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目 次

	`
务4里77米州四北水冶区外间积及 FM _{2.5} 可决泰路的健康//	,
雾霾重污染期间北京居民对高浓度 PM _{2.5} 持续暴露的健康风险及其损害价值评估 谢元博,陈娟,李巍(1 长白山 PM _{2.5} 中水溶性离子季节变化特征研究 赵亚南,王跃思,温天雪,戴冠华(9 青岛大气颗粒物数浓度变化及对能见度的影响 柯馨姝,盛立芳,孔君,郝泽彤,屈文军(15)
青岛大气颗粒物数浓度变化及对能见度的影响 村馨姝,盛立芳,孔君,郝泽彤,屈文军(15)
重庆市大气二匹英污染水平及季节变化 张晓岭,卢益,朱明吉,蹇川,郭志顺,邓力,孙静,张芹,罗财红(22)
西南地区再生铝冶炼行业二哌英大气排放 卢益,张晓岭,郭志顺,蹇川,朱明吉,邓力,孙静,张芹(30)
西南地区新型干法水泥生产中的二噁英大气排放 张晓岭,卢益,蹇川,郭志顺,朱明吉,邓力,孙静,张芹(35)
- D. III-) - I. D. II- P. J. D. I. J. D. A. D. D. A. D.	
模拟不同排放源排放颗粒及多环芳烃的粒径分布研究	í
川东北地区元素大气沉降通鼻及其季节变化	í
青庄市结山坡 2001。2010 年齡沉降亦化 — 全海祥 马苇苇 河烟)
杭州市办公场所至内空气中 PBDEs 的污染现状与特征 将欣慰,孙鑫,裴小强,金漫形,李云龙,沈字优(41 模拟不同排放源排放颗粒及多环芳烃的粒径分布研究 符海欢,田娜,商惠斌,张彬,叶素芬,陈晓秋,吴水平(46 川东北地区元素大气沉降通量及其季节变化 童晓宁,周厚云,游镇烽,汤静,刘厚均,黄颖,贺海波(53 重庆市铁山坪 2001~2010 年酸沉降变化 余德祥,马萧萧,谭炳全,赵大为,张冬保,段雷(60 汉江上游金水河流域氮湿沉降 王金杰,张克荣,吴川,张全发(66 麦秸及其烟尘中正构脂肪酸的组成 刘刚,李久海,吴丹,徐慧(73 兰州市室内大气降尘环境磁学特征及其随高度变化研究 吴铎,魏海涛,赵瑞瑞,张蕊,刘建宝(79 中亚热带针阔混交林土壤-大气界面释汞通量研究 马明,王定勇,申源源,孙荣国,黄礼昕(85 水稻秸秆生物炭对耕地土壤有机碳及其 CO ₂ 释放的影响 柯跃进,胡学玉,易卿,余忠(93 黄海和东海海域溶解铋地球化学分布特征 吴晓丹,宋金明,吴斌,李学刚(100 浑河上游(清原段)水环境中重金属时空分布及污染评价 马迎群,时瑶,秦延文,郑丙辉,赵艳民,张雷(108)
(X.仁工///) 建水闩机, 以须, 似. (M.) 以, 水, 大川, 木, 大, 大, 大川, 木, 大,	/
友情及共阳至中上性构脂加酸的组取)
三州巾室内人气降尘外境幽学特征及其随高度变化研究 ————————————————————————————————————)
中业热带针阔泥交林土壤-大气界面释汞迪量研究)
水稻秸秆生物炭对耕地土壤有机碳及其 CO ₂ 释放的影响 柯跃进,胡学玉,易卿,余忠(93)
黄海和东海海域溶解铋地球化学分布特征 吴晓丹,宋金明,吴斌,李学刚(100)
浑河上游(清原段)水环境中重金属时空分布及污染评价 马迎群,时瑶,秦延文,郑丙辉,赵艳民,张雷(108)
POCIS 采样技术应用于九龙江流域水环境中雌激素的检测)
降雨条件下岩溶地下水微量元素变化特征及其环境意义)
福林河流域地表水水化学主喜子特征及控制因素·	/
- Managara Pangara P	`
一	/
J 7 何小尔·西加烈杀虫风及军问刀·甲存证。)
水稻种植对中业热带红壤丘陵区小流域氮磷养分输出的影响 宋立芳,王毅,吴金水,李勇,李裕元,孟岑,李航,张满意(150 黄东海表层沉积物中磷的分布特征 宋国栋,刘素美,张国玲(157 河流沉积物中有机磷提取剂(NaOH-EDTA)提取比例与机制研究 张文强,单保庆,张洪,唐文忠(163 沉积物短期扰动下 BAPP 再生和转化机制 武晓飞,李大鹏,汪明(171 三峡库区典型农村型消落带沉积物风险评价与重金属来源解析 敖亮,雷波,王业春,周谐,张晟(179 太湖东部不同类型湖区疏浚后沉积物重金属污染及潜在生态风险评价	`
*************************************)
更东海表层沉积初中僻的分布特征 · · · · · · · · · · · · · · · · · · ·)
河流沉积物中有机磷提取剂(NaOH-EDTA)提取比例与机制研究 ····································)
沉积物短期扰动下 BAPP 再生和转化机制 武晓飞,李大鹏,汪明(171)
三峡库区典型农村型消落带沉积物风险评价与重金属来源解析 敖亮,雷波,王业春,周谐,张晟(179)
太湖东部不同类型湖区疏浚后沉积物重金属污染及潜在生态风险评价	
)
滇池沉积物中主要污染物含量时间分异特征研究 王心宇,周丰,伊旋,郭怀成(194)
浓度层析荧光光谱局部匹配溢油鉴别技术)
光电 Fenton 技术处理污泥深度脱水液研究 · · · · · · · · · · · · · · · · · · ·	í
同步脱氧除磷颗粒污泥硝化反硝化特性试验研究	í
为好情拥名淡波流玩程大物的复数长期给完性守险研究	1
为公公全公司的证据从证上了的历史的任务中的一个专家的方面, 如)
太湖东部不问类型湖区城沒后讥帜物里金属污染及浴任生态风应评价)
水稻光合同化碳在土壤中的矿化和转化动态 ········ 谭立敏,彭佩钦,李科林,李宝珍,聂三安,葛体达,童成立,吴金水(233土地利用及退耕对喀斯特山区土壤活性有机碳的影响 ·········· 廖洪凯,李娟,龙健,张文娟,刘灵飞(240)
工地利用及逐种利格别特坦区工集活性有机恢的影响)
水稻土团聚体 Cu²+吸附过程中铝的溶出及土壤溶液 pH 变化 许海波,赵道远,秦超,李玉姣,董长勋(248)
Cr(Ⅵ)对两种黏土矿物在单一及复合溶液中Cu(Ⅱ)吸附的影响 ············· 刘娟娟,梁东丽,吴小龙,屈广周,钱勋(254)
· 海水时长对 2 种从枝蓿相 (AM) 直蓿侵氿 2 种湿肿植物的影响	/
他小时以AJ 5 什么仅图依(AM) 具图反来 2 件业地值初时影响 与 百益, 工病腐, 工格允(203)
太湖水质与水生生物健康的关联性初探 ··················周笑白,张宁红,张咏,牛志春,刘雷,于红霞(271))
太湖水质与水生生物健康的关联性初探 ····································)))
Cr(Ⅵ)对两种黏土矿物在单一及复合溶液中Cu(Ⅱ)吸附的影响)
- 基制药废水对发光细菌刍性毒性的评价研究 杜丽娜 杨帆 穆玉峰 全芸術 左剑恶 高俊发 全忻 滕丽君 汤薪琛(286))
- 基制药废水对发光细菌刍性毒性的评价研究 杜丽娜 杨帆 穆玉峰 全芸術 左剑恶 高俊发 全忻 滕丽君 汤薪琛(286))
- 基制药废水对发光细菌刍性毒性的评价研究 杜丽娜 杨帆 穆玉峰 全芸術 左剑恶 高俊发 全忻 滕丽君 汤薪琛(286))
某制药废水对发光细菌急性毒性的评价研究 ··· 杜丽娜, 杨帆, 穆玉峰, 余若祯, 左剑恶, 高俊发, 余忻, 滕丽君, 汤薪瑶(286 异丙甲草胺与锌共存对斜生栅藻毒性手性差异影响 ····································)
某制药废水对发光细菌急性毒性的评价研究 ··· 杜丽娜, 杨帆, 穆玉峰, 余若祯, 左剑恶, 高俊发, 余忻, 滕丽君, 汤薪瑶(286 异丙甲草胺与锌共存对斜生栅藻毒性手性差异影响 ····································)
某制药废水对发光细菌急性毒性的评价研究 ··· 杜丽娜, 杨帆, 穆玉峰, 余若祯, 左剑恶, 高俊发, 余忻, 滕丽君, 汤薪瑶(286 异丙甲草胺与锌共存对斜生栅藻毒性手性差异影响 ····································)
某制药废水对发光细菌急性毒性的评价研究 ··· 杜丽娜, 杨帆, 穆玉峰, 余若祯, 左剑恶, 高俊发, 余忻, 滕丽君, 汤薪瑶(286 异丙甲草胺与锌共存对斜生栅藻毒性手性差异影响 ····································)
某制药废水对发光细菌急性毒性的评价研究 ··· 杜丽娜, 杨帆, 穆玉峰, 余若祯, 左剑恶, 高俊发, 余忻, 滕丽君, 汤薪瑶(286 异丙甲草胺与锌共存对斜生栅藻毒性手性差异影响 ····································)
某制药废水对发光细菌急性毒性的评价研究 · · · 杜丽娜,杨帆,穆玉峰,余若祯,左剑恶,高俊发,余忻,滕丽君,汤薪瑶(286 异丙甲草胺与锌共存对斜生栅藻毒性手性差异影响 · · · · · · · · · · · · · · · · · · ·)))))))
某制药废水对发光细菌急性毒性的评价研究 · · · 杜丽娜,杨帆,穆玉峰,余若祯,左剑恶,高俊发,余忻,滕丽君,汤薪瑶(286 异丙甲草胺与锌共存对斜生栅藻毒性手性差异影响 · · · · · · · · · · · · · · · · · · ·)))))))
某制药废水对发光细菌急性毒性的评价研究 · · · 杜丽娜,杨帆,穆玉峰,余若祯,左剑恶,高俊发,余忻,滕丽君,汤薪瑶(286 异丙甲草胺与锌共存对斜生栅藻毒性手性差异影响 · · · · · · · · · · · · · · · · · · ·)))))))))
某制药废水对发光细菌急性毒性的评价研究 · · · 杜丽娜,杨帆,穆玉峰,余若祯,左剑恶,高俊发,余忻,滕丽君,汤薪瑶(286 异丙甲草胺与锌共存对斜生栅藻毒性手性差异影响 · · · · · · · · · · · · · · · · · · ·)))))))))
某制药废水对发光细菌急性毒性的评价研究 · · · 杜丽娜,杨帆,穆玉峰,余若祯,左剑恶,高俊发,余忻,滕丽君,汤薪瑶(286 异丙甲草胺与锌共存对斜生栅藻毒性手性差异影响 · · · · · · · · · · · · · · · · · · ·)))))))))))
某制药废水对发光细菌急性毒性的评价研究 · · · 杜丽娜,杨帆,穆玉峰,余若祯,左剑恶,高俊发,余忻,滕丽君,汤薪瑶(286 异丙甲草胺与锌共存对斜生栅藻毒性手性差异影响 · · · · · · · · · · · · · · · · · · ·	
某制药废水对发光细菌急性毒性的评价研究 · · · 杜丽娜,杨帆,穆玉峰,余若祯,左剑恶,高俊发,余忻,滕丽君,汤薪瑶(286 异丙甲草胺与锌共存对斜生栅藻毒性手性差异影响 · · · · · · · · · · · · · · · · · · ·	
某制药废水对发光细菌急性毒性的评价研究	
某制药废水对发光细菌急性毒性的评价研究 · · · 杜丽娜,杨帆,穆玉峰,余若祯,左剑恶,高俊发,余忻,滕丽君,汤薪瑶(286 异丙甲草胺与锌共存对斜生栅藻毒性手性差异影响 · · · · · · · · · · · · · · · · · · ·	

