Available online at:
http://journal.unila.ac.id/index.php/tropicalsoil
DOI: 10.5400/jts.2012.17.3.189

Root-induced Changes in the Rhizosphere of Extreme High Yield Tropical Rice: 2. Soil Solution Chemical Properties

Erry Purnomo[1,*], Dodik Choiron[1], Raina Yulia[1], Hakimah Halim[2], Krisdianto[3], Anna Hairani[4] and Mitsuru Osaki[5]

[1]*Silviculture Study Program, Faculty of Forestry, Lambung Mangkurat University, Banjarbaru Campus, South Kalimantan 70714, Indonesia. *Present address: Faculty of Agriculture University of Borneo Tarakan. East Kalimantan 77123, Indonesia, e-mail: erry_purnomo@borneo.ac.id.*
[2]*Faculty of Agriculture, Lambung Mangkurat University, Banjarbaru Campus, South Kalimantan 70714, Indonesia.*
[3]*Faculty of Mathematics and Science, Banjarbaru Campus, South Kalimantan 70714, Indonesia*
[4]*Balittra, Loktabat, Banjarbaru, South Kalimantan*
[5]*Laboratory of Rhizosphere Environment Technology, Division of Bio-systems Sustainability, Graduate School of Agriculture, Kita-9, Nishi-9, Kitaku, Sapporo 060-8589, Japan.*

Received 26 April 2012 / accepted 16 August 2012

ABSTRACT

Our previous studies showed that the extreme high yield tropical rice (Padi Panjang) produced 3-8 t ha^{-1} without fertilizers. We also found that the rice yield did not correlate with some soil properties. We thought that it may be due to ability of root in affecting soil properties in the root zone. Therefore, we studied the extent of rice root in affecting the chemical properties of soil solution surrounding the root zone. A homemade rhizobox (14x10x12 cm) was used in this experiment. The rhizobox was vertically segmented 2 cm interval using nylon cloth that could be penetrated neither root nor mycorrhiza, but, soil solution was freely passing the cloth. Three soils of different origins (Kuin, Bunipah and Guntung Papuyu) were used. The segment in the center was sown with 20 seeds of either Padi Panjang or IR64 rice varieties. After emerging, 10 seedlings were maintained for 5 weeks. At 4 weeks after sowing, some chemical properties of the soil solution were determined. These were ammonium (NH_4^+), nitrate (NO_3^-), phosphorus (P) and iron (Fe^{2+}) concentrations and pH, electric conductivity (EC) and oxidation reduction potential (ORP). In general, the plant root changed solution chemical properties both in- and outside the soil rhizosphere. The patterns of changes were affected by the properties of soil origins. The release of exudates and change in ORP may have been responsible for the changes soil solution chemical properties.

Keywords: Ammonium, electrical conductivity, iron, nitrate, oxidation reduction potential, pH, phosphorus

INTRODUCTION

In rice growing areas of South Kalimantan Province, the local cultivars are preferred by local farmers. Most of the areas are swamplands in which water fluctuation is unpredictable. Growing modern rice varieties in this area is almost impossible. Seedlings of modern rice varieties are too short to cope with a high water fluctuation. In addition, modern rice varieties are usually susceptible to severe soil condition (Purnomo *et al*. 2009). The local rice seedlings are older (ca. 6 month old). So, they are tall seedlings (*c.a*. 1 m), therefore, they can survive in the high water level fluctuation and they are more tolerance to severe soil condition.

More than 100 local varieties can be found in South Kalimantan. Some of them show yield more than 3 Mg ha^{-1} without fertilizers after transplanting (Hasegawa *et al*. 2004). Our previous studies showed that there was a tropical rice cultivar (Padi Panjang) produced 3-8 Mg ha^{-1} without fertilizer. It was also found that the rice yield was not correlated with some soil properties. We thought that it may be due to ability of root in affecting soil properties in- and out-side of the rhizosphere (Purnomo *et al*. 2010).

The plant roots have ability to influence the physical, chemical and biological properties of rhizosphere soil. Physically, root exudates may clog pores and may provide a buffer against desiccation at lower water contents and reduce structural degradation of rhizosphere soil by slaking (Hallett *et al*. 2003). Chemically, exudates from the plant root can change pH (Wang *et al*. 2006) and the nutrient concentration (Wang *et al*. 2005; Purnomo *et al*. 2010). Biologically, root exudates can invite microorganism to anchor in rhizosphere. For example, P solubilizing bacteria (Purnomo *et al*. 2005a) and mycorrhiza (Purnomo *et al*. 2007).

This work investigated the effect of the rice roots in changing the chemical properties of soil solution in the rhizosphere and bulk soil.

MATERIALS AND METHODS

Soil Used

Soils used for the experiment were collected from the three villages, namely, Kuin, Bunipah and Guntung Papuyu. The soil characteristics are shown in Table 1.

Rhizobox

The experiment was carried out in glass using a homemade rhizobox developed by Wang *et al.* (2002). The rhizobox illustration can be seen in Figure 1. Rhizobox design was similar to the one used by Purnomo *et al*. (2010), except that in the present study, the nylon cloth could not be penetrated neither by plat root nor by mycorrhiza. So, only water could freely penetrate. The rhizobox was also equipped with 10 cm ceramic cup and vacuum suction per segment as shown in Figure 1.

