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环渤海芦苇湿地磷的吸附容量及释放风险评估

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摘要: 滨海湿地地处陆海交汇的关键带, 是磷的“汇”、“源”和“转化器”, 在全球磷循环过程中扮演着十分重要的角色, 其对水体磷素的截留能力日益受到关注. 本文以环渤海地区芦苇湿地沉积物为研究对象, 利用批处理实验研究了湿地磷的吸附容量和释放风险. 结果表明, 湿地沉积物磷的最大吸附容量 ($Q_{\max}$) 为 $693.7 \sim 2117.2 \text{ mg} \cdot \text{kg}^{-1}$, 平均值为 $1468.6 \text{ mg} \cdot \text{kg}^{-1}$, $Q_{\max}$ 的大小顺序为七里海湿地 > 北大港湿地 > 南大港湿地 > 辽河三角洲湿地 > 寿光滨海湿地 > 黄河三角洲湿地. 环渤海湿地沉积物磷吸附主要受 Ca、Mg 和 TOC 含量的影响. 环渤海湿地磷吸附饱和度 (DPS) 和释放风险指数 (ERI) 分别为 $0.28\% \sim 4.50\%$ 和 $0.53\% \sim 10.10\%$, 结果表明除寿光滨海湿地磷释放风险为中度风险外, 其它湿地磷释放风险较低. 总之, 环渤海地区芦苇湿地沉积物具有较强磷吸附能力, 沉积物为水体磷的“汇”, 沉积物释磷风险较低. 建议在环渤海污染治理过程中充分发挥滨海湿地对磷的净化拦截作用, 以降低陆源污染对近海水环境的影响.

关键词: 环渤海湿地; 表层沉积物; 磷吸附容量; 磷吸附饱和度; 释放风险指数

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Phosphorus Storage Capacity and Loss Risk in Coastal Reed Wetland Surrounding Bohai Sea

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Abstract: Coastal wetland, at the intersection of land and sea, is considered as a “sink”, “source”, and “transformer” of phosphorus (P). Coastal wetland plays an important role in the global P cycle, and its ability to retain excessive P in water receives increasing attention. In this study, the coastal reed wetland sediments surrounding the Bohai Sea were sampled to investigate P adsorption capacity and loss risk by conducting batch experiments. Results show that the maximum P adsorption capacity ($Q_{\max}$) was $693.7 \sim 2117.2 \text{ mg} \cdot \text{kg}^{-1}$, with an average of $1468.6 \text{ mg} \cdot \text{kg}^{-1}$. The $Q_{\max}$ decreased in the order of Qilihai Wetland > Beidagang Wetland > Nandagang Wetland > Liaohe Delta Wetland > Shouguang Coastal Wetland > Yellow River Delta Wetland. The P adsorption capacity was related to the contents of Ca, Mg, and TOC. The degree of P adsorption saturation (DPS) and loss risk index (ERI) of the coastal wetland were $0.28\% \sim 4.50\%$ and $0.53\% \sim 10.10\%$, respectively. The ERI suggested that the P loss risk was relatively low for coastal reed wetland surrounding the Bohai Sea except for the moderate loss risk for Shouguang coastal wetland. In summary, the reed coastal wetland around Bohai Sea demonstrated significantly P storage capacity and served as a P sink for water P. We recommend to fully utilize the coastal wetland to reduce point or non-point source pollution (e.g., P) during the remediation or recovery of the polluted Bohai Sea.

Key words: coastal wetland; surface sediment; P adsorption capacity; degree of P adsorption saturation; emission risk index

磷是农田生态系统必需的营养元素, 是影响作物生长和产量的关键因素^[1]. 为增加粮食产量, 土壤磷肥使用量逐年增加, 而作物对磷素的利用率为 $10\% \sim 20\%$ ^[2], 大部分的磷在土壤中日益累积, 有效磷含量明显增加, 1980~2007年, 中国农田土壤有效磷平均从 $7.4 \text{ mg} \cdot \text{kg}^{-1}$ 增加到 $24.7 \text{ mg} \cdot \text{kg}^{-1}$ ^[3]. 当土壤中磷素累积量超过土壤吸附饱和度, 土壤中磷素的流失风险会急剧增大^[4]. 土壤当中过量的磷素可以通过径流或渗漏到达水体导致富营养化, 造成湖泊和近海水环境恶化, 严重影响了地区经济可持续发展^[5]. 根据2013~2017年中国近海环境质量公报显示, 我国近海主要污染因子是无机氮和活性磷酸盐.