沉积物短期扰动下 BAPP 再生和转化机制

武晓飞,李大鹏*,汪明

(苏州科技学院环境科学与工程学院,苏州 215011)

摘要:以太湖梅梁湾的沉积物和上覆水为材料,研究了沉积物不同扰动方式条件下,悬浮物中不同形态磷数量分布的变化特征,并且探讨了其对悬浮物中可被生物利用颗粒态磷(BAPP)的影响. 结果表明,扰动使得上覆水中溶解性磷酸盐(DIP)的含量有所降低,与反复扰动相比,持续扰动作用下的下降幅度略大. 试验期间,悬浮物中弱吸附态磷(NH₄Cl-P)、钙结合态磷(Ca-P)与残余磷(Res-P)占总磷(Tot-P)的百分比平均值分别增加了 2.97%、12.23%、4.09%(持续扰动)和 3.53%、10.35%、2.07%(反复扰动),非闭蓄态铁铝结合态磷(Fe/Al-P)则分别下降了 5.55%(持续扰动)、1.78%(反复扰动),说明扰动促进了易释放态磷向难释放态磷的转化. 然而,悬浮物上 BAPP含量却未相应降低,反而升高,分别从 20.68%(初始状态)升高至 49.27%(平均值,持续扰动)和 57.92%(平均值,反复扰动). 这表明单纯地以悬浮物中的 NH₄Cl-P、非闭蓄态 Fe/Al-P 等易释放态磷来估算 BAPP是不合理的.

关键词:持续扰动; 反复扰动; 可被生物利用颗粒态磷; 磷形态; 悬浮物中图分类号: X131.2 文献标识码: A 文章编号: 0250-3301(2014)01-0171-08

Regeneration and Transformation of BAPP in Suspended Solids Under Shortterm Sediment Disturbance

WU Xiao-fei, LI Da-peng, WANG Ming

(Department of Environmental Science and Engineering, University of Science and Technology of Suzhou, Suzhou 215011, China)

Abstract: The change of phosphorus forms in suspended solids under short-term sediment disturbance of different modes and its influence on BAPP in suspended solids were investigated, using sediments and overlying water from Meiliang Bay. The results showed that the concentrations of DIP in the overlying water decreased under disturbance. The concentrations of DIP under continuous disturbance were lower than those under intermittent disturbance. The NH₄Cl-P, Ca-P and Res-P concentrations increased by 2. 97%, 12. 23%, 4. 09% under continuous disturbance and 3. 53%, 10. 35%, 2. 07% under intermittent disturbance and the non-occluded Fe/Al-P decreased by 5. 55% under continuous disturbance and 1. 78% under intermittent in suspended solids during the experiment, indicating that sediment disturbance could promote the transformation of sedimentary phosphorus from mobile forms to refractory forms. According to the speculation, the content of BAPP should decrease. However, it increased from 20. 68% (initial state) to 49. 27% (average, under continuous disturbance) and 57. 92% (average, under intermittent disturbance). This result indicated that it is problematic to estimate the BAPP using solely the mobile phosphorus forms, such as NH₄Cl-P and non-occluded Fe/Al-P.

