 胡建林, 孔海江 (626)

不同方法判定南京臭氧生成敏感区的差异陈柑羽, 李勋, 李琳, 秦墨梅, 谢鸣捷, 王鸣, 李婧楠, 胡建林 (635)

2006~2021年夏半年上海臭氧浓度特征及其大气环流背景分析郑庆锋, 梁萍, 段玉森, 林燕芬, 张宋嘉, 徐卫忠 (645)

基于大气成分观测网的山西省近地面O₃体积分数分布特征李莹, 王淑敏, 裴坤宁, 闫世明, 孙鸿博, 张逢生, 高兴艾 (655)

伊宁市夏季大气臭氧生成机制及减排策略王文婷, 谷超, 李丽明, 李新琪, 郑镇森, 耿春梅, 王晓丽, 杨文 (668)

运城市四季VOCs特征、来源及臭氧形成敏感物种阴世杰, 刘新罡, 刘亚非, 李晨露, 张晨, 张欢, 王正, 程强 (678)

郑州市冬夏季污染过程中大气VOCs污染特征、来源解析及活性分析赖梦洁, 张栋, 于世杰, 宋鑫帅, 李晓, 张瑞芹 (689)

郑州市PM_{2.5}中有机酸的污染特征、来源解析及二次生成李子涵, 董喆, 尚璐琪, 孔梓涵, 李晓, 张瑞芹 (700)

中国三大城市群PM_{2.5}浓度非线性变化分析吴舒祺, 顾杨阳, 张天岳, 赵文吉 (709)

基于LEAP模型的临港新片区中长期碳排放预测及减排潜力分析吴琼, 马昊, 任洪波, 郭明星, 陈鹏, 李琦芬 (721)

碳交易背景下中国华北地区碳代谢格局变化郑宏媚, 沈方, 许光耀, 关欣 (732)

考虑区域特点和车型差异的氢燃料电池汽车全生命周期减碳预测分析马菁, 蔡旭, 张春梅, 兰利波, 陈轶嵩, 付佩 (744)

我国主要河流水系硝态氮污染特征及定量源解析韦英怀, 胡敏鹏, 陈丁江 (755)

不同时空尺度下土地利用结构与空间格局对苏州水质的影响谭娟, 熊丽君, 王卿, 任志文, 朱丹丹, 王敏 (768)

深圳市2015~2021年雨源型河流水质时空变化及其对降雨的响应韦必颖, 成建梅, 苏晓煜, 程天舜 (780)

河南黄河改道区浅层地下水化学特征与主控污染源解析王帅, 任宇, 郭红, 曹文庚, 李祥志, 肖舜禹 (792)

北京西山岩溶地下水化学特征及成因分析郭高轩, 代垠东, 许亮, 朱琳, 欧志亮, 戚琦, 辛宝东 (802)

店埠河流域地表水-地下水化学特征及其成因分析郑涛, 秦先燕, 吴剑雄 (813)

张家口地区枯水期地下水化学特征及其成因机制分析金爱芳, 殷秀兰, 李长青, 李文娟, 庞菊梅, 金晓媚 (826)

黄河中下游典型抗性细菌及抗性基因污染分布闵威, 高明昌, 孙绍芳, 宋茜茜, 邱立平 (837)

制药废水中抗生素抗性的污染特征、检测手段和控制方法彭安萍, 高虎, 张新波 (844)

水体组分对聚苯乙烯纳米颗粒聚沉行为的影响汤端阳, 郑文丽, 陈关潼一, 陈思莉, 陈尧, 赵晓丽, 汪浩 (854)

富磷废弃钙基生物炭对水体中铅的去除刘天, 吕思璐, 杜兴国, 程敏, 谢燕华 (862)

壳聚糖改性生物炭的制备及其对水溶液中Cd²⁺的吸附机制姜凌, 安靖玥, 岳小琼, 李亚雄, 夏秋乐, 祝婷文佳, 柴丽红 (873)

硼掺杂介孔炭吸附四环素的效能与机制邹震, 许路, 乔伟, 唐茂森, 金鹏康 (885)

磁性含磷油茶壳生物炭对水中磺胺甲噁唑的吸附特性韩帅鹏, 唐李文, 刘勤, 林家亮, 李晓慢, 程建华, 胡勇有 (898)

广东省高分辨率温室气体排放清单及特征卢清, 唐明双, 廖彤, 黄志烟, 钟庄敏, 宋佩珊, 沈劲, 张智胜, 梁小明, 孙家仁, 陈来国 (909)

辽河口“退塘还湿”修复区生态系统CO₂交换及其环境调控刘思琪, 陈虹, 邢庆会, 程浩, 韩建波, 徐雪梅 (920)

生物炭施用两年后对热带地区稻菜轮作土壤N₂O和CH₄排放的影响胡煜杰, 唐瑞杰, 胡天怡, 陈琦琦, 汤水荣, 阮延正, 孟磊 (929)

生物炭改良盐碱地研究与应用进展魏盈, 焦乐, 张鹏, 刘福德, 肖辉, 董辰辰, 孙红文 (940)

免耕对农田土壤团聚体的影响研究: Meta分析徐芝萍, 饶越悦, 孟艳, 温媛, 孟维伟, 王旭清, 李宗新, 刘开昌, 代红翠 (952)

黔中喀斯特地区典型县域碳储量时空演变及多情景模拟预测: 以普定县为例李月, 罗红芬 (961)

不同改良剂对酸性紫色土团聚体和有机碳的影响李越, 徐曼, 谢永红, 王颖, 黄容, 谢军, 王子芳, 高明 (974)

Ca改性生物炭对土壤磷赋存形态影响及稳定化机制张超, 翟付杰, 单保庆 (983)

秦岭中段不同恢复阶段弃耕农田植物多样性变化及其驱动因素闫成龙, 薛悦, 王艺菲, 康海斌, 王得祥 (992)

我国典型制药厂污染场地中抗生素的污染特征及生态风险杨炳彬, 黄争, 赵建亮, 何良英, 刘有胜, 胡立新, 石义静, 应光国 (1004)

广州市土壤多环芳烃污染特征及风险评估邹子航, 陈莲, 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 (1015)

基于源导向的土壤重金属风险评价及管控因子分析潘泳兴, 陈盟, 王楠楠 (1026)

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罗豪杰, 潘俊, 陈小霞, 张敏, 沈良辰, 李歆, 丁平, 蔡丹, 蔡立梅, 胡国成 (1038)

基于参数优化和蒙特卡罗模拟的砷污染地块健康风险评估袁贝, 刘虎鹏, 杜平, 陈娟, 张云慧, 张昊 (1049)

基于APCS-MLR和PMF模型的赤泥堆场周边耕地土壤重金属污染源解析沈智杰, 李杰芹, 李彩霞, 廖泽源, 梅楠, 罗程钟, 王定勇, 张成 (1058)

PE-Cd复合污染土壤中Cd释放迁移特征及机制王迪, 徐绍辉, 邵明艳, 林青 (1069)

氯代乙烯的厌氧微生物还原脱氯特性李伟, 刘贵平, 刘峻, 吕良华, 乔文静, 余欣, 张晓琦, 蒋建东 (1080)

昭通市农田土壤和蔬菜重金属污染评价及相关性分析张好, 董春雨, 杨海婵, 孙思静, 韩宇, 黄祖志, 张乃明, 包立 (1090)

钝化剂对轻中度镉污染农田的安全利用效果王晓晶, 张东明, 曹阳, 吕家琰, 代允超 (1098)

氧化石墨烯负载铁锰复合材料对镉污染土壤的钝化修复袁婧, 吴骥子, 连斌, 袁峰, 孙淇, 田欣, 赵科理 (1107)

关键生育期施加外源灌溉水对水稻镉吸收转运的影响周霞, 胡雨丹, 周航, 陈琼, 谭文韬, 曾鹏, 辜娇峰, 廖柏寒 (1118)

外源锌对镉胁迫下玉米幼苗生长及根系构型分级的影响张辉红, 魏畅, 柳海涛, 张静静, 刘芳, 赵颖, 张雪海, 李鸽子, 姜瑛 (1128)

稀土元素铈对镉胁迫下小麦幼苗生长的缓解效应张静静, 徐正阳, 焦秋娟, 范丽娜, 刘芳, 赵颖, 宋佳, 化党领, 李鸽子, 柳海涛 (1141)

根施伯克氏菌对小麦镉吸收转运的两段式阻控作用郭佳佳, 王常荣, 刘仲齐, 黄青青, 张长波, 黄永春, 薛卫杰, 孙约兵 (1150)

高密度聚乙烯微塑料与氯嘧磺隆对大豆生长和根际细菌群落的复合胁迫效应胡晓玥, 滑紫微, 姚伦广, 杜丽, 牛秋红, 李玉英, 闫路, 陈兆进, 张浩 (1161)

微塑料的人体富集及毒性机制研究进展包亚博, 王成尘, 彭吾光, 依代倩, 向萍 (1173)

机器学习在微塑料识别与环境风险评估中的应用研究进展白润昊, 范瑞琪, 刘琪, 刘勤, 严昌荣, 崔吉晓, 何文清 (1185)

微塑料与农田土壤中典型污染物的复合污染研究进展侯宇晴, 李冰, 王金花, 宋文慧, 王兰君, 王军, 朱鲁生 (1196)