Treatments

The treatments of the experiment are shown in Table 2.

Rice Cultivation

Twenty rice seeds were sown at the middle segment of the rhizobox (see Figure 1) under saturated soil condition. At the 3rd day, seedlings were thinned to 10. The high plant density was deliberately done to create a rhizosphere soil and bigger impact of root on the soil. Seven days after emerging, the rhizobox was filled with deionized water to 1 cm depth and maintained till the end of growing period. To protect from pest attack the rhizoboxes were covered with a mosquito net. The plants were grown for 5 weeks.

Table 1. Selected soil properties.

Soil Properties*)	Soil origin**)		
	Kuin (3°22’24’’S; 114°32’19’’E)	Bunipah (3° 27’52’’S; 114 °32’54’’E)	Guntung. Papuyu (3 °27’44’’S; 114 °36’50’’E)
Particle size analysis (%)[1]			
Sand	2.08	2.51	0.83
Silt	61.20	73.82	57.85
Clay	36.72	23.67	41.32
Texture	Silty clay loam	Silty loam	Silty clay
Organic C (g kg^{-1})[2]	48.6 (high)	35.6 (high)	32.4 (high)
Total N (g kg^{-1})[3]	2.8 (moderate)	2.4 (moderate)	3.2 (moderate)
C/N	17 (high)	14 (moderate)	10 (low)
$P_{Bray\ 1}$ (mg kg^{-1})[4]	3.510 (very low)	3.104 (very low)	9.220 (very low)
P_2O_5 (mg kg^{-1})[5]	497 (high)	444 (high)	289 (moderate)
K_2O (mg kg^{-1})[6]	876 (very high)	630 (very high)	357(moderate)
pH H_2O[7]	4.02 (very acidic)	4.28 (very acidic)	4.18 (very acidic)
Exch.-Ca (cmol+ kg^{-1})[8]	4.47 (low)	3.89 (low)	3.94 (low)
Exch.-Mg (cmol+ kg^{-1})[8]	5.48 (high)	6.63 (high)	6.05 (high)
Exch.-Na (cmol+ kg^{-1})[8]	0.04 (low)	1.34 (very high)	0.32 (moderate)
Exch.-K (cmol+ kg^{-1})[8]	0.25 (low)	0.32 (moderate)	0.09 (very low)
KTK (cmol+ kg^{-1})[9]	32.50 (high)	27.25 (high)	39.00 (high)
Base saturation (%)	44 (moderate)	42 (moderate)	43 (moderate)
EC (dS m^{-1})[10]	0.2	0.1	0.02
Al saturation (%)[11]	2.15 (very low)	2.38(very low)	0.5(very low)

Note: *) Procedure of measurements are described in [1] Gee and Bouder (1986); [2]Yeomans and Bremner (1988); [3]Bremner and Mulvaney (1982); [4]John (1970); [5]Olsen and Sommers (1982); [6]Knudsen *et al*. (1982); [7]McLean (1982); [8]Thomas (1982);[9]Rhoades (1982a); [10]Rhoades (1982b) ;[11]Exchangeable Al, Dougan and Wilson (1974). **)The values obtained were categorized as described in Djaenuddin *et al*. (1994).

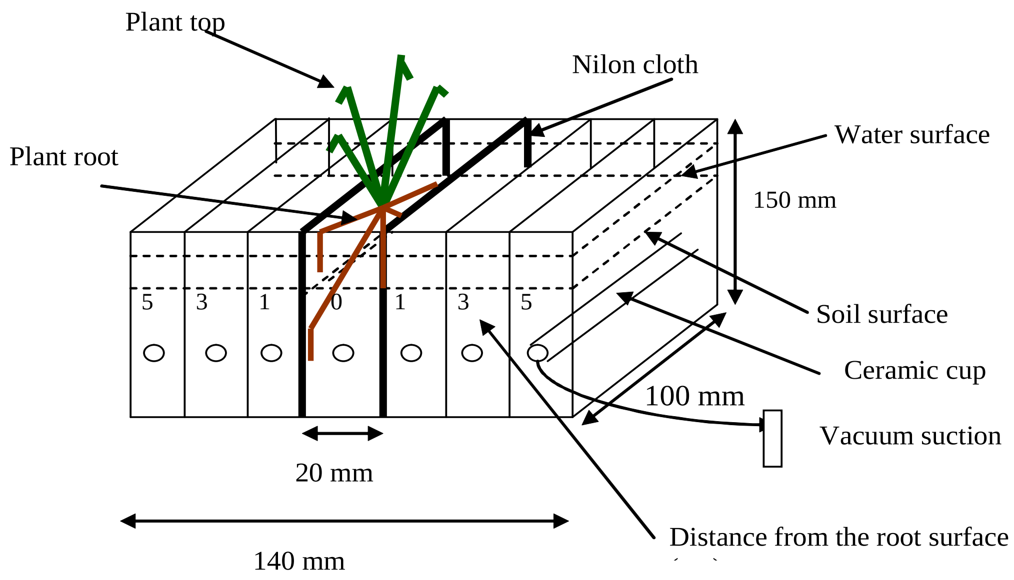

Figure 1. Lay out of rhizobox.