Key words: continuous disturbance; intermittent disturbance; bioavailable particulate phosphorus; phosphorus forms; suspended solids

水体氮磷等营养物质主要储蓄在沉积物中^[1,2],其在风浪和人为等因素扰动作用下会加快沉积物中的氮磷等营养元素向水体释放. 然而,研究表明,扰动作用下水体中增加的磷主要以颗粒态磷为主^[3,4],但颗粒态磷中仅有可被生物利用颗粒态磷(BAPP)才能被浮游生物利用. BAPP 与悬浮物上不同形态磷的数量分布密切相关. 因此,扰动对 BAPP 含量的影响极为明显. 然而,迄今为止,人们对扰动作用下 BAPP 的再生及转化规律尚不明确.

Ellison等^[4]利用藻类培养方法通过测定生物可利用磷(BAP)和溶解态磷(DTP)来间接计算BAPP,并指出BAPP与悬浮物浓度及其沉降速度密切相关.李大鹏等^[5]利用悬浮物上藻类利用态磷来

表征颗粒态磷生物有效性的方法分析了沉积物扰动下 BAPP 的变化规律及其对水体生物有效磷的贡献,并指出扰动导致颗粒态磷生物有效性显著降低. 然而,上述研究均是采用间接方法测定 BAPP. 实际上,藻类会优先利用溶解态磷,在溶解态磷含量减少的情况下才利用 BAPP,使得测定结果的代表性大打折扣. 因此,本研究通过收集悬浮物,利用藻类培养方法直接测定 BAPP,力求测定结果能够真实地代表 BAPP. 另外,沉积物扰动方式对上覆水中不同

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作者简介:武晓飞(1986~), 男,硕士研究生, 主要研究方向为浅水湖泊修复理论, E-mail; szhkjwxf@163. com

* 通讯联系人,E-mail:ustsldp@163.com

形态磷有显著影响,如持续扰动过程中由于没有沉降过程,并且颗粒物质间的摩擦力作用显著大于某些形态磷的化学键力,使得内源磷由易释放态磷向难释放态磷转化受到影响;而反复扰动不仅具有沉降过程,而且颗粒物质间摩擦力的作用时间也仅体现在扰动过程中.因此,对比两者对 BAPP 再生及转化的影响将为完善浅水湖泊磷迁移转化理论提供理论依据.

基于此,本研究采用持续扰动和反复扰动方式, 以太湖梅梁湾沉积物和上覆水为材料,以 BAPP 的 变化规律以及悬浮物上不同形态磷数量分布规律为 对象,分析了扰动对 BAPP 再生、转化的作用机制.

1 材料与方法

1.1 沉积物与上覆水的采集

利用进口大口径柱状采样器 (Rigo Co. 直径 110 mm 高 500 mm)于 2012年9月采集梅梁湾 (N 31°31′33.6″, E 120°12′32.4″) 沉积物,并现场切得表层 1 cm 的沉积物样品,装袋,立即用冰盒保存 (4℃)送至实验室,过孔径为 1 mm 的铁筛,对沉积物进行搅拌使其充分混匀.同时取采样点上覆水 100 L. 沉积物和上覆水理化性质见表 1.

表 1 梅梁湾沉积物和上覆水的理化性质

Table 1 Physicochemical properties of sediments and overlying water from Meiliang F	Table 1	Physicochemical	properties of	sediments and	overlying water	from Meiliang Ba
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项目	DO	На	含水率	有机质	DTP	Tot-P	叶绿素 a	不同粗	立径所占质量	分数/%
坝目	$/ \text{ mg} \cdot \text{L}^{-1}$	рп	/%	/%	$/ \text{ mg} \cdot \text{L}^{-1}$	/ mg·g -1	/μg•L ⁻¹	<5 μm	5 ~ 50 μm	50 ~ 250 μm
沉积物			30. 89	3. 38		0. 201		19. 24	79. 98	0. 78
上覆水	3. 52	8			0. 021		4. 859			

1.2 试验方法

选择 2 个 5 L 圆形容器作为试验装置(d=17 cm, h=25 cm),分别标记为 E1 和 E2,放入取自梅梁湾湿沉积物 200 g,并沿器壁缓慢加入采样点上覆水 3 L.

试验周期为13 h,从早上08:00 开始,采用恒速搅拌机(IKA RW20 digital)对沉积物进行扰动(140 r·min⁻¹). 其中,E1 为持续扰动(08:00~21:00). E2 为反复扰动,每间隔3 h 扰动1次,每次扰动持续0.5 h,并从早上08:00 开始第1次扰动. 扰动过程中让沉积物充分悬浮. 在E2 每次扰动结束时,立即分别采集悬浮物,同时采集E1 悬浮物,并用于磷形态分析以及BAPP的测定,同时从水面以下10 cm处采集水样,测定上覆水中总磷(TP)、溶解性总磷(DTP)、溶解性磷酸盐(DIP). 同时监测溶解氧(DO)、pH值的变化. 并在E2 每次扰动所间隔的3 h 内每间隔1 h 对 E1、E2 分别取样测定上覆水中TP、DTP、DIP含量,同时监测 DO、pH值的变化. 每次采完水样,立即向容器中补充等量上覆水.

1.3 分析方法

TP 是将水样采用过硫酸钾消解后钼锑抗分光 光度法测定(美国 HACH DR2800 分光光度计); DTP 是将水样经过 0.45 μm 滤膜过滤后的滤液消解后测定; DIP 含量是将水样经过 0.45 μm 滤膜过滤后直接测定.

悬浮物中磷的形态分析方法参考 Hieltjes 和 Lijklema 提出的 H&L 4 步连续提取法^[6](表 2),每

个样品有3个平行样,相对误差<5%. 悬浮物中总 磷(Tot-P)含量为各步提取磷的总和. 藻类可利用 磷(AAP)采用 0.1 mol·L⁻¹NaOH 溶液提取法进行 测定. 悬浮物上 BAPP 的测定选用 Ellison 等[4]的方 法来做藻类分析试验,测定 BAPP 的含量,试验中所 用藻类为铜绿微囊藻(Microcysis aeruginosa). 具体 方法为将藻在无磷 BG11 (Bull-Green Medium) 培养 液中饥饿培养 7 d, 供试验所用. 取 30 mL 无磷 BG11 培养液并加入 0.01 g 悬浮物湿样以及经过饥 饿培养的藻液 0.3 mL,每个样品有 3 个平行样. 在 温度为 24℃ ±2℃,光照度为2 000 lx,亮暗比为 14 h :10 h 条件下培养,每天早中晚各摇动一次,于 14 d 取样测定上覆水中叶绿素 a 含量(water Pam s/n edee0225 叶绿素仪). 同时分别用不同已知磷浓度 来培养饥饿藻类.14 d 后测定上覆水中叶绿素 a 含 量,通过拟合曲线,得出量化悬浮物中 BAPP 含量 公式.

上覆水中 DO 和 pH 值分别通过便携式溶解氧测定仪(美国 HACH HQ30d)和数显 pH 计(pHs-3TC,武汉)测定.

沉积物含水率的定义为 105℃烘干 12 h 的质量 损失,有机质含量的定义为 550℃灼烧 2.5 h 的质量 损失.

