The Long-Term Effect of Blanket Phosphorus Fertilizer Application on the Available P Content in Sawah Soils: Comparative Study in Java, Indonesia

Darmawan[1], Kazutake Kyuma[2], Tsugiyuki Masunaga[3] Asmar[1], Irwan Darfis[1] and Toshiyuki Wakatsuki[4]

Received 7 July 2008 / accepted 24 December 2008

ABSTRACT

The Long-Term Effect of Blanket Phosphorus Fertilizer Application on the Available P Content in Sawah Soils: Comparative Study in Java, Indonesia (Darmawan, K. Kyuma, T. Masunaga, Asmar, I. Darfis, and T. Wakatsuki): In order to evaluate the effects of long-term phosphorus fertilizer application on the sawah soils, a comparative study was conducted in Java Island as a pioneer of Green Revolution (GR) technology application in Indonesia. Soil samples taken in 1970 by Kawaguchi and Kyuma were compared with new sample taken from the same site or the sites close to 1970 in 2003. The results showed that available phosphorus (P) sharply increased during the study period. The average content of available P in topsoil layer changed from 10.5±11.6 mg kg^{-1} P in 1970 to 19.6±22.4 mg kg^{-1} P in 2003, or increased by 118%. Long-term application of 125 kg super-phosphate [$Ca(H_2PO_4)_2$] per hectares per cropping season as P fertilizers was also affected the profile distribution of available P in whole sites studied, especially in Vertisols. The land management differences between seedfarms planted with rice in monoculture systems whole study period and non-seedfarms cultivated rice and upland crops in some rotation patterns found affected the changing rate of available P in the soils. During the period of 1970-2003, average content of available P in seedfarms changed from 15.7±16.2 mg kg^{-1} P to 31.1±29.1 mg kg^{-1} P while in non-seedfarm from 6.9±8.7 mg kg^{-1} P to 11.5±8.2 mg kg^{-1} P in 1970 and 2003, respectively. The great variation on the changing rate of available P observed in this study indicated that general chemical fertilizers recommendation in Indonesia was caused excess P input in some sites, but insufficient in others. To avoid the adverse effect of P fertilizer application in the future, recommendation of P should be based on the site characteristic and taking into account of natural resources contribution.

Keywords: Available phosphorus, Java, seedfarms, sawah

INTRODUCTION

Java Island is the main rice bowl for Indonesia. From 8.5 million irrigated sawah in Indonesia, about 5 million hectares located in Java and contributed more than half total rice production in this country. The term sawah refers to a leveled and bounded rice fields with an inlet and an outlet for irrigation and drainage (Wakatsuki *et al*. 1998). Introduction of green revolution (GR) technology through using high yielding varieties (HYVs) of rice, chemical fertilizers, and improving irrigation facilities and cropping intensity has increased rice production in Indonesia from 18.0 million Mg in 1969 to 51.9 million Mg in 2000 (IRRI 2001; Indonesia Ministry of Agriculture 2001). Implementation of GR in Java had increased the average sawah productivity from 2.0 Mg ha^{-1} to 4.5 Mg ha^{-1} and changed cultivation intensity from 1.5 to 2.5 in 1970 and 2001, respectively (Kawaguchi and Kyuma 1977; Ostsuka 2001).

During the GR period, Indonesia Ministry of Agriculture urged the rice farmers to add 150 kg urea [$CO(NH_2)_2$], 125 kg super-phosphate [$Ca(H_2PO_4)_2$] and 100 kg muriate of potash (KCl) per hectare per cropping season. Although the soils in Java mostly derived from volcanic origin materials that might be

[1] Faculty of Agriculture Andalas University, Padang-25163, Indonesia.
[2] Emeritus Professor of Kyoto University, 606-8501, Japan
[3] Faculty of Life and Environmental Science, Shimane University, Matsue 690-8504, Japan
[4] Faculty of Agriculture, Kinki University, Nara 332-7204, Japan

J. Tanah Trop., Vol. 14, No. 1, 2009: 9-18
ISSN 0852-257X

involved the nutrient content in sawah, especially phosphorus (P). Researchers in Japan found that continuous application of phosphate fertilizer resulted in the accumulation of P in the plough layer of sawah due to negligible leaching (Ando, 1983; Yoshiike, 1983). In Korea, the mean content of available P in surface soil of sawah increased gradually from 25.8 mg kg^{-1} P_2O_5 in 1960s to 55.0 mg kg^{-1} P_2O_5 in 1990s (RDA, 1999). Although many research reported that long-term inputs of high phosphate fertilizers in intensive crops areas has resulted in significant P enrichment in soil profile (Sharpley *et al.*, 1993; Simard *et al.*, 1995) and excess P found beyond what is needed for optimum crop yield (Tunney *et al.*, 1997), but there is no such research reported about Indonesia, especially Java, as a pioneer of GR technology in this country. This paper aim to discuss about the effect of P fertilizer application during the period of 1970-2003 on the changes of available P content in sawah soil in Java related to land management differences.