水中微/纳塑料电化学检测及去除的研究进展郑伟康, 刘振中, 项晓方 (1210)

基于分布式认知理论的农户面源污染治理支付意愿影响因素郭晨浩, 李林霏, 夏显力 (1222)

《环境科学》征订启事(825) 《环境科学》征稿简则(836) 信息(897, 1106, 1149)

基于参数优化和蒙特卡罗模拟的砷污染地块健康风险评估

袁贝^{1,2}, 刘虎鹏^{1,2}, 杜平^{1*}, 陈娟¹, 张云慧¹, 张昊¹

(1. 生态环境部土壤与农业农村生态环境监管技术中心, 北京 100012; 2. 中国环境科学研究院, 北京 100012)

摘要: 风险评估是污染地块风险管理的关键环节. 而在具体 As 污染地块管理实践中, 基于污染物总量和默认参数的方法难以获得符合实际的健康风险, 进而不能达到后期修复治理等管控要求, 目前越来越多的研究通过考虑生物有效性、修正参数、结合概率模型等方法开展风险评估. 以某大型 As 污染地块为典型案例, 布设 432 个采样点并采集不同深度土壤样品, 分析 As 污染程度及分布特征, 通过文献调研和 Monte Carlo 模拟修正模型参数, 并在此基础上开展概率风险评估, 比较探讨传统方法与概率方法对健康风险评估结果的影响. 结果表明, 研究区域表层土壤 $\omega(\text{As})$ 范围为 2.70 ~ 97.0 mg·kg⁻¹, 空间变异系数为 0.61, 空间连续性较弱. 传统风险评估方法所得致癌风险和危害指数分别为 2.12E-4 和 8.36, 高估了实际风险水平, 结合模型参数修正和概率风险评估发现, 成人和儿童的非致癌风险处于可接受水平, 致癌风险相较传统方法降低近 1 个数量级. 考虑 As 相对生物有效性 (RBA) 后, 总致癌风险的 95% 分位值为 1.24E-5, 相较未修正对应的风险值 1.95E-5, 降幅可达 36.41%. 研究区域土壤 As 对成人和儿童的致癌风险超过可接受风险水平 1E-6, 其中经口摄入土壤是主要暴露途径. 此外, 敏感性分析结果显示, As 含量、每日土壤摄入量 and 儿童暴露期对健康风险影响相对较大. 研究结果可为砷污染地块精准风险评估提供方法理论依据, 并为地块的精细化风险管控提供思路.

关键词: 污染地块; 砷 (As); 参数修正; 相对生物有效性 (RBA); 概率风险评估

中图分类号: X53 文献标识码: A 文章编号: 0250-3301(2024)02-1049-09 DOI: 10.13227/j.hj.kx.202302163

Health Risk Assessment for an Arsenic-contaminated Site Based on Monte Carlo Simulation and Parameters Optimization

YUAN Bei^{1,2}, LIU Hu-peng^{1,2}, DU Ping^{1*}, CHEN Juan¹, ZHANG Yun-hui¹, ZHANG Hao¹

(1. Technical Centre for Soil, Agriculture and Rural Ecology and Environment, Ministry of Ecology and Environment, Beijing 100012, China; 2. Chinese Research Academy of Environmental Sciences, Beijing 100012, China)

Abstract: Risk assessment is a critical part of risk management for contaminated sites. However, in the specific management practice of As-contaminated sites, it is difficult to obtain realistic health risks for contaminated sites based on the total amount of pollutants and determined values of the model, thus preventing the control requirements of later remediation to be met. An increasing number of studies have recently been conducting risk assessments by considering bioavailability, modification parameters, and combined probabilistic models. To improve the accuracy of risk assessment results, taking a large As-contaminated site as a case, 432 sampling sites were set up and collected at different depths to analyze the level and distribution characteristics of As pollution, and probabilistic risk assessment was conducted with the modification of model parameters through literature research and Monte Carlo simulation. Then, the impact of traditional methods and probabilistic methods on health risk assessment was explored in comparison. The results indicated that $\omega(\text{As})$ in the top soil of the study area ranged from 2.70-97.0 mg·kg⁻¹, with a spatial variation coefficient of 0.61 and weaker spatial continuity. The carcinogenic risk and hazard index obtained by the traditional risk assessment method were 2.12E-4 and 8.36, respectively, which obviously overestimated the actual risk level and were not conducive to the refined management of As-contaminated sites. Combined with modification of model parameters and probabilistic risk assessment, the non-carcinogenic risk for adults and children was found to be at an acceptable level, and the carcinogenic risk was reduced by nearly an order of magnitude compared to that in the conventional method. Considering the relative biological effectiveness (RBA) of As, the 95% quantile of the total carcinogenic risk was 1.24E-5, a reduction of up to 36.41% compared to the uncorrected corresponding risk value of 1.95E-5. The carcinogenic risk of soil As for adults and children in the study area exceeded acceptable risk levels 1E-6, with oral ingestion of soil being the primary route of exposure. In addition, the results of the sensitivity analysis of the parameters showed that As concentration, daily oral ingestion rate of soils, and exposure duration of children had relatively larger effects for health risks. This work will provide a methodological and theoretical basis for achieving accurate risk assessment of As-contaminated sites and provide concepts for refined risk management.

Key words: contaminated site; arsenic (As); model parameters modification; relative bioavailability (RBA); probabilistic risk assessment

工业化和城市化进程的持续加快导致大量污染地块遗留, 威胁人类居住环境健康, 限制土地再开发利用^[1,2]. 重金属是地块主要污染物类型之一, 因其高蓄积性和高毒性而备受关注^[3], 其中砷污染地块最受关注. 据统计, 纳入建设用地土壤污染状况调查名录的污染地块中, As 污染地块占比为 53.2%^[4]. 暴露于超过安全剂量的砷污染环境中, 受体人群的皮肤、呼

吸系统和消化系统等均会受到不同程度的损害^[5], As 已被世卫组织列入一类致癌物清单.

健康风险评估是在污染识别基础上开展毒性评

收稿日期: 2023-02-21; 修订日期: 2023-04-17

基金项目: 国家重点研发计划项目 (2020YFC1806304)

作者简介: 袁贝 (1998 ~), 女, 硕士研究生, 主要研究方向为土壤污染风险管控, E-mail: yuanbei202206@163.com

* 通信作者, E-mail: duping@craes.org.cn

估和暴露评估以定量表征污染物对受体人群健康风险的过程,是污染地块管理过程中的重要一环^[6]。目前我国已构建较为系统和完善的建设用地风险评估技术体系,且风险评估可为污染地块的修复治理提供依据。然而,现行《建设用地土壤污染风险评估技术导则》(HJ 25.3-2019)在污染地块风险管理实践中表现出一定的局限性^[7,8]。特别是针对 As 污染地块,采用导则推荐模型和参数推算得到污染控制值远低于其环境背景值,很难满足其实际修复需求^[9]。模型参数和情景假设过于保守是影响 As 污染地块风险评估准确性的重要原因,如以含量最大值计算风险和经口摄入吸收因子(ABS_o)取值为 1 等。通过调研国内 2012~2021 年 223 个 As 污染地块发现,绝大多数是依据土壤背景值、国家或地方土壤环境质量标准制定,依据风险评估过程确定修复目标值的地块占比仅 1.3%。以标准值或区域背景值作为污染地块修复目标值不利于实现科学有效和精细化的污染地块风险管理。

模型参数是决定健康风险评估精确性的基础,导则推荐的传统风险评估基于确定数值的参数计算,可能导致高估或低估实际风险水平^[10,11]。尤其是针对污染面积大且污染分布复杂的大型污染地块,以污染物均值或最大值计算得到的风险值不能全面反映真实情况^[12]。近年来,概率分析方法在污染地块风险管控中发挥重要作用, Monte Carlo 模拟是常用来量化不确定性的概率风险评估方法^[13,14]。基于 Monte Carlo 模拟方法的概率风险评估可以传递参数不确定性,提供更加丰富完整的风险特征信息^[15]。如黄剑波等^[16]基于 Monte Carlo 模拟评估土壤重金属健康风险,并得到风险超过可接受水平的概率。此外,上述方法可为风险评估后的精细管控和修复提供理论依据。如 Zhang 等^[17]将生物可给性和 Monte Carlo 模拟同时纳入风险评估计算,所得修复目标值是传统方法推导值的数十倍。

除暴露参数选择的不确定性外,暴露情景假设过于保守也是影响 As 污染地块风险评估准确性的主要原因。随着对土壤污染物环境迁移和体内暴露等风险评估涉及过程认知的不断丰富和土壤污染物调查分析技术的发展进步,目前,优化风险评估过程在 As 污染地块风险管理中越来越受到重视。例如,美国环保署(US EPA)引入 As 的体外人体可给性测试,评估经口摄入土壤途径人体对 As 的利用度;英国提出基于“不同介质健康风险或允许摄入量等效”原则来确定 As 的修复目标值等^[18,19]。其中,US EPA 提出结合 As 相对生物有效性(relative bioavailability, RBA)的方法已得到广泛认可和应用^[20,21]。生物有效性是指污