2 结果与讨论

2.1 对上覆水中磷含量的影响

扰动使上覆水中不同形态磷(DIP、DTP、PP、

表 2 悬浮物中磷形态及提取方法

Table 2	Species	αf	phosphorus	and	sequential	extraction	methods
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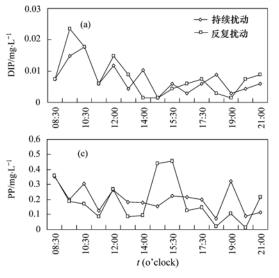
磷形态	提取方法
弱吸附态磷(NH ₄ Cl-P)	称取过 100 目筛网的悬浮物干样 0.05 g 于比色管中,加入 50 mL 1 mol·L $^{-1}$ NH ₄ Cl 溶液 (pH = 7),振荡 2 h, 离心,取上清液经过 0.45 μm 滤膜过滤后直接测定
铁铝结合态(Fe/Al-P)	将上步残渣清洗 2 次,加入 50 mL 0. 1 mol·L $^{-1}$ NaOH,振荡 17 h,离心,取上清液经过 0. 45 μ m 滤膜过滤后直接测定
钙结合态磷(Ca-P)	将上步残渣清洗 2 次,加入 50 mL 0.5 mol·L $^{-1}$ HCl,振荡 17 h,离心,取上清液经过 0.45 μm 滤膜过滤后直接测定
残渣磷(Res-P)	将上步残渣清洗 2 次,灼烧 5 h(550℃),加入 30 mL 1.0 mol·L $^{-1}$ HCl,振荡 16 h,离心,取上清液经过 0.45 μm 滤膜过滤后直接测定

TP)含量发生了明显的变化(图1). 由图1(a)可 见,不同扰动方式下,上覆水中 DIP 的变化规律相 似. 试验初期, 2 种扰动方式下上覆水的 DIP 含量 都显著升高,并迅速达到整个试验间期的最大值 (持续扰动: 0.018 mg·L⁻¹; 反复扰动: 0.024 mg·L-1). 反复扰动下,上覆水中 DIP 大部分时间 均高于持续扰动. 这主要与扰动方式不同有关. 持 续扰动下,沉积物始终处于悬浮状态,显著增加了上 覆水中的无机颗粒态物质和黏土矿物的含量,在释 放 DIP 的同时也吸收 DIP^[7],并且易于达到动态平 衡. 而对于反复扰动而言,停止扰动后,悬浮物处于 自由沉降阶段,减少了颗粒物质对 DIP 的捕捉几率, 从而降低了对 DIP 的吸附,而被悬浮颗粒吸附的 DIP 在沉降过程中又会向水体解析. 然而,在反复 扰动条件下,发现一个非常重要的现象,即每次扰动 过程中(0.5 h 的扰动与后续 3 h 自由沉降成为 1 次 扰动),DIP 的变化趋势均为升高随后降低,并且,随 着扰动次数的增加, DIP 的升高幅度逐渐降低 (0.024、0.015、0.007、0.009 mg·L⁻¹). 这暗示了

反复扰动间对 DIP 的释放存在内在联系,即先前的 扰动有降低后续扰动下内源磷释放的趋势.

随着试验的进行,不同扰动方式下,DIP 均呈显著降低趋势,DIP 的平均值分别为 $0.007~\text{mg·L}^{-1}$ (持续扰动)、 $0.008~\text{mg·L}^{-1}$ (反复扰动),并低于初始状态 $(0.01~\text{mg·L}^{-1})$. 这主要归因于扰动促进了细颗粒胶体物质 [8,9] 与 DIP 的接触几率,同时强化了吸收大量 DIP 的小颗粒态物质的絮凝作用,有利于其沉降,从而降低了上覆水中 DIP 的含量. 同时,扰动还有助于悬浮物中 Fe_{cx} 含量的增加,强化了对水体中 DIP 的吸附作用 [10].

由图 1(b)可见,持续扰动下,上覆水中 DTP 大体上呈现下降的趋势,但试验结束时,DTP 发生暴发性释放.这可能与吸附在颗粒态物质上 DTP 的释放以及聚集、絮凝、沉降效果的恶化有关[11]. 反复扰动下,DTP 的变化趋势与持续扰动相似,但 DTP 含量略低于持续扰动状态. 但是每次扰动过程中,DTP 均呈现先升高后降低的趋势,但其变化幅度要明显小于 DIP[图 1(a)],并随着扰动次数增加而呈



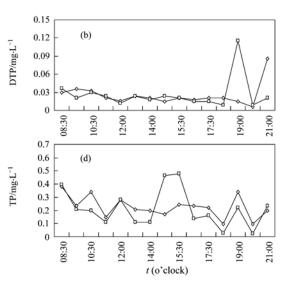


图1 上覆水中不同形态磷的变化规律

Fig. 1 Variation of different phosphorus forms in the overlying water

降低趋势. 扰动强化了大气复氧,使得上覆水、悬浮物系统中溶解氧含量增加(图 2),一方面强化了溶解性有机磷(DOP)的氧化^[12],另一方面促进了DOP与腐殖酸的接触几率,从而降低其生物有效性^[4].

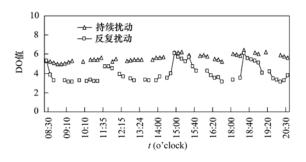


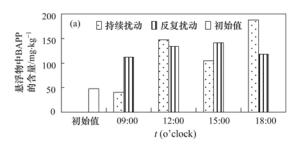
图 2 上覆水中 DO 的变化规律

Fig. 2 Variation of DO in the overlying water

颗粒态磷(PP)的变化规律与TP表现出相似的趋势[图1(c)、1(d)].持续扰动和反复扰动状态下,上覆水中TP、PP的含量均呈先升高再降低的趋势.反复扰动下,每次扰动后上覆水中TP、PP的含量都会增加,并在停止扰动之后迅速降低,这可能是沉积物再悬浮促进了内源磷向上覆水中的迁移,而在停止扰动后,进入到上覆水中的颗粒态物质会在重力作用下自由沉降,再次回归到沉积物中.试验初始期间,持续扰动下,上覆水中TP、PP含量波动较大,导致这样现象的原因可能是扰动过程在促进内源磷向上覆水迁移的同时也强化了上覆水中颗粒态物质的聚集、絮凝作用,有利于小颗粒态物质向沉积物的迁移.随着扰动的继续,上覆水中TP、PP的变化逐渐趋于平缓,这可能由于颗粒态物质聚集、絮凝作用得到强化.

2.2 悬浮物中 BAPP 数量分布规律

扰动作用显著改变了上覆水中颗粒物质的数量 分布,同时,促进了磷与颗粒物质的接触,强化了颗 粒物质对磷的捕捉和吸附;然而,扰动在使得颗粒 物质处于水动力作用下的同时,也使得颗粒物质受



到摩擦力的影响,而摩擦力会导致化学键力较小的弱吸附态磷、铁铝结合态磷化学键断裂,从而改变上覆水中不同形态磷分布(图1). 在此,也改变了悬浮物上 BAPP 的数量分布(图3).

图 3(a)显示,持续扰动下,悬浮物中 BAPP 的数量分布呈增加的趋势,而反复扰动下,则呈先增加后降低的趋势,但始终保持在高于初始值(48.194 mg·kg⁻¹)的水平.同样,BAPP 占 Tot-P 的百分比也呈增加的趋势[图 3(b)].表明沉积物扰动导致悬浮物中 BAPP 含量增加.这主要归因于悬浮物对水体中 DIP 的吸附[图 1(a)],也可能与悬浮物中不同形态磷间的相互转化有密切关系.悬浮物中 BAPP含量的增加间接地促进了水体富营养化的进程.

