Available online at:
http://journal.unila.ac.id/index.php/tropicalsoil
DOI: 10.5400/jts.2018.v23i2.55

The Role of Inundation Types of Tidal Swampland on the Chemical Properties of Potentially Acid Sulphate Soils under Fertilizer and Lime Application

Arifin Fahmi[1*], Muhammad Alwi[1] and Dedy Nursyamsi[2]

[1]Indonesian Swampland Agricultural Research Institute
[2] Indonesian Center for Agricultural Land Resources Research and Development
*Jl. Kebun Karet, Loktabat Utara, Banjarbaru (South Kalimantan), *e-mail: fahmi.nbl@gmail.com*

Received 16 August 2017/ accepted 27 April 2018

ABSTRACT

Generally, fertilizer application increases soil fertility, on the other hand fertilizer application leads to the alteration of soil chemical balances in which the magnitude of changes is determined by soil properties. The research aimed to study the soil chemical properties of potentially acid sulphate soils (PASS) originally from two types of tidal swampland as influenced by the application fertilizers and lime. A pot experiment was carried out in a glasshouse. Soil samples were taken from PASS originated from two types of tidal swampland, i.e. PASS in type B tidal swampland (PASS-B) and PASS in type C tidal swampland (PASS-C). The experiment was arranged in single factor of completely randomized design, consisting of six levels of urea, SP-36, and KCl fertilizers and lime that were determined based on *Decision Support System* software (DSS). Soil pH, total nitrogen (N), available phosphorus (P), exchangeable potassium (K) and iron (Fe) were measured periodically every four weeks, soil redox potential (Eh) was measured every week, leaf color index was measured every two weeks. The dynamics of soil pH, concentration of P, K, Fe and N of PASS were influenced by the application of fertilizer rates and lime, although, the magnitude of their changes were influenced by inundation type of tidal swampland. These facts were mainly associated with the presence of Fe mineral in both soils, the different concentration of Fe^{2+} in PASS-B and PASS-C may be related to land hydrological condition of type B tidal swampland that is frequently flooded as origin of PASS-B.

Keywords: Fertilization, inundation types, potentially acid sulphate soils, soil chemical properties, tidal swampland

ABSTRAK

Aplikasi pupuk meningkatkan kesuburan tanah, di sisi lain diketahui bahwa aplikasi pupuk juga merubah keseimbangan kimia tanah dimana besaran dari perubahan tersebut ditentukan oleh sifat asli tanah. Penelitian ini bertujuan untuk mempelajari perubahan sifat kimia tanah akibat aplikasi beberapa dosis pupuk dan kapur pada tanah sulfat masam potensial (PASS) dari dua tipologi lahan pasang surut. Percobaan dilaksanakan di rumah kaca. Contoh tanah PASS diambil dari lahan pasang surut tipologi B (PASS-B) dan lahan pasang surut tipologi C (PASS-C). Percobaan menggunakan rancangan acak lengkap dengan satu faktor yang terdiri dari beberapa dosis pupuk urea, SP-36, dan KCl serta kapur, dimana perhitungannya didasarkan atas aplikasi *Decision Support System* (DSS). Beberapa sifat tanah seperti pH tanah, nitrogen total (N), fosfor teresedia (P), kalium dapat ditukar (K) dan besi (Fe) diukur secara periodik setiap empat minggu; redoks potensial (Eh) diukur setiap minggu sedangkan indeks warna daun diukur setiap dua minggu. Dinamika pH tanah, konsentrasi P, K, Fe serta kandungan N pada PASS dipengaruhi oleh aplikasi pupuk dan kapur, walaupun besaran dari perubahan semua sifat kimia tanah tersebut dipengaruhi oleh tipologi luapan lahan pasang surut. Kondisi tersebut terutama terkait dengan keberadaan mineral Fe dalam tanah PASS-B dan PASS-C. Perbedaan konsentrasi Fe^{2+} pada PASS-B dan PASS-C terkait dengan kondisi hidrologi lahan pasang surut tipologi B yang sering mengalami penggenangan sebagai asal tanah PASS-B.

Kata kunci: Lahan pasang surut, pemupukan, tanah sulfat masam potensial, tipologi luapan lahan, sifat kimia tanah

J Trop Soils, Vol. 23, No. 2, 2018: 55-64
ISSN 0852-257X ; E-ISSN 2086-6682

INTRODUCTION

About 500,000 km^2 of acid sulfate soils (ASS) is spread worldwide, and mainly found in coastal zones (Sullivan *et al.* 2012). Based on the tidal inundation and drainage intensity, tidal swampland is divided into four types, *i.e.* type A, B, C and D. Type A is the tidal swampland that experiences inundation at high or low tide and undergoes draining every day. Type B is the tidal swampland that experiences inundation only at high tide and undergoes draining every day. Type C is the tidal swampland that does not experience inundation even at high or low tide, but undergoes draining every day. Type D is the tidal swampland that does not experience inundation at high or low tide and undergoes a little bit of draining (Kselik 1990).

Each type of tidal swampland has specific characteristics and fertility level. Grant *et al.* (2012) indicated that the fluctuation of annual groundwater table affects the productivity of an ecosystem. Generally, soil in Type A tidal swampland is more fertile than that in others. Further, soil in Type B tidal swampland is more fertile than that in C and D types, which is related to water quality on each type of the tidal swampland.

Most of rice fields on tidal swampland have low productivity, in which their productivity is lower than irrigated rice fields (Senewe and Alfons 2011). An effort to improve land productivity is fertilizer application, however, fertilizer application may be ineffective if the fertilizer applied is based on the recommendation for rice grown on irrigated fields. Potential loss of soil nutrients may be uncontrollable since the fertilizer application method does not consider the nature properties of surrounding environment and needs of plants based on their growth stages (Bindraban *et al.* 2016). The efficiency of fertilizer application may be improved through the 4R Nutrient Stewardship Principle, *i.e.* the use of fertilizer from the right source, at the right rate, at the right time, and in the right place (IPNI 2014).

