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Research article

Phosphorus release from acid sulfate wetland soils in response to pH and dissolved oxygen alteration

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ABSTRACT

Phosphorus (P) release from wetland soils is an important process for its widespread ecological impacts. The availability of soil P is determined by the type of sediments and their complex interaction with environmental drivers. This study investigated the potential of net P release in acid sulfate wetland soils of Tram Chim National Park (Vietnam). The lab-scale experiments were conducted on intact soil cores (to the 20 cm depth) at three sites with different dominant vegetation communities (*Eleocharis dulcis* (S1), mixed lotus and *Eleochris dulcis* (S2), and *Melaleuca Cajuputi* (S3)) to quantify soil P fractions and measure P release fluxes from the acid soils in response to changes in water pH and dissolved oxygen (DO). The results showed that labile P fraction, or the most available P in soils, accounted for less than 23% of measured P. Non-labile P was the most abundant fraction, either in the surface (0-10 cm) or deeper (10-20 cm) layers, and accounted for more than 47% of measured P species. P release rates increased significantly with increasing pH and DO availability. pH is the primary factor driving P release in acid sulfate wetland soils. The highest release rates of P were recorded at pH 11.0 under the oxic condition. This study suggests that P pools in acid sulfate wetland soils are highly sensitive to changes in the water column that could occur during the regulated flooding for water-level management.

Key words: Acid sulfate soil, wetland, phosphorus release, phosphorus fractionation

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INTRODUCTION

Tram Chim National Park in the Mekong Delta of Vietnam is the hotspot of important habitats for conserving *Melaleuca* forest ecosystem and many rare waterbirds[1]. Acid sulfate soils in Tram Chim National Park typically contain iron sulfides such as FeS or pyrite (FeS_2), which can be oxidized while exposed to the air due to a wide range of anthropogenic activities (e.g. drainage and excavation) and natural phenomena (e.g. drought) and causes the environmental acidification[2]. Water level regulation is the most important management strategy to conserve the ecosystem in the Tram Chim National Park. Tram Chim has a criss-cross canal system that allows the water to flow in and out easonally. The seasonal hydrologic regime builds up the biodiversity by creating distinctive patterns of habitat areas for grass communities such as *Eleocharis*, *Panicum*, *Triticum*, and wild rice[3]. Seasonal flooding also alters pH and dissolved oxygen in the water column. Deeper areas are not well mixed with the flood water and maintain a vertical stratification of oxygen. The reduced soils promote the reduction of ferrous iron, thus increases the pH closer to 7 seasonally[3,4]. The counter effects can occur in shallow areas of the wetland. Aquatic ecosystems surrounded by agricultural lands can experience occasional nutrient loads from the catchment area and promote algal blooms that can significantly reduce the water oxygen content and increase the pH as high as 11.0[5,6]. High pH water in the fertilizer-overuse catchment can also increase wetland water pH if the wetland water levels are regulated with the catchment water inflows[7]. Consequently, any disruption of the natural hydrology regime would cause a shift of flora communities to a less desirable pattern for the native fauna by limiting their food resources[3].

Rice paddies cover most of the land surrounding Tram Chim National Park and interfere with natural water flow to introduces substrates into the wetland. Phosphorus (P) loadings into wetlands have been noticed to increase due to agricultural activities[8]. As an essential macronutrient, P is important for photosynthesis, respiration and carbohydrate metabolism[9,10]. Studies of P cycling processes have provided insight of the great variability of aquatic ecosystems. Highly bioavailable dissolved P is converted into less – bioavailable particulate and organic fractions as the consequence of uptake onto wetland soils or by phytoplankton[11]. The reserved phosphorus within wetland soils may then be remobilized via various biotic (i.e., assimilation by plants, plankton,

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periphyton, and microbes) and abiotic processes (i.e., sedimentation, soil adsorption, precipitation, and exchange mechanism) under the disruptive condition of redox condition and pH due to anthropogenic or natural forces[12]. Particularly, pH increases due to fertilizer applications can enhance P availability in acidic soils. However, the extent of this effect depended on the interaction of soluble P with the available Fe minerals in acidic soils[13]. Consequently, acidic wetlands located in the agricultural catchments such as the Tram Chim National Park are strongly vulnerable to a rapid internal P recycling.

Several chemical forms of P can enter wetlands during the flooding events, including dissolved inorganic P, dissolved organic P, particulate inorganic P, and particulate organic P. The labile and refractory components of dissolved and particulate organic P fractions can be distinguished further. Theoretically, organic and particulate P forms must be converted into inorganic forms before being bioavailable[12]. The interrelationship between soil P contents and the external environmental conditions affects wetland functions. The P forms in soils changed in accompanying to a change in the external environmental conditions. In addition, the relative pool sizes and the transformation of P compounds in wetland determine the dynamics of P exchange at the soil-water interface. If the concentration of dissolved phosphates in the interstitial water is significantly higher than that in the upper water layers, the soils may act as an important P source[14]. The rate of P release from the soils defines the concentration of bioavailable dissolved inorganic P in the water column and disturbs ecosystem resilience across different scales. In the field, P release from wetland soils is a critical process that can be strongly modified by a complex biological P cycle including the vegetation succession[15].