试验期间, BAPP 的平均值分别为 119.959 mg·kg⁻¹ (持续扰动)、126.125 mg·kg⁻¹ (反复扰动), 其在 Tot-P 中所占百分比的平均值分别为 49.27% (持续扰动)、57.92% (反复扰动),显著高于初始值(48.194 mg·kg⁻¹、20.68%),且反复扰动增加量要略高于持续扰动.表明反复扰动更有助于BAPP 在悬浮物中的集聚.这与铁铝结合态磷(Fe/Al-P)和钙结合态磷(Ca-P)在悬浮物中数量分布的变化(图4)是相符的.悬浮物中 Fe/Al-P 和 Ca-P 含量的平均值分别为 125 mg·kg⁻¹、92.5 mg·kg⁻¹ (持续扰动)和 121.25 mg·kg⁻¹、80 mg·kg⁻¹ (反复扰动).显然,持续扰动相比于反复扰动更有利于促进了易释放态磷向难释放态磷的转化.这与 BAPP 的增加趋势是相反的,暗示了 BAPP 可能与 Fe/Al-P、Ca-P 之间存在内在联系.

2.3 悬浮物中磷赋存形态的变化

磷的生物有效性及迁移能力与其赋存形态密切相关^[13,14],沉积物扰动条件下,会对水环境因子产生显著影响,进而改变悬浮物上不同形态磷的数量分布(图 4).

图 4(a)显示,试验期间,持续扰动和反复扰动下,悬浮物中弱吸附态磷(NH₄Cl-P)含量呈先升高

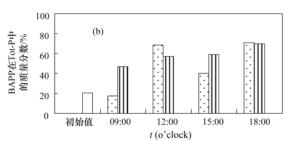


图 3 悬浮物中 BAPP 的数量分布及其在总磷中的质量分数

Fig. 3 Distribution of BAPP and Percentage of BAPP in total P in the suspended solids

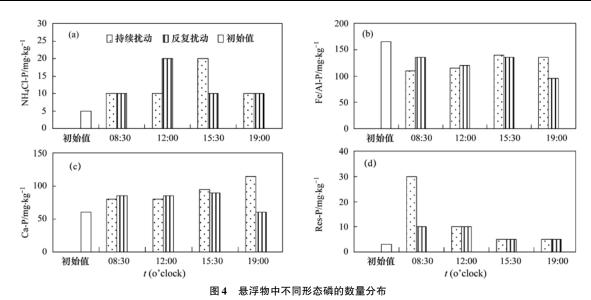


Fig. 4 Distribution of phosphorus forms in the suspended solids

再降低的趋势,并在试验结束时保持在较低值(10 mg·kg⁻¹),但却始终高于初始值(5 mg·kg⁻¹).另外,持续扰动和反复扰动下,悬浮物中 NH₄Cl-P含量占 Tot-P百分比的平均值分别为 5.12%、5.68%,明显高于初始值(2.15%),其可能是水体中的 DIP向悬浮物迁移的结果,也可能是悬浮物中其他形态磷向 NH₄Cl-P 转化所导致.且相对于持续扰动,反复扰动对这种迁移转化的效果更为明显.

图 4(b)显示,持续扰动作用下,悬浮物中 Fe/Al-P 含量逐渐增加,其占 Tot-P 的百分比也呈增加趋势(图 5).而反复扰动作用下,Fe/Al-P 则呈降低趋势,其占 Tot-P 的百分比在 51.06% ~ 56.25%间波动(图 5).但是,Fe/Al-P 含量及其占 Tot-P 的百分比均低于初始值(165 mg·kg⁻¹;70.82%).并且,持续扰动下,Fe/Al-P 占 Tot-P 百分比的平均值(51.53%)略低于反复扰动(54.86%).

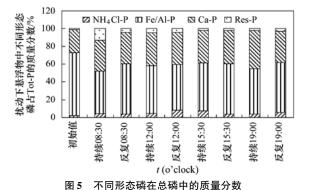


Fig. 5 Percentage of different phosphorus forms in total P in the suspended solids

悬浮物中 Fe/Al-P 由闭蓄态 Fe/Al-P 和非闭蓄态 Fe/Al-P 两部分组成^[15,16],非闭蓄态 Fe/Al-P 也

表示为 AAP^[15]. 沉积物再悬浮降低了悬浮物中 Fe/ Al-P的含量,但对于非闭蓄态 Fe/Al-P,在试验结束 时,其含量只是略低于初始值(98 mg·kg⁻¹),并且 其占 Fe/Al-P 的百分比都明显高于初始值 (59.39%). 这与以往研究中的沉积物再悬浮促进 了悬浮物中非闭蓄态 Fe/Al-P 释放是不相符的[17]. 在试验结束时,持续扰动下悬浮物中非闭蓄态 Fe/ Al-P占 Fe/Al-P的百分比达到了 65.19%, 而反复 扰动更是高达94.74%(图6). 其原因可能是由于 持续扰动为水体提供了更好的复氧条件(图2). 而 水体溶解氧含量的增加有利于 Fe2+ 向 Fe3+ 的转化, 生成 Fe(OH),并在水体氧含量充足的情况下继续 被氧化成晶体铁氧化物,强化了对磷的固定能 力[18,19],虽然这部分被固定的磷主要以闭蓄态 Fe/ Al-P 的形态存在[20],但由于沉积物在扰动过程中可 能会对 Fe/Al-P 的化学键造成破坏,促进了闭蓄态 Fe/Al-P 的释放,导致在 Fe/Al-P 中以非闭蓄态 Fe/ Al-P 为主. 而对于反复扰动而言,尽管扰动过程中 也有利于水体复氧,增加 Fe(OH), 的生成,但在其 自由沉降阶段,由于复氧条件的消失导致水体中氧 含量降低(图 2),不利于 Fe(OH), 继续向晶体铁氧 化物的转化,使水体中 Fe3+ 主要以 Fe(OH), 的形 式存在,而 Fe(OH),对磷的固定能力较弱[18],进而 导致悬浮物中 Fe/Al-P 主要以非闭蓄态 Fe/Al-P 的 形式存在,并所占 Fe/Al-P 的百分比明显高于持续 扰动.

在图 4(c)中可以发现, Ca-P含量逐渐增加,并且, Ca-P占 Tot-P的百分比也高于初始状态(25.75%). 其原因可能是扰动增加了 Ca^{2+} 与磷酸

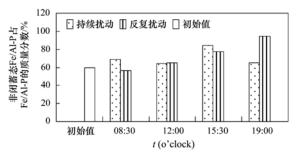


图 6 非闭蓄态 Fe/Al-P 在 Fe/Al-P 中的质量分数

Fig. 6 Percentage of non-occluded Fe/Al-P of Fe/Al-P in the suspended solids

根的碰撞几率,促进了 Ca-P 的生成. 尽管有研究表 明,pH 值高于 8 才有利于 Ca-P 的生成^[21],但本研 究中,由于扰动作用,pH 呈增加趋势,接近8(图 7),而扰动状态下 Ca2+与磷酸根的接触几率的增加 则可能弥补了 pH 值略小于 8 的不利条件. 由于 Fe(OH), 的生成增加了上覆水中的 H+的含量[18], 且其处于反复扰动条件下,因上覆水中溶解氧含量 相对较低的缘故,抑制了Fe(OH)3向晶体铁氧化物 的转化,减少了水体中 H+的消耗[21],但在试验中并 未发现上覆水中 pH 明显降低,这可能就是因为在 抑制 Ca-P 生成时也消耗了水体中的 H+. 除此之 外,与持续扰动相比,反复扰动下 Ca2+ 与磷酸根的 碰撞几率较低也可能会导致 Ca-P 含量下降. 试验 期间, Ca-P占 Tot-P的百分比始终高于初始值 (25.75%). 这表明,沉积物扰动有利于其他形态磷 向 Ca-P 的转化.