Fertilizer application may improve soil fertility. In addition, fertilizer application can trigger changes of soil chemical balance (Liu *et al.* 2010). The dynamics of soil chemical balance due to fertilizer and organic material application are determined by the indigenous properties of soil (Adeniyan *et al.* 2011), in which related to the type of clay minerals, water content, and organic matter content (Ghiri and Abtahi 2012; Yuan *et al.* 2016; Singh *et al.* 2016). However, information regarding the type of tidal swampland is essential to understand the dynamics of soil chemical properties, and therefore necessary for agricultural management on Potentially Acid Sulphate Soils (PASS). The experiment was conducted to study the soil chemical properties of PASS type B (PASS-B) and C (PASS-C) of tidal swampland as affected by the application of fertilizer and lime.

MATERIALS AND METHOD

Experimental Setup

A greenhouse experiment was conducted on PASS that was originated from two types of tidal swampland, *i.e.*; PASS-B and PASS-C, each of them was set as individual experimental set. The experiment was conducted from April to July 2013 in the glasshouse of *Indonesian Swampland Agricultural Research Institute*. The treatments were arranged to verify a fertilization software as known "Decision Support System *Pemupukan Padi Lahan Rawa*" (DSS). The treatments consisted of six rates of fertilizer package (Urea, SP-18 and KCl) and lime. Treatment P1 to P5 were calculated from fertilizer package rate as a result of DSS software (100% recommendation rate was set as hypothesis treatment), whereas P6 was calculated from fertilizer rate based on leaf colour index. The treatments applied were:

1. Fertilizer package of 50% of DSS recommendation rate (P1).
2. Fertilizer package of 75% of DSS recommendation rate (P2).
3. Fertilizer package of 100% of DSS recommendation rate (P3).
4. Fertilizer package of 125% of DSS recommendation rate (P4).

Table 1. Soil properties of PASS-B and PASS-C.

Soil properties	PASS-B	PASS-C	Method
pH	3.62	3.10	H_2O 5 ; 1
Total N (%)	0.47	0.50	Kjeldahl
Phosphorus (mg kg^{-1})	7.48	4.87	Bray 1
Exch-K (C mol(+) kg^{-1})	0.23	0.30	NH_4OAc pH 4.8

Table 2. Rates of fertilizers and lime applied on PASS-B and PASS-C.

Treatments	Rates of fertilizer and lime (kg ha^{-1})							
	PASS-B				PASS-C			
	Urea	SP 18	KCl	Lime	Urea	SP 18	KCl	Lime
P 1	133	81	47	7,200	157	114	36	12,300
P 2	199	120	68.3	7,200	236	171	53	12,300
P 3	265	161	103	7,200	315	228	71	12,300
P 4	331	201	126	7,200	393	285	89	12,300
P 5	473	241	136	7,200	472	342	107	12,300
P 6	100	175	50	0	100	200	41	0

5. Fertilizer package of 150% of DSS recommendation rate (P5).
6. Fertilizer package based on leaf colour index recommendation (P6) (control).

Soil sampling and Rice Planting

Based on observation on the field and their chemical properties, the soils were characterized as PASS-B and PASS-C (Table 1). Observation in the field showed that the soil comprises of sulphidic material, jarosite mineral and sulfuric horizon. About 200 kg fresh soil samples were collected from top soil 0-15 cm at Belandean Research Station (represented tidal swamp land of Type B) and Jejangkit Village (represented tidal swamp land of Type C). Ten kilogram of those soils were placed into plastic pots. Rice seedlings (age of two weeks) were planted in the pots. Aquadest was added to maintain the water level as 3.0 cm above soil surface during the experiment. Three days after planting, fertilizer of urea, SP-18, KCl and lime were applied according to the treatments (Table 2).

Soil Analysis and Leaf Colour Index Measurement

The soil pH was measured in a soil to water ratio of 1:5, available P was extracted using Bray 1 method, exchangeable K and Fe were extracted using NH_4OAc pH 4.8 and measured using AAS (atomic absorption spectrometry) and total N was determined by Kjeldahl method as described by *Balai Penelitian Tanah* (2012). These parameters were measured every four weeks periodically. In addition, each week leaf colour was measured using leaf colour index and soil redox potential was measured directly on the field using Hana (HI 8424) instrument.

RESULTS AND DISCUSSION

Soil Acidity

Soil pH is the major driver for soil fertility (Sahrawat 2015). Figure 1 showed that the soil pH of PASS-B and PASS-C under all treatments were

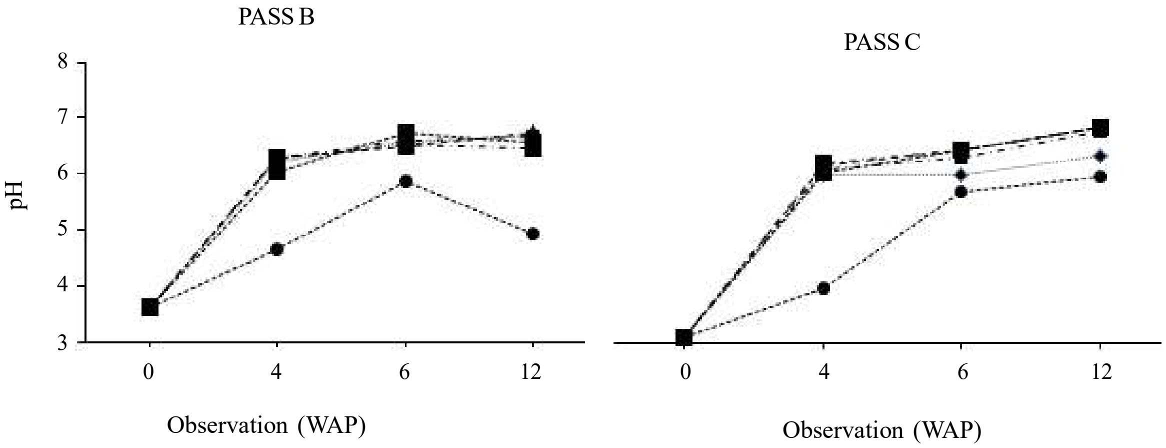

Figure 1. Changes of soil pH under application of fertilizers and lime treatments on PASS-B and PASS-C during 12 weeks observation. P1: ······◆······ , P2: – · ■ · –, P3: – – ▲ – –, P4: – · ■ · –, P5: - - - ■ - - -, P6: - - - ● - - - .