MATERIALS AND METHODS

Description of Study Area and Sampling Sites

Java is the smallest among the five biggest islands in Indonesia archipelago. It lies between 05°52’34’’ S to 08°46’46’’ S and 105°12’40’’ E to 114°35’38’’ E. Although the total land area of this island is just 132,187 km^2, which is about 7 percent of the total land area of Indonesia, but more than half of Indonesian people lives here. Figure 1 shows Java Island and distribution of sampling sites both in 1970 and 2003. Most of the sampling sites were located in the northern part along the coastal plain, because southern part of Java is mountainous and difficult to access.

Among 46 sampling sites in 1970, four of them (site number 2, 4, 5, and 40) were not sampled in 2003 because land use changed to non-agricultural purposes and two sites (number 15 and 30) changed to other crop cultivation were also excluded in this study. For the remained 40 sites in 2003, twenty-five of them were identified as the original sites with 1970’s confirming with the description sheets made by Kawaguchi and Kyuma in 1977 and/or information from the landowners and the old farmers nearby the sites. Since 15 sites could not be confirmed as the original due to land use changed and lack of information, soil were collected from the closest site to 1970’s sampling areas.

From 40 sites studied, 18 located in seedfarms, where the GR technology was firstly applied in the middle of 1960s and the other 22 in non-seedfarms. Seedfarm was established in Java to bridge the GR technology transfer from IRRI to the farmers. However, by the time going, seedfarms also function as food security buffering for the whole country and

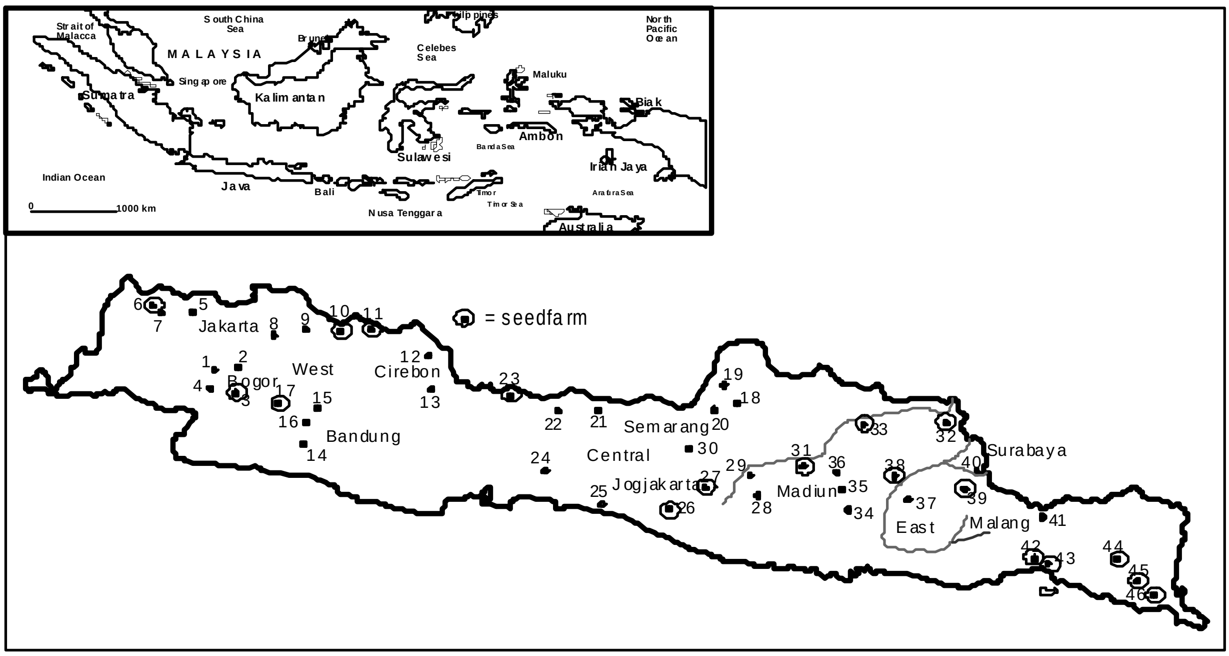


Figure 1. The map of Indonesia and distribution of sampling site in Java Island.

mostly planted rice whole year round. To support seedfarms function, Indonesian government provide all the needs for rice cultivation, included chemical fertilizers, pesticides and better irrigation facilities (Indonesia Ministry of Agriculture, 2001; Darmawan *et al.*, 2006). Non-seedfarms, on the other hand, is local farmer sawah which planted rice and upland crops in some rotation pattern. Non-seedfarms usually applied less chemical fertilizers, and cropping pattern depended on the available of water and farmers‘ budget.