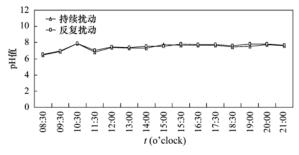


图 7 上覆水中批 pH 的变化规律

Fig. 7 Variation of pH in the overlying water

图 4(d)显示,持续扰动和反复扰动作用下,残余磷(Res-P)均呈下降趋势,并保持在明显低于其它形态磷的水平.由于 Res-P属于难释放态磷,悬浮物中其含量又相对较低,导致在研究中常常忽视其数量分布的变化.试验期间,Res-P在 Tot-P所占的比例无论是平均值还是试验结束时的值都大于初始值(1.29%).这表明,沉积物扰动可能促进了悬浮物中其他形态磷向 Res-P 的转化,且相对于持续

扰动,反复扰动似乎更有利于 Res-P 的生成,这可能 是因为持续扰动提高了破坏 Res-P 化学键的几率.

试验期间, 虽然 NH₄Cl-P 占 Tot-P 百分比平均 值分别由 2.15% (初始值)上升到 5.12% (持续扰 动)和5.68%(反复扰动),但同为易释放态磷的非 闭蓄态 Fe/Al-P 的百分比平均值则分别从 42.06% (初始值)下降到 36.51% (持续扰动)和 40.28% (图 8). 与易释放态磷不同,难释放态磷中的 Ca-P 和 Res-P 则表现出增加的趋势(图 5),其分别从 25.75%、1.29%(初始值)增加到了37.98%、 5.38%(持续扰动)和36.1%、3.36%(反复扰动). 对于新增加的 Ca-P 而言,其磷酸盐主要来自上覆水 中的 DIP^[22], 而在扰动过程中悬浮物中的易释放态 磷很容易转化成 DIP 释放到上覆水中. 除此之外, Li 等[23,24] 在研究中发现, 扰动相对于未扰动而言, 不同形态磷间的转化速度明显较快. 这似乎表明扰 动更有利于易释放态磷向难释放态磷的转化,促进 了悬浮物中难释放态磷含量的增加.

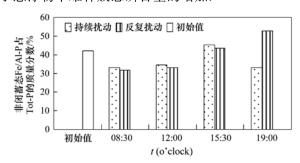


图 8 非闭蓄态 Fe/Al-P 在 Tot-P 中的质量分数

Fig. 8 Percentage of non-occluded Fe/Al-P in total P in the suspended solids

2.4 BAPP 与悬浮物中不同形态磷的相关性分析 BAPP 与不同形态磷有密切关系,研究中分析 了 BAPP 与扰动下不同形态磷间的相关性(表3).

表 3 显示,悬浮物中 BAPP 与 Fe/Al-P、Ca-P 都 具有较好的相关性,反而与 NH₄Cl-P、AAP 等易释 放态磷的相关性较差,王琦等^[25]在研究中也有类似的发现. 这表明只是单纯的以易释放态磷来表征 PP 的生物有效性可能是不科学的. 事实上,藻类在生命活动过程中也会利用部分闭蓄态 Fe/Al-P 和 Ca-P,虽然闭蓄态 Fe/Al-P 和 Ca-P 都属于难释放态磷,但并不代表其不可被藻类所利用. 藻类在生长代谢的过程中不但可以溶解部分 Ca-P 而且其代谢物质还可能会与悬浮物中的铁等金属离子发生络合作用^[25-27],促进了悬浮物中磷的释放. 除此之外,Ca-P 的组成成分也会影响 PP 的生物有效性,如

	Table 3 Correlation of various phosphorus fractions and BAPP in the suspended solids						
	BAPP	$\mathrm{NH_4Cl} ext{-P}$	Fe/Al-P	Ca-P	Res-P	AAP	
BAPP	1						
$\mathrm{NH_4}$ Cl-P	-0.059	1					
Fe/Al-P	0.320	0. 269	1				
Ca-P	0.490	0. 149	0.812	1			
Res-P	-0.774	-0.183	-0.348	-0.218	1		
AAP	0.080	0. 391	0.458	0. 268	-0.514	1	

表 3 BAPP 与悬浮物中不同形态磷的相关关系

Ca-P 中的磷酸二钙(Ca_2 -P)和磷酸八钙(Ca_8 -P). Ca_2 -P和 Ca_8 -P是可被生物直接利用的,且 Ca_2 -P的生物有效性还要高于 Fe/Al-P,为优先利用磷源,但 Ca_2 -P在 Ca-P中的百分比较少,与 Ca-P和 Ca-P

3 结论

- (1) 沉积物扰动有利于降低上覆水中不同形态磷(DIP、DTP、PP、TP)的含量. 反复扰动下,每1次扰动过程中,DIP、DTP 均呈先升高后降低的趋势,但随着扰动次数增加,DIP 和 DTP 升高的幅度逐渐降低. 这暗示扰动间对内源磷迁移转化存在内在联系.
- (2) 沉积物扰动对悬浮物中不同形态磷的数量分布具有显著的影响. 反复扰动作用下, NH₄Cl-P的增加幅度略低于持续扰动, Fe/Al-P 的下降幅度高于持续扰动,但两种扰动方式下悬浮物中非闭蓄态 Fe/Al-P 含量都低于初始值. 除此之外,悬浮物中 Ca-P 和 Res-P 的含量则都有所增加,且持续扰动作用下增幅较大,说明持续扰动更有利于促进易释放态磷向难释放态磷的转化.
- (3) 试验期间,悬浮物中 BAPP 含量均有所增加,且反复扰动下增幅较大. 这与沉积物扰动促进了易释放态磷向难释放态磷转化的结论是恰好相反的,表明只是单纯的以悬浮物中的 NH₄Cl-P、非闭蓄态 Fe/Al-P 等易释放态磷来表示 BAPP 可能是不合理的,有些难释放态磷在相应的条件下也有可能被藻类所利用.

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HUANJING KEXUE

Environmental Science (monthly)