滨海湿地位于陆地生态系统和海洋生态系统的过渡地带, 是磷输送、累积和再生的重要场所^[6], 特

殊的水动力作用以及咸淡水交汇使得环境因子频繁变化, 导致滨海湿地沉积物具有磷“源”和“汇”的双重作用. 湿地磷的含量和形态, 对水体磷截留去除、吸附容量及潜在的释放风险已经引起众多学者关注. 长江口潮滩潜在生物可利用磷主要是弱吸附态磷、铁结合态磷和有机磷, 约占总磷的 33.16% , 是导致水体富营养化的潜在因素^[7]. 闽江口湿地无机磷占总磷的 66.21% , 且总磷含量的均值为 $737 \text{ mg} \cdot \text{kg}^{-1}$, 相对较高, 其污染指数为 $0.819 \sim 1.618$, 总体上为轻度污染^[8]. 黄河三角洲新生湿地对外源

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磷有较强的吸附能力, 沉积物磷释放风险较小^[9]. 环渤海湿地土壤中的磷主要是无机磷, 且主要是不易释放的钙磷^[10]. 莱州湾滨海湿地总磷 (TP) 浓度随沉积深度变化不明显, 但未来应该考虑沉积物磷形态的差异^[11]. 目前对环渤海湿地磷的含量、形态和控制因素开展了研究, 而对湿地磷的吸附容量和释放风险认识有限. 本文以环渤海地区湿地表层沉积物为研究对象, 通过批处理实验分析了湿地磷的吸附容量和释放风险, 阐明了湿地对沉积物磷吸附固定和释放风险的影响, 旨在为环渤海地区湿地的保护利用和近海磷污染防治提供基础数据.

1 材料与方法

1.1 样品采集与处理

环渤海地区河流众多, 在大河河口发育了面积广大的滨海湿地. 环渤海主要的芦苇湿地共设置 6 个研究样地 (图 1), 分别为: 寿光滨海湿地, 黄河三角洲湿地, 南大港湿地, 北大港湿地, 七里海湿地, 辽河三角洲湿地. 每个样地核心区选取 3 采样点, 每个采样点用柱状沉积物采集器随机采集 3~5 个沉积物样品, 表层沉积物 (0~20 cm) 混合均匀后密封保存, 样品经冷冻干燥后, 去除杂质, 粉碎过 100 目筛, 于 4℃ 冰箱中冷藏保存待用.

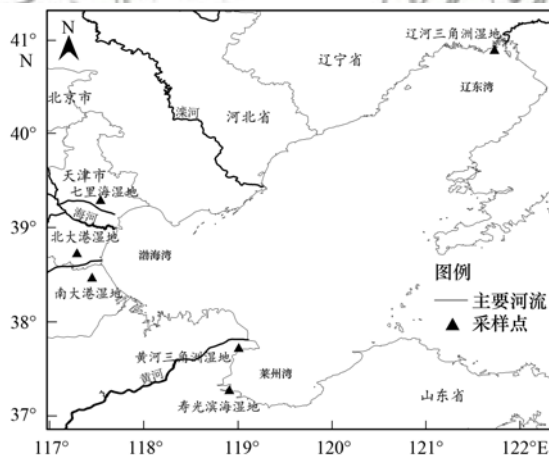


图 1 采样点分布示意

Fig. 1 Sample sites covered in this study

1.2 实验方法

1.2.1 沉积物磷最大吸附容量 ($Q_{\max}$) 的测定

取样品 0.500 0 g 于 50 mL 离心管中, 依次加入 50 mL 用 0.01 mol·L⁻¹ 的 KCl 配制的不同浓度的 KH₂PO₄ 溶液, 其中可溶性磷浓度 (c_0) 依次为 0.00、0.50、1.00、2.50、5.00、10.00、15.00、30.00、50.00、75.00、100.00、120.00、160.00 和 240.00 mg·L⁻¹. 混匀后于恒温摇床中振荡, 温度控制在 25℃. 24 h 后在离心机上用 4 000 r·min⁻¹ 离心 10 min. 用连续流分析仪测定上清液中磷含量. 吸附数

据利用修订的 Langmuir 模型拟合^[12], 拟合得到沉积物磷的最大吸附容量 ($Q_{\max}$)、吸附常数 (K), 计算沉积物本底吸附磷 (NAP)、临界平衡磷浓度 (EPC₀), 计算方法详见文献^[12].

1.2.2 磷释放风险的评估方法

根据土壤有效磷 (Olsen-P) 的含量和沉积物磷的最大吸附量, 磷吸附饱和度 (DPS)^[13] 可以根据式 (1) 获得:

$$DPS = \text{Olsen-P} / (Q_{\max} + \text{Olsen-P}) \times 100\% \quad (1)$$

根据黄清辉等提出的方法^[14], 用磷吸附饱和度 (DPS) 和磷吸附指数 (PSI) 计算沉积物磷释放风险指数 (ERI):

$$ERI = (DPS/PSI) \times 100 \quad (2)$$

1.2.3 沉积物的常规指标的测定

沉积物 pH 采用 pH 计测定 (土水比为 1:2.5); 总磷 (TP) 采用浓硫酸-高氯酸溶后, 钼锑抗比色法测定; 总有机碳 (TOC) 采用元素分析测定; 活性铁 (Fe_{ox}) 草酸铵浸提, 采用 ICP-AES 上机测定^[15]; 钙和镁采用 Mehlich 3 通用浸提剂浸提后采用原子吸收分光光度计 (TAS-990) 测定^[15]. 粒度采用激光衍射仪测定 (Mastersizer 2000, Malvern, England). 实验中每个样品均重复测定 3 次, 并加入国家标准土样 GBW07333 进行质控, 标样的测定误差小于 5%.