Soil Sampling and Interview

The study used soil samples taken by Kawaguchi and Kyuma in 1970 as references. These soil samples had been air dried and kept in sealed plastic bottles in a storage room. The second sampling was done in April and December 2003 from the same or closest to original sites in 1970. Soil samples were collected from each horizon in a profile at the respective sites by using 100 cm^3 core samplers to determine the bulk density of soil. Composite soil samples from the each horizon were also collected as well for chemical analyses. To ensure the reliability of 1970 soil samples, our analytical data and the original data from Kyoto University was compared. Both analytical results were found very similar with less than 5% difference (data not published). In order to get the latest information about the changes of rice cultivation systems and productivity in seedfarms and non-seedfarms during the period of 1970 and 2003, we interviewed the seedfarms staffs and the farmers on the respective sites assisted by the counterparts as interpreter.

Laboratory and Statistical Analyses

The air-dried soil samples were ground and passed through a 2-mm sieve. Available P was extracted by Bray 2 method and the content was determined by colorimetric with UV/VIS Spectrophotometer (Jasco V-530) (Bray and Kurtz 1945). The SPSS version 11.0 for Windows program was used to statistically examine the effect of GR on the changes of some soil chemical properties during the period of 1970 and 2003. The mean values for the samples taken in 1970 were compared with 2003 samples by using the land management difference (seedfarms and non-seedfarms) as blocks and the results were presented in Tables 1 and 2.

RESULTS AND DISCUSSION

The Effect of Long-term Phosphorous Fertilizer Application on the Change of Available P

Table 1 shows the location and change of available P content during the period of 1970-2003 on each sampling site. The available P content in top soil found increased in whole site, except in site number 1, 9, 25 and 37, where the available P decreased by -6%, -18%, -20% and -5 %, respectively. Since all of them are located in non-seedfarms, the decreasing of available P in those sites might be due to by irregular application of phosphorous fertilizer during the period of study. According to Lansing *et al.* (2001), application rates of chemical fertilizers by Java’s and Bali’s farmers are much lower than government recommendation. Darmawan *et al.* (2006) stated that application of chemical fertilizers in non-seedfarms also influence by the farmer’s budget. This condition is quite different as compare with seedfarms, where all of the needs for rice cultivation were supplied by the government.

During the study period, average available P content changed from 10.5±11.6 mg kg^{-1} P in 1970 to 19.1±22.4 mg kg^{-1} P in 2003 or increased by 118%, and statistically significant at 0.1% levels (Table 1). The available P content found greatly varied from one site to another in this study. In 1970, the available P content ranged from 1.4 mg kg^{-1} P (site number 28, non-seedfarm) to 64.9 mg kg^{-1} P (site number 32, seedfarm), and in 2003 it was ranged from 3.2 mg kg^{-1} P (site number 41, non-seedfarm) to 280.4 mg kg^{-1} P (site number 32, seedfarm). Long-term application of chemical P fertilizer had increased the available P content in the soils. The similar results were also found by Yoshiike (1983) in Japan, Lee *et al.* (2004) in Korea and Zhang *et al.* (2005) in China.

From 40 sites studied, 10 of them (site number 3, 10, 13, 21, 28, 35, 36, 39, 41 and 44) observed had very low in available P content in 1970 (≤ 10 mg kg^{-1} P_2O_5). It was contradictory with values observed in site number 6, 26, 27, 32, 33 and 45, where the available P content were higher than 50 mg kg^{-1} P_2O_5 (Table 1). Since all of sites with high available P were located in seedfarms, the discrepancies of these results could be affected by the adoption history of GR technology in Indonesia. According to Indonesia Ministry of Agriculture (1995), the adoption of GR was not once –and-for-all change in technology. In systems consisted of using HYVs of rice, chemical

Table 1. The changes of available P content in top soil (*** denote significance at 0.1% levels).