Vol. 35 No. 1 Jan. 15, 2014

CONTENTS

As Assenced Partins of Water-Schale less in Play, and Changhai Mentation as a Generative Right and Exposure Design (IRS) James, W. W. West, W. W. Tamwer, et al. [1]. Second Variation of Water-Schale less in Play, and Changhai Mentation and Design of Water Schale less in Play, and Changhai Mentation [1]. A proceedings of the State of Manager of Changing (IRS) and In Second Variation [2]. A proceeding of Water Schale less in Play, and Changing (IRS) and In Second Variation [2]. A proceeding of Water Schale less in Play, and and Changing (IRS) and In Second Variation [2]. A proceeding of Water Schale less in Play, and and a proceeding of Water Schale less in Play, and a proceeding of Water In Variation of PURIO's from Markon Proceeding Comment Klim with Polescolary in the Schale less in Play, Nava (IRS), Wite-ling, ILS (IRS), Nava (IRS)	CONTENTS	
Samed Water-Saleh Lee in PN, 4 al Changlad Mentain ZIAO Yaram, WANG Yara, WA	An Assessment of PM _{2.5} Related Health Risks and Impaired Values of Beijing Residents in a Consecutive High-Level Exposure	During Heavy Haze Days
Variation of Almospheric Pariade Number Concentrations in Uniphos and Its Impact on visibility Concentration of ARDVIN in the Attemphore of College (17) and 18 Secondary Variation Characterization of ARDVIN in the Managebore of College (17) and 18 Secondary Variation Managebore Existion of APDVIN from Newton Processing General Secondary Variation ARDVIN in the ARDVIN in Secondary Variation Mealings (18) and the Secondary Variation of APDVIN in Managebore Existion of APDVIN in Managebore Existion of APDVIN in Managebore (18) and the Secondary Variation of		······ XIE Yuan-bo, CHEN Juan, LI Wei (1)
Concentration of PAIDPS in the Aumophor of Cheeping (five and In Secural Variation — 1211, PAID Kan-ling, GO 500) Annumbration of AUDPS from Security (with March 1914) Annumbration of AUDPS from March 1914 Protection of Patricks and Patricks (1914) Annumbration of AUDPS from March 1914 Protection for Patricks (1914) Annumbration of AUDPS from March 1914 Protection of Patricks and Patricks (1914) Annumbration of AUDPS from March 1914 Protection of Patricks and Patricks (1914) Annumbration of Audps from March 1914 Protection of Patricks and Patricks (1914) Annumbration of Audps from March 1914 Protection of Patricks (1914) Annumbration of Audps from March 1914 Protection of Patricks (1914) Annumbration of Audps from March 1914 Protection of March 1914		
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Pollution State and Characteristics of Pillick in Indoor. An of Hangdane Experience of Proceedings of Pillick in Indoor. An of Hangdane Experience Processing Place and Susseal Variations of Elevents in Northean of Schaum, Control China TON Naso-ning, 2010. How-year, 701. Cheerings, et al. (5) Minopheric Poposition Places and Susseal Variations of Elevents in Northean of Schaum, Control China TON Naso-ning, 2010. How-year, 701. Cheerings, et al. (5) We Inspection of Managheric Nations of the Indoor Waterhood in the Upper Hunjiang River WAM Jin-jee, 2414-NE Secong, WI Cham, et al. (7) We Inspection of Annual Processing Places and Company of the Common Composition of Academics Vision and Its States and Composition of Places (Hangdane) and Olg. Scheleus in Arabic Sail Experience of Hangdane Composition of Disorded Recent in the Video Sca and East China Sca. W. H. Wang, M. Wang, S. Will Yung, et al. (9) Conclusional Distribution of Disorded Recent in the Video Sca and East China Sca. W. W. Nicoland, S. Will Yung, et al. (10) Temporal-special Distribution of Disorded Recent in the Video Sca and East China Sca. W. W. Nicoland, S. Will Yung, et al. (10) Temporal-special Distribution and Disorder Scane in the Cycle Recent Scane and Composition of Disorder Composition of Disorder Recent in the Video Sca and East China Sca. MA Yingsaya, SHI Yun, (NI Yunwan, et al. (10) Temporal-special Distribution and Disorder Scane in the Cycle Recent Unpaired Composition of Tomogenic Composition of Nicoland Scane and Composition of Composition of Disorder Composition of Composition of Composition of Disorder Composition of Disorde		
See Destruition of Particle and Polycyclic Anomaic Hydrocarbos in Particle Emission from Smalated Emission Sources TON No. Sealing, 2010 Hospan, vol. 146, 167, 167, 167, 167, 167, 167, 167, 16		
Amougher's Poposition Phones and Secondal Variations of Elements in Northeast of Schums, Lentul China TUNK Xusoning, 2010, Han-yan, VOL Chercheng, et al. 55 Transl in Acid Disposition of Techniquing Conging During 2011/2019 YLD Position of Manage Posit		
Frend in Ariol Deposition at Tiechungira, Congage Baring 2001–2010 — "YU Dessings, MA Xian-vino, TAN Kinegungan, et al. (6) Chemical Compositions of n-Mikanois. Acada in Whata Stars and In Simale "URC Age, and the Congage Congression of the Congage C		
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Central Compositions of a-Mannie Archis in Ward Store and Its Smake		
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Mercuny Phones from Confice-Roundlerd Footsoche Heid in Central Subtropical Foots Zone Max Max, WANG Ding-yong, SHEN Yaun-yuan, ed. (83) Reported five Stams Birchart on Organic Carbon and CD, Release in Anable Scil Coecelemical Distribution of Dissolved Bissenth in the Yellow Sea and East Clinia Sca Temporal-spital Distribution and Pollution Assessment of Heavy Metals in the Upper Reaches of Hambe River (Qinguan Section), Northest Clinia Max Ving-quan, SHI Yao, Qin Yuawwan, ed. (108) Determination of Estopoguic Componels in Water of Jislong River Using Polar Organic Chemical Integrative Sumpler Max Ving-quan, SHI Yao, Qin Yuawwan, ed. (108) Determination of Estopoguic Componels in Water of Jislong River Using Polar Organic Chemical Integrative Sumpler Max Ving-quan, SHI Yao, Qin Yuawwan, ed. (108) Determination of Estopoguic Componels in Water of Jislong River Using Polar Organic Chemical Integrative Sumpler Max Ving-quan, SHI Yao, Qin Yuawwan, ed. (108) May Varintion Chametricis and Environmental Sumfacial Cardion in Kard Gomenhart var Cliffs (Max Such in Yako Niko Phane), LI Yoogay, ed. (117) Major Integrative Standard Statistics of Standard Standard Cardion Integrative Sumpler Taxo Cardion Standard Standard Standard Standard Standard Cardion Integrative Standard		
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Forms and Spatial Distribution Characteristics of Nitrogen in Zya River Basin and the Possible Cantrals ZHAO Yu., SHAN Baso-qing, ZHANG Wen-qiang, et al. (131)	Determination of Estrogenic Compounds in Water of Jiulong River Using Polar Organic Chemical Integrative Sampler	······· ZHANG Li-peng, WANG Xin-hong, LI Yong-yu, et al. (117)