Information about the soil distribution of P forms and their potential release in Tram Chim National Park would aid to assess P availability in the typical acid wetlands. This is essentially useful to promote management quality and achieve management targets in protecting the natural reserves. The objectives of this study were to i) quantify phosphorus fractions in acid sulfate wetland soils; ii) determine the effects of pH and dissolved oxygen content on the phosphorus release from acid wetland soils.

MATERIALS AND METHODS

Sampling and chemical analysis

Tram Chim National Park is located in Dong Thap Muoi region, in Tam Nong district, Dong Thap province (10.67^o,105.43^o). Tram Chim National Park is a wetland area of 7,313 hectares, classified in the special-use forest system of Vietnam (Figure 1). This place is the habiltat of many precious bird species. The natural vegetation community covering the Tram Chim National Park presents a significant division between *Melaleuca* forests, seasonally inundated grassland and permanently inundated swamp. Main factors contributed to the vegetation patchiness in the Tram Chim National Park are terrain elevation, flood depth and duration of flooding[1].

Soil samples were collected at three different sites, three replicates per site, (i.e., the dominant site of *Eleocharis dulcis* (S_1), the site of a mixture of lotus *Nelumbo nucifera* and *Eleocharis dulcis* (S_2) and the *Melaleuca Cajuputi* forest (S_3)) having distinct characteristics of historical drainage. *Melaleuca* forest covers about 41.0% of the total area. *Eleocharis dulcis* represents the grass community which is a desirable food for red-crowned crane, an extremely rare native fauna[3]. Lotus *Nelumbo nucifera* is abundant in permanently inundated swamps which are located on old riverbeds and shallow streams[1]. Every soil core (diameter of 20 cm) was collected until 20 cm of depth and divided into two sub-samples (i.e., surface soil to 10 cm of depth (SS) and sub-surface soil from 10 to 20 cm of depth (DS)) to determine moisture, pH, soil organic matter (SOM), total phosphorus (TP), inorganic P fractions and cation exchange capacity (CEC) (Figure 1). Water samples were also collected to use in the P release experiments with the intact soil cores. Soil pH was determined in a solution of soil and water (1:2.5). Organic matter content (SOM) (% of dry soil) were measured using based on the weight loss in 2.5 g of soil burned at 550°C to a constant weight after a complete oven drying at 105°C. The homogenized soil samples were also subjected to chemical measurements such as total phosphorus (TP), cation exchange capacity (CEC), and total Ca, Al, Fe and Mg. Total P and metal concentrations (Fe, Al, Mg and Ca) were measured with $X-$ray Fluorescence Spectroscopy (XRF)[16]. Cation exchange capacity (CEC) was determined by colorimetric method with cobaltihexamine chloride (0.05N)[17].

Phosphorus fractionation

Soil samples were subjected to sequential inorganic P fractionation using a modified fractionation procedure of inorganic P according to a previous study[13]. The procedure fractionates $NaHCO_3$–extractable P, also called labile–P (LP), which is the most available fraction to biota. The solid remaining from $NaHCO_3$