1.3 数据处理

实验数据采用 Excel 2010 作图, 吸附等温线数据采用 Origin 8.0 拟合处理, 采用 SPSS 19.0 进行数据单因素方差分析.

2 结果与分析

2.1 环渤海湿地沉积物基本理化性质

环渤海不同芦苇湿地沉积物的理化性质如表 1 所示. 湿地沉积物呈弱碱性, pH 为 8.00~8.60, 渤海湾湿地 (如南大港湿地和七里海湿地) pH 较高 (8.56~8.60), 其它地区湿地 pH 范围在 8.00~8.14. 沉积物 TOC 含量为 5.7~32.1 g·kg⁻¹, 其中渤海湾湿地 (七里海湿地, 北大港湿地) 的 TOC 含量为 28.4~32.1 g·kg⁻¹, 显著大于其它滨海湿地 ($P < 0.05$). 湿地沉积物中黏粒含量范围为 6.4%~21.9%, 黄河三角洲湿地黏粒含量最高 (21.9%), 而寿光滨海湿地的黏粒含量 (7.6%) 较低. 沉积物中总磷 (TP) 的含量为 516~1 887 mg·kg⁻¹, 平均值为 1 081 mg·kg⁻¹, 渤海湾的北大港湿地和七里海湿地 TP 含量明显高于其它地区, 而黄河三角洲湿地的 TP 含量最低. 环渤海地区沉积物 Fe_{ox} 的含量变化范围分别为 2 011~4 428 mg·kg⁻¹, 其中北大港湿地 Fe_{ox} 的含量显著高于其它地区. 沉积物中的 Ca 含量

变化范围为7 010 ~ 9 956 mg·kg⁻¹,南大港湿地的Ca含量显著高于其它地区. 沉积物中的Mg含量变化范围为1 038 ~ 2 408 mg·kg⁻¹,不同湿地的Mg含

量差异显著,其中辽东湾湿地和渤海湾湿地(七里海湿地)的Mg含量显著高于莱州湾湿地(寿光滨海湿地)和黄河三角洲湿地.

表 1 样点理化性质表征¹⁾

Table 1 Physical and chemical properties of studied samples							
地点	pH	黏粒(<5 μm) /%	TOC /g·kg ⁻¹	TP /mg·kg ⁻¹	Fe _{ox} /mg·kg ⁻¹	Ca /mg·kg ⁻¹	Mg /mg·kg ⁻¹
寿光滨海湿地	8.13 ± 0.02b	7.6 ± 0.7b	5.7 ± 2.3c	1 183 ± 190bc	2 814 ± 517bc	7 013 ± 247b	1 272 ± 66cd
黄河三角洲湿地	8.13 ± 0.12b	21.9 ± 7.2a	9.3 ± 6.4bc	516 ± 28d	2 529 ± 878bc	7 010 ± 1 691b	1 038 ± 76d
南大港湿地	8.56 ± 0.00a	12.1 ± 0.5b	11.4 ± 2.3bc	1 183 ± 242bc	2 011 ± 221c	9 956 ± 1 609a	1 566 ± 225bc
北大港湿地	8.00 ± 0.12b	6.4 ± 2.4bb	28.4 ± 7.3ab	1 887 ± 538a	4 428 ± 710a	8 994 ± 121ab	1 629 ± 158b
七里海湿地	8.60 ± 0.21a	10.9 ± 6.7b	32.1 ± 21.6a	1 716 ± 586ab	2 940 ± 212bc	9 035 ± 980ab	2 392 ± 339a
辽河三角洲湿地	8.14 ± 0.22b	12.8 ± 4.4b	9.3 ± 6.4bc	1 053 ± 80c	3 113 ± 248b	7 466 ± 1 351b	2 408 ± 127a

1)不同小写字母表示显著性水平 $P < 0.05$,下同

2.2 环渤海湿地沉积物对磷的等温吸附特征

环渤海地区湿地沉积物等温吸附实验数据拟合结果如图2所示,相关参数如表2所示.结果表明,改进Langmuir模型能较好地对不同沉积物等温吸附过程进行拟合, R^2 均在0.93以上,这说明该模型能较好地反映磷在环渤海地区沉积物的吸附行为.具体来说,就是在磷浓度较低的情况下,湿地沉积物会出现磷的负吸附,即存在着磷的解吸现象,而随着磷浓度的增大,开始发生磷的吸附行为.环渤海湿地的沉积物 $Q_{\max}$ 范围是693.7 ~ 2 117.2 mg·kg⁻¹,平均值为1 468.6 mg·kg⁻¹. $Q_{\max}$ 的大小顺序为七里海湿地 > 北大港湿地 > 南大港湿地 > 辽河三角洲湿地 > 寿光滨海湿地 > 黄河三角洲湿地.其中渤海湾滨海湿地的 $Q_{\max}$ 数值(1 611.3 ~ 2 117.2 mg·kg⁻¹)明显高于辽东湾湿地 $Q_{\max}$ 值,而辽东湾湿地 $Q_{\max}$ 值又高于莱州湾湿地 $Q_{\max}$ 值.其中七里海湿地的 $Q_{\max}$ 值最大,为2 117.2 mg·kg⁻¹,黄河三角洲湿地的 $Q_{\max}$ 值最小,为693.7 mg·kg⁻¹. $Q_{\max}$ 值越大,表明湿地沉积物对水体磷的吸附能力越强.湿地沉积物对磷的吸附结合能 K 值在9.24 ~ 117.19 L·mg⁻¹之间变化,不同 K 值变化同 $Q_{\max}$ 变化类似,即渤海湾湿地 > 辽

东湾湿地 ≈ 莱州湾湿地.