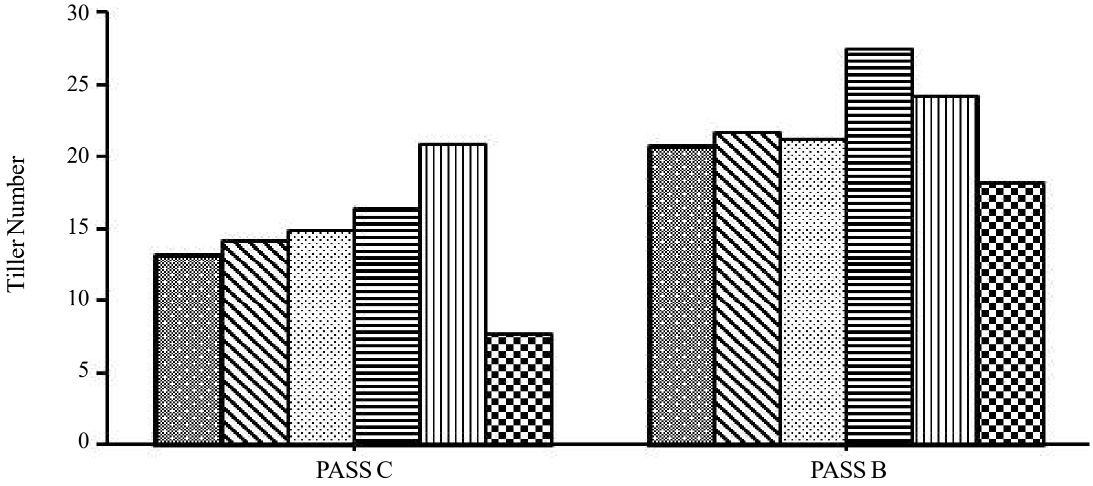

Figure 2. Tiller number of rice plant at maximum vegetatif stage under application of fertilizers and lime treatments on PASS-B and PASS-C. P1: ▩, P2: ▧, P3: ▒, P4: ▤, P5: ▥, P6: ▦

increased. Soil inundation increases pH of acid soil due to reduction process or carbonat and bicarbonat dissolution (Fageria *et al.* 2011; Fahmi *et al.* 2012; Wang *et al.* 2013a). Besides reduction processes, lime treatment significantly increased soil pH. Treatments P1 to P5 resulted in higher soil pH compared to P6 treatment (Figure 1). Lime application decreased acidity which is resulted from pyrite oxidation or hydrolysis of Al and Fe as reported by Shamshuddin *et al.* (2014). It is indicated that incubation method may become as an excellent method to determine lime requirement for PASS.

According to Hairani and Susilawati (2013) soil pH of ASS increased after two weeks of inundation. The results of current study showed that the soil pH increased since the first week until the fourth week of observation, subsequently after 4 week after planting (WAP) the soil pH tended to be constant (Figure 1). The increase of soil pH occurred since the first week until the fourth week of observation especially for P6 (control), which may be related to the presence of Fe-hydr(oxide) in these soils, but in detail, the increase of soil pH in PASS-B was higher than in PASS-C. The changes of soil pH due to redox reaction in soil is determined by the presence and availability of Fe-hydr(oxide) minerals in soil (Reddy and DeLaune 2008). The average Fe content in PASS-B was 850 mg kg^{-1}, whereas PASS-C contained 675 mg Fe kg^{-1} (Figure 6).

However, soil pH of PASS-B was lower than PASS-C at 12 WAP (Figure 1), this fact may be explained by better performance of rice plant at maximum vegetative stage on PASS-B than on PASS-C (Figure 2). The presence of plants correlates with an increase in acidification of ASS,

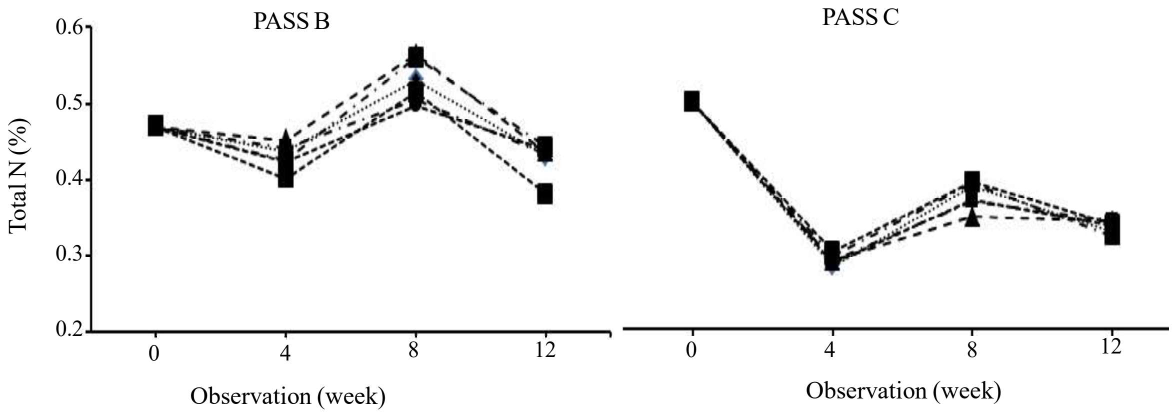

Figure 3. Total N content under application of fertilizers and lime treatments on PASS-B and PASS-C during 12 weeks observation. P1: ······◆······ , P2: – · ■ · –, P3: – –▲– –, P4: – · ■ · –, P5: ---■---, P6: ---●---