染物通过皮肤接触、经口摄入或呼吸吸入途径被吸收进入生物体的量,包括绝对生物有效性和 RBA^[22]。针对 As 污染地块,导则(HJ 25.3-2019)推荐参数经口摄入吸收因子(ABS_o)为 1,即土壤 As 进入人体后被全部吸收并产生健康效应,然而实际上仅部分 As 生物有效性会产生健康风险。生物有效性可连通污染物含量与摄入剂量,有研究表明,基于此方法评估污染地块健康风险更具准确性^[23]。且目前已有指南文件规范 As 生物有效性的测试方法和程序,相较其他方法,基于生物有效性开展 As 污染地块风险评估更具实操性和规范性。我国也在实际管理实践中探索优化风险评估过程对 As 污染地块适用性,如雷城英等^[24]通过修正暴露参数和考虑生物有效性推算某 As 污染矿区场地的健康风险,得到更具实际应用价值的修复目标值。

鉴于此,本研究以某大型 As 污染地块为例,调查分析污染地块土壤中 As 污染特征,基于蒙特卡罗模拟拟合浓度数据,通过文献调研修正暴露参数,且充分考虑 As 生物有效性对风险评估的影响,在此基础上应用蒙特卡罗模拟开展概率风险评估。综合参数本土化、生物有效性分析和概率风险评估方法优化 As 污染地块风险评估过程,准确估计土壤 As 污染的健康风险,以期为研究区域土壤污染风险管控及后期修复治理提供更精准的科学依据。

1 材料与方 法

1.1 污染地块概况

如图 1 所示,研究区域为某大型 As 污染化工遗留地块,总面积近 542 667 m²,其北部有一个占地面积约 40 000 m²水池。地块的工业生产活动始于 2002 年,以生产二甲醚、甲醇等为主,主要设施已于 2018 年停工拆除。此前,地块所在区域南部为耕地,北部主要进行石灰石开采活动。前期调查结果显示,历史生产活动和设备拆除、客土等原因造成的地块土壤较大扰动是研究区域土壤 As 主要来源。土壤 As 污染范围分布广、超标范围深,且 As 有效态比例较低(0.000 3%~0.403%),说明通过淋溶途径污染地下水的环境风险较小。根据城市规划和设计,该地块未来用地情景为居住用地、公共管理与公共服务用地,属于《土壤环境质量 建设用地土壤污染风险管控标准(试行)》(GB 36600-2018)中规定的第一类用地^[25]。

1.2 样品采集和测试分析

污染地块采样布点遵循《建设用地土壤污染状况调查技术导则》(HJ 25.1-2019),结合专家判断和系统布点方法共设置土壤采样点 432 个,采样点分布见图 1。本地块土壤厚度为 0.2~9.0 m,采用锤击式

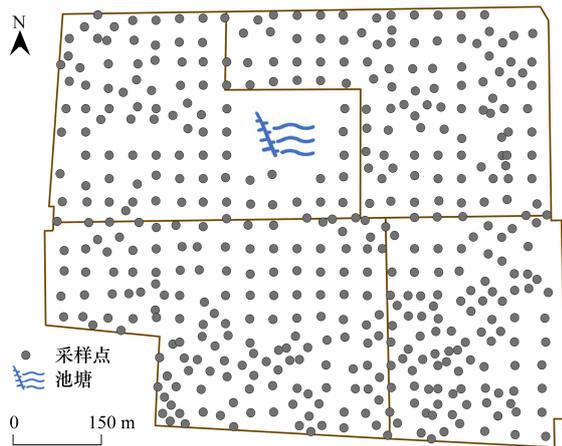


图1 研究区域范围及采样分布示意
Fig. 1 Study area and soil sampling sites

钻机(GP-50型和DP-15型)进行土壤钻探取样,依据地块土层结构分层采样,直至采集到基岩层为止.采用四分法取约1 kg土壤,清除植物根茎、砾石及其它杂质后装入聚乙烯塑料袋中保存.

土壤样品送至实验室内自然风干,过2 mm尼龙筛备用.土壤样品经 $\text{HNO}_3\text{-HCl-HClO}_4$ 消解后,使用原子荧光分光光度计(AFS,普析PF51)测定土壤As含量.样品采集和测试分析过程中均按照检测方法及相关规范要求严格进行质量控制,包括实验室平行样、实验室空白样、标准样品(国家标准土壤GSS-27)和加标回收等,均符合相关要求.

1.3 概率健康风险评估

依据《建设用地土壤污染风险评估技术导则》(HJ 25.3-2019)推荐模型开展成人和儿童的健康风险评估(包括致癌风险和非致癌风险)^[26].研究区域土壤主要污染物为As,暴露途径主要包括经口摄入土壤、皮肤接触土壤和吸入土壤颗粒物^[27].致癌风险和危害指数的计算公式详见导则(HJ 25.3-2019)附录A和附录C,其可接受风险水平分别为 $1\text{E-}6$ 和1.

Monte Carlo模拟作为一种量化风险评估不确定性的概率分析方法,已在污染地块健康风险评估领域得到广泛应用和认可^[28].本研究基于Monte Carlo模拟方法得到土壤As对健康风险的概率分布,主要流程和内容包括:①确定风险评估模型的随机变量;②构建随机变量的分布模型;③设置模型参数并运行模型;④分析模拟结果^[29].

1.4 数据分析

结合Crystal Ball 11.1.2.4(Oracle, USA)和Microsoft Excel 2019软件进行概率健康风险评估,设置软件在95%置信度下运行10 000次迭代.应用Origin 2023(Origin Lab, MA)和ArcGIS 10.8(ESRI, USA)进行数据分析和制图.

2 结果与讨论

2.1 土壤砷污染特征

污染地块表层土壤As含量统计特征如图2所示.表层土壤 $\omega(\text{As})$ 范围为 $2.70\sim 97.0\text{ mg}\cdot\text{kg}^{-1}$,均值为 $13.02\text{ mg}\cdot\text{kg}^{-1}$.分别有70.37%和7.01%的采样点表层土壤As含量超过背景值($9.3\text{ mg}\cdot\text{kg}^{-1}$)和相关标准(GB 36600-2018)规定的筛选值($20\text{ mg}\cdot\text{kg}^{-1}$),所有采样点表层土壤As含量均未超过管制值($120\text{ mg}\cdot\text{kg}^{-1}$)^[30].污染程度可用污染指数(P_i),即污染物含量和背景含量比值,进行直观判断.研究区域 P_i 均值介于1和2之间,说明处于轻微污染水平^[31].统计结果显示,变异系数为0.61,说明该污染地块表层土壤As含量存在较大空间分布差异.

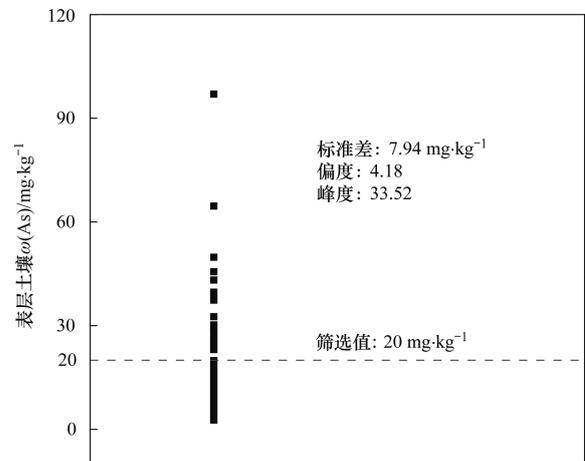


图2 污染地块表层土壤As含量统计
Fig. 2 Statistical characteristics of topsoil As concentration in the contaminated site

污染物含量分布受土壤性质、生产布局等诸多因素影响^[32, 33].进一步分析研究区域土壤As污染特征,得到如图3和图4所示的土壤As空间分布.绝大多数表层土壤As含量未超过筛选值,超标部分多以超过1~3倍为主.研究区域表层土壤As分布的空间连续性较差,局部区域污染严重.总体来看,土壤As检出含量随采样深度增加呈升高趋势变化,深层污染程度相对更为严重.深层土壤 $\omega(\text{As})$ 范围为 $0.91\sim 220.4\text{ mg}\cdot\text{kg}^{-1}$,均值为 $23.02\text{ mg}\cdot\text{kg}^{-1}$.超过背景值、筛选值和管制值的土壤样品占比分别为84.13%、25.48%和1.44%.污染深度基本处于0~6.0 m,仅部分点位As污染深度大于6.0 m但不超过9.0 m,主要集中在研究区域西北部.