Sampling code	Location	Available Phosphorus P-1970	Available Phosphorus P-2003	Change (%)	USDA Taxonomy
		mg kg^{-1} P			
In-1	Non-seed farm	5.0	4.7	-6	Aeric Epiaquepts
In-3	Seedfarm	3.2	17.2	429	Aeric Epiaquepts
In-6	Seedfarm	23.5	33.8	44	Typic Epiaquepts
In-7	Non-seed farm	6.1	7.1	17	Typic Halaquepts
In-8	Non-seed farm	4.6	10.9	138	Typic Kanhapludults
In-9	Non-seed farm	5.1	4.2	-18	Vertic Epiaquepts
In-10	Seedfarm	4.1	9.9	139	Aeric Endoaqualfs
In-11	Seedfarm	4.6	6.2	36	Vertic Epiaquepts
In-12	Non-seed farm	11.4	13.2	15	Vertic Endoaquepts
In-13	Non-seed farm	4.1	6.8	67	Typic Dystropepts
In-14	Non-seed farm	6.4	7.1	10	Typic Endoaquepts
In-16	Non-seed farm	5.2	14.0	171	Mollic Fragiaquepts
In-17	Seedfarm	4.6	9.9	115	Aeric Epiaquerts
In-18	Non-seed farm	8.3	14.4	74	Vertic Endoaquepts
In-19	Non-seed farm	15.7	27.4	75	Aquic Eutropepts
In-20	Non-seed farm	12.9	37.9	195	Typic Calciaquepts
In-21	Non-seed farm	4.5	5.1	14	Aeric Epiaquerts
In-22	Non-seed farm	7.8	8.3	6	Aeric Epiaquerts
In-23	Seedfarm	12.9	20.3	58	Typic Natraquerts
In-24	Non-seed farm	5.7	7.3	27	Typic Endoaquepts
In-25	Non-seed farm	9.5	7.6	-20	Vertic Endoaquepts
In-26	Seedfarm	33.6	79.5	137	Aeric Epiaquepts
In-27	Seedfarm	28.8	39.0	35	Aeric Epiaquepts
In-28	Non-seed farm	1.4	8.1	465	Typic Dystrustepts
In-29	Non-seed farm	6.8	11.8	74	Typic Epiaquerts
In-31	Seedfarm	5.0	19.8	295	Typic Calciaquerts
In-32	Seedfarm	65.0	126.2	94	Typic Epiaquerts
In-33	Seedfarm	23.6	38.3	63	Aeric Endoaquerts
In-34	Non-seed farm	7.8	19.6	151	Aeric Epiaquepts
In-35	Non-seed farm	2.3	5.2	126	Typic Calciaquerts
In-36	Non-seed farm	4.0	13.9	247	Typic Epiaquerts
In-37	Non-seed farm	15.1	14.4	-5	Typic Epiaquepts
In-38	Seedfarm	14.4	27.2	89	Aeric Epiaquepts
In-39	Seedfarm	2.9	12.6	339	Aeric Epiaquepts
In-41	Non-seed farm	2.3	3.2	38	Typic Epiaquepts
In-42	Seedfarm	10.6	28.8	170	Typic Epiaquerts
In-43	Seedfarm	5.0	17.7	251	Aeric Endoaquerts
In-44	Seedfarm	4.1	19.8	381	Fluvaquentic Epiaquepts
In-45	Seedfarm	30.1	36.7	22	Aeric Epiaquepts
In-46	Seedfarm	5.9	15.6	167	Typic Calciaquerts
Mean		10.8	20.3	87.5	
SD		11.9	22.4		
T-test			***		

fertilizers and pesticides were just applied in seedfarms as a bridge of technology transfer from research center (mostly for IRRI) to the farmer in Java. Kyuma wrote that in 1970 most of seedfarms already applied GR technology, but in non-seedfarms, however, the farmers still plant rice in traditional way (private note in soil profile description sheet in 1970).

The Effect of Long-term Phosphorous Fertilizer Application on the Changes of Profile Distribution Pattern of Available P

Long-term application of phosphorus fertilizer had affected the profile distribution of available P in Java. Figure 2 and 3 show the profile distribution of available P in 1970 and 2003 in each sampling site in seedfarms and non-seedfarms, respectively. Those figures clearly show the effect of GR technology on the changes of available P in sawah soils. Profile distribution of available P in 1970 reflected the condition in the beginning of GR application. From 18 sites located in seedfarm, 8 of them (site number 6, 23, 26, 27, 32, 33, 38 and 45) had high available P content in 1970 (Figure2). Indicating that, those sites already applied P fertilizer as a GR technology component. In non-seedfarm, on the other hand, from total 22 sites only 4 sites found with high available P content in 1970 (Figure 3). These results were in agreement with the Indonesian Ministry of Agriculture (1995) statement. Adoption processes of GR was firstly applied in seedfarm, and gradually expanded to the sawah nearby.