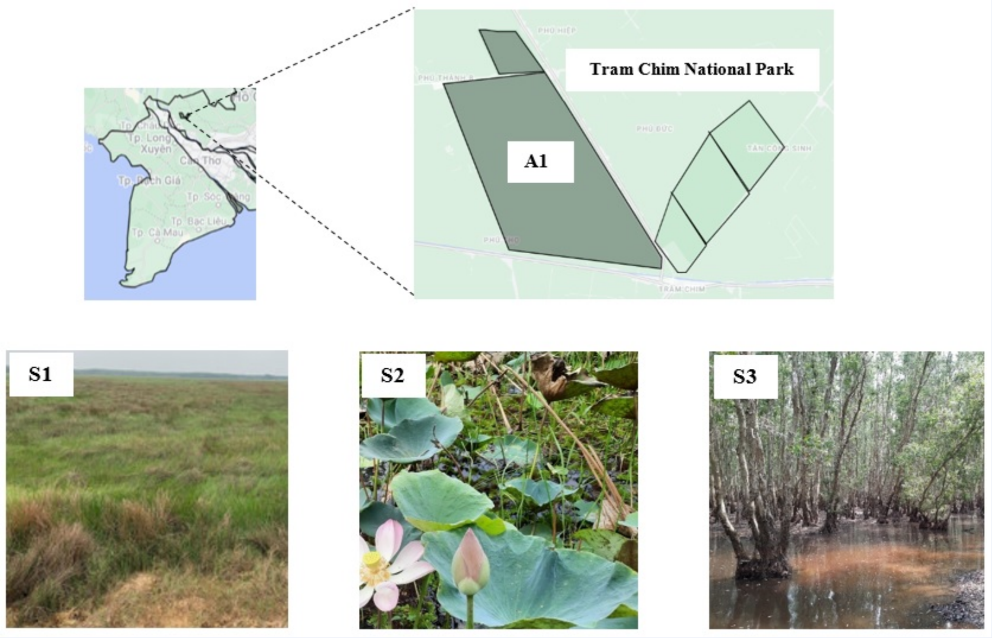

Figure 1: Sampling sites in the Division A1 of Tram Chim National Park (S1: *Eleocharis dulcis* coverage with historical natural drainage before permanent flooding from 2016; S_2: mixed coverage of lotus and *Eleocharis dulcis* with long-term permanent flooding; S_3: *Melaleuca Cajuputi* coverage with historical natural drainage before permanent flooding from 2016)

extraction is continuously extracted with HCl solution to fractionate the moderately labile P (MLP). The further fractionation with NaOH solution extracts the non—labile P (NLP). The amount of $PO_4{}^{3-}$-P in every extraction was determined using the ascorbic acid method[14].

Phosphorus release experiment

To estimate the P release rate, soil cores were incubated under the manipulated condition of water columns (Figure 2). The increase of $PO_4{}^{3-}$-P concentration in the water column over the incubation for 10 to 15 days was used to calculate phosphorus fluxes. efore the incubation experiments, each core is refilled with a volume of the intrinsic wetland water (*ca.* 10 cm depth) without any disturbance to sediment cores. During the incubation, water pH was adjusted to different pH ranges (4.0 ± 0.5, 7.0 ± 0.5 and 11.0 ± 0.5). The water columns were sparged continuously with air or N_2 gas at a height of 5 cm above the sediment-water interface. At the end of the air sparging period for 10 days, water was withdrawn and refilled with the new water. The sediment core were then continually sparged with N_2 for the other 10-day incubation. The water sampling and measurement were accomplished according to the previous study[14]. DO concentrations were maintained above 6.0 mg l^{-1} during the air sparging and less than 0.5 mg l^{-1} during the N_2 sparging. After the first 2-hours of gas sparging, first water sample were taken and measured for $PO_4{}^{3-}$-P concentration . 4mL-aliquots of water were daily sampled after every hour from 9 am to 16 pm. P release rates (mg h^{-1}) were calculated using a least squares linear regression of $PO_4{}^{3-}$-P concentrations in the overlying water over the incubation time. Areal P release rates (mg m^{-2} h^{-1}) were cumulative release rates after normalizing to the sediment surface area of sediment cores.

Statistical analysis

Repeated-measures ANOVA analysis was used to analyze the differences in the P release rates of soils under different conditions of pH and DO across the sites. Variation of P fractions between surface and deep soils was analyzed using independent sample t-tests. The relationship between variables was evaluated using correlation analysis. IBM SPSS Statistics 29.0.1.0 (USA) was used for all analyses.

RESULTS AND DISCUSSION

Soil analysis indicated the change of soil properties with the soil depth and across the sites (Table 1). The