环渤海地区的本底吸附态磷(NAP)的变化范围为0.172 ~ 17.812 mg·kg⁻¹,其中寿光滨海湿地的NAP值(17.812 mg·kg⁻¹)显著高于其它湿地NAP值(0.172 ~ 2.214 mg·kg⁻¹).湿地沉积物的临界磷平衡浓度(EPC₀)的变化范围为0.002 ~ 0.213 mg·L⁻¹,同样表现为寿光滨海湿地的EPC₀值高于其它湿地.环渤海地区沉积物NAP和EPC₀值变化规律基本一致.

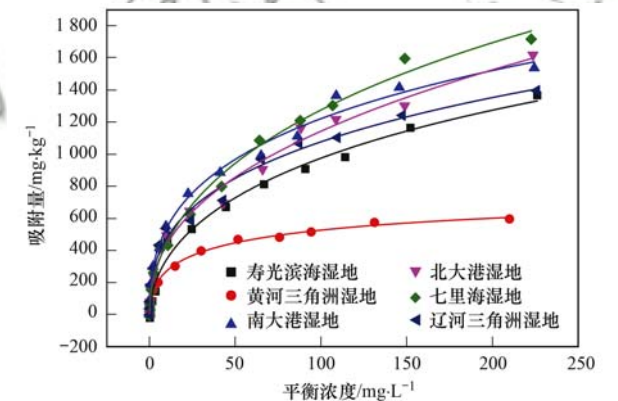


图 2 不同湿地沉积物对磷的等温吸附曲线

Fig. 2 Phosphorus adsorption isothermal curves of sediments from different wetlands

表 2 不同湿地沉积物的Langmuir模型等温吸附特征值

Table 2 Parameters of phosphorus adsorption isotherms for different wetland sediments					
湿地	$Q_{\max}$ /mg·kg ⁻¹	K /L·mg ⁻¹	NAP/mg·kg ⁻¹	EPC ₀ /mg·L ⁻¹	R^2
寿光滨海湿地	1 071.8 ± 166.7de	12.75 ± 4.47b	17.812 ± 0.859a	0.213 ± 0.052a	0.959
黄河三角洲湿地	693.7 ± 267.7e	9.24 ± 2.36b	0.172 ± 0.058c	0.002 ± 0.000c	0.957
南大港湿地	1 611.3 ± 157.9bc	22.91 ± 6.04b	0.216 ± 0.036c	0.003 ± 0.000bc	0.959
北大港湿地	1 904.2 ± 102.1ab	55.59 ± 26.68a	0.287 ± 0.066c	0.008 ± 0.002bc	0.938
七里海湿地	2 117.2 ± 314.1a	56.31 ± 7.46a	2.214 ± 1.937b	0.065 ± 0.071b	0.962
辽河三角洲湿地	1 413.3 ± 85.0cd	29.39 ± 15.18b	0.572 ± 0.542c	0.022 ± 0.025bc	0.954

2.3 湿地沉积物对磷吸附/释放风险评估

环渤海湿地沉积物磷吸附指数(PSI)变化范围为31.84 ~ 60.11,平均值为47.02. PSI在不同地区

湿地表现出一定的差异(图3),尤其是黄河三角洲湿地显著低于其它地区.环渤海地区湿地沉积物磷吸附饱和度(DPS)变化范围为0.28% ~ 4.50%,平

均值为 1.49%。寿光滨海湿地 DPS 数值最高,显著高于其它湿地。七里海湿地 DPS 同样也显著高于其它地区(除寿光外)。参照黄清辉等提出的由 PSI 和 DPS 等因素构成的磷释放风险指数(ERI),把 ERI 分成 4 个等级,分别为高度风险($ERI > 25\%$)、较高风险($20\% < ERI < 25\%$)、中度风险($10\% < ERI < 20\%$)和较低风险($ERI < 10\%$)。环渤海地区湿地沉积物磷释放风险指数(ERI)为 0.53%~10.10%(图 3),只有寿光滨海湿地的释磷风险为中度风险,其余湿地释磷风险较低。