Tabel 2. Treatments for the rhizobox study.

Treatments *)	Notes		Treatment combination		
Soil origin:	Exchangeable Na	Clay content (%)	1	2	3
Kuin	low	37	√		
Bunipah	Very high	24		√	
Guntung Papuyu	moderate	41			√
Rice varieties:					
Padi Panjang	Extreme high yield local variety		√	√	√
IR64	Improved variety, as a comparison		√	√	√

*) each treatment was replicated 4 times.

Soil Solution Sampling

At 4 weeks after sowing, the soil solution of each segment was collected using a vacuum sample bottle as shown in Figure 1. The soil solution samples were kept in the refrigerator (4 ^{o}C) till the next day.

Soil Analysis

Soil properties analyses prior to planting were carried out for characterizing the soils used in the experiment. The soil properties used in this experiment are demonstrated in Table 1.

Soil Solution Analysis

The soil solution samples were analysed for their concentrations in ammonium (NH_4^+-N), nitrate (NO_3^--N), and phosphorus (P), pH, electric conductivity (EC), and oxidation reduction potential (ORP). The NH_4^+ and NO_3^- concentrations were measured colorimetrically using methods described in Kempers and Zweers (1986) and in Yang *et al.* (1998), respectively. While, P was determined using methods described in John (1970). The pH, EC and ORP were measured directly by inserting its electrode to the soil solution.

Data Analysis

Standard errors were shown to indicate data variation in measured soil solution as affected by treatments.

RESULTS AND DISCUSSION

Changes in NH_4^+ and NO_3^- Concentrations in Soil Solution

The NH_4^+ concentrations in various distances from the rhizosphere are shown in Figure 2. The pattern of NH_4^+ change from the rhizophere of soils from Kuin (Figure 2a) and Guntung Papuyu (Figure 2c) were similar. In these soils, the soluble NH_4^+ concentrations in soils grown with Padi Panjang cultivar and IR64 varieties were always lower than that in control soil without plant. It was observed that the NH_4^+ concentration of control soil was approximately 30 mg L^{-1}. It was likely that plants took up via mass flow mechanism when the level of NH_4^+ concentration was more than 10 mg L^{-1}. This might indicate that some amount of NH_4^+ was adsorbed by the soil colloids. It was also noticed that there was a depletion phenomenon of NH_4^+ concentration in the rhizosphere. This only occurred when the initial NH_4^+ concentration was approximately 30 mg L^{-1}.

The limit of mass flow action of NH_4^+ can also be observed in soil from Bunipah (Figure 2b). It was found that the NH_4^+ concentration was approximately 10 mg L^{-1}. It was likely that plant was unable to absorb NH_4^+ from the outside of the rhizosphere. In low NH_4^+ concentration, there was accumulation of NH_4^+ in the rhizosphere (Figure 2b).

It was also found that accumulation NH_4^+ occurred at soil collected from Bunipah. Zhang and George (2009) suggested that the accumulation of ions in the rhizosphere may be due to high mass flow transport of ions in the root surface. However, this did not occur to soil from Kuin and Guntung Papuyu. This might relate to the higher clay fraction content of these soils leading to a slower flow. In previous study (Purnomo *et al*. 2010) such accumulation did not appear in soil rhizosphere. This was because soil NH_4^+ was less mobile compared to soluble NH_4^+.

Compared to NH_4^+ pattern, the NO_3^- concentrations in all soils (Figure 3) were negligible. These were consistence with the NO_3^- concentration in the soil (Purnomo *et al*. 2010). The low NO_3^- concentrations were also observed in the control soil without plant. This indicated that the nitrification process was inhibited under waterlogged condition (Purnomo *et al.* 2000a and b).

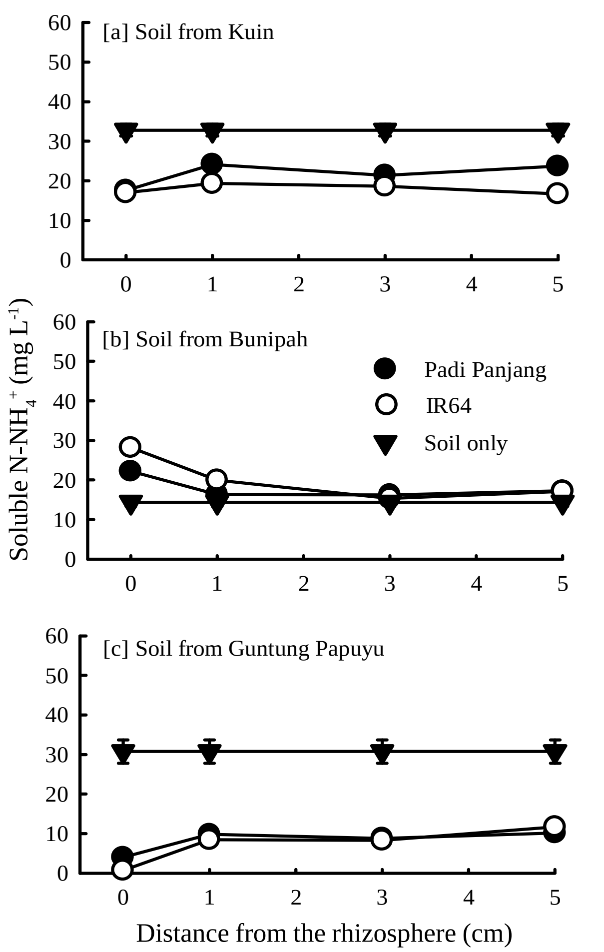

Figure 2. Soluble NH_4^+ concentrations at various distances from the rhizosphere. Bars indicate the standard error of means.