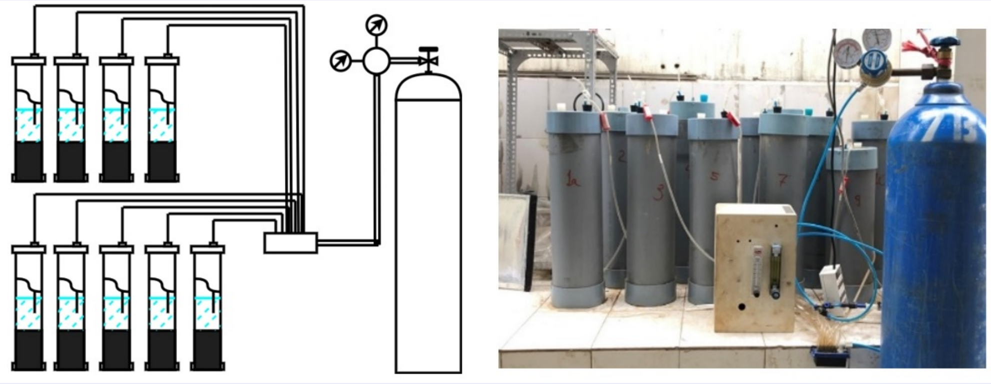

Figure 2: Phosphorus release experiments with intact soil cores

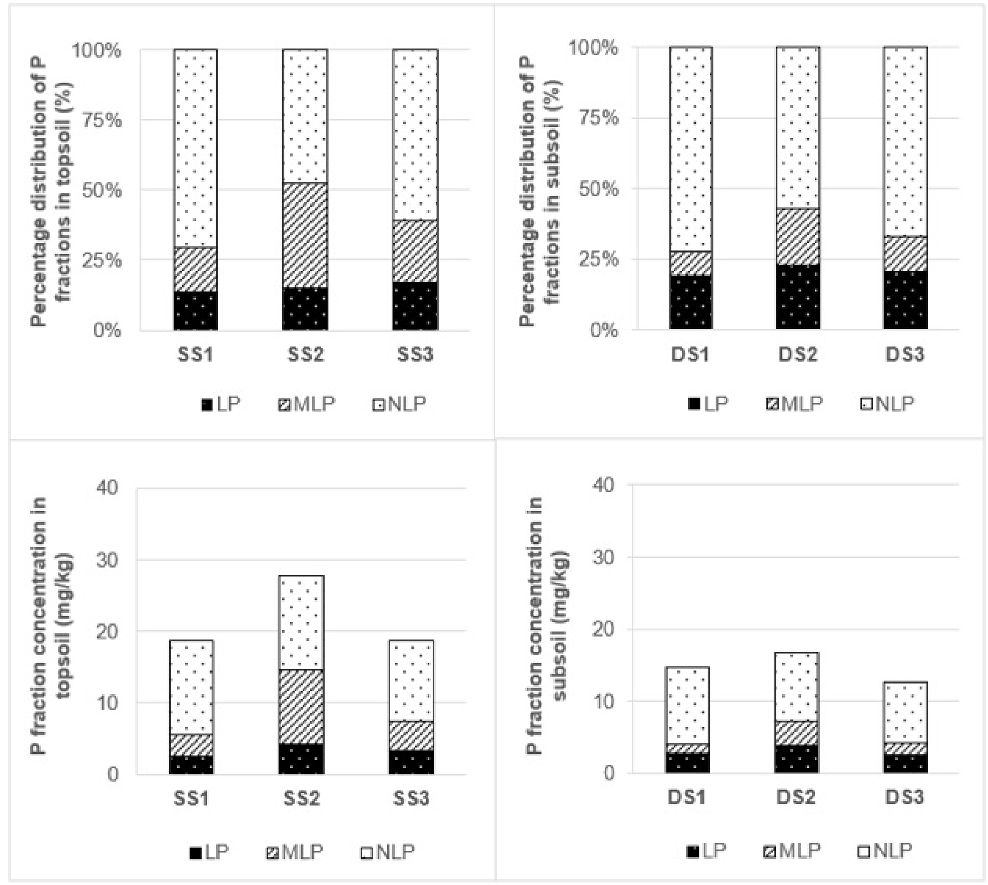

Figure 3: Distribution of P fractions in surface soils (SS) and deep soils (DS) of different sites