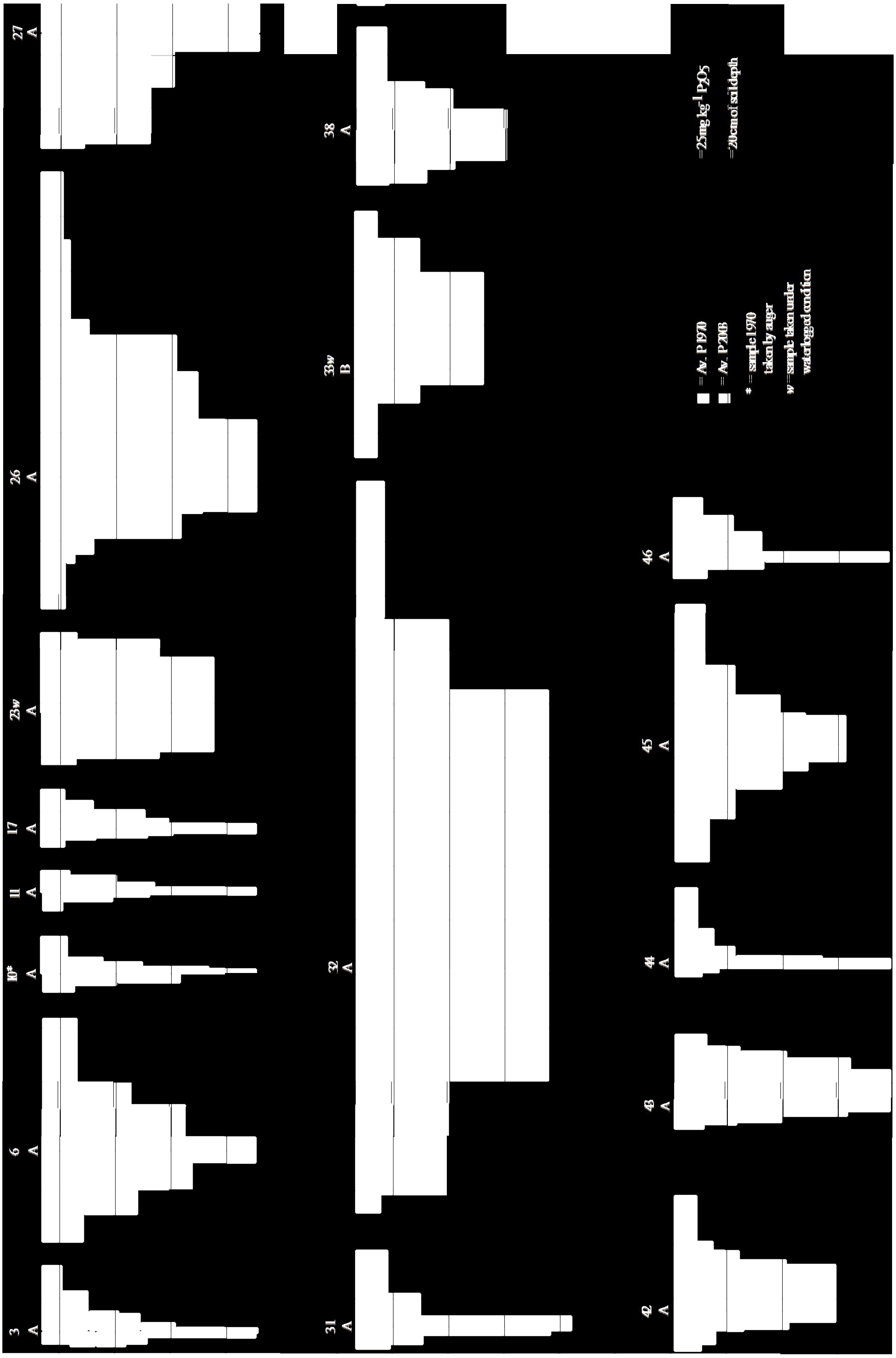
Application of P fertilizer for more than three decades affected available P content in topsoil and deeper soil layer as well. Figure 2 and 3 show the comparison between the profile distribution of available P in 1970 and 2003. Although available P content mostly found accumulated in the surface soil layer, it was also affect the lower soil layer. This condition observed in all sites studied especially in the sites which are belong to Vertisols (site number 12, 23, 32, 33 and 43) (Table 1). The ability to form deep crack as peculiar characteristic of Vertisols could be the main reason for this phenomenon (Brady and Weil, 2002).

The profile distribution of available P show in figure 2 and 3 were indicated the pathway of P transfer out of sawah. Accumulation of available P in surface soil will make easier for P to flow away through surface runoff, which is commonly accepted by most researchers. And the increasing of available P observed in deeper soil layer indicate that some of P also loss through leaching where both of these processes are potential to be non-point pollution resources of the water body nearby. Many researchers report that leaching is significant pathway of P losses from high P status soils (Heckrath *et al*., 1995; Chalmers and Withers 1998; Turner and Haygarth 1998; Zhang *et al*., 2003). Higher P fertilization rates resulted in more accumulation at top soil layer and deeper downward P movement in soil profile (Shan *et al*., 2005).

The Effect of Land Management on the Changing Rate of Available P in Java Sawah Soils.

Although seedfarms and non-seedfarms were located in the same island, the land management systems differences between them had create dissimilar result on the available content in the soils. Table 2 shows the changing rate of available P content during the period of 1970-2003. It was clear that seedfarms planted rice whole year and received much more P fertilizer was accumulated P higher as compared with in non-seedfarms where the application of fertilizers mostly depended on the farmers' s budget with less rice cultivation intensity. During the study period, the average content of available P increase from 15.7±16.2 mg kg^{-1} P to 31.1±29.2 mg kg^{-1} P in seedfarms and from 6.9±3.9 mg kg^{-1} P to 11.5±8.2 mg kg^{-1} P in non-seedfarms. The changing rate of available P in seedfarms and non-seedfarms were 159% and 85% and statistically significant at 1% and 0.1%, respectively. Continuous application of 125 kg super-phosphate [$Ca(H_2PO_4)_2$] per hectare per cropping season as P fertilizer in Java, especially in seedfarms during GR period could be responsible for this result (Lansing *et al*., 2001).

Table 2. The effect of land management practices between non-seedfarm and seedfarm on the changes of available P content in the topsoil.



.Figure 2. The profile distribution of available P on each sampling sites located in seedfarm. A = original site; B = close to original site.