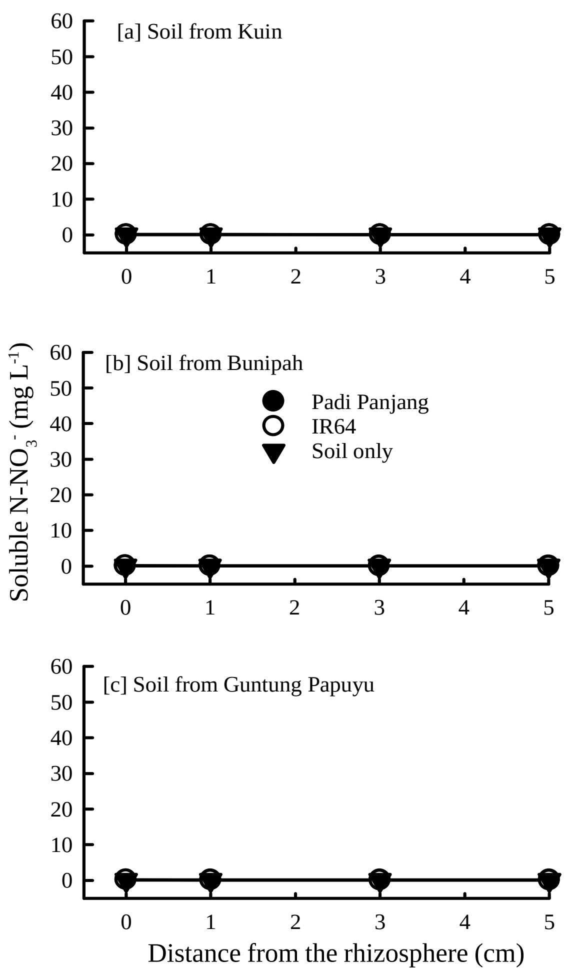

Figure 3. Soluble NO_3^- concentrations at various distances from the rhizosphere. Bars indicate the standard error of means.

Changes in P Concentration in Soil Solution

Figure 4 shows the concentration PO_4^{3-} in the soil solution of various distances from the rhizosphere. In all soils used the amount of PO_4^{3-} was negligible in control soil. However, with the present of rice plant, there was an accumulation of PO_4^{3-} in the rhizophere for soil from Kuin (Figure 4a) and from Guntung Papuyu (Figure 4c). In Kuin soil, the accumulation of PO_4^{3-} in the rhizosphere of Padi Panjang cultivar was higher than of IR64 variety. While, in soil from Guntung Papuyu, the accumulation of PO_4^{3-} in the rhizophere of Padi Panjang cultivar and IR64 varieties was similar. The accumulation of PO_4^{3-} in the rhizosphere was not common (Purnomo *et al*. 2010). It may be suggested that accumulation of soluble PO_4^{3-} in the rhizosphere as a result of the dissolution of P in the rhizosphere soil. This was true for soil from Kuin and Guntung Papuyu which had high clay content (Table 1). It was also observed that the high soluble PO_4^{3-} in the rhizosphere was consistent with result of Baldovinos and Thomas (1967). They found that soil with high clay content had more available P. The absence of soluble P in soil from Bunipah might be due to abundance Soluble Fe^{2+} as shown in Figure 5.

Changes in Fe^{2+} Concentration in Soil Solution

The patterns of Fe^{2+} concentration in the soil solution in various distances from the rhizosphere are demonstrated in Figure 5. In the rhizosphere, the presence of plant roots increased the soluble Fe^{2+}, except for rhizosphere of IR64 cultivar grown on soil from Kuin. The increasing of Fe^{2+} in the soil solution from Bunipah might be due to exudate that was able to keep the Fe^{2+} in the soil solution (Hansen *et al*. 2006). In this study, the effect exudates on concentration Fe^{2+} was clear in soil from Bunipah. It was found that this soil had a coarser texture than the other two soils. It was suggested that the mobility