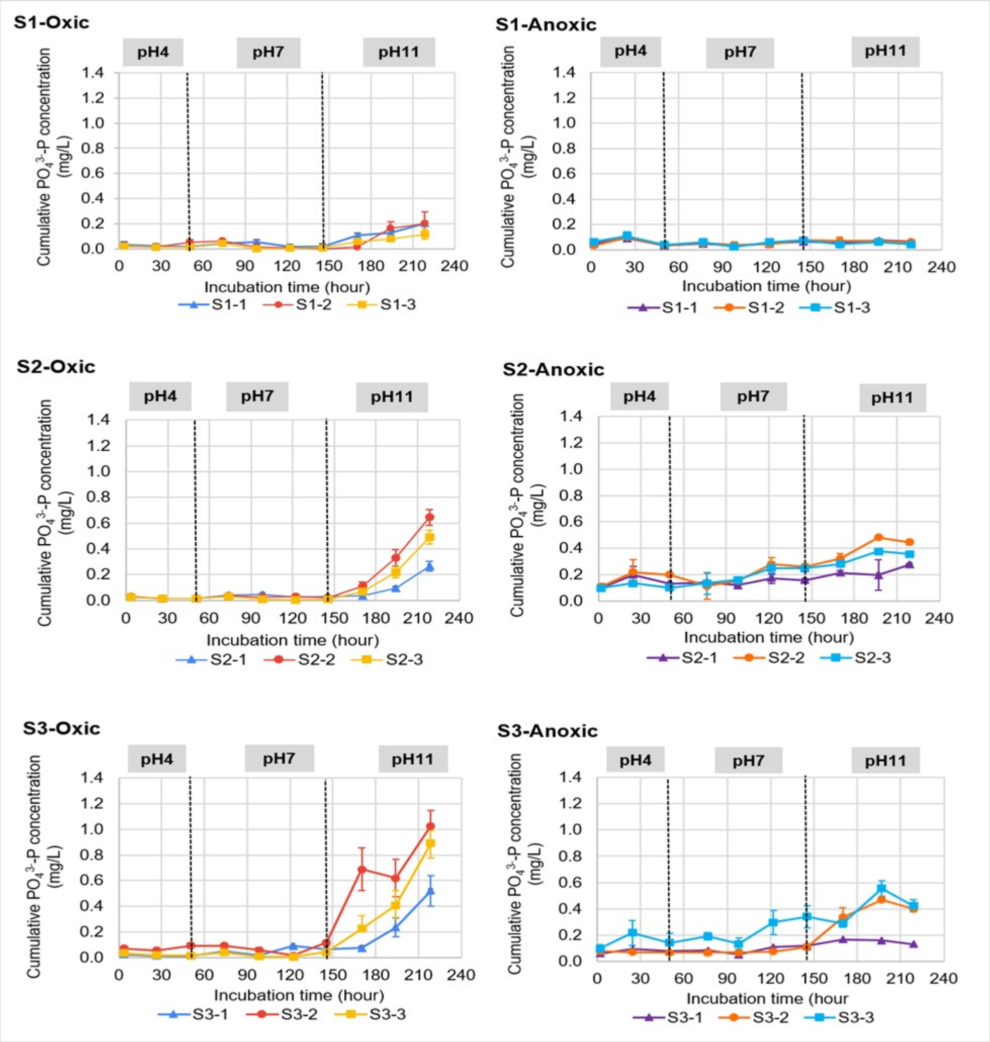

Figure 4: Cumulative PO_4^{3-}-P concentrations (mean ± SE, n = 3) in the water column under different conditions of pH and DO.

average soil pHs ranged from 4.53 to 5.48. Lower pH values were recorded in site S3 dominated by *Melaleuca Cajuputi* with a historical drainage before the current permanent flooding. A different depth-profile of soil properties (SOM, TP, and CEC) was observed in site S2 compared to the others. In site S1 and S3, surface soils to a depth of 10 cm contained significantly lower contents of SOM, TP and CEC compared to deep soils (from 10 cm to 20 cm of depth). The trend was opposite between surface and deep soils in site S2. Highest contents of SOM (4.89 ± 0.10%) and TP (1060.1 ± 19.1 mg kg^{-1}) were recorded in the surface soils of site S2 covered with lotus and *Eleocharis dulcis* over the long-term permanent flooding. On the other hand, lowest contents of SOM (1.34 ± 0.03%) and TP (303.1 ± 14.7mg kg^{-1}) were recorded in the surface soils of site S3 having *Melaleuca Cajuputi* coverage and a similar hydrological regime of site S1. Average CECs were also remarkably lower in the soils of site S3 (0.65 - 0.78 cmol+kg^{-1}) compared to the other sites (5.13 – 8.26 cmol+kg^{-1}), which accompanied the pattern of SOM, TP and metal contents across the sites. Total concentrations of metals (Fe, Al, Mg, and Ca) in deep soils were slightly higher than those in surface soils. Between the sites, the metal concentrations in site S3 were significantly lower than other sites. Fe and Al were dominated and accounted for about 12.90 -14.90% of soil weights, particularly Fe concentrations in site S3 were significantly lower, about 6.08 – 8.40% of soil weights. Ca and Mg were also equally distributed but accounted for very small portions of less than 0.53% of soil weights.

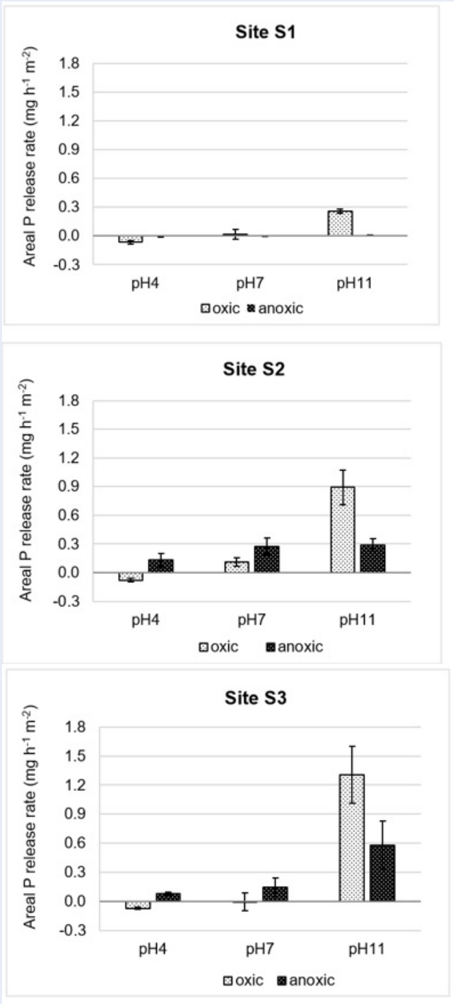

Figure 5: Areal P release rates (mean ± SE, n = 3) in acid wetland soils under different conditions of pH and DO.