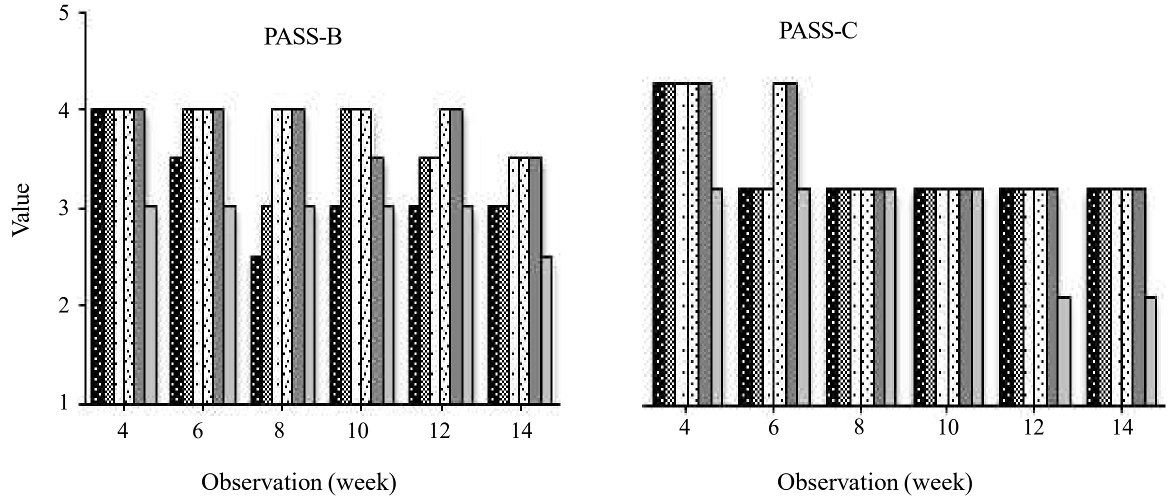

Figure 4. Leaf colour index of rice plant under application of fertilizers and lime treatments on PASS-B and PASS-C during 14 weeks observation. P1:▩, P2:▦, P3:⬚, P4:▤, P5:□, P6:■.

the mechanism for this condition is due to transport of oxygen down the soil by aerenchymatous tissue, then release the oxygen into the rhizosphere (Michael *et al.* 2017). Rice plant with better performance has stronger oxidation power on surrounding root environment as suggested by Dufey *et al.* (2009). According to Michael *et al.* (2017) oxidation power has led large increase of soil acidity at surrounding of root environment. Moreover, plant with better performance may influence on nutrient uptake, rice plant with better performance may release more H^+ ions to absorb NH_4^+ and other cations.

Total N in Soil

Nitrogen biogeochemical reaction in wetland is greatly different with upland, it is greatly dynamic, especially influenced by the presence of water or hydrological condition of land. Although, urea has applied three days after planting, total N contents under all treatments in PASS-B and PASS-C on 4 WAP was decreased (Figure 3). However, based on leaf colour index, only the rice plant in the PASS-C treatments indicated deficiency symptoms of N (Figure 4). This means the amount of N that applied through fertilization has no effect on N availability in soil and uptake by plant. According to Dong *et al.* (2012) only about 20% of N absorbed by plant is derived from fertilizer that applied on the soil, whereas at least 80% is derived from indigenous supply, one mechanism in enhancing nutrient supply in wetland soil is through soil flooding process. This result is in line with the study of Koyama (1981) that about 40-80% of total N taken up by rice plant is derived from organic-N through mineralization process.

The decrease of total N on 4 WAP or three weeks after fertilizer application indicated that the volatilization process was occured. The finding by Norman *et al.* (2009) showed that at twenty days after urea application, loss of N through volatilization processes reaches up to 25%. Loss of N under flood condition may occur through volatilization processes, most of N applied to the soil would be transformed into NH_4^+ that may lose to the air. Loss of NH_4^+on the flooded rice field through volatilization processes reaches up to 60% (Xing and Zhu 2000). Lower total N contents in PASS-C than in PASS-B indicated that more N has lost via volatilization process in PASS-C than in PASS-B. It can be attributed with higher Fe content in PASS-B than in PASS-C (Figure 8). Iron coupled with anaerobic NH_4^+ oxidation will produce Fe^{2+}, N_2 and NO_2 (Yang *et al.* 2012).

Moreover, NH_4^+ may be fixed by negative charge of soil colloids. Ammonium fixation may occur in all soil types, the process is running very fast, less than 30 minutes after fertilizer application and the amount of ammonium fixed by the soil colloids may reach 10% to 25% (Drury and Beauchamp 1991; Trehan 1996). According to Keerthisinghe *et al.* (1984), ammonium fixation process is positively correlated to vermiculite clay mineral content in soil, and according to Alwi (2011) that PASS in the location of study contain vermiculite clay mineral.

Available P

All rates of P fertilizer applied to the soils increased P availability (Figure 5). The increase may be caused by soil inundation throughout the experiment. Previous study by Fahmi *et al.* (2012)

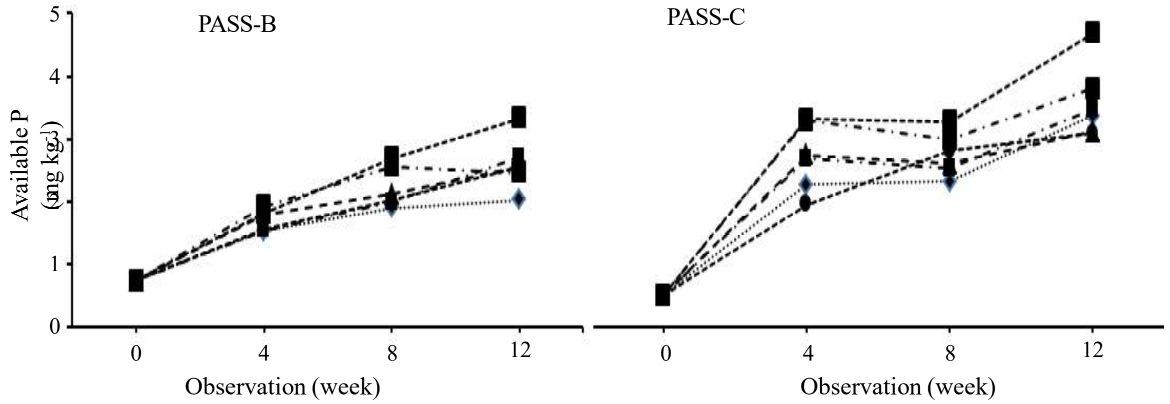

Figure 5. The amount of available P under application of fertilizers and lime treatments on PASS-B and PASS-C during 12 weeks observation. P1: ……◆……, P2: – · ■ · –, P3: – –▲– –, P4: – · ■ · –, P5: ---■---, P6: ---●---

also reported that soil inundation increased P availability. Soil inundation improves soil chemical properties such as increasing soil pH and P availability. This condition is related to reductive condition of soil. Soil inundation stimulated Fe^{3+} reduction in the soil, and P dissolution was correlated to Fe^{3+} reduction (Morris and Hesterberg, 2010). Phosphorus fertilizer was applied in various rates, however, there was no difference in P availability measured in the soils (Figure 5). The result indicates that P fertilizer application in this experiment was not able to influence on P availability and soil buffering of P in soil solution. Fahmi *et al.* (2005) reported that soil P adsorption capacity of PASS on the research site may reach up to 800 mg kg^{-1}, indicating that P balance in soil solution will not change if P fertilizer is applied to the soil in low amount.