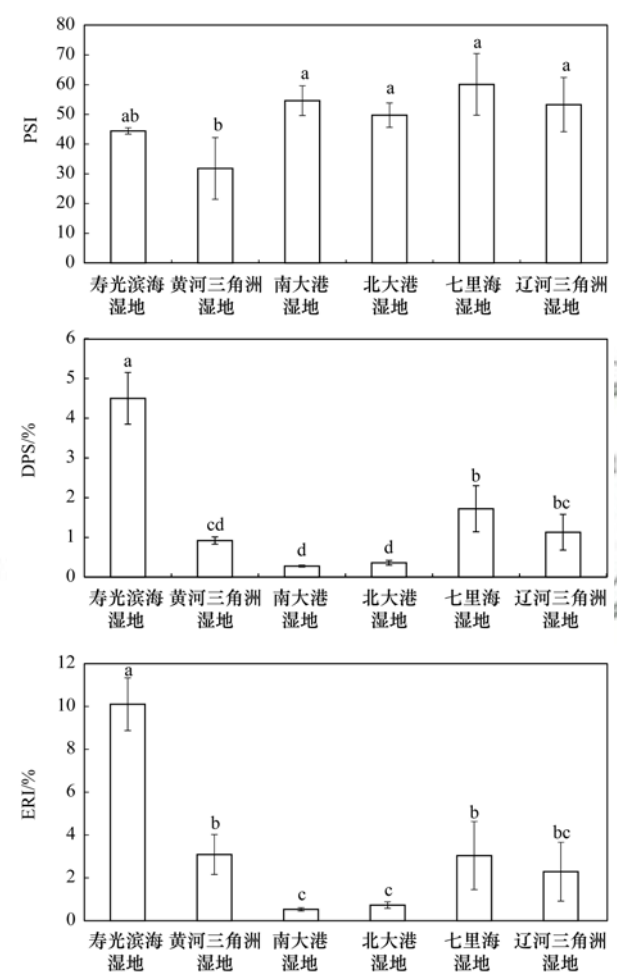


图3 环渤海滨海湿地沉积物磷的 PSI、DPS 和 ERI 特征

Fig. 3 Phosphorus PSI, DPS, and ERI values for different wetlands

3 讨论

3.1 环渤海湿地磷吸附固定特点和主要影响因素

湿地沉积物对磷吸附作用是湿地除磷的主要过程和机制^[16]。已有研究表明,沉积物对磷吸附主要受沉积物黏粒类型与含量、有机质含量、Fe、Al 氧化物、Ca、Mg 含量及沉积物 pH 的影响^[17]。一般来说,对于 pH < 6.5 沉积物而言,无定型、非晶质的铁铝氧化物被认为是磷的主要吸附剂,而对与 pH > 7.5 沉积物而言,钙和镁被认为是磷的主要吸附固定剂^[18]。本研究中相关性分析的结果表明(表 3),环渤海地区磷吸附的主要基质是 Ca 和 Mg,这与环渤海湿地磷主要形态为钙磷是一致的。李洁等^[10]发现环渤海湿地土壤中的磷主要是无机磷,且主要是不易释放的钙磷。Ca²⁺ 促进沉积物中的磷吸附,Ca²⁺ 浓度越大沉积物对磷的吸附量越大^[19]。而通过主成分分析,发现交换性钙镁含量对磷吸附的贡献率达到 47%^[20]。沉积物有机质含量显著影响磷素的吸附。有机质对沉积物磷吸附作用较为复杂,具体表现为增加、降低或无影响。有机质中含有酸性和低分子有机物,通过溶解作用和竞争吸附降低沉积物对磷的吸附^[21]。同时,有机质同金属离子通过络合或桥键作用增加了沉积物对磷吸附能力^[22]。本研究表明,环渤海湿地有机质的积累有利于增加对水体磷的吸附。

沉积物对磷的等温吸附实验研究表明,在磷浓度较低情况下,沉积物存在向上覆水体释放磷素即解吸的现象,这可能与沉积物含有一定量的本底吸附态磷(NAP)有关。NAP 可以指示水体磷的污染程度,与水体富营养化程度显著相关,污染程度越高的湖泊其 NAP 值越高^[13,23],如太湖严重富营养化和中度富营养化沉积物 NAP 值分别为 44~380 mg·kg⁻¹ 和 12~15 mg·kg⁻¹^[12]。环渤海湿地 NAP 的变化范围为 0.172~17.812 mg·kg⁻¹,显著低于严重富营养化和中度富营养化的内陆湖泊湿地,这说明环渤海滨海湿地引发水体富营养化风险较低。其中寿光滨

表3 环渤海地区沉积物理化性质与磷吸附参数的相关性¹⁾

Table 3 Correlation analysis between physicochemical properties and P adsorption parameters for wetland sediments

项目	pH	粒度	TOC	TP	Fe _{ox}	Ca	Mg
Q_{max}	0.399	-0.362	0.513 *	0.809 **	0.408	0.516 *	0.498 *
DPS	0.010	-0.279	-0.142	-0.068	-0.123	-0.370	-0.090
K	0.203	-0.407	0.551 *	0.783 **	0.563 *	0.236	0.412
MBC	-0.300	0.291	-0.337	-0.478 *	-0.346	-0.009	-0.277
ERI	-0.052	-0.218	-0.227	-0.179	-0.175	-0.447	-0.228
NAP	-0.073	-0.302	-0.197	-0.001	-0.103	-0.287	-0.251
EPC ₀	0.026	-0.357	0.030	0.065	-0.060	-0.286	-0.060