Correlation analysis showed that SOM positively correlated with TP ($r = 0.861$, $p < 0.05$) and CEC also positively correlated with Fe ($r = 0.927$, $p < 0.01$), Al ($r = 0.919$, $p < 0.01$) and Ca ($r = 0.973$, $p < 0.01$). The significant interactions between metals were also revealed in the acid wetland soils. Positive correlations were found between Fe and Al ($r = 0.852$, $p < 0.05$), between Fe and Ca ($r = 0.986$, $p < 0.01$), as well as between Al and Ca ($r = 0.897$, $p < 0.01$). The revealed relationships suggest that biotic and abiotic active mechanisms regulate the P release from the acid wetlands soils[18]. The mineralization of degradable organic matter is postulated as the most important process driving the P release in many cases[19]. The adsorption and co-precipitation of P on the pH-dependent charged surface of minerals, particularly calcium sulfate, iron and aluminum oxides, and organic particulates were early recognized in aquatic ecosystems[20,21].

In addition, the study found significantly higher concentrations of NLP fraction in surface soils compared to deep soils across the sites ($p < 0.01$) (Figure 3). Moreover, LP and MLP fractions were positively correlated to each other ($r = 0.832$, $p < 0.05$). The LP fraction, or the most available P, accounted for less than 23% of the measured P and correlated significantly with pH ($r = 0.845$, $p < 0.05$). The NLP fraction, or the Fe- and Al-adsorbed and precipitated P, was the dominant fraction and accounted for 47 – 72% of measured P. The soils in site S2 contained higher concentrations of the most available P fractions (i.e., LP and MLP) than the other soils in site S1 and site S3. The significant differences of P fractions between the sites and along the soil depth were mainly due to the differences in vegetation communities and the distribution of Fe and Al minerals in acid wetland soils. The NLP fractions or Fe and Al-bound P fractions were mostly concentrated near the sediment surface and can be transported easily by moderate water flows[14]. The most available P fractions such as LP and MLP fractions were associated to organic matter sources which were strongly determined by macrophyte communities[22]. This is reasonable since the SOM contents in surface soils of site S2 were recorded higher than that in site S1 and site S3 (Table 1). These bioavailable fractions are highly regulated by microorganism activities and plant uptakes, therefore only contribute the smaller portions of soil TP pools.

The soil incubation under different conditions of pH and DO showed the remarkable increases of PO_4^{3-}-P concentrations in the water column with pH 11.0 and the oxic condition across the sites (Figure 4). The estimation of P release rate demonstrated that highest P release rates were recorded at pH 11.0 under the oxic condition in all sites, about 1.306 ± 0.294 $mg.h.m^{-2}$ in site S3, 0.892 ± 0.184 $mg.h.m^{-2}$ in site S2 and 0.259 ± 0.024 $mg.h.m^{-2}$ in site S1 (Figure 5). Under the anoxic condition ($DO < 0.5$ mg/L), P release rates slightly increased with pH 7.0 and 11.0, except for the soils in site S1 due to the low availability of LP and MLP fractions. Across the sites, anoxic release rates at pH 11.0 were lower than oxic release rates while the opposite trend was recorded at pH 4.0 and 7.0. The adsorption of P could occasionally occur at pH 4.0 and 7.0 regardless of the redox condition (Figure 5). Significant responses of P release with pH changes indicated the primary role of pH in driving P dynamics in acid wetland soils. Meanwhile, DO availability regulated the P release of acid wetland soils in a complicated way while interacting with pH change.

Table 1: Physicochemical characteristics of acid wetland soils (mean ± SE, n = 3)