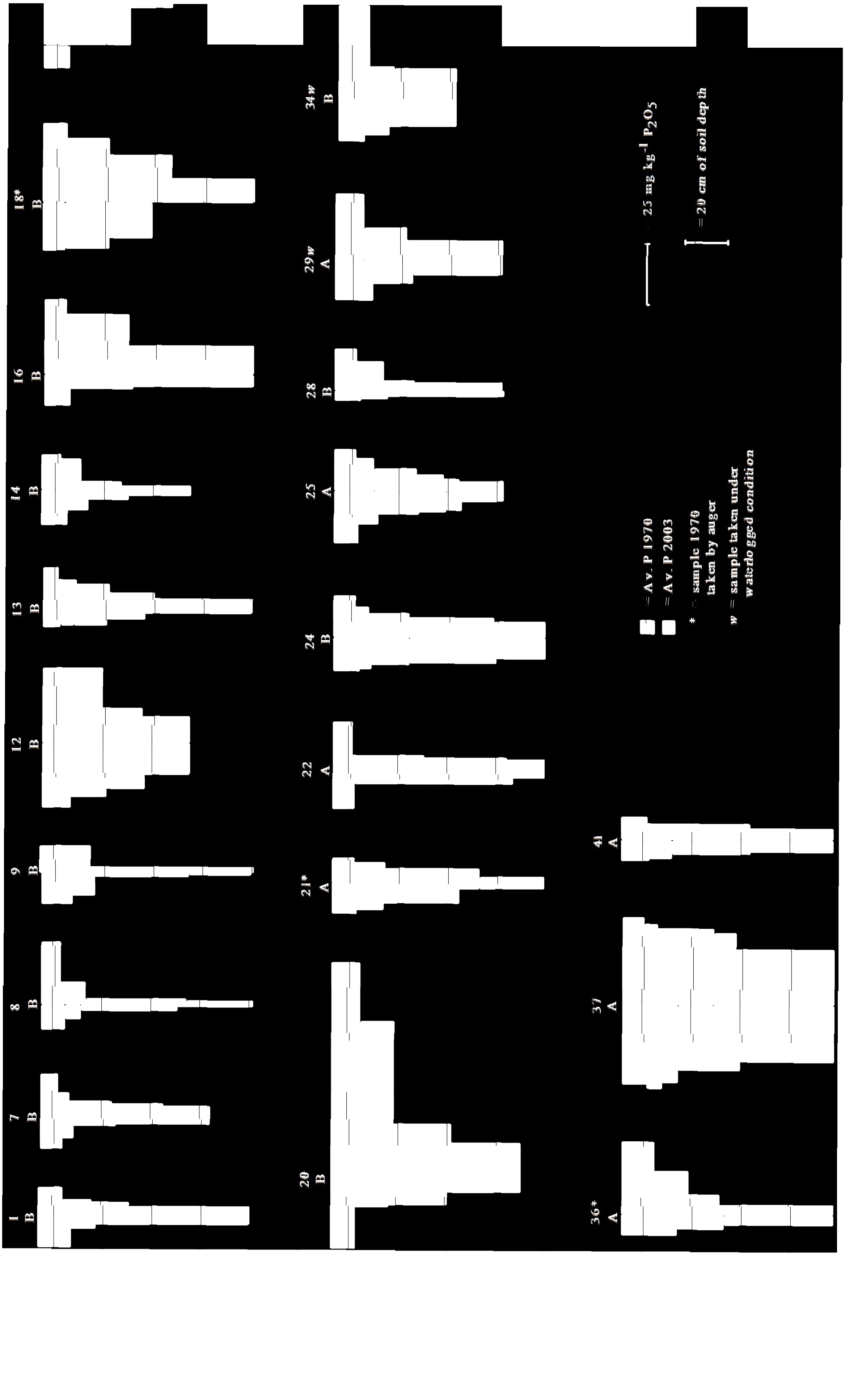
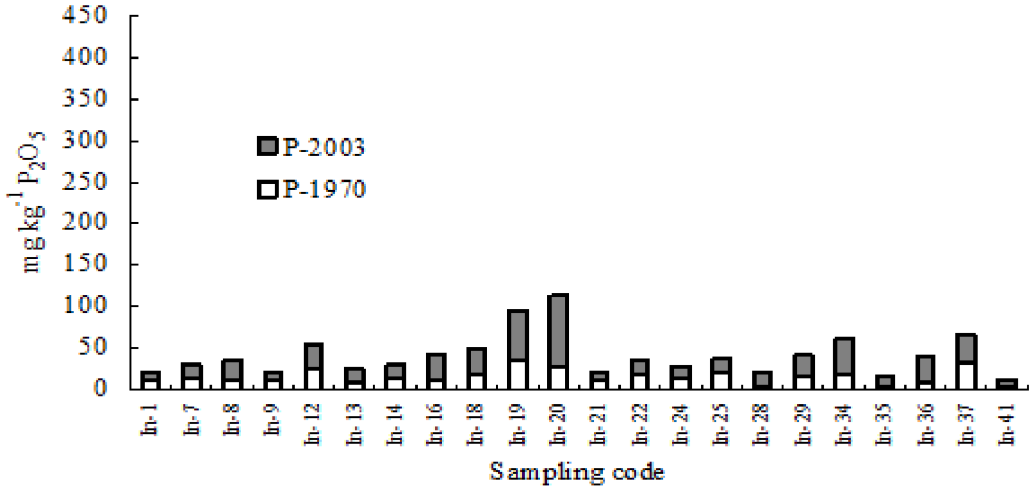


Figure 3. The profile distribution of available P content on each sampling sites located in non-seedfarm. A = original site; B = close to original site.