Higher availability of P in PASS-C than in PASS-B was related to the difference of Fe content in both of soil types as shown in negative correlation of P availability and Fe concentration (Figure 6).

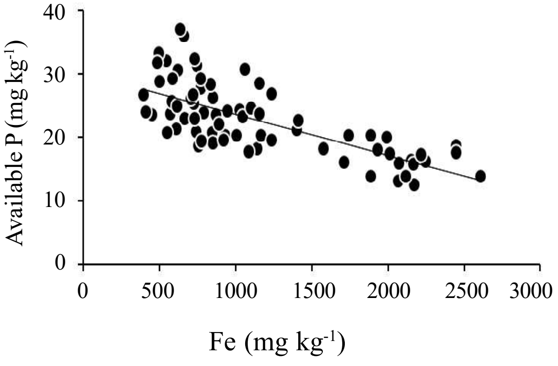

Figure 6. The relationship of available P and Fe concentration on PASS-B and PASS-C during 12 weeks observation.

Concentration of Fe in PASS-B was higher than PASS-C (Figure 8). According to Loeb *et al.* (2008) ; Zak *et al.* (2010) and Wang *et al.* (2013b) poorly Fe-crystalline such as ferrihydrite has important role on P dissolution in wetland soils. Under anoxic condition, formation of ferrous phosphate minerals serves as an additional P sink for soil (Rothe *et al.* 2014). This means P availability in ASS was determined by physio-chemical soil characteristics, such as pH and redox potential (Aggenbach *et al.* 2013; Cusell *et al.* 2014; Baken *et al.* 2015), the presence of Fe-(hydr)oxides, especially for soil with low of P content (Zhang and Huang 2007).

In addition, lower P availability in PASS-B than PASS-C might be also caused by higher Fe-crystalline mineral contained in PASS-C. Soil inundation that occurred frequently on type B related to this condition. Chi *et al.* (2010) reported that formation of poorly Fe-crystalline is more dominant than well Fe-crystalline in soil with poor aeration, and Johnston *et al.* (2009) suggested that poorly crystalline Fe-oxides near the soil surface was increased following tidal inundation. Different types of Fe-(hydr)oxides in soils are the main factor affecting the bioavailability and mobility of P (Guzman *et al.* 1994).

Exchangeable K

Potassium has essential functions in enzyme activation, osmoregulation, regulation of cellular pH, cellular cation-anion balance, regulation of transpiration by stomata, and the transport of assimilates (Dobermann and Fairhurst, 2000). Based on the category of soil K content developed by Dobermann and Fairhurst (2000) Figure 7 shows that exchangeable K in PASS-B and PASS-C are in adequate category. Fertilizer application increased

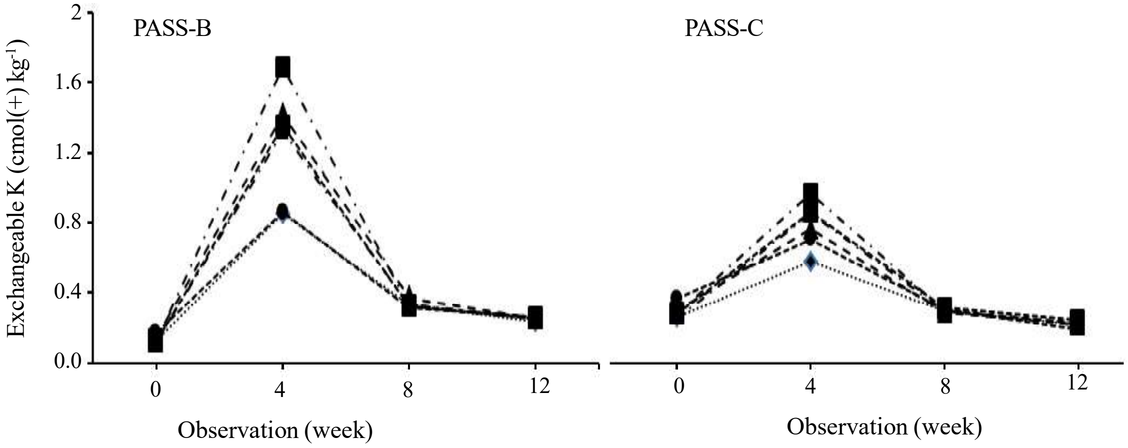

Figure 7. The amount of exchangeable K under application of fertilizers and lime treatments on PASS-B and PASS-C during 12 weeks observation. P1: ······◆······ , P2: – · ■ · –, P3: – –▲– –, P4: – · ■ · –, P5: ---■---, P6: ---●---

exchangeable K in both soils, but exchangeable K in PASS-B was higher than PASS-C, especially for observation that conducted on 4 WAP. The difference in exchangeable K concentrations between PASS-B and PASS-C is likely associated with the different rates of fertilizer applied (Table 2).

Exchangeable K concentrations in PASS-B and PASS-C measured at 8 WAP and 12 WAP were declined compared to that measured at 4 WAP (Figure 7), indicating that K fixation by clay mineral was occurred, as previously indicated that PASS contain vermiculite, smectite and kaolinite minerals (Alwi 2011). Raheb and Haedari (2011) showed that the presence of vermiculite mineral results in large fixation capacity of soil.