Site	Soil sample	pH	SOM %	CEC cmol+kg^{-1}	TP mg kg^{-1}	Fe g kg^{-1}	Al g kg^{-1}	Ca g kg^{-1}	Mg g kg^{-1}
S1	SS1	4.71 ± 0.21	2.16 ± 0.06	5.13 ± 0.56	581.3 ± 27.2	130.5 ± 2.0	141.4 ± 7.1	3.7 ± 0.3	4.3 ± 0.5
	DS1	5.10 ± 0.12	2.99 ± 0.09	8.26 ± 0.22	898.7 ± 26.4	134.3 ± 3.5	149.7 ± 2.4	4.4 ± 1.1	4.8 ± 0.1
S2	SS2	5.48 ± 0.35	4.89 ± 0.10	7.12 ± 1.08	1060.1 ± 19.1	129.2 ± 1.5	144.2 ± 3.5	4.1 ± 0.2	3.4 ± 0.9
	DS2	5.33 ± 0.15	2.12 ± 0.96	5.69 ± 1.57	621.6 ± 10.7	130.0 ± 0.9	143.5 ± 1.1	4.0 ± 0.2	5.3 ± 0.3
S3	SS3	4.72 ± 0.24	1.34 ± 0.03	0.65 ± 0.49	303.1 ± 14.7	60.8 ± 4.7	135.1 ± 5.6	1.3 ± 0.3	3.2 ± 0.2
	DS3	4.53 ± 0.36	2.35 ± 0.16	0.78 ± 0.01	879.5 ± 23.4	84.0 ± 1.6	139.3 ± 2.2	1.9 ± 0.1	2.9 ± 0.1

Table 2: Repeated-measures ANOVA for P release rate in acid wetland soils

Source	F (Repeated measures)	P
Oxic condition		
Between subjects		
Site	11.412	<0.01
Within subjects		
pH	55.445	< 0.001
pH x Site	6.555	<0.05
Anoxic condition		
Between subjects		
Site	7.712	< 0.05
Within subjects		
pH	7.329	< 0.05
pH x Site	3.031	0.123

Repeated measures ANOVA analysis also showed the significant differences of P release rates between the sites under either oxic or anoxic conditions and the significant impact of pH on P release rate in acid wetland soils (Table 2). The P values for the between-subjects factors were less than 0.01 under oxic condition and 0.05 under anoxic condition. This represents the probability that the sites with different dominant vegetation communities in acid wetlands may release phosphorus at different extents. The spatial heterogeneity of soil processes can influence the associated vegetation community structure and vice versa[23]. The spatial distribution of vegetation and the extent of several ecologically important processes are potentially altered during the wetland creation. Organic matter decomposition, nitrogen and phosphorus mineralization, elemental weathering from parent material, exogenous loading and accumulation of nutrients, and the internal mobility of nutrients are all processes that determine the macrophytic patches and the geochemical fragmentation of nutrient pools[24]. The P reallocation in wetland soils could be a function of the soil characteristics, soil and water P-pool sizes, and the biotic processes such as organic matter decomposition and macrophyte P uptakes[25]. In addition, the P values less than 0.001 and 0.05 for the within-subjects factor under oxic and anoxic conditions, respectively, indicates the statistically significant difference of P release rates resulting from different water pHs in the particular sampling sites. The pH effects under oxic conditions were associated significantly to the site characteristics since the P value for the interation between pH and site was less than 0.05 (Table 2).

The pH effect on soil P dynamics in acid sulfate soils was also demonstrated in previous studies. Accordingly, the release of available inorganic P through mineral weathering plays critical role in acid wetland soils[26]. Compared to the stable primary minerals (i.e., apatite, strengite and variscite), the dissolution rate of secondary P minerals bearing Ca, Fe, and Al depended on soil pH[27]. Increasing soil pH led to a quick solubilization of Fe and Al phosphates whereas Ca phosphates could only dissolve with pH values higher than 8[21]. P release from acid sulfate soils can be modified or reduced in association with P adsorption on variable-charge minerals such as Fe-oxides. Under acidic condition, the release of soil P was balanced by the adsorption of available P on positively charged surfaces and formation of insoluble Al and Fe precipitates[28]. The alkaline condition, however, could actuate a reverse with negatively charged surfaces of minerals. It is also important to note that the relative contribution of P adsorption depends on the degree of P saturation of soil contituents, rather than on the total P content.

The modified effect of redox potential on the soil release was also reported in a previous study for acid sulfate wetland soils in Thailand[29]. Reduced redox potentials contributed to the increase of soil P release following the reduction of ferric phosphate and ferric hydrous oxides to release Fe^{2+} and PO_4^{3-} at low pHs (4.0 – 6.0)[2,29,30]. However, anoxic conditions also maintained high P sorption capacity of acid soils in tropical forests[31]. High P sorption in anoxic soils can be attributed to: i) the formation of Fe- and Al-bearing mineral with higher surface area for P sorption capacity and ii) the pH increase as a consequence of Fe reduction process and the associated effects on hydroxylation and surface area of Al and organo-Al complexes[32]. Higher concentrations of Al in site S1 and site S2 suggest that the P sorption at pH 11.0 under anoxic condition may significantly balance the P release rate as compared to that in site S3 (Table 1 and Figure 5).