2.2 传统健康风险评估

识别研究区域主要污染物为As,结合As毒性特点和地块土壤污染特征确定As主要由经口摄入土壤、皮肤接触土壤和呼吸吸入土壤颗粒物这3种途

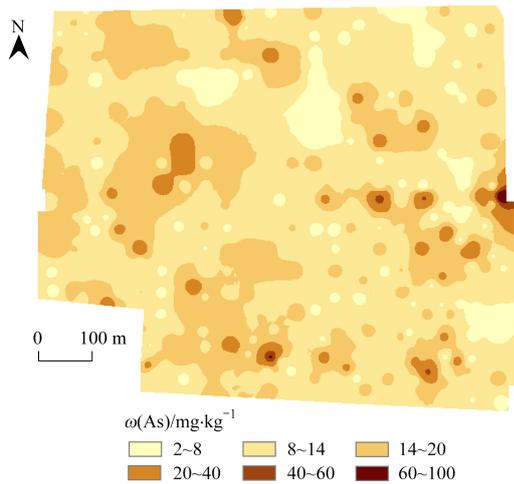


图3 污染地块表层土壤As含量空间分布

Fig. 3 Distribution of top soil As concentration in the contaminated site

径对受体人群造成危害。地块规划用途为第一类用地,评估的受体人群包括成人和儿童。暴露评估模型是简化和规范化污染地块风险评估程序的重要手段,在借鉴国外理论经验基础上,我国已构建本土化的暴露模型和暴露参数数据库。因此,采用导则(HJ 25.3-2019)推荐模型及模型参数展开风险评估,以使评估结果更加真实合理。

由上所述,基于保守原则以As含量最大值进行计算,结果如图5所示,经口摄入土壤是研究区域主

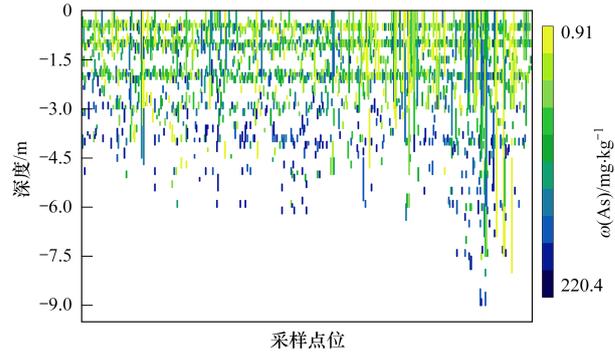
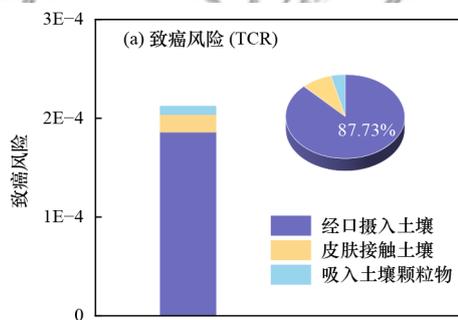


图4 污染地块土壤As含量垂向分布

Fig. 4 Vertical distribution of soil As concentration in the contaminated site

要暴露途径,该途径对致癌风险和非致癌风险的贡献率分别高达87.73%和77.38%。从致癌风险结果来看,As的总致癌风险为2.12E-4,远超过可接受风险水平1E-6,说明研究区域土壤As对受体人群存在致癌风险。特别是经口摄入土壤途径的致癌风险高达1.86E-4,相较另外两种暴露途径更应受到关注。同样地,As的危害指数为8.36,是可接受危害指数1的8.36倍,说明研究区域土壤As对受体人群存在一定的非致癌风险。其中,皮肤接触土壤途径的危害指数仅为5.52E-1,说明土壤As经该暴露途径对受体人群的非致癌风险可忽略。

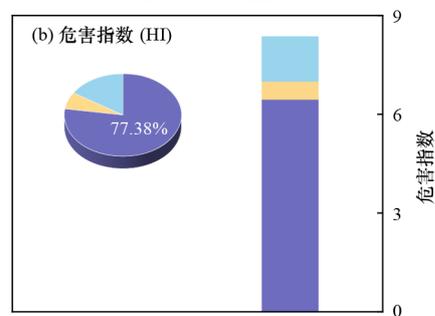


图5 研究区域土壤砷的健康风险

Fig. 5 Health risk of soil As in the study area

2.3 概率风险评估

2.3.1 模型参数修正

污染物含量是不可忽略的重要模型参数之一。传统风险评估常通过输入污染物含量最大值得到风险的单一估计,这一过程忽视了土壤污染物分布的异质性和复杂性,高估了实际的风险水平。本研究基于Monte Carlo模拟方法拟合土壤As含量的概率分布函数,分布函数的特征参数如表1所示,土壤样品As含量近似呈对数正态分布。应用Monte Carlo模拟方法开展概率风险评估时,需输入土壤As含量的对数正态分布函数。

为减少风险评估过程的不确定性,依据文献

表1 应用蒙特卡罗模拟污染地块土壤As含量的分布函数

项目	可能的分布函数	分布函数关键参数/mg·kg ⁻¹	
		均值	标准差
As	对数正态	12.96	6.86

资料对暴露参数进行进一步修正。居民生活水平随着社会发展有很大提升,相应地,人群特征及暴露行为模式暴露参数也处于不断更新变化中,包括成人和儿童的身高、体重、每日摄入土壤量和暴露皮肤表面积等^[34]。并且,暴露参数还具有鲜明的区域特征,Lin等^[35]采用结合土壤地理特点的示踪元素法,研究揭示我国儿童土壤摄入量的

地域差异. 因此, 应尽可能选取实测或可靠区域的实际暴露参数, 例如本研究空气中可吸入悬浮颗粒物 (PM₁₀) 浓度的取值参照污染地块所在地区

2021 年生态环境质量公报 (0.033 mg·m⁻³). 综上, 确定风险评估模型部分参数取值和来源如表 2 所示.

表 2 健康风险评估模型参数取值

Table 2 Parameter value of health risk assessment model

参数	单位	函数分布	成人	儿童	文献
体重(BW)	kg	正态分布	均值: 57.03; 标准差: 1.18	均值: 16.68; 标准差: 1.48	[22]
暴露期(ED)	a	均匀分布	最小值: 0; 最大值: 24	最小值: 0; 最大值: 6	[29]
暴露频率(EF)	d·a ⁻¹	三角分布	最小值: 180; 最可能值: 350; 最大值: 365		[29]
每日摄入土壤量(OSIR)	mg·d ⁻¹	对数正态	均值: 50; 标准差: 75	均值: 100; 标准差: 50	[36, 37]
每日空气呼吸量(DAIR)	m ³ ·d ⁻¹	单点分布	15.7	7.5	[36, 37]
暴露皮肤表面积(SAE)	cm ²	单点分布	5 518.45	2 848.01	[25, 38]
致癌效应平均时间(AT _{ca})	d	单点分布	28 543	28 543	[25, 39]

对于污染物毒性参数, 依据导则(HJ 25. 3-2019)附录 B 的外推模型公式, As 在呼吸吸入暴露途径下对应的致癌斜率因子和参考剂量除与 As 呼吸吸入单位致癌因子和呼吸吸入参考浓度有关外, 还与成人体重和成人每日空日呼吸量有关. 由前所述, 本研究

中, 成人每日呼吸量取值参照《中国人群环境暴露参数手册(成人卷)》^[36], 成人体重取值参照 2020 年发布的《中国居民营养与慢性病状况报告》(取成年男性和成年女性体重的平均值)^[38]. 风险评估模型涉及的 As 的毒性参数具体取值和来源如表 3 所示.

表 3 As 致癌斜率因子和参考剂量取值¹⁾

Table 3 Slope factors (SF) and corresponding reference dose (RfD) values of As

As	致癌斜率因子(以污染物/体重计)(mg·kg ⁻¹ ·d ⁻¹) ⁻¹			参考剂量(以污染物/体重计)(mg·kg ⁻¹ ·d ⁻¹) ⁻¹		
	SF _o	SF _d	SF _i	RfD _o	RfD _d	RfD _i
数值	1.50E+00	1.50E+00	1.76E+01	3.00E-4	3.00E-4	3.66E-6
文献	[25]	[25]	[25, 36, 38]	[25]	[25]	[25, 36, 38]

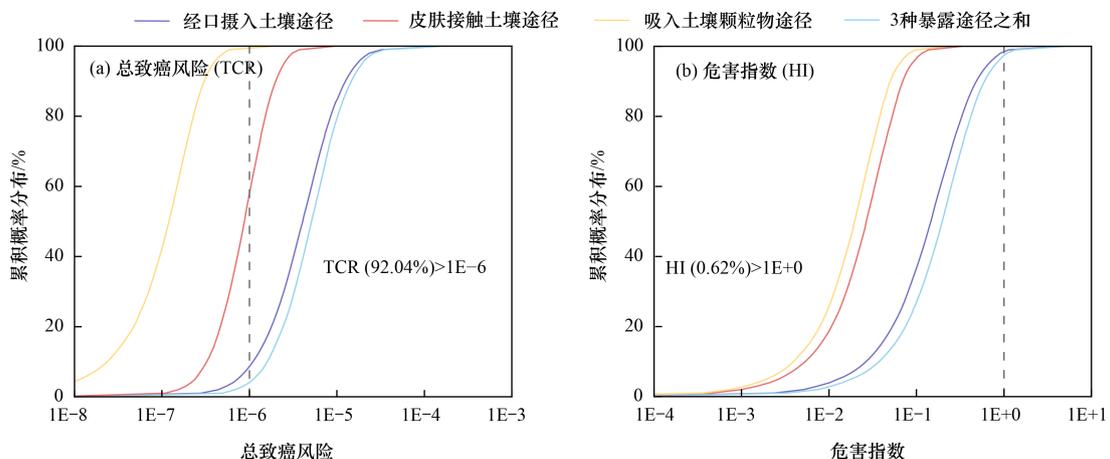
1) 下标“o”、“d”和“i”分别表示经口摄入土壤、皮肤接触土壤和吸入土壤颗粒物途径

2.3.2 概率健康风险评估

基于 Monte Carlo 模拟计算研究区域成人和儿童口摄入土壤、皮肤接触土壤和吸入土壤颗粒物这 3 种暴露途径的概率健康风险, 得到风险概率分布结果如图 6 所示.