Ferro Concentration

Ferro concentrations in PASS-B and PASS-C increased on 4 WAP, and gradually decreased to the lowest value at 12 WAP (Figure 8). The decrease of Fe^{2+} concentration may be associated with precipitation of Fe^{2+} with P to form vivianite mineral under high pH and high P concentration. According to Heiberg *et al.* (2010) and Nanzyo *et al.* (2012) the formation of vivianite mineral is occurred in anaerob condition, high pH and high P concentration. Nriagu (1972) also reported that vivianite is stable under pH 6 to 9. According to Li *et al.* (2012) the precipitation of Fe^{2+}—P is soundly crystallized to vivianite if the molar ratio of Fe^{2+} to P is more than 1.5. The equation that illustrates the vivianite mineral formation is as follows (Heiberg *et al.* 2010):

$$3\ Fe^{2+} + 2\ PO_4^{3-} + 8\ H_2O = Fe_3(PO_4)\ 8\ H_2O$$

The concentration of Fe^{2+} in PASS-B was higher than PASS-C (Figure 8), this condition may be related to Type B hydrological condition of tidal

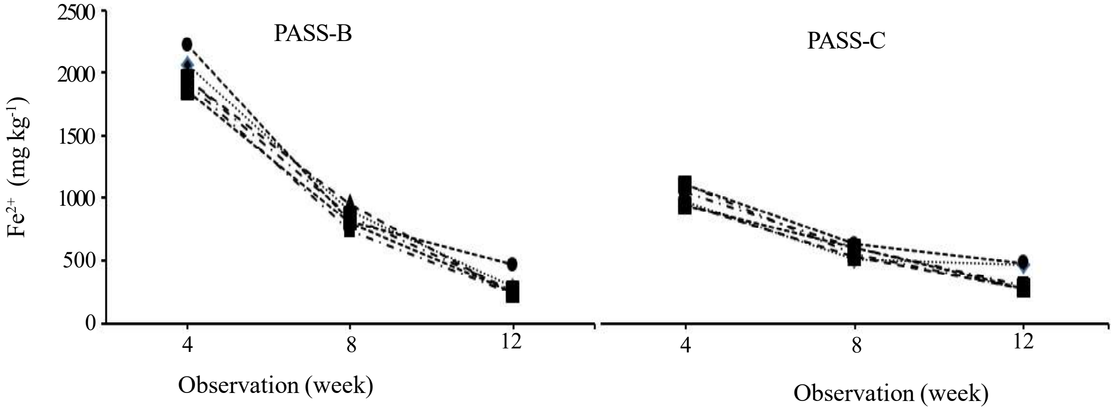

Figure 8. Ferro concentration under application of fertilizers and lime treatments on PASS-B and PASS-C during 12 weeks observation. P1: ······◆······ , P2: – · ■ · –, P3: – –▲– –, P4: – · ■ · –, P5: ---■---, P6: ---●---

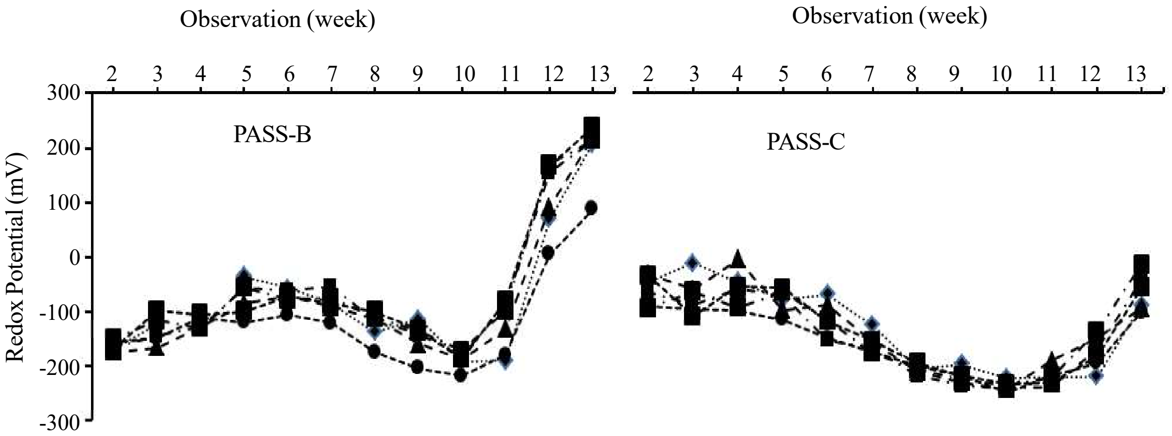

Figure 9. Redox potential under application of fertilizers and lime treatments on PASS-B and PASS-C during 12 weeks observation. P1:·······◆······ , P2: – · ■ · –, P3: – –▲ – ·, P4: – · ■ · –, P5: ---■---, P6: ---●---

swampland of PASS-B soil that is frequently flooded. According to Reddy and DeLaune (2008) the soils that are frequently flooded or alternately flooded and dried may contain abundant of poorly Fe-crystalline and less well Fe-crystalline. Furthermore, poorly Fe-crystalline has high solubility and easily reducible compared to well Fe-crystalline (Bonneville *et al.* 2009). Brennan and Lindsay (1998) indicated that Fe-crystalline plays a major role on Fe solubility in soil solution only under stable and oxidative condition.

Redox Potential

Redox potential is the major driver that determines wetland soil fertility (Sahrawat 2015). Soil Eh value in the range of 100 to -100 mV is categorized as reductive condition (Reddy and DeLaune 2008). The results presented here suggested that PASS-B and PASS-C were in reductive condition during the experiment (Figure 9). This condition occurred due to both soils were inundated during the observation. Soil inundation may lead soil in anaerobic condition, consequently the amount of oxygen (O_2) may decrease. Gradually the oxygen as an electron acceptor is replaced by other elements such as NO_3, Mn, Fe, SO_4, CH_4 (Reddy and De Laune 2008). In this case the sequence of the shifts is regulated by many factors, such as soil reducing bacteria species and availability of elements as an acceptor and donor of electron.

In detail, until 4 WAP, PASS-B was more reductive compared to PASS-C, *i.e.* average Eh of PASS-B was in the range of < -100 mV and > -100 mV in the PASS-C, respectively (Figure 9). This phenomenon can be attributed to the higher Fe^{2+} concentration in PASS-B than in PASS-C (Figure 8). Based on Eh value, most of Fe in soil solution is in reductive forms (Reddy and DeLaune 2008).

In general, Eh increased at 10 to 12 WAP, suggesting there have been occurred rapid oxidation process especially on PASS-B. This fact was correlated to soil pH and Fe solubility in the soils. Stumm and Morgan (1996) indicated that Fe oxidation may increase 100 folds in circumneutral pH, but the rate of reaction is limited by the availability of reducible Fe. Reddy and De Laune (2008) suggested that the rate of redox reaction is determined by the availability of electron acceptor and donor.