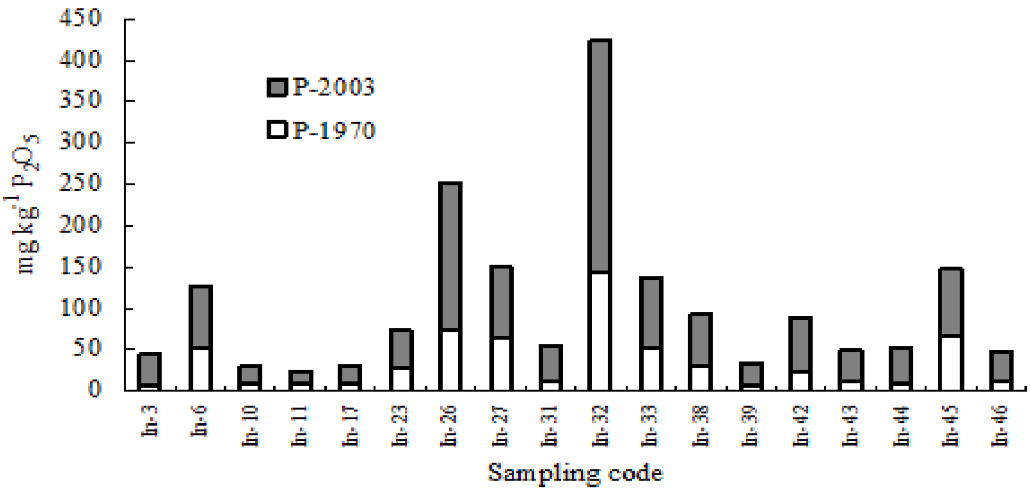


Figure 4. The available P content (mg P_2O_5 kg^{-1}) observed in top-soil of non-seedfarm (upper) and seedfarm (lower).

Figure 4 show the available P content in topsoil layer on each sampling site in 1970 and 2003. The great variation on the changes of available P values, indicated that the chemical fertilizers recommendation in Indonesia was made in general and did not taking into account of potential contribution of natural resources. For examples, site number 26 and 32 in seedfarms. Although the available P content observed in 1970 from these two sites already high, the same amount of P they received every cropping season with the other sites increased the available P in these two sites higher compared to other sites. Roche (1994) wrote that chemical fertilizers recommendation in Indonesia was made in general and did not based on site specific information. This method create some insufficiency in some places, but also excess in the others. Lansing *et al.* (2001) state that general P fertilizer recommendation potential to caused environmental pollution problem, especially in the sites where the original P content is high some places, but also excess in the others. Lansing *et al.* (2001) state that general P fertilizer recommendation potential to caused environmental pollution problem, especially in the sites where the original P content is high.

CONCLUSIONS

To support the adoption process of GR technology and food security buffering, Indonesian government established many seedfarms in Java Island which was chosen as a pioneer to adopt this new rice cultivation systems. To engage with these purposes, seedfarms was planted with rice whole year round and supplied with all the needs for rice cultivation. In non-seedfarms, on the other hand, farmers planted rice and upland crops in some rotation patterns and applied less chemical fertilizers. The land management differences between seedfarms and non-seedfarms created some discrepancies on the available P content. Although the available P content in seedfarms and non-seedfarms observed similar in 1970, but in 2003, however, this gap found wider. Seedfarms which received more phosphorus fertilizer increased faster in available P as compared to in non-seedfarms. The general chemical fertilizers recommendation seemed responsible to create the great variation of available P content in the soils and potent to cause environmental pollution problem. To avoid the worse condition in the future, chemical fertilizer recommendation should be based on the specific site characteristic and also taking into account of natural resources contribution. To formulate the suitable and efficient nutrient management in Java and Indonesia as a whole, study on the nutrient mass balance in some key point is needed.

ACKNOWLEDGEMENTS

The authors would like to express their deep gratitude to Ministry of Education, Science, Sport and Culture of Japan for the financial assistance for this study. The deepest appreciation goes to Dr. Fahmuddin Agus, Dr. Subagjo and Mr. Arsil Saleh from the Center of Soils and Agro-climate Research and Development (CSARD) Bogor, Indonesia for providing the necessary support during soils sampling on Java.