围为 7.41E-5 ~ 5E+0, 均值为 1.97E-1, HI 大于 1 的概率仅为 0.62%. 值得注意的是, 基于 Monte Carlo 模拟计算得到危害指数的 95% 分位值小于 1, 可认为 As 对成人和儿童的非致癌风险处于可接受水平. 经口摄入土壤途径致癌风险和危害商的 95% 分位值分别为 1.70E-5 和 6.68E-1, 分别占总致癌风险和危害指数(95% 分位值)的 87.18% 和 82.78%. 经口摄入土壤是研究区域土壤 As 的主要暴露途径, 这与传统风

由图 6(a) 可见, 总致癌风险 (TCR) 的范围为 1.48E-8 ~ 1.62E-4, 均值为 5.12E-6, TCR 大于 1E-6 的概率为 92.04%. 图 6(b) 显示, 危害指数 (HI) 的范



虚线表示可接受风险水平, TCR 和 HI 超过可接受风险水平概率分别为 92.04% 和 0.62%

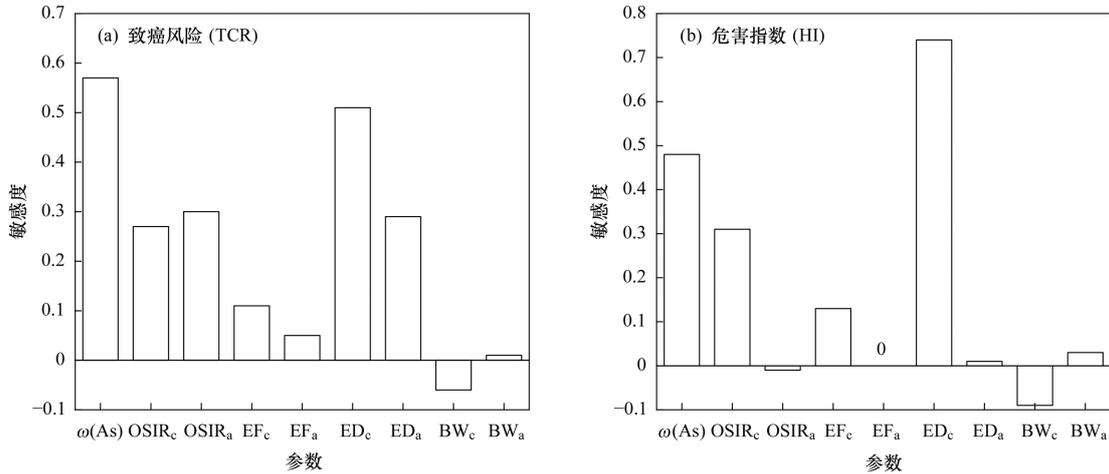
图 6 研究区域土壤 As 的概率健康风险

Fig. 6 Probabilistic health risk of soil As in the study area

险评估结论一致. 与传统风险评估相比, 概率风险评估可以得到更为丰富和真实的风险信息, 计算所得研究区域的健康风险 95% 分位值降低近 1 个数量级.

为探究暴露参数对研究区域土壤 As 致癌风险和非致癌风险的影响, 运行 Crystal Ball 11. 1. 2. 4 软件得到敏感性分析结果. 由图 7 可知, 对于致癌风险, As 含量和儿童暴露期是主要的敏感参数, 敏感度均超

过 50%, 其次是儿童暴露期和成人和儿童每日摄入土壤量; 对于非致癌风险, 儿童暴露期是主要的敏感参数, 敏感度高达 74%, 其次依次是 As 含量、儿童每日摄入土壤量, 敏感度分别为 48% 和 31%. 综上, 研究区域的风险管理除控制污染含量外, 还应重点关注每日土壤摄入量 and 儿童暴露期, 以有效防范健康风险.



OSIR_c、EF_c、ED_c 和 BW_c 表示儿童; OSIR_a、EF_a、ED_a 和 BW_a 表示成人

图 7 研究区域土壤 As 致癌风险和危害指数的参数敏感性分析

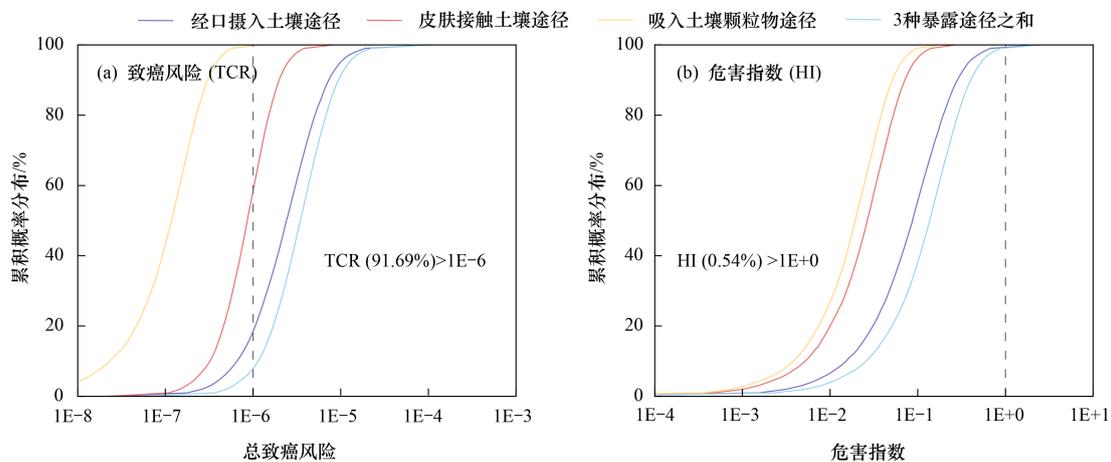
Fig. 7 Parameter sensitivity analysis of the total carcinogenic risk and hazard index for soil As in the study area

2.4 RBA 修正

土壤 As 进入人体后只有部分会被吸收作用, 因此, 根据总量推算健康风险是不符合实际的保守估计^[40]. 越来越多的研究考虑重金属生物有效性对经口摄入暴露的影响, 例如, 张加文等^[41]和保欣晨等^[42]结合实测目标重金属生物有效性和生物可给性计算健康风险, 结果显著低于基于总量评估的风险值. US EPA 较早推动将测定土壤 As 生物有效性纳入污染地块风险评估体系, 并取得系统和科学的研究成

果^[43]. US EPA 通过体内测试方法, 即使用模式动物给药暴露来确定 As 生物有效性, 取上述结果的 95% 分位值作为推荐经验值. 本研究依据 US EPA 推荐经验值, 即 RBA 值为 0.6, 修正土壤 As 经口摄入土壤途径的健康风险^[44].

如图 8 所示, 使用 RBA 值修正后, TCR 的范围为 $5.36E-8 \sim 1.10E-4$, TCR 大于 $1E-6$ 的概率为 91.69%; HI 的范围为 $1.22E-5 \sim 2.68E+0$, HI 大于 1 的概率仅为 0.54%. TCR 的和 HI 的均值分别为 3.47E



虚线表示可接受风险水平, TCR 和 HI 超过可接受风险水平概率分别为 91.69% 和 0.54%

图 8 RBA 修正后研究区域土壤 As 的概率健康风险

Fig. 8 Probabilistic health risk of soil As in the study area after adjustment with RBA values

-6 和 $1.37E-1$, 超过可接受风险水平的概率分别为 91.69% 和 0.54%。对于非致癌风险, 修正前后均可忽略其健康影响。对于致癌风险, 尽管修正前后都不可接受, 但引入 RBA 值后的致癌风险计算值相较之前有一定程度的降低, 其中 95% 分位值的降幅达到

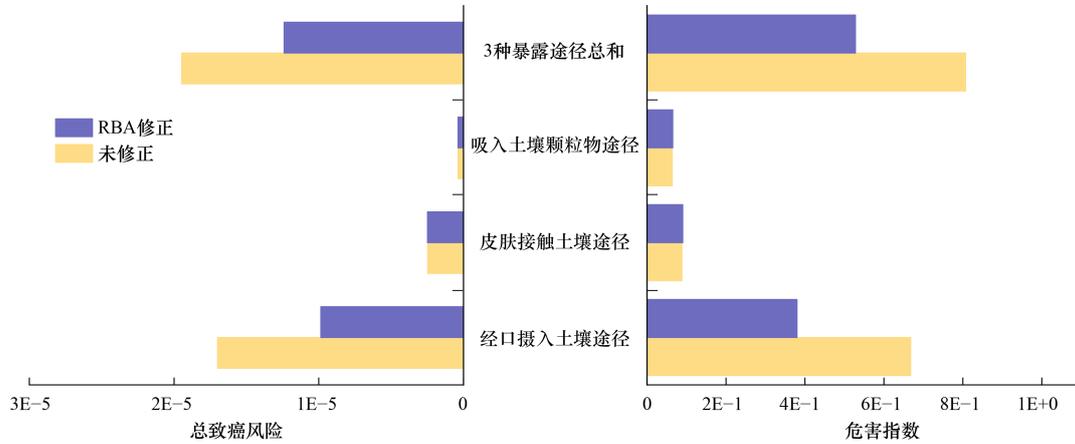


图9 研究区域土壤As致癌风险和危害指数的95%分位值

Fig. 9 The 95% quantile values of the total carcinogenic risk and hazard index for soil As in the study area