CONCLUSIONS

When fertlizers and lime were applied to PASS originated from type A and B of tidal swampland, their soil chemical properties changed. Soil pH, P availability and exchangeable K concentration were increased, whereas total N, Fe concentration and Eh were not affected by the treatments. However, total N, Fe concentration and Eh changed during the experiment. The alteration of soil chemical properties is mainly associated with the soil redox condition and the Fe concentration in both soils, in which Fe concentration might be related to land hydrological condition. In addition, the dynamic of total N and exchangeable K concentration in both soils is related to vermiculite clay mineral content in the soils.

ACKNOWLEDGEMENTS

The Research was financed by the Ministry of Agriculture of the Republic Indonesia. The authors would like to thank Mrs Nurita and Mrs Yulia Raihana for their assistance.

REFERENCES

Adeniyan ON, AO Ojo, OA Akinbode and JA Adediran. 2011. Comparative study of different organic manures and NPK fertilizer for improvement of soil chemical properties and dry matter yield of maize in two different soils. *J Soil Sci Environ Manage* 2: 9-13.

Aggenbach CJS, H Backx, WJ Emsens, AP Grootjans, LPM Lamers, AJP Smolders, PJ Stuyfzand, L Wolejko and R Van Diggelen. 2013. Do high iron concentrations in rewetted rich fens hamper restoration? *Preslia* 85:405-420.

Alwi M. 2011. Inaktivasi Pirit dan Jarosit Terlapuk Melalui Pelindian dan Penggunaan Biofilter di Tanah Sulfat Masam. (Disertasi). Institut Pertanian Bogor, Bogor. 170 p. (in Indonesian).

Baken S, M Verbeeck, D Verheyen, J Diels and E Smolders. 2015. Phosphorus losses from agricultural land to natural waters are reduced by immobilization in iron-rich sediments of drainage ditches. *Water Research* 71: 160-170.

Balai Penelitian Tanah. 2012. *Analisis Kimia Tanah, Tanaman, Air dan Pupuk.* Second Edition. Badan Penelitian dan Pengembangan Pertanian. Departemen Pertanian. Bogor. 136 p. (in Indonesian).

Bonneville S, T Behrends and P Van Cappellen. 2009. Solubility and dissimilatory reduction kinetics of iron (III) oxyhydroxides: A linear free energy relationship. *Geochimica Cosmochimica Acta* 73: 5273-5282.

Brennan EW and WL Lindsay. 1998. Reduction and oxidation effect on the solubility and transformation of iron oxides. *Soil Sci Soc Am J* 62: 930-937.

Bindraban PS, C Dimkpa, L Nagarajan, A Roy and R Rabbinge. 2016. Revisiting fertilisers and fertilisation strategies for improved nutrient uptake by plants. *Biol Fertil Soils* 51: 897-911.

Chi G, X Chen, Y Shi and T Zheng. 2010. Forms and profile distribution of soil Fe in the Sanjiang Plain of Northeast China as affected by land uses. *J Soils Sediment* 10: 787-795.

Cusell C, A Kooijman, F Fernandez, G Van Wirdum, JJM Geurts, EE Van Loon, K Kalbitz, and LPM Lamers. 2014. Filtering fens: Mechanisms explaining phosphoruslimited hotspots of biodiversity in wetlands adjacent to heavily fertilized areas. *Sci Tot Environ* 481: 129-141.

Dobermann A and T Fairhurst. 2000. *Rice : Nutrient Disorders and Nutrient Management.* IRRI. Makati city, The Fhillipines, 191 p.

Dong NM, KK Brandt, J Sørensen, NN Hung, CV Hach, PS Tan and T Dalsgaard. 2012. Effects of alternating wetting and drying versus continuous flooding on fertilizer nitrogen fate in rice fields in the Mekong Delta, Vietnam. *Soil Biol Biochem* 47: 166-174.

Drury CF and EG Beauchamp. 1991. Ammonium fixation, release, nitrification, and immobilization in high- and low-fixing soils. *Soil Sci Soc Am J* 55: 125-129.

Dufey I, P Hakizimana, X Draye, S Lutts and P Bertin. 2009. QTL mapping for biomass and physiological parameters linked to resistance mechanisms to ferrous iron toxicity in rice. *Euphytica* 167: 143-160.

Fageria NK, GD Carvalho, AB Santos, EPB Ferreira and AM Knupp. 2011. Chemistry of lowland rice soils and nutrient availability. *Commun Soil Sci Plant Anal* 42: 1913-1933.

Fahmi A, S Nurzakiah and E Purnomo. 2005. Evaluasi teknik persiapan contoh tanah dan metode analisis tanah untuk pengukuran fosfat di lahan pasang surut. *J Trop Soils* 10: 85-90. (in Indonesian).

Fahmi A, B Radjagukguk, and BH Purwanto. 2012. The Leaching of iron and loss of phosphate in acid sulphate soil due to rice straw and phosphate fertilizer application. *J Trop Soils* 17: 19-24.

Ghiri MN and A Abtahi. 2012. Factors affecting potassium fixation in calcareous soils of southern Iran. *Arch Agron Soil Sci* 12: 335-352.

Grant RF, AR Desai, and BN Sulman. 2012. Modelling contrasting responses of wetland productivity to changes in water table depth. *Biogeosciences* 9: 4215-4231.

Guzman G, E Alcantara and V Barro´n. 1994. Phytoavailability of phosphate adsorbed on ferrihydrite, hematite, and goethite. *Plant Soil* 159: 219-225.

Hairani A and A Susilawati 2013. Changes of soil chemical properties during rice straw decomposition in different type of acid sulphate soil. *J Trop Soils* 18: 99-103.

Heiberg L, TV Pedersen, HS Jensen, C Kjaergaard and HCB Hansen. 2010. A comparative study of phosphate sorption in lowland soils under oxic and anoxic conditions. *J Environ Qual* 39: 734-743.

IPNI. 2014. http://www.nutrientstewardship.com/4r-news/newsletter/ipni-issues-4r-plant-nutrition-manual. International Plant Nutrition Institute. (Accesed on April 05, 2018)

Johnston SG, AF Keene, RT Bush, ED Burton, LA Sullivan, D Smith, AE McElnea, MA Martens and S Wilbraham. 2009. Contemporary pedogenesis of severely degraded tropical acid sulfate soils after introduction of regular tidal inundation. *Geoderma* 149: 335-346.