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Factors Influencing the Variability in Soil Heterotrophic Respiration from Terrestrial Ecosystem in China XIE Wei, CHEN Shu-tao, HU Zheng-hua (334) Study on the Distinguishing of Root Respiration from Soil Microbial Respiration in a Leynus chinensis Steppe in Inner Mongolia, China Nitrous Oxide Flux at the Water-Air Interface of the Rivers in Nanjing During Summer HAN Yang, ZHENG You-fei, WU Rong-jun, et al. (348) Effects of Antiseptic on the Analysis of Greenhouse Gases Concentrations in Lake Water XIAO Qi-tao, HU Zheng-hua, James Deng, et al. (356) Electricity Generation of Surplus Sludge Microbial Fuel Cell Enhanced by Biosurfactant PENG Hai-li, ZHANG Zhi-ping, LI Xiao-ming, et al. (365) Fe-ZSM-5 Catalysts with Different Silica-Alumina Ratios for N ₂ O Catalytic Decomposition LU Ren-jie, ZHANG Xin-yan, HAO Zheng-ping (371) Inhibition of Chlorobenzene Formation via Various Routes During Waste Incineration by Ammonium Sulfate and Urea YAN Mi, QI Zhi-fu, LI Xiao-dong, et al. (380) County Scale Characteristics of CO ₂ Emission's Spatial-Temporal Evolution in the Beijing-Tianjin-Hebei Metropolitan Region WANG Hao, CHEN Cao-cao, PAN Tao, et al. (385)		
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Nitrous Oxide Flux at the Water-Air Interface of the Rivers in Nanjing During Summer HAN Yang, ZHENG You-fei, WU Rong-jun, et al. (348) Effects of Antiseptic on the Analysis of Greenhouse Gases Concentrations in Lake Water XIAO Qi-tao, HU Zheng-hua, James Deng, et al. (356) Electricity Generation of Surplus Sludge Microbial Fuel Cell Enhanced by Biosurfactant PENG Hai-li, ZHANG Zhi-ping, LI Xiao-ming, et al. (365) Fe-ZSM-5 Catalysts with Different Silica-Alumina Ratios for N2O Catalytic Decomposition LU Ren-jie, ZHANG Xin-yan, HAO Zheng-ping (371) Inhibition of Chlorobenzene Formation via Various Routes During Waste Incineration by Ammonium Sulfate and Urea YAN Mi, QI Zhi-fu, LI Xiao-dong, et al. (380) County Scale Characteristics of CO2 Emission's Spatial-Temporal Evolution in the Beijing-Tianjin-Hebei Metropolitan Region WANG Hao, CHEN Cao-cao, PAN Tao, et al. (385)	Inhibition of the Activity of Sulfate-reducing Bacteria in Produced Water from Oil Reservoir by Nitrate Bioconversion of Cellulose to Methane by a Consortium Consisting of Four Microbial Strains	
Effects of Antiseptic on the Analysis of Greenhouse Gases Concentrations in Lake Water XIAO Qi-tao, HU Zheng-hua, James Deng, et al. (356) Electricity Generation of Surplus Sludge Microbial Fuel Cell Enhanced by Biosurfactant PENG Hai-li, ZHANG Zhi-ping, LI Xiao-ming, et al. (365) Fe-ZSM-5 Catalysts with Different Silica-Alumina Ratios for N2O Catalytic Decomposition LU Ren-jie, ZHANG Xin-yan, HAO Zheng-ping (371) Inhibition of Chlorobenzene Formation via Various Routes During Waste Incineration by Ammonium Sulfate and Urea YAN Mi, QI Zhi-fu, LI Xiao-dong, et al. (380) County Scale Characteristics of CO2 Emission's Spatial-Temporal Evolution in the Beijing-Tianjin-Hebei Metropolitan Region WANG Hao, CHEN Cao-cao, PAN Tao, et al. (385)	Inhibition of the Activity of Sulfate-reducing Bacteria in Produced Water from Oil Reservoir by Nitrate Bioconversion of Cellulose to Methane by a Consortium Consisting of Four Microbial Strains	
Electricity Generation of Surplus Sludge Microbial Fuel Cell Enhanced by Biosurfactant	Inhibition of the Activity of Sulfate-reducing Bacteria in Produced Water from Oil Reservoir by Nitrate Bioconversion of Cellulose to Methane by a Consortium Consisting of Four Microbial Strains Factors Influencing the Variability in Soil Heterotrophic Respiration from Terrestrial Ecosystem in China Study on the Distinguishing of Root Respiration from Soil Microbial Respiration in a Leynus chinensis Steppe in Inner Mongolia,	HAO Tian, DU Peng-fei, DU Bin, et al. (304) YOU Di-jie, CHEN Xiao-guo, XIANG Hui-yi, et al. (313) YANG De-yu, ZHANG Ying, SHI Rong-jiu, et al. (319) WU Jun-mei, MA An-zhou, CUI Meng-meng, et al. (327) XIE Wei, CHEN Shu-tao, HU Zheng-hua (334) China SHI Jing-jing, GENG Yuan-bo (341)
Fe-ZSM-5 Catalysts with Different Silica-Alumina Ratios for N2O Catalytic Decomposition	Inhibition of the Activity of Sulfate-reducing Bacteria in Produced Water from Oil Reservoir by Nitrate Bioconversion of Cellulose to Methane by a Consortium Consisting of Four Microbial Strains Factors Influencing the Variability in Soil Heterotrophic Respiration from Terrestrial Ecosystem in China Study on the Distinguishing of Root Respiration from Soil Microbial Respiration in a Leymus chinensis Steppe in Inner Mongolia, Nitrous Oxide Flux at the Water-Air Interface of the Rivers in Nanjing During Summer	HAO Tian, DU Peng-fei, DU Bin, et al. (304) YOU Di-jie, CHEN Xiao-guo, XIANG Hui-yi, et al. (313) YANG De-yu, ZHANG Ying, SHI Rong-jiu, et al. (319) WU Jun-mei, MA An-zhou, CUI Meng-meng, et al. (327) XIE Wei, CHEN Shu-tao, HU Zheng-hua (334) China SHI Jing-jing, GENG Yuan-bo (341) HAN Yang, ZHENG You-fei, WU Rong-jun, et al. (348)
Inhibition of Chlorobenzene Formation via Various Routes During Waste Incineration by Ammonium Sulfate and Urea	Inhibition of the Activity of Sulfate-reducing Bacteria in Produced Water from Oil Reservoir by Nitrate Bioconversion of Cellulose to Methane by a Consortium Consisting of Four Microbial Strains Factors Influencing the Variability in Soil Heterotrophic Respiration from Terrestrial Ecosystem in China Study on the Distinguishing of Root Respiration from Soil Microbial Respiration in a Leymus chinensis Steppe in Inner Mongolia, Nitrous Oxide Flux at the Water-Air Interface of the Rivers in Nanjing During Summer Effects of Antiseptic on the Analysis of Greenhouse Gases Concentrations in Lake Water	HAO Tian, DU Peng-fei, DU Bin, et al. (304) YOU Di-jie, CHEN Xiao-guo, XIANG Hui-yi, et al. (313) YANG De-yu, ZHANG Ying, SHI Rong-jiu, et al. (319) WU Jun-mei, MA An-zhou, CUI Meng-meng, et al. (327) XIE Wei, CHEN Shu-tao, HU Zheng-hua (334) China SHI Jing-jing, GENG Yuan-bo (341) HAN Yang, ZHENG You-fei, WU Rong-jun, et al. (348) XIAO Qi-tao, HU Zheng-hua, James Deng, et al. (356)
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Characterization and Soil Environmental Safety Assessment of Super Absorbent Polymers in Agricultural Application	Inhibition of the Activity of Sulfate-reducing Bacteria in Produced Water from Oil Reservoir by Nitrate Bioconversion of Cellulose to Methane by a Consortium Consisting of Four Microbial Strains Factors Influencing the Variability in Soil Heterotrophic Respiration from Terrestrial Ecosystem in China Study on the Distinguishing of Root Respiration from Soil Microbial Respiration in a Leymus chinensis Steppe in Inner Mongolia, Nitrous Oxide Flux at the Water-Air Interface of the Rivers in Nanjing During Summer Effects of Antiseptic on the Analysis of Greenhouse Gases Concentrations in Lake Water Electricity Generation of Surplus Sludge Microbial Fuel Cell Enhanced by Biosurfactant Fe-ZSM-5 Catalysts with Different Silica-Alumina Ratios for N ₂ O Catalytic Decomposition Inhibition of Chlorobenzene Formation via Various Routes During Waste Incineration by Ammonium Sulfate and Urea	HAO Tian, DU Peng-fei, DU Bin, et al. (304) YOU Di-jie, CHEN Xiao-guo, XIANG Hui-yi, et al. (313) YANG De-yu, ZHANG Ying, SHI Rong-jiu, et al. (319) WU Jun-mei, MA An-zhou, CUI Meng-meng, et al. (327) XIE Wei, CHEN Shu-tao, HU Zheng-hua (334) China SHI Jing-jing, GENG Yuan-bo (341) HAN Yang, ZHENG You-fei, WU Rong-jun, et al. (348) XIAO Qi-tao, HU Zheng-hua, James Deng, et al. (356) PENG Hai-li, ZHANG Zhi-ping, LI Xiao-ming, et al. (365) LU Ren-jie, ZHANG Xin-yan, HAO Zheng-ping (371)
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