1) * 表示在 0.05 水平上显著相关, ** 表示在 0.01 水平上显著相关(双尾检验)

海湿地的 NAP 值显著高于其它湿地,结合寿光滨海湿地 ERI 指数为中度风险,说明寿光滨海湿地存在磷释放风险,有可能引发水体富营养化. 寿光滨海湿地磷污染与受纳水体小清河磷含量超标有关. 孙伟等^[24]研究小清河中 TP 浓度为 $0.19 \sim 0.57 \text{ mg} \cdot \text{L}^{-1}$, 均值为 $0.35 \text{ mg} \cdot \text{L}^{-1}$, 其含量超出《地表水环境质量标准》Ⅲ类水质标准.

3.2 环渤海湿地磷的释放特征及主要影响因素

沉积物磷的吸附饱和度(DPS)用以评估沉积物对磷的吸附容量的指标及指示磷径流、淋溶流失的风险^[22]. DPS 的大小可以作为衡量沉积物含磷水平和评估沉积物对磷吸附容量的可靠指标^[25~26], DPS 越高,磷释放到上覆水体中的风险也越大. 有研究表明,土壤磷吸附饱和度小于 10%,土壤磷的解吸量很少,超过此值,土壤磷的解吸量随土壤磷吸附饱和度的增加而增加,当土壤的 DPS 值大于 25% 时,磷素就会有流失的危险^[27]. 另有研究表明可以将 DPS 值大于 15% 作为土壤磷素的流失的临界值^[28]. Gao 等^[29]发现闽江河口的鳊鱼滩湿地 DPS 为 18.29%,大量磷从沉积物释放上覆水中,增加湿地的富营养化风险. 本研究中,环渤海芦苇湿地 DPS 值变化范围为 0.28%~4.50%,说明环渤海芦苇湿地磷素流失风险较低,具有较大的固定去除水体磷的潜力.

沉积物对磷的平衡吸附浓度(EPC_0)是决定沉积物磷吸附或释放的重要指标. 当上覆水可溶性磷浓度 $> \text{EPC}_0$, 沉积物会吸附水体中的磷,沉积物作为“磷汇”,反之则向水体释放磷,沉积物作为“磷源”. 而环渤海地区 EPC_0 的变化范围为 $0.002 \sim 0.213 \text{ mg} \cdot \text{L}^{-1}$, 寿光滨海湿地的 EPC_0 值 ($0.213 \text{ mg} \cdot \text{L}^{-1}$) 明显大于其它地区. 杭州湾滨海湿地的 EPC_0 值为 $0.034 \sim 0.049 \text{ mg} \cdot \text{L}^{-1}$, 扮演磷“汇”的角色^[30]. 佛罗里达 Okeechobee 湿地,由于湿地恢复前为农田,因此表层 0~2 cm 的 EPC_0 为 $0.8 \sim 3.3 \text{ mg} \cdot \text{L}^{-1}$, 是水体磷“源”^[31]. 环渤海芦苇湿地是河口淤积地基础上建造的湿地,湿地磷负荷较低,总体表现为水体磷“汇”.

环渤海芦苇湿地中寿光滨海湿地释磷风险为中度风险,其它湿地为较低风险. 相比较南方河口滩涂湿地,环渤海湿地整体上磷释放风险较低. 如珠江河口芦苇湿地 ERI 值为 40.45%~78.26%^[32],其沉积物中的磷易释放到上覆水体中,磷释放风险为高度风险. 闽江河口天然湿地 ERI 值为 9.47%~13.74%^[33],互花米草入侵对土壤磷潜在释放风险具有一定削弱作用. ERI 数值说明环渤海芦苇湿地沉积物释磷风险整体处于较低水平,这与环渤海芦苇湿地至今未发生大规模的富营养化情况相符.

4 结 论

本研究表明环渤海芦苇湿地具有较强的吸附截留磷的能力,沉积物磷的最大吸附容量为 $693.7 \sim 2117.2 \text{ mg} \cdot \text{kg}^{-1}$, 平均值为 $1468.6 \text{ mg} \cdot \text{kg}^{-1}$, 磷的最大吸附量主要受湿地沉积物 Ca、Mg 和 TOC 含量的影响. 环渤海芦苇湿地磷吸附饱和度(DPS)和释放风险指数(ERI)表明除寿光滨海湿地磷释放风险为中度风险外,其它湿地磷释放风险较低. 因此,建议在保护湿地生态的同时,应充分发挥滨海湿地对磷素拦截和净化功能,降低磷素对近海的环境污染.