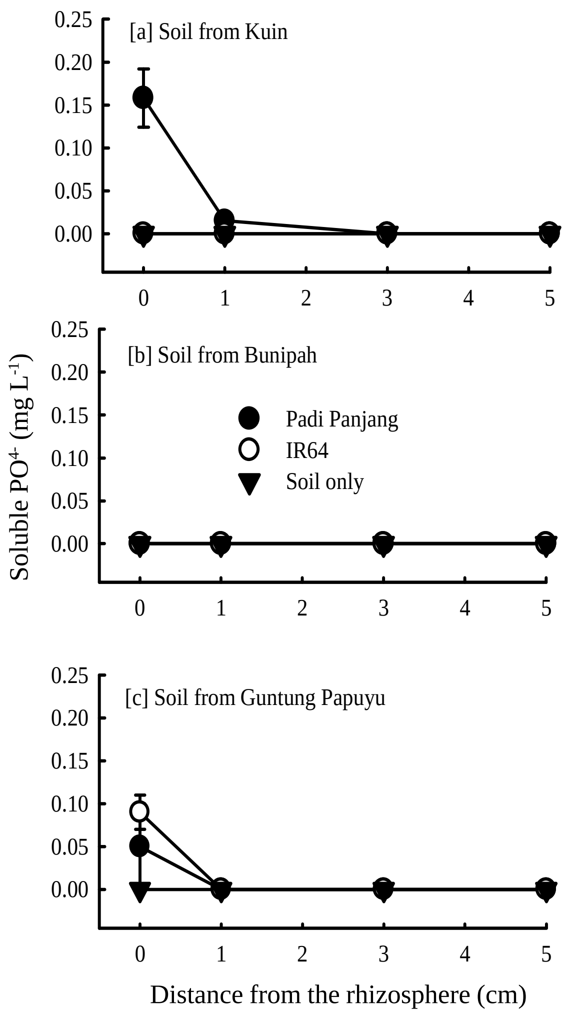

Figure 4. Soluble PO_4^{3-} concentrations at various distances from the rhizosphere. Bars indicate the standard error of means.

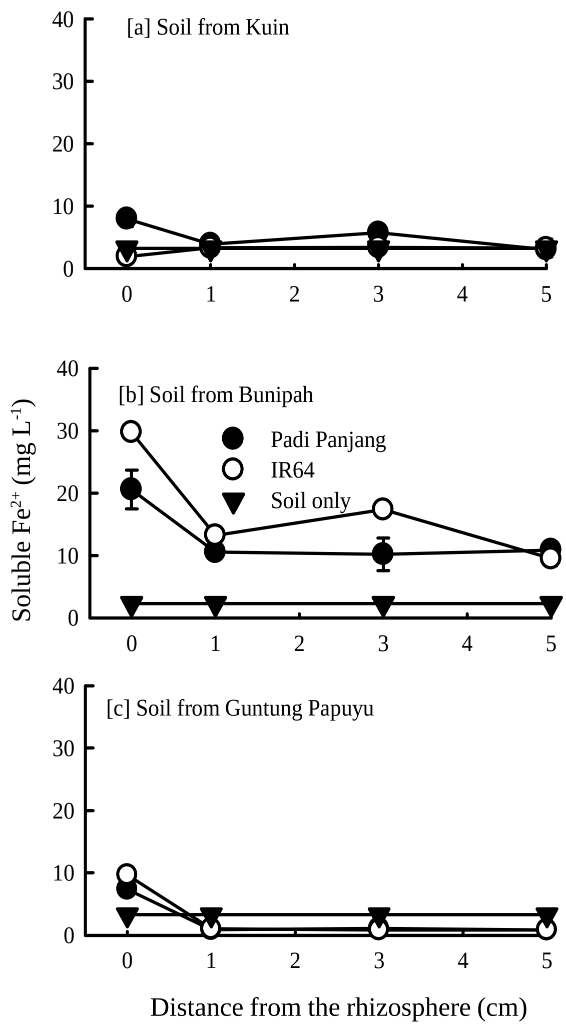

Figure 5. Soluble Fe^{2+} concentrations at various distances from the rhizosphere. Bars indicate the standard error of means.

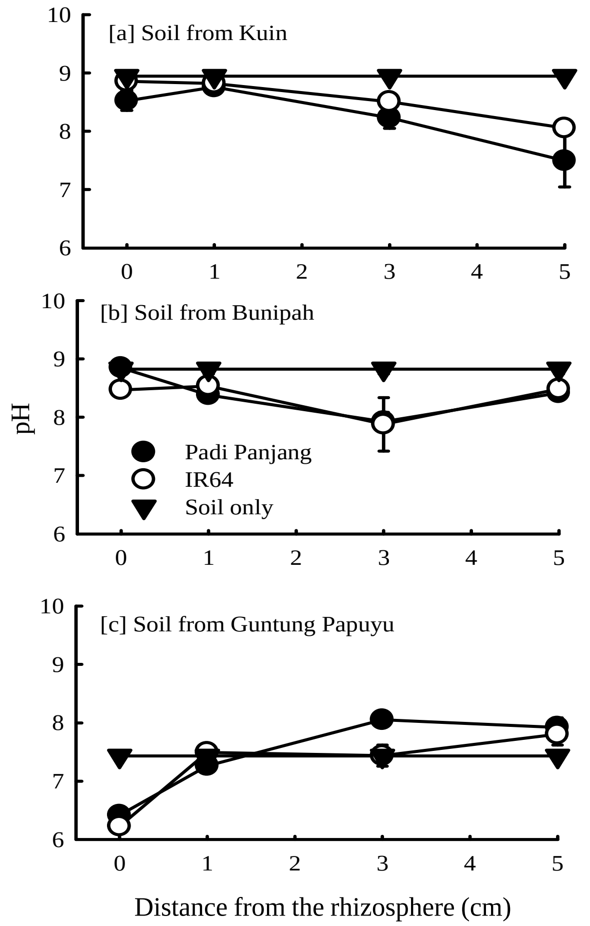

Figure 6. pH of soil solution at various distances from the rhizosphere. Bars indicate the standard error of means