3 结论

(1) 案例地块表层土壤 $\omega(\text{As})$ 均值为 $13.02 \text{ mg}\cdot\text{kg}^{-1}$, 处于轻微污染水平, 分别有 70.37% 和 7.01% 采样点超过背景值和筛选值。工业生产活动加速 As 在土壤中累积, 导致土壤 As 的局部污染和空间分布异质性。设备拆除过程中对土壤造成较大扰动, 表层土壤 As 可向深层土壤迁移扩散, 进一步加剧了土壤 As 空间分布不确定性。土壤 As 空间分布复杂性是导致暴露风险评估存在不确定性的主要原因。

(2) 传统风险评估结果表明, As 的总致癌风险和危害指数分别为 $2.12E-4$ 和 8.36, 说明研究区域土壤 As 的健康风险不可忽略。然而, 传统方法在暴露情景刻画、模型参数选取等方面多是基于保守原则, 高估了研究区域实际的风险水平。精细化风险评估结果表明, 污染地块土壤 As 对受体人群致癌风险超过可接受致癌风险 $1E-6$ 的概率高于 90%, 而非致癌风险处于可接受风险水平的概率高于 95%。并且引入 As 生物有效性可显著降低经口摄入的健康风险。对比来看, 两种方法均可得出经口摄入土壤是研究区域土壤 As 主要暴露途径的一致结论, 不同的是, 精细化的风险评估方法可以得到更为丰富和真实的风险信息。

(3) 针对 As 污染地块, 现行风险评估导则的适用性不强, 制约 As 污染地块开展精细化风险评估的主要原因包括对土壤 As 暴露途径认知的不完善和实测数据的难以获取等。未来污染地块管理实践中, 应从

36.41% (图 9), 可以认为基于 As 总量而非生物有效性的风险评估高估了实际的健康风险。因此, 有必要考虑将生物有效性纳入风险评估体系, 以满足更科学、更精准的污染地块风险管理需求。这也与 Caussy^[45] 和 Kuppasamy 等^[46] 观点存在一致性。

精细化调整风险评估模型参数、充分考虑重金属污染物生物有效性、结合概率分析方法等角度出发, 以实现精准风险评估, 避免对 As 污染地块的过度修复。借鉴 USEPA 开展大量基础研究确定 As 的 RBA 值的经验, 未来研究应更注重广泛开展 As 生物有效性的基础实验, 积累不同土壤性质条件下 As 毒性、生物有效性等基本数据, 形成适应我国的 As 理化性质和毒理参数数据库, 推动尽快建立相关技术标准指南。

参考文献:

- [1] Li X N, Jiao W T, Xiao R B, *et al.* Contaminated sites in China: countermeasures of provincial governments [J]. *Journal of Cleaner Production*, 2017, **147**: 485-496.
- [2] 廖晓勇, 崇忠义, 阎秀兰, 等. 城市工业污染场地: 中国环境修复领域的新课题 [J]. *环境科学*, 2011, **32**(3): 784-794.
Liao X Y, Chong Z Y, Yan X L, *et al.* Urban industrial contaminated sites: a new issue in the field of environmental remediation in China [J]. *Environmental Science*, 2011, **32**(3): 784-794.
- [3] Yan K, Wang H Z, Lan Z, *et al.* Heavy metal pollution in the soil of contaminated sites in China: Research status and pollution assessment over the past two decades [J]. *Journal of Cleaner Production*, 2022, **373**, doi: 10.1016/j.jclepro.2022.133780.
- [4] 生态环境部. 全国污染地块土壤环境管理系统 [EB/OL]. <http://222.190.123.53:8080/pub/jshbw/ywxt/trhjglxt/index.html>, 2022-12-16.
- [5] Mahimairaja S, Bolan N S, Adriano D C, *et al.* Arsenic contamination and its risk management in complex environmental settings [J]. *Advances in Agronomy*, 2005, **86**: 1-82.
- [6] 陈梦舫, 骆永明, 宋静, 等. 中、英、美污染场地风险评估导则异同与启示 [J]. *环境监测管理与技术*, 2011, **23**(3): 14-18.
Chen M F, Luo Y M, Song J, *et al.* Comparison of USA, UK and

- Chinese risk assessment guidelines and the implications for China [J]. *The Administration and Technique of Environmental Monitoring*, 2011, **23**(3): 14-18.
- [7] Dong Z M, Liu Y J, Duan L C, *et al.* Uncertainties in human health risk assessment of environmental contaminants: a review and perspective[J]. *Environment International*, 2015, **85**: 120-132.
- [8] 姜林, 梁竞, 钟茂生, 等. 复杂污染场地的风险管理挑战及应对[J]. *环境科学研究*, 2021, **34**(2): 458-467.
- Jiang L, Liang J, Zhong M S, *et al.* Challenges and response to risk management of complex contaminated sites [J]. *Research of Environmental Sciences*, 2021, **34**(2): 458-467.
- [9] 周友亚, 姜林, 张超艳, 等. 我国污染场地风险评估发展历程概述[J]. *环境保护*, 2019, **47**(8): 34-38.
- Zhou Y Y, Jiang L, Zhang C Y, *et al.* Development of risk assessment of contaminated sites in China [J]. *Environmental Protection*, 2019, **47**(8): 34-38.
- [10] 王蕊, 陈楠, 张二喜. 基于总量与形态的矿区周边土壤重金属生态风险与健康风险评估[J]. *环境科学*, 2022, **43**(3): 1546-1557.
- Wang R, Chen N, Zhang E X. Ecological and health risk assessments based on the total amount and speciation of heavy metals in soils around mining areas [J]. *Environmental Science*, 2022, **43**(3): 1546-1557.
- [11] 张秀秀, 朱昌达, 王飞, 等. 南京城郊不同土地利用类型农业土壤多环芳烃污染特征及风险评价[J]. *环境科学*, 2023, **44**(2): 944-953.
- Zhang X X, Zhu C D, Wang F, *et al.* Pollution characteristics and risk assessment of polycyclic aromatic hydrocarbons in agricultural soils of different land use types in Nanjing suburbs [J]. *Environmental Science*, 2023, **44**(2): 944-953.
- [12] 孙兴凯, 黄海, 王海东, 等. 大型污染场地修复过程中的问题探讨与工程实践[J]. *环境工程技术学报*, 2020, **10**(5): 883-890.
- Sun X K, Huang H, Wang H D, *et al.* Discussion of problems in the process of large-scale contaminate sites remediation and project practice [J]. *Journal of Environmental Engineering Technology*, 2020, **10**(5): 883-890.
- [13] 杨湜烟, 刘杏梅, 徐建明. 土壤重金属污染健康风险评估新视角——概率风险评估的源起及展望[J]. *土壤学报*, 2022, **59**(1): 28-37.
- Yang S Y, Liu X M, Xu J M. New perspectives about health risk assessment of soil heavy metal pollution—origin and prospects of probabilistic risk analysis [J]. *Acta Pedologica Sinica*, 2022, **59**(1): 28-37.
- [14] Peng J Y, Zhang S, Han Y Y, *et al.* Soil heavy metal pollution of industrial legacies in China and health risk assessment[J]. *Science of the Total Environment*, 2022, **816**, doi: 10.1016/j.scitotenv.2021.151632.
- [15] U. S. Environmental Protection Agency. Risk assessment guidance for superfund: Volume III - Part A, process for conducting probabilistic risk assessment [R]. Washington: Office of Emergency and Remedial Response, U. S. Environmental Protection Agency, 2001.
- [16] 黄剑波, 姜登登, 温冰, 等. 基于蒙特卡罗模拟的铅锌冶炼厂周边农田土壤重金属健康风险评估[J]. *环境科学*, 2023, **44**(4): 2204-2214.
- Huang J B, Jiang D D, Wen B, *et al.* Contamination and probabilistic health risk assessment of heavy metals in agricultural soils around a lead-zinc smelter [J]. *Environmental Science*, 2023, **44**(4): 2204-2214.
- [17] Zhang R H, Han D, Jiang L, *et al.* Derivation of site-specific remediation goals by incorporating the bioaccessibility of polycyclic aromatic hydrocarbons with the probabilistic analysis method [J]. *Journal of Hazardous Materials*, 2020, **384**, doi: 10.1016/j.jhazmat.2019.121239.
- [18] U. S. Environmental Protection Agency. Standard operating procedure for an in vitro bioaccessibility assay for lead and arsenic in soil [R]. Washington: U. S. Environmental Protection Agency, 2017.
- [19] Department for Environment, Food and Rural Affairs. Guidance on the legal definition of contaminated land [R]. London: Department for Environment, Food and Rural Affairs, 2008.
- [20] 孙刚, 刘针延, 夏梦帆, 等. 基于生物可利用性的砷污染土壤修复目标值研究[J]. *环境科学学报*, 2022, **42**(11): 267-274.
- Sun G, Liu Z Y, Xia M F, *et al.* Target for remediation based on bioavailability in arsenic-contaminated soil [J]. *Acta Scientiae Circumstantiae*, 2022, **42**(11): 267-274.
- [21] 李士伟. 污染土壤中典型重金属的人体生物有效性研究[D]. 南京: 南京大学, 2017.
- [22] 唐文忠, 孙柳, 单保庆. 土壤/沉积物中重金属生物有效性和生物可利用性的研究进展[J]. *环境工程学报*, 2019, **13**(8): 1775-1790.
- Tang W Z, Sun L, Shan B Q. Research progress of bioavailability and bioaccessibility of heavy metals in soil or sediment [J]. *Chinese Journal of Environmental Engineering*, 2019, **13**(8): 1775-1790.
- [23] Sun Y M, Shen J L, Sun Z Q, *et al.* A bibliometric analysis and assessment of priorities for heavy metal bioavailability research and risk management in contaminated land [J]. *Environmental Geochemistry and Health*, 2023, **45**(6): 2691-2704.
- [24] 雷城英, 李玉进, 王梦珂, 等. C-RAG模型在砷污染场地中的修正及应用研究[J]. *生态毒理学报*, 2021, **16**(1): 147-154.
- Lei C Y, Li Y J, Wang M K, *et al.* Research on modification and application of C-RAG model in arsenic contaminated site [J]. *Asian Journal of Ecotoxicology*, 2021, **16**(1): 147-154.
- [25] GB 36600-2018, 土壤环境质量 建设用地土壤污染风险管控标准(试行)[S].
- [26] HJ 25.3-2019, 建设用地土壤污染风险评估技术导则[S].
- [27] Li J, Fan J T, Jiang J Y, *et al.* Human health risk assessment of soil in an abandoned arsenic plant site: implications for contaminated site remediation [J]. *Environmental Earth Sciences*, 2019, **78**(24), doi: 10.1007/s12665-019-8715-0.
- [28] Öberg T, Bergbäck B. A review of probabilistic risk assessment of contaminated land (12 pp) [J]. *Journal of Soils and Sediments*, 2005, **5**(4): 213-224.
- [29] Yuan B, Cao H L, Du P, *et al.* Source-oriented probabilistic health risk assessment of soil potentially toxic elements in a typical mining city [J]. *Journal of Hazardous Materials*, 2023, **443**, doi: 10.1016/j.jhazmat.2022.130222.
- [30] 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.
- [31] 李强, 曹莹, 何连生, 等. 典型冶炼行业场地土壤重金属空间分布特征及来源解析[J]. *环境科学*, 2021, **42**(12): 5930-5937.
- Li Q, Cao Y, He L S, *et al.* Spatial distribution characteristics and source analysis of soil heavy metals at typical smelting industry sites [J]. *Environmental Science*, 2021, **42**(12): 5930-5937.
- [32] 刘庚, 石瑛, 田海金, 等. 某大型神渣场地土壤As污染特征及生态风险评估[J]. *环境科学*, 2018, **39**(12): 5639-5646.
- Liu G, Shi Y, Tian H J, *et al.* Soil pollution characteristics and