参考文献:

- [1] 袁佳慧. 太湖稻麦轮作农田土壤磷素生物有效性研究[D]. 哈尔滨: 东北农业大学, 2018.
Yuan J H. Availability of soil P in a rice-wheat cropping rotation in Taihu Lake Region [D]. Harbin: Northeast Agricultural University, 2018.
- [2] 高静. 长期施肥下我国典型农田土壤磷库与作物磷肥效率的演变特征[D]. 北京: 中国农业科学院, 2009.
Gao J. Evolution characteristics of soil phosphorus pool and efficiency of phosphorus fertilizer in typical cropland of China under long-term fertilizations [D]. Beijing: Chinese Academy of Agricultural Sciences, 2009.
- [3] Li H, Huang G, Meng Q, *et al.* Erratum to: integrated soil and plant phosphorus management for crop and environment in China. A review [J]. *Plant and Soil*, 2013, **373**(1-2): 1011.
- [4] Hesketh N, Brookes P C. Development of an indicator for risk of phosphorus leaching [J]. *Journal of Environmental Quality*, 2000, **29**(1): 105-110.
- [5] Smith V H, Schindler D W. Eutrophication science: where do we go from here? [J]. *Trends in Ecology & Evolution*, 2009, **24**(4): 201-207.
- [6] 刘景双. 湿地生物地球化学研究 [J]. *湿地科学*, 2005, **3**(4): 302-309.
Liu J S. Wetland biogeochemistry research [J]. *Wetland Science*, 2005, **3**(4): 302-309.
- [7] 欧冬妮, 刘敏, 侯立军, 等. 河口潮滩沉积物磷的季节性累积和生物有效性 [J]. *海洋科学*, 2007, **31**(2): 20-26.
Ou D N, Liu M, Hou L J, *et al.* Seasonal accumulation and bioavailabilities of phosphorous in the tidal flat surface sediments from the Yangtze estuary [J]. *Marine Sciences*, 2007, **31**(2): 20-26.
- [8] 赖月婷, 吴如林, 龚开晟, 等. 闽江口湿地沉积物各形态磷分布特征及风险评价 [J]. *水土保持学报*, 2019, **33**(1): 171-177, 185.
Lai Y T, Wu R L, Gong K S, *et al.* Distribution characteristics and risk assessment of phosphorus speciation in the sediments of Min River Estuary wetland [J]. *Journal of Soil and Water Conservation*, 2019, **33**(1): 171-177, 185.
- [9] 孙军娜, 徐刚, 邵宏波. 黄河三角洲新生湿地磷分布特征及吸附解吸规律 [J]. *地球化学*, 2014, **43**(4): 346-351.
Sun J N, Xu G, Shao H B. Fractionation and adsorption-desorption characteristics of phosphorus in newly formed wetland soils of Yellow River Delta, China [J]. *Geochimica*, 2014, **43**(4): 346-351.
- [10] 李洁, 张文强, 金鑫, 等. 环渤海滨海湿地土壤磷形态特征研究 [J]. *环境科学学报*, 2015, **35**(4): 1143-1151.