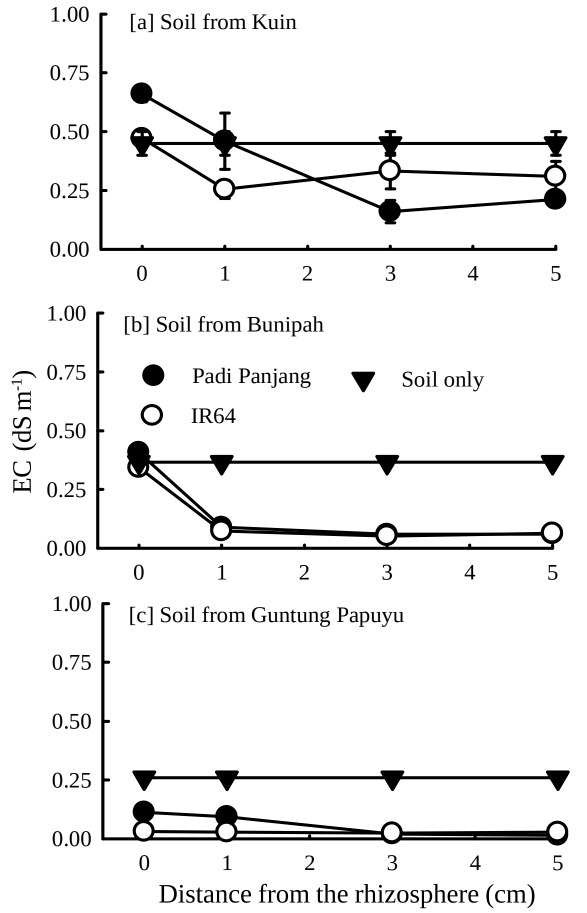

Figure 7. EC of soil solution at various distances from the rhizosphere. Bars indicate the standard error of means.

of exudates faster that in the coarses soil resulted more effect on keeping Fe^{2+} soluble.

Changes in Soil Solution pH

The effect of plant on pH of soil solution can be seen in Figure 6. It was observed that the soil solution pHs were much higher than soil pHs. Purnomo *et al*. (2009) observed that soil pH ranged 4.3-5.5. The higher soil solution pH compared to soil pH was unexpected. However, a study of Usui *et al*. (2003) showed the change of pH of ponded water related to the CO_2 concentration. As the CO_2 concentration decreased in the day time the pH of ponded water increased. In contrast, in the night time pH of ponded water decreased as the CO_2 concentration increased. According Boon and Vincent (2003) the rise in pH was a direct result of rapid photosynthetic carbon fixation by the algae, which removed dissolved CO_2 from the pond water more rapidly than it could be replaced by either bacterial respiration or from the air across the pond-air interface. This results in a shift in the carbonate-bicarbonate equilibrium to produce CO_2 and hydroxyl ions, as shown in Equation 1 and 2.

$$2\,HCO_3^- \longleftrightarrow CO_3^{2-} + H_2O + CO_2 \qquad [1]$$

$$CO_3^{2-} + H_2O \longleftrightarrow 2\,OH^- + CO_2 \qquad [2]$$

In the present study, soil solution was sampled during the day time and its pH was immediately measured. Therefore, the high pH reading may be associated with CO_2 depletion in the soil solution.

Changes in soil solution EC

In general the presence of plant roots reduced the EC readings. The decreasing in EC were very clear in soil solution outside of the rhizosphere. The EC's at the rhizosphere were higher than outside of the rhizosphere (Figure 7). The decreasing in EC in the soil solution as affected by the presence of plant was also found by Purnomo *et al*. (2005b).

Changes in Soil Solution ORP

The effect of the presence of plant on ORP at various distances from the rhizosphere can be seen

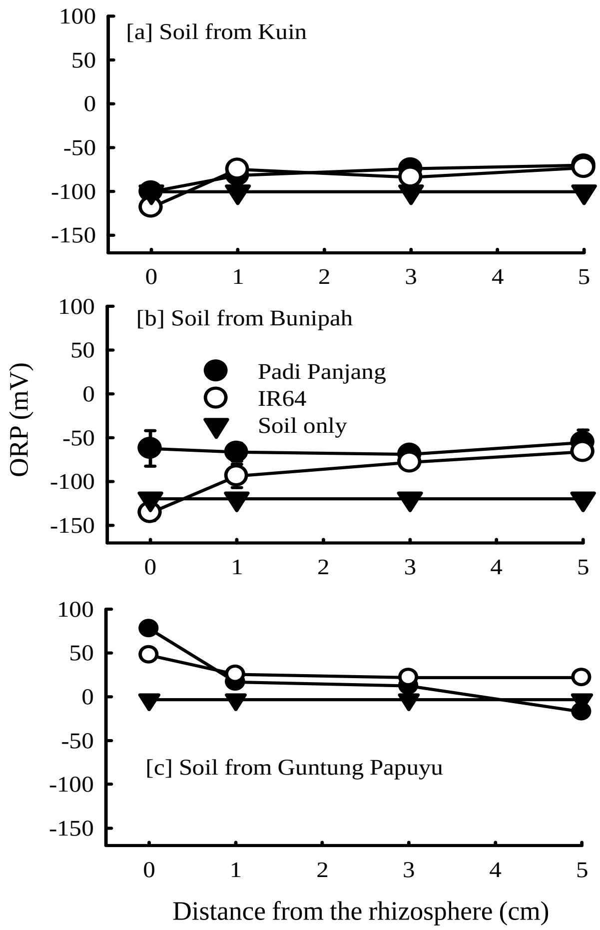

Figure 8. ORP of soil solution at various distances from the rhizosphere. Bars indicate the standard error of means.