- ecological risk assessment of As at a large-scale arsenic slag-contaminated site [J]. *Environmental Science*, 2018, **39** (12): 5639-5646.
- [33] Wu Y F, Li X, Yu L, *et al.* Review of soil heavy metal pollution in China: spatial distribution, primary sources, and remediation alternatives [J]. *Resources, Conservation and Recycling*, 2022, 181, doi: 10.1016/j.resconrec.2022.106261.
- [34] 杨彦, 张梦迪, 陈浩佳, 等. 中国人群暴露参数研究进展[J]. *环境科学研究*, 2022, **35**(9): 2205-2215.
Yang Y, Zhang M D, Chen H J, *et al.* Research progress in environmental exposure factors of Chinese population [J]. *Research of Environmental Sciences*, 2022, **35**(9): 2205-2215.
- [35] Lin C Y, Wang B B, Cui X Y, *et al.* Estimates of soil ingestion in a population of Chinese children [J]. *Environmental Health Perspectives*, 2017, **125**(7), doi: 10.1289/EHP930.
- [36] 段小丽. 中国人群暴露参数手册概要(儿童卷)概要[M]. 北京: 中国环境出版社, 2016.
Duan X L. Highlights of the Chinese exposure factors handbook (children) [J]. Beijing: China Environmental Science Press, 2016.
- [37] 赵秀阁, 段小丽. 中国人群暴露参数手册(成人卷)概要[J]. 北京: 中国环境出版社, 2014.
Zhao X G, Duan X L. Highlights of the Chinese exposure factors handbook (adults) [J]. Beijing: China Environmental Science Press, 2014.
- [38] 中国居民营养与慢性病状况报告(2020年)[J]. *营养学报*, 2020, **42**(6): 521.
- [39] World Health Organization (WHO). World health statistics 2020: monitoring health for the SDGs, sustainable development goals [EB/OL]. <https://www.who.int/data/gho/publications/world-health-statistics>, 2020-05-13.
- [40] Ruby M V, Schoof R, Brattin W, *et al.* Advances in evaluating the oral bioavailability of inorganics in soil for use in human health risk assessment [J]. *Environmental Science & Technology*, 1999, **33** (21): 3697-3705.
- [41] 张加文, 田彪, 罗晶晶, 等. 土壤重金属生物可利用性影响因素及模型预测[J]. *环境科学*, 2022, **43**(7): 3811-3824.
Zhang J W, Tian B, Luo J J, *et al.* Effect factors and model prediction of soil heavy metal bioaccessibility [J]. *Environmental Science*, 2022, **43**(7): 3811-3824.
- [42] 保欣晨, 马骄阳, 徐武美, 等. 西南某矿区土壤重金属的人体生物有效性及健康风险评估[J]. *土壤学报*, 2023, **60**(2): 458-468.
Bao X C, Ma J Y, Xu W M, *et al.* Human bioavailability and health risk assessment of heavy metals in soils from a mining area of southwest China [J]. *Acta Pedologica Sinica*, 2023, **60** (2): 458-468.
- [43] U. S. Environmental Protection Agency. Guidance for evaluating the oral bioavailability of metals in soils for use in human health risk assessment [R]. Washington: U. S. Environmental Protection Agency, 2007.
- [44] U. S. Environmental Protection Agency. Compilation and review of data on relative bioavailability of arsenic in soil [R]. Washington: U. S. Environmental Protection Agency, 2012.
- [45] Caussy D. Case studies of the impact of understanding bioavailability: arsenic [J]. *Ecotoxicology and Environmental Safety*, 2003, **56**(1): 164-173.
- [46] Kuppasamy S, Venkateswarlu K, Megharaj M, *et al.* Risk-based remediation of polluted sites: a critical perspective [J]. *Chemosphere*, 2017, **186**: 607-615.