- Li J, Zhang W Q, Jin X, *et al.* Detection of phosphorus components in the soils of coastal wetlands surrounding Bohai Sea [J]. *Acta Scientiae Circumstantiae*, 2015, **35**(4): 1143-1151.
- [11] Cao L, Song J M, Li X G, *et al.* Geochemical characteristics of soil C, N, P, and their stoichiometrical significance in the coastal wetlands of Laizhou Bay, Bohai Sea [J]. *Clean-Soil Air Water*, 2015, **43**(2): 260-270.
- [12] Zhou A M, Tang H X, Wang D S. Phosphorus adsorption on natural sediments: modeling and effects of pH and sediment composition [J]. *Water Research*, 2005, **39**(7): 1245-1254.
- [13] Jin X C, Wang S R, Bu Q Y, *et al.* Laboratory experiments on phosphorous release from the sediments of 9 lakes in the middle and lower reaches of Yangtze River region, China [J]. *Water, Air, and Soil Pollution*, 2006, **176**(1-4): 233-251.
- [14] 黄清辉, 王子健, 王东红, 等. 太湖表层沉积物磷的吸附容量及其释放风险评估 [J]. *湖泊科学*, 2004, **16**(2): 97-104.
- Huang Q H, Wang Z J, Wang D H, *et al.* Phosphorus sorption capacity of the surface sediment in the Lake Taihu and risk assessment of phosphorus release [J]. *Journal of Lake Sciences*, 2004, **16**(2): 97-104.
- [15] Pant H K, Reddy K R. Phosphorus sorption characteristics of estuarine sediments under different redox conditions [J]. *Journal of Environmental Quality*, 2001, **30**(4): 1474-1480.
- [16] Reddy K R, Kadlec R H, Flaig E, *et al.* Phosphorus retention in streams and wetlands: a review [J]. *Critical Reviews in Environmental Science and Technology*, 1999, **29**(1): 83-146.
- [17] Antoniadis V, Kolimati R, Efstratiou E, *et al.* Effect of soils with varying degree of weathering and pH values on phosphorus sorption [J]. *CATENA*, 2016, **139**: 214-219.
- [18] Reddy K R, DeLaune R D. *Biogeochemistry of wetlands: science and applications* [M]. Boca Raton: CRC Press, 2008.
- [19] 金晓丹, 吴昊, 王启明, 等. 钙离子和 pH 对长江河口青草沙水库水体磷浓度的影响 [J]. *环境工程技术学报*, 2016, **6**(5): 462-468.
- Jin X D, Wu H, Wang Q M, *et al.* Impact of calcium and pH on content of phosphorus in water of Qingcaosha reservoir of Yangtze Estuary [J]. *Journal of Environmental Engineering Technology*, 2016, **6**(5): 462-468.
- [20] 洪欠欠, 颜晓, 魏宗强, 等. 长期施肥与土壤性质对水稻土磷吸附的影响 [J]. *中国土壤与肥料*, 2018, (3): 61-66, 84.
- Hong Q Q, Yan X, Wei Z Q, *et al.* Effects of long-term fertilization on phosphorus sorption and soil properties in paddy soil [J]. *Soil and Fertilizer Sciences in China*, 2018, (3): 61-66, 84.
- [21] 杨芳, 何园球, 李成亮, 等. 不同施肥条件下旱地红壤磷素固定及影响因素的研究 [J]. *土壤学报*, 2006, **43**(2): 267-272.
- Yang F, He Y Q, Li C L, *et al.* Effect of fertilization on phosphorus fixation in upland red soil and its affecting factors [J]. *Acta Pedologica Sinica*, 2006, **43**(2): 267-272.
- [22] Sekhon B S, Bhumbra D K, Sencindiver J, *et al.* Using soil survey data for series-level environmental phosphorus risk assessment [J]. *Environmental Earth Sciences*, 2014, **72**(7): 2345-2356.
- [23] Wang S R, Jin X C, Pang Y, *et al.* Phosphorus fractions and phosphate sorption characteristics in relation to the sediment compositions of shallow lakes in the middle and lower reaches of Yangtze River region, China [J]. *Journal of Colloid and Interface Science*, 2005, **289**(2): 339-346.
- [24] 孙伟, 张守本, 杨建森, 等. 小清河水环境质量评价及主要污染物入海通量研究 [J]. *海洋环境科学*, 2017, **36**(3): 366-371.
- Sun W, Zhang S B, Yang J S, *et al.* Quality assessment of aquatic environment and fluxes of major pollutants to the Xiaoqing river estuary [J]. *Marine Environmental Science*, 2017, **36**(3): 366-371.
- [25] 邵兴华, 章永松, 林咸永, 等. 三种铁氧化物的磷吸附解吸特性以及与磷吸附饱和度的关系 [J]. *植物营养与肥料学报*, 2006, **12**(2): 208-212.
- Shao X H, Zhang Y S, Lin X Y, *et al.* Phosphorus adsorption and desorption properties of three synthetic iron oxides and their relation to phosphorus adsorption saturation [J]. *Plant Nutrition and Fertilizer Science*, 2006, **12**(2): 208-212.
- [26] Nair V D, Graetz D A. Phosphorus saturation in spodosols impacted by manure [J]. *Journal of Environmental Quality*, 2002, **31**(4): 1279-1285.
- [27] Hooda P S, Rendell A R, Edwards A C, *et al.* Relating soil phosphorus indices to potential phosphorus release to water [J]. *Journal of Environmental Quality*, 2000, **29**(4): 1166-1171.
- [28] Chrysostome M, Nair V D, Harris W G, *et al.* Laboratory validation of soil phosphorus storage capacity predictions for use in risk assessment [J]. *Soil Science Society of America Journal*, 2007, **71**(5): 1564-1569.
- [29] Gao D Z, Chen G X, Li X F, *et al.* Reclamation culture alters sediment phosphorus speciation and ecological risk in coastal zone of southeastern China [J]. *Clean-Soil Air Water*, 2018, **46**(11): 1700495.
- [30] 梁威. 杭州湾滨海湿地磷素迁移转化特征及净化功能 [D]. 北京: 中国林业科学研究院, 2012.
- Liang W. The phosphorus transfer and refining of Hangzhou Bay coastal wetland [D]. Beijing: Chinese Academy of Forestry, 2012.
- [31] Bhadha J H, Harris W G, Jawitz J W. Soil phosphorus release and storage capacity from an impacted subtropical wetland [J]. *Soil Science Society of America Journal*, 2010, **74**(5): 1816-1825.
- [32] 叶妹. 珠江淇澳岛湿地沉积物磷的赋存形态及释放风险评估研究 [D]. 广州: 暨南大学, 2013.
- Ye M. Research on the phosphorus fractions and releasing risk assessment in wetland sediments of Qi'ao island of Pearl River [D]. Guangzhou: Jinan University, 2013.
- [33] 安婉丽, 高灯州, 刘晴晴, 等. 互花米草入侵对闽江口湿地土壤磷形态及释放风险的影响 [J]. *水土保持学报*, 2016, **30**(6): 214-219.
- An W L, Gao D Z, Liu Q Q, *et al.* Influences of spartina alterniflora invasion on phosphorus forms and releasing risk in Min River Estuarine wetlands [J]. *Journal of Soil and Water Conservation*, 2016, **30**(6): 214-219.

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