in Figure 8. It was likely that the presence of plant roots increased the ORP of the soil solution outside the rhizosphere. In the rhizosphere, the ORP were higher of Padi Panjang cultivar that the IR64 variety. This can be seen in soils from Bunipah (Figure 8b) and Guntung Papuyu (Figure 8c). It was believed that root of rice was able to oxidize the soil (Kirk, 2003). In this study, it was observed that the root effect on ORP of soil solution outside the rhizosphere was more obvious in soil from Bunipah. It is suggested that the coarser texture may lead to faster diffusion of oxygen to the soil-solution system.

CONCLUSIONS

It can be concluded that the presence of plant roots affected some chemical properties of soil solution. It was found that there were decreasing in NH_4^+ concentration at all distances from the rhizosphere. This occurred when the soil had high NH_4^+ concentrations. On the other hand, in low NH_4^+ concentration, there was accumulation in the rhizosphere. While for NO_3^-, the amount was negligible at all distance from the rhizosphere. It was observed that the amount of P in soil solution may be associated with the Fe^{2+}. As the soluble Fe^{2+} existed, the P disappeared from the soil solution. Exudates may be responsible for Fe^{2+} in the soil solution. This was observed in soil from Bunipah which had a coarser texture. It was also found that pH readings of the soil solution were much higher than that in soil. The presence of plant root lowered the pH of the soil solution. The nutrient uptake by plant caused the decrease in EC. The higher ORP in soil solution in the presence of rice plant reflected the oxidation power of this plant.

ACKNOWLEDGEMENTS

We thank the Directorate General of Higher Education, Indonesian Ministry of National Education, for financing the work. The University of Hokkaido for supplying the nylon cloth and chemicals was greatly appreciated. Thank was extended to PT Adaro Indonesia for providing the excellent facility for working. We also acknowledge the constructive criticisms from Prof. Dr. Soni Isnaini and an anonymous reviewer of Journal of Tropical Soils.

REFERENCES

Baldovinos F and GW Thomas. 1967. The effect of soil clay content on phosphorus uptake. *Soil Sci Soc Am J* 31: 680-682.

Boon AG and AJ Vincent. 2003. Odour generation. In: Mara D and N Horan (eds) *The Handbook of Water and Water Waste Microbiology*. Academic Press. P 819

Bremner JM and CS Mulvaney. 1982. Nitrogen-total. In: AL Page, RH Miller and DR Keeney (eds), Methods of Soil Anlysis II, Chemical and Microbiological Properties, 2nd edition. ASA, Madison, Wisconsin, pp. 595-624.

Djaenuddin D, Basuni, S Hardjowigeno, H Subagjo, M Sukardi, Ismangun, DS Marsudi, N Suharta, L Hakim, Widagdo, J Dai, V Suwandi, S Bachri and ER Jordens. 1994. *Land Suitability for Agricultural and Silviculture Plants*. Laporan Teknis No. 7. Versi 1.0. April 1994. Center for Soil and Agroclimate Research, Bogor.

Dougan WK and AL Wilson. 1974. The absorptiometric determination of aluminium in water. A comparison of some chromogenic reagent and the development of an improved method. *Analyst* 99: 413-430.

Gee GW and JW Boulder. 1986. Particle size analysis. In: A Klute (ed). *Methods of Soil Analysis I, Physical and Mineralogy Methods*, 2nd edition. ASA, Madison, Wisconsin, pp. 383-412.

Hallett PD, DC Gordon and AG Bengough (2003) Plant influence on rhizosphere hydraulic properties: direct measurements using a miniaturized infiltrometer. *New Phytol* 157: 597-603.

Hansen NC, BG Hopkins, JW Ellsworth and VD Jolley. 2006. Iron nutrition in field crops. In: Barton LL and J Abadia (eds). *Iron Nutrition in Plants and Rhizospheric Microorganisms.* Springer, P.O. Box 17, 3300 AA Dordrecht, The Netherlands, pp. 23-60.

Hasegawa T, E Purnomo, Y Hashidoko, M Osaki and G Rusmayadi. 2004. Grain yield and its variation of local rice varieties grown on acid sulphate soil in South Kalimantan. *Japanese J Crop Sci* 73: 220-221.

John MK 1970. Colorimetric determination of phosphorus in soil and plant materials with ascorbic acid. *Soil Sci* 100: 214-220.

Kempers AJ and A Zweers. 1986. Ammonium determination in soil extract by the salicylate method. *Comm in Soil Sci Plant Anal* 17: 715-723.

Kirk GJD. 2003. Rice root properties for internal aeration and efficient nutrient acquisition in submerged soil. *New Phytol* 159 : 185-194.