CONTENTS

Impacts of Anthropogenic Emission Reduction on Urban Atmospheric Oxidizing Capacity During the COVID-19 Lockdown	ZHU Jian-lan, QIN Mo-mei, ZHU Yan-hong, <i>et al.</i> (617)
Transport and Potential Sources Regions of Double High Pollution in Nanjing by Different Synoptic Situations	QIN Yang, HU Jian-lin, KONG Hai-jiang (626)
Differences of Three Methods in Determining Ozone Sensitivity in Nanjing	CHEN Gan-yu, LI Xun, LI Lin, <i>et al.</i> (635)
Characteristics of Ozone Concentration in Shanghai and Its Associated Atmospheric Circulation Background During Summer Half-years from 2006 to 2021	ZHENG Qing-feng, LIANG Ping, DUAN Yu-sen, <i>et al.</i> (645)
Distribution Characteristics of Near Surface Ozone Volume Fraction in Shanxi Province Based on Atmospheric Composition Observation Network	LI Ying, WANG Shu-min, PEI Kun-ning, <i>et al.</i> (655)
Photochemical Mechanism and Control Strategy Optimization for Summertime Ozone Pollution in Yining City	WANG Wen-ting, GU Chao, LI Li-ming, <i>et al.</i> (668)
Characteristics, Sources, and Ozone-sensitive Species of VOCs in Four Seasons in Yuncheng	YIN Shi-jie, LIU Xin-gang, LIU Ya-fei, <i>et al.</i> (678)
Pollution Characteristics, Source Analysis, and Activity Analysis of Atmospheric VOCs During Winter and Summer Pollution in Zhengzhou	LAI Meng-jie, ZHANG Dong, YU Shi-jie, <i>et al.</i> (689)
Pollution Characteristics, Sources, and Secondary Generation of Organic Acids in PM _{2.5} in Zhengzhou	LI Zi-han, DONG Zhe, SHANG Lu-qi, <i>et al.</i> (700)
Nonlinear Variations in PM _{2.5} Concentration in the Three Major Urban Agglomerations in China	WU Shu-qi, GU Yang-yang, ZHANG Tian-yue, <i>et al.</i> (709)
Medium and Long-term Carbon Emission Projections and Emission Reduction Potential Analysis of the Lingang Special Area Based on the LEAP Model	WU Qiong, MA Hao, REN Hong-bo, <i>et al.</i> (721)
Dynamic Analysis on Carbon Metabolism of the Northern Region of China Under the Background of Carbon Emission Trading Policy	ZHENG Hong-mei, SHEN Fang, XU Guang-yao, <i>et al.</i> (732)
Carbon Reduction Analysis of Life Cycle Prediction Assessment of Hydrogen Fuel Cell Vehicles; Considering Regional Features and Vehicle Type Differences	MA Jing, CAI Xu, ZHANG Chun-mei, <i>et al.</i> (744)
Nitrate Pollution Characteristics and Its Quantitative Source Identification of Major River Systems in China	WEI Ying-huai, HU Min-peng, CHEN Ding-jiang (755)
Effects of Land Use Structure and Spatial Pattern at Different Temporal and Spatial Scales on Water Quality in Suzhou Creek	TAN Juan, XIONG Li-jun, WANG Qing, <i>et al.</i> (768)
Spatial-temporal Variation in Water Quality of Rain-source Rivers in Shenzhen from 2015 to 2021 and Its Response to Rainfall	WEI Bi-ying, CHENG Jian-mei, SU Xiao-yu, <i>et al.</i> (780)
Chemical Characteristics of Shallow Groundwater in the Yellow River Diversion Area of Henan Province and Identification of Main Control Pollution Sources	WANG Shuai, REN Yu, GUO Hong, <i>et al.</i> (792)
Chemical Characteristics and Genetic Analysis of Karst Groundwater in the Beijing Xishan Area	GUO Gao-xuan, DAI Yin-dong, XU Liang, <i>et al.</i> (802)
Hydrochemical Characteristics and Its Origin of Surface Water and Groundwater in Dianbu River Basin	ZHENG Tao, QIN Xian-yan, WU Jian-xiong (813)
Hydrochemical Characteristics and Genesis Mechanism of Groundwater in the Dry Period in the Zhangjiakou Area	JIN Ai-fang, YIN Xiu-lan, LI Chang-qing, <i>et al.</i> (826)
Distribution of Typical Resistant Bacteria and Resistance Genes in Source Water of the Middle and Lower Reaches of the Yellow River	MIN Wei, GAO Ming-chang, SUN Shao-fang, <i>et al.</i> (837)
Contamination Characteristics, Detection Methods, and Control Methods of Antibiotic Resistance in Pharmaceutical Wastewater	PENG An-ping, GAO Hu, ZHANG Xin-bo (844)
Effect of Water Components on Aggregation and Sedimentation of Polystyrene Nano-plastics	TANG Duan-yang, ZHENG Wen-li, CHEN Guan-tong-yi, <i>et al.</i> (854)
Lead Removal from Water by Calcium-containing Biochar with Saturated Phosphate	LIU Tian, LÜ Si-lu, DU Xing-guo, <i>et al.</i> (862)
Preparation of Chitosan-modified Biochar and Its Adsorption Mechanism for Cd ²⁺ in Aqueous Solution	JIANG Ling, AN Jing-yue, YUE Xiao-qiong, <i>et al.</i> (873)
Efficacy and Mechanism of Tetracycline Adsorption by Boron-doped Mesoporous Carbon	ZOU Zhen, XU Lu, QIAO Wei, <i>et al.</i> (885)
Adsorption Properties of Magnetic Phosphorous Camellia Oleifera Shells Biochar to Sulfamethoxazole in Water	HAN Shuai-peng, TANG Li-wen, LIU Qin, <i>et al.</i> (898)
High Resolution Emission Inventory of Greenhouse Gas and Its Characteristics in Guangdong, China	LU Qing, TANG Ming-shuang, LIAO Tong, <i>et al.</i> (909)
Ecosystem CO ₂ Exchange and Its Environmental Regulation of a Restored Wetland in the Liaohe River Estuary	LIU Si-qi, CHEN Hong, XING Qing-hui, <i>et al.</i> (920)
Effects of Biochar Application Two Years Later on N ₂ O and CH ₄ Emissions from Rice-Vegetable Rotation in a Tropical Region of China	HU Yu-jie, TANG Rui-jie, HU Tian-yi, <i>et al.</i> (929)
Research and Application Progress of Biochar in Amelioration of Saline-Alkali Soil	WEI Ying, JIAO Le, ZHANG Peng, <i>et al.</i> (940)
Effect of No-tillage on Soil Aggregates in Farmland: A Meta Analysis	XU Yi-ping, RAO Yue-yue, MENG Yan, <i>et al.</i> (952)
Spatio-temporal Evolution and Multi-scenario Simulation of Carbon Storage in Karst Regions of Central Guizhou Province: Taking Puding County as an Example	LI Yue, LUO Hong-fen (961)
Effects of Different Modifiers on Aggregates and Organic Carbon in Acidic Purple Soil	LI Yue, XU Man, XIE Yong-hong, <i>et al.</i> (974)
Effect of Ca Modified Biochar on the Chemical Speciation of Soil Phosphorus and Its Stabilization Mechanism	ZHANG Chao, ZHAI Fu-jie, SHAN Bao-qing (983)
Plant Diversity Changes and Its Driving Factors of Abandoned Land at Different Restoration Stages in the Middle of the Qinling Mountains	YAN Cheng-long, XUE Yue, WANG Yi-fei, <i>et al.</i> (992)
Contamination Characteristics and Ecological Risk of Antibiotics in Contaminated Sites of Typical Pharmaceutical Factories in China	YANG Jiong-bin, HUANG Zheng, ZHAO Jian-liang, <i>et al.</i> (1004)
Pollution Characteristics and Risk Assessment of Polycyclic Aromatic Hydrocarbons in Soils of Guangzhou	ZOU Zi-hang, CHEN Lian, ZHANG Pei-zhen, <i>et al.</i> (1015)
Quantifying the Contribution of Soil Heavy Metals to Ecological and Health Risk Sources	PAN Yong-xing, CHEN Meng, WANG Xiao-tong (1026)
Potential Ecological Risk Characteristics and Source Apportionment of Heavy Metals in Farmland Soils around Typical Factories in Hunan Province Based on Monte-Carlo Simulation	LUO Hao-jie, PAN Jun, CHEN Xiao-xia, <i>et al.</i> (1038)
Health Risk Assessment for an Arsenic-contaminated Site Based on Monte Carlo Simulation and Parameters Optimization	YUAN Bei, LIU Hu-peng, DU Ping, <i>et al.</i> (1049)
Pollution Source Apportionment of Heavy Metals in Cultivated Soil Around a Red Mud Yard Based on APCS-MLR and PMF Models	SHEN Zhi-jie, LI Jie-qin, LI Cai-xia, <i>et al.</i> (1058)
Characteristics and Mechanism of Cd Release and Transport in Soil Contaminated with PE-Cd	WANG Di, XU Shao-hui, SHAO Ming-yan, <i>et al.</i> (1069)
Characterization of Reductive Dechlorination of Chlorinated Ethylenes by Anaerobic Consortium	LI Wei, LIU Gui-ping, LIU Jun, <i>et al.</i> (1080)
Analysis of Heavy Metal Pollution Evaluation and Correlation of Farmland Soil and Vegetables in Zhaotong City	ZHANG Hao, DONG Chun-yu, YANG Hai-chan, <i>et al.</i> (1090)
Safe Utilization Effect of Passivator on Mild to Moderate Cadmium Contaminated Farmland	WANG Xiao-jing, ZHANG Dong-ming, CAO Yang, <i>et al.</i> (1098)
Simultaneous Immobilization of Cadmium and Arsenic in Paddy Soils with Novel Fe-Mn Combined Graphene Oxide	YUAN Jing, WU Ji-zi, LIAN Bin, <i>et al.</i> (1107)
Effects of the Application of Irrigation Water Containing Zn at the Key Growth Period on the Uptake and Transport of Cd in Rice	ZHOU Xia, HU Yu-dan, ZHOU Hang, <i>et al.</i> (1118)
Effects of Exogenous Zinc on Growth and Root Architecture Classification of Maize Seedlings Under Cadmium Stress	ZHANG Hui-hong, WEI Chang, LIU Hai-tao, <i>et al.</i> (1128)
Mitigative Effect of Rare Earth Element Cerium on the Growth of Zinc-stressed Wheat (<i>Triticum aestivum</i> L.) Seedlings	ZHANG Jing-jing, XU Zheng-yang, JIAO Qiu-juan, <i>et al.</i> (1141)
Two-stage Inhibition Effects of <i>Burkholderia</i> sp. Y4 Application on Cadmium Uptake and Transport in Wheat	GUO Jia-jia, WANG Chang-rong, LIU Zhong-qi, <i>et al.</i> (1150)
Effects of Combined Stress of High Density Polyethylene Microplastics and Chlorimuron-ethyl on Soybean Growth and Rhizosphere Bacterial Community	HU Xiao-yue, HUA Zi-wei, YAO Lun-guang, <i>et al.</i> (1161)
Human Accumulation and Toxic Effects of Microplastics: A Critical Review	BAO Ya-bo, WANG Cheng-chen, PENG Wu-guang, <i>et al.</i> (1173)
Overview of the Application of Machine Learning for Identification and Environmental Risk Assessment of Microplastics	BAI Run-hao, FAN Rui-qi, LIU Qi, <i>et al.</i> (1185)
Research Process on the Combined Pollution of Microplastics and Typical Pollutants in Agricultural Soils	HOU Yu-qing, LI Bing, WANG Jin-hua, <i>et al.</i> (1196)
Research Progress in Electrochemical Detection and Removal of Micro/Nano Plastics in Water	ZHENG Wei-kang, LIU Zhen-zhong, XIANG Xiao-fang (1210)
Factors Influencing Willingness of Farmers to Pay for Agricultural Non-point Source Pollution Control Based on Distributed Cognitive Theory	GUO Chen-hao, LI Lin-fei, XIA Xian-li (1222)