Keerthisinghe G, K Mengel and SK De Datta. 1984. The release of nonexchangeable ammonium (15N labeled) in wetland rice soils. *Soil Sci Soc Am J* 48: 291-294.

Koyama T. 1981. The transformation and balances of nitrogen in Japanese paddy fields. *Fertil Res* 2: 261-278.

Kselik RAL. 1990. Water management on acid sulphate soils Pulau Petak, South Kalimantan. *Papers Workshop on Acid Sulphate Soils in The Humid Tropics : Water management and soil fertility.* Agency for Agricultural Research and Development/AARD, and The Land and Water Resource Group/LAWOO. Jakarta. pp. 249-276.

Li Q, X Wang, D Kan, R Bartlett, G Pinay, Y Ding and W Ma. 2012. Enrichment of Phosphate on Ferrous Iron Phases during Bio-Reduction of Ferrihydrite. *Int J Geosci* 3: 314-320.

Liu E, C Yan, X Mei, W He, SH Bing, L Ding, Q Liu, S Liu and T Fan. 2010. Long-term effect of chemical fertilizer, straw, and manure on soil chemical and biological properties in Northwest China. *Geoderma* 158: 173-180.

Loeb R, LPM Lamers and JGM Roelofs. 2008. Prediction of phosphorus mobilization in inundated floodplain soils. *Environ Poll* 156: 325-331.

Michael PS, RW Fitzpatrick and RJ Reid. 2017. Effects of live wetland plant macrophytes on acidification, redox potential and sulphate content in acid sulphate soils. *Soil Use Manage* 33: 1-11.

Morris AJ and DL Hesterberg. 2010. Mechanisms of phosphate dissolution from soil organic matter. In: RJ Gilkes and N Prakongkep (eds). *Soil Solutions for a Changing World.* 19th World Congress of Soil Science. Brisbane, Australia, pp. 37-39.

Nanzyo M, H Onodera, E Hasegawa, K Ito and H Kanno. 2012. Formation and dissolution of vivianite in paddy field soil. *Soil Sci Soc Am J* 77: 1452-1459.

Norman RJ, CE Wilson Jr, NA Slaton, BR Griggs, JT Bushong and EE Gbur. 2009. Nitrogen fertilizer sources and timing before flooding dry-seeded, delayed-flood rice. *Soil Sci Soc Am J* 73: 2184-2190.

Nriagu J. 1972. Stability of vivianite and ion-pair formation in the system $Fe_3(PO_4)^{2-}H_3PO_4$-H_2O, *Geochimica et Cosmochimica Acta* 36: 459-470.

Raheb A and A Heidari. 2011. Clay mineralogy and its relationship with potassium forms in some paddy and non-paddy soils of northern Iran. *Australian J Agric Eng* 2: 169-175.

Reddy KR and RD Delaune. 2008. *The Biogeochemistry of Wetland : Science and Application*. CRC Press. New York. 774 p.

Rothe M, T Frederichs, M Eder, A Kleeberg and M Hupfer. 2014. Evidence for vivianite formation and its contribution to long-term phosphorus retention in a recent lake sediment: a novel analytical approach. *Biogeosciences* 11: 5169-5180.

Sahrawat KL. 2015. Redox potential and pH as major drivers of fertility in submerged rice soils: a conceptual framework for management. *Commun Soil Sci Plant Anal* 46: 1597-1606.

Shamshuddin J, AE Azura, MARS Shazana, CI Fauziah, QA Panhwar and UA Naher. 2014. Properties and management of acid sulfate soils in Southeast Asia for sustainable cultivation of rice, oil palm, and cocoa. In: DL Sparks (eds). *Adv Agron* 124: 91-142

Senewe RE and JB Alfons. 2011. Kajian adaptasi beberapa varietas unggul baru padi sawah pada sentra produksi padi di seram bagian barat provinsi maluku. *J Budidaya Pertanian* 7: 60-64.

Singh M, B Sarkar, B Biswas, J Churchman and NS Bolan. 2016. Adsorption-desorption behavior of dissolved organic carbon by soil clay fractions of varying mineralogy. *Geoderma* 280: 47-56.

Stumm W and JJ Morgan. 1996. *Aquatic Chemistry: Chemical Equilibria and Rates in Natural Waters.* John Wiley and Sons, Inc. 1022 p.

Sullivan L, R Bush, E Burton, C Ritsema and M van Mensvoort. 2012. Acid sulfate soils. In: PM Huang, Y Li and ME Sumner (eds). *Handbook of Soil Sciences: Resource Management and Environmental Impacts*. CRC Press, Boca Raton, Florida, pp. 21-26.

Trehan SP. 1996. Immobilization of 15 NH_4^+ in three soils by chemical and biological processes. *Soil Biol Biochem* 28: 1021-1027.

WangY, X Liu, C Butterly, C Tang and J Xu. 2013a. pH change, carbon and nitrogen mineralization in paddy soils as affected by Chinese milk vetch addition and soil water regime. *J Soils Sediment* 13: 654-663.

Wang X, F Liu, W Tan, W Li, X Feng and DL Sparks. 2013b. Characteristics of phosphate adsorption-desorption onto ferrihydrite: comparison with well-crystalline Fe (hydr)oxides. *Soil Science* 178: 1-11.

Xing GX and ZL Zhu. 2000. An assessment of N loss from agricultural fields to the environment in China. *Nutr Cycl Agroecosys* 57: 67-73.

Yang WH, AK Weber and WL Silver. 2012. Nitrogen loss from soil through anaerobic ammonium oxidation coupled to iron reduction. *Nature Geoscience* 1-4.

Yuan C, LM Mosley, R Fitzpatrick and P Marschner. 2016. Organic matter addition can prevent acidification during oxidation of sandy hypersulfidic and hyposulfidic material: Effect of application form, rate and C/N ratio. *Geoderma* 276: 26-32.

Zak D, C Wagner, B Payer, J Augustin and J Gelbrecht. 2010. Phosphorus mobilization in rewetted fens : The effect of altered peat properties and implications for their restoration. *Ecol Appl* 20: 1336-1349.

Zhang JZ and X Huang. 2007. Relative importance of solid-phase phosphorus and iron on the sorption behavior of sediments. *Environ Sci Tech* 41: 2789-2795.