Knudsen D, GA Peterson and PF Prafit. 1982. Lithium, sodium and potassium. In: AL Page, RH Miller and DR Keeney (eds). *Methods of Soil Analysis II, Chemical and Microbiological Properties*, 2nd edition. ASA, Madison, Wisconsin, pp. 225-246.

McLean EO 1982. Soil pH and lime requirement. In: AL Page, RH Miller and DR Keeney (eds). *Methods of Soil Anlysis. II. Chemical and Microbiological Properties*, 2nd edition. ASA, Madison, Wisconsin. pp. 199-224.

Olsen SR and LE Sommers.1982. Phosphorus. In: AL Page, RH Miller and DR Keeney (eds). Methods of Soil Analysis II, Chemical and Microbiological Properties, 2nd edition. ASA, Madison, Wisconsin, pp. 403-430.

Purnomo E, AS Black, CJ Smith and MK Conyers. 2000a. The distribution of net nitrogen mineralisation within surface soil. 1. Field study under wheat crop. *Aust J Soil Res* 38: 129-140.

Purnomo E., AS Black and MK Conyers. 2000b. The distribution of net nitrogen mineralisation within surface soil. 2. Factors influencing the distribution of net N mineralisation. *Aust J Soil Res* 38: 643-652.

Purnomo E, M Sarwani, A Jumberi, A Mursyid, T Hasegawa, Y Hashidoko, T Shinano, S Honma and M Osaki. 2005a. Phosphorus nutrition of high yielding local rice varieties grown without fertilizer on acid sulphate soil. *Soil Sci Plant Nutr* 51: 679-681.

Purnomo E, ML Setiawan, H Halim, D Choiron, R Yulia, T Shinano, Y Hashidoko, T Hasegawa and M Osaki. 2005b. Padi lokal, tanpa pupuk dengan hasil 8 ton per hektar. *Kompas*. 21 September 2005 (in Indonesian).

Purnomo E, M Turjaman, A Hairani and A Mursyid. 2007. Fungsi rizosfer dalam mendukung tanaman padi tropika berdaya hasil ekstrim tinggi tanpa pupuk di lahan pasang surut: Isolasi, identifikasi dan estimasi kemampuan mikroorganisme penambat N, pelarut P, pelarut K dan mikoriza**.** *Laporan Akhir Tahun II*. Hibah Bersaing Perguruan Tinggi. Tahun Anggaran 2007 (in Indonesian).

Purnomo E, T Hasegawa, Y. Hashidoko, JS Presto and M Osaki. 2009. Nitrogen nutrition of some local rice varieties grown without fertilizer on acid sulphate soil area in South Kalimantan. *J Trop Soil* 14: 41-47.

Purnomo E, Y Hashidoko, T Hasegawa and M Osaki. 2010. Extreme high yield of tropical rice grown without fertilizer on acid sulfate soil in South Kalimantan, Indonesia. *J Trop Soil* 15: 33-38.

Rhoades JD 1982a. Cation exchange capacity. In: AL Page, RH Miller and DR Keeney (eds). *Methods of Soil Analysis II, Chemical and Microbiological Properties*, 2nd edition. ASA, Madison, Wisconsin, pp. 149-158.

Rhoades JD 1982b. Soluble salts. In: AL Page, RH Miller and DR Keeney (eds). *Methods of Soil Analysis II, Chemical and Microbiological Properties*, 2nd edition. ASA, Madison, Wisconsin, pp. 167-180.

Thomas GW. 1982. Exchangeable cations. In: AL Page, RH Miller and DR Keeney (eds). *Methods of Soil Analysis II, Chemical and Microbiological Properties*, 2nd edition. ASA, Madison, WI, pp. 159-166.

Usui Y, MIM Mowjood and T Kasubuchi. 2003. Absorption and emission of CO_2 by ponded water of a paddy field. *Soil Sci Plant Nutr* 49: 835-857

Wang Z, J Shen and F Zhang. 2006. Cluster-root formation, carboxylate exudation and proton release of Lupinus pilosus Murr as affected by medium pH and P deficiency. *Plant Soil* 287: 247-256.

Wang Z, Shan Xiao-quan and S Zhang. 2002. Comparison between fractionation and bioavailability of trace elements rhizosphere and bulk soils. *Chemosphere* 46: 1162-1171.

Wang ZY, JM Kelly and JL Kovar. 2005. Depletion of macro-nutrients from rhizosphere soil solution by juvenile corn, cottonwood, and switchgrass plants. *Plant Soil* 270: 213-221.

Yang JE, EO Skogley, BE Schaff and JJ Kim. 1998. A simple spectrophotometric determination of nitrate in water, resin and soil extract. *Soil Sci Soc Am J* 62: 1108-1115.

Yeomans JC and JM Bremner. 1988. A rapid and precise method for routine determination of organic carbon in soil. *Commun Soil Sci Plan* 19: 1467-1476.

Zhang Jun-Ling and E George. 2009. Rhizosphere effects on ion concentrations near different zone of Norway spurce (*Picea abies* (L.) Karst.) and root types of Douglas-fir (*Pseudotsuga menziesii* L.) seedlings. *Plant Soil* 322: 209-218.