The present work has quantified the soil P fractions which are likely to remobilize into the water column in the acid wetland of Tram Chim National Park. The potential of soil P release under the alteration of water pH and DO has also been estimated in lab-scale microcosms with the contact soil cores from the unique sites of different dominant vegetation communities. Fe- and Al-bound P species were the major source of P release with changing pH and DO concentration in the water column of acid wetlands. These results imply that the water level regulation in wetlands developed on acid sulfate soils should consider properties of the water source and the heterogeneous terrain in specific wetland areas. In an agricultural watershed, the drainage water from rice paddy fields could have higher pH values than the intrinsic pH in acid wetlands[33]. A managed flooding of acid sulfate soils in Tram Chim National Park with neutral or alkaline water and an enough aeration into the shallow wetland areas would promote the significant release of P and the consequent shift of biodiversity. Our findings shed light on the importance of water quality for the cycling and fate of P in acid sulfate wetland soils.

CONCLUSIONS

This study investigated the fate of P in the acid sulfate soils of Tram Chim National Park, a protected area for wetland biodiversity. A major focus was on soil P speciation and the potential effects of water pH and DO on soil P release process. There is a need to monitor the water source prior to a flooding event with specific concerns of pH and DO parameters. The important processes such as mineral solubilization and desorption are likely to occur in response to fluctuating conditions in the water column of acid sulfate soil wetlands. Fe- and Al-bound P species in soils were the major sources of P release under alkaline and oxic conditions. The neutral pH could promote soil P release under anoxic condition but likely depended on P availability in acid sulfate soils. The monitoring of these processes during regulated flooding events in the field would be useful to better predict prospective environmental outcomes and develop the appropriate strategy for water-level management in acid wetlands.

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COMPETING INTERESTS

The authors declare that we have no competing interests.

AUTHOR CONTRIBUTION

Nguyen Xuan Que Vo: Conceptualization, Methodology, Supervision, Writing – original draft, review & editing. Tran Thi Phi Oanh: Data curatiom, Formal analysis. Nguyen Xuan Phuong Vo: Supervision, review & editing. All authors read and approved the final manuscript.

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Bài nghiên cứu

Giải phóng phốt-pho từ đất ngập nước nhiễm phèn do sự thay đổi pH và hàm lượng oxy hòa tan trong nước

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TÓM TẮT

Quá trình giải phóng phốt-pho (P) từ đất ngập nước là một quá trình quan trọng với nhiều tác động sinh thái ở quy mô lớn. Lượng P ở dạng sẵn có cho sinh vật sử dụng được xác định bởi loại trầm tích và ảnh hưởng phức tạp của các yếu tố môi trường. Nghiên cứu này khảo sát khả năng giải phóng P của đất ngập nước nhiễm phèn tại Vườn Quốc gia Tràm Chim (Việt Nam). Các thí nghiệm trong điều kiện phòng thí nghiệm được tiến hành trên các lõi đất còn nguyên vẹn (độ sâu 20 cm) được thu tại ba vị trí thu mẫu có đặc điểm quần xã thực vật chiếm ưu thế khác nhau (S1 – vùng cỏ năng (*Eleocharis dulcis*), S2 – vùng thực vật hỗn hợp gồm sen và cỏ năng, và S3 – vùng tràm (*Melaleuca Cajuputi*)) để định lượng hàm lượng các dạng P trong đất và dòng P hòa tan được giải phóng từ đất phèn vào nước mặt trong điều kiện thay đổi độ pH và hàm lượng oxy hòa tan (DO) trong nước. Kết quả cho thấy dạng P không bền (LP), hay dạng P dễ hòa tan và là nguồn dinh dưỡng sẵn có cho sinh vật, chiếm ít hơn 23% tổng hàm lượng P trong đất. Dạng P bền (NLP) là dạng P có phân bố nhiều nhất trong đất, bao gồm đất bề mặt (đến độ sâu 10 cm) và đất sâu hơn (10 cm-20 cm), chiếm hơn 47% tổng hàm lượng P trong đất. Tốc độ giải phóng P được ghi nhận tăng đáng kể khi độ pH tăng và DO được làm giàu nhờ quá trình sục không khí. Kết quả cho thấy pH là yếu tố quan trọng thúc đẩy sự giải phóng P trong đất ngập nước nhiễm phèn. Tốc độ giải phóng P cao nhất được ghi nhận ở điều kiện pH 11,0 và có sục không khí. Nghiên cứu này cho thấy rằng các bể chứa P trong đất ngập nước nhiễm phèn rất nhạy cảm với những thay đổi độ pH và hàm lượng DO của nước mặt, có thể xảy ra do hoạt động quản lý mực nước điều tiết lũ.

Từ khoá: đất phèn, đất ngập nước, giải phóng phốt-pho, phân đoạn phốt- pho

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