REFERENCES

Ando, J. 1983. Future of phosphorus resources and suggested direction for Japan. Jpn. J. Soil Sci. Plant Nutr. 54: 164-169 (in Japanese with English summary).

Brady, N.C. and R.R. Weil. 2002. The Nature and Properties of Soils, 10th ed, Macmillan New York, pp. 76-119.

Bray, R.H. and L.T. Kurtz. 1945. Determination of Total, Organic and Available Phosphorus in Soils. Baltimore. Soil Science 59: 39-45.

Chalmers, A.G. and P.J.A. Withers. 1998. Phosphorus leaching from soils enriched with phosphorus loading from organic manures. In: R.H. Foy and R. Dils (Eds). Practical and innovative measures for the control of agricultural phosphorus losses to water. An OECD Sponsored workshop, pp. 144-145.

Darmawan, K. Kyuma, A. Saleh, H. Subagjo, T. Masunaga, and T. Wakatsuki. 2006. The effect of green revolution technology during the period of 1970-2003 on sawah soils properties in Java, Indonesia; I. Carbon and nitrogen distribution under different land managements practice and soils types. Soil Sci. Plant Nutr. 52 (5): 634 - 644.

Heckrath, G., P.C. Brookes, P.R. Poulton, and K.W.T. Guolding. 1995. Phosphorus leaching from soil containing different phosphorus concentrations in the Broadbalk Experiment. J. Environ. Qual. 24: 904-910.

Indonesian Ministry of Agriculture 2001. Produksi Padi di Indonesia (The Rice Production of Indonesia), Jakarta (in Indonesian).

IRRI. 2001. Annual Report for 2001. International Rice Research Institute, Los Banos, Philiphines.

Kawaguchi, K and K. Kyuma. 1977. Paddy soil in tropical Asia. Their material, nature and fertility. The Univ. Press of Hawaii, Honolulu, pp. 258.

Lansing, J.S., J.N. Kremer, V. Gerhart, P. Kremer, A. Arthawiguna, S.K.P. Sutara, Suprapto, I.B. Suryawan, I.G. Arsana, V.C. Scarborough, J. Schoenfelder, and K. Mikita. 2001. Volcanic fertilization of Balinese rice paddies. Ecol. Econ. 38: 383-390.

Lee, C.H., C.Y. Park, K.D. Park, W.T. Jeon, and P.J. Kim. 2004. Long-term effects of fertilization on the forms and availability of soil phosphorus in rice paddy. Chemosphere 56: 299-304.

Otsuka, K. 2001. Role of agricultural research in poverty reduction: lesson from the Asian experience. Food Policy 25: 447-462.

RDA 2001. Survey on fertilizer application rates in farmer's fields. In: Evaluation Study on Environmental Effects by Fertilizer Use inn Cultivation Lands. RDA. Suwon, pp. 3-46 (in Korean with English summary).

Roche, F.C. 1994. The technical and price efficiency of fertilizer use in irrigated rice production. Bull. Indo. Econ. Stud. 30: 59-83.

Sharpley, A.N., Daniel and T.C. Edward. 1993. Phosphorus movement in the landscape. J. Produc. Agric. 6: 492-500.

Simard, R.R., D. Cluis, G. Gangbazo, and S. Beauchemin. 1995. Phosphorus status of forest and agricultural soils from a watershed of high animal density. J. Environ. Qual., 24: 1010-1017.

Shan, Y.H., L.Z. Yang, T.M. Yan, and J.G. Wang. 2005. Downward movement of phosphorus in paddy soil installed in large scale monolith lysimeters. Agric. Ecosyst. Environ. 111: 270-278.

Tunney, H., A. Breeuwsma, P.J.A. Withers, and P.A.I. Ehlert. 1997. Phosphorus fertilizer strategies: present and future. In: H. Tunney, O.T. Carton, P.C. Brook and A.E. Johnston (Eds), Phosphorus Loss from Soil to

Water. CAB International Press, Cambridge, UK, pp. 177-203.

Turner, B.L and P.M. Haygarth. 1998. Phosphorus in leachate from grassland soils. In: R.H. Foy and R. Dils (Eds). Practical and innovative measures for the control of agricultural phosphorus losses to water. An OECD Sponsored workshop, pp. 152-153.

Wakatsuki, T., Y. Shinmura, E. Otoo and G.O. Olaniyan. 1998. African-based sawah system for the Integrated Watershed Management of the Small Inland Valleys of West Africa. FAO, Water Report, No. 17: 56-79.

Yoshiike, A. 1983. The status of fertilized phosphate accumulation in agricultural land soil. Jpn. J. Soil Sci. Plant Nutr. 54: 255-261 (in Japanese with English summary).

Zhang, H.C., Z.H. Cao, Q.R. Shen and M.H. Wong. 2003. Effect of phosphate fertilizer application on phosphorus (P) losses from paddy soils in Taihu Lake Region: I. Effect of phosphate fertilizer rate on P losses from paddy soils. Chemosphere 50: 695-701.