THESIS APPROVAL

GRADUATE SCHOOL, KASETSART UNIVERSITY

Doctor of Philosophy (Soil Science)
DEGREE

Soil Science	Soil Science
FIELD	**DEPARTMENT**

TITLE: Available Phosphorus (Bicarbonate P) in Acid Soil Amended with Phosphate Rocks

NAME: Miss Chanida Charanworapan

THIS THESIS HAS BEEN ACCEPTED BY

THESIS ADVISOR
(Associate Professor Anchalee Suddhiprakarn, Ph.D.)

THESIS CO-ADVISOR
(Professor Irb Kheoruenromne, Ph.D.)

THESIS CO-ADVISOR
(Professor Robert J. Gilkes, Ph.D.)

THESIS CO-ADVISOR
(Miss Wanpen Wiriyakitnateekul, Ph.D.)

DEPARTMENT HEAD
(Assistant Professor Somchai Anusontpornperm, Ph.D.)

APPROVED BY THE GRADUATE SCHOOL ON

DEAN
(Associate Professor Gunjana Theeragool, D.Agr.)

THESIS

AVAILABLE PHOSPHORUS (BICARBONATE P) IN ACID SOIL AMENDED WITH PHOSPHATE ROCKS

CHANIDA CHARANWORAPAN

A Thesis Submitted in Partial Fulfillment of
the Requirements for the Degree of
Doctor of Philosophy (Soil Science)
Graduate School, Kasetsart University
2013

Chanida Charanworapan 2013: Available Phosphorus (Bicarbonate P) in Acid Soil Amended with Phosphate Rocks. Doctor of Philosophy (Soil Science), Major Field: Soil Science, Department of Soil Science. Thesis Advisor: Associate Professor Anchalee Suddhiprakarn, Ph.D. 194 pages.

Thailand has extensive areas of acid soils, Ultisols and Oxisols. They occupy approximately 44% of the total country area. A major problem of these soils is phosphorus deficiency which constrains plant growth and productivity. For remediating the phosphorus deficiency in soils, phosphate rock (PR), an alternative mineral fertilizer, is commonly used. The soil incubation technique was applied to investigate the influence of soil properties on PR dissolution and to determine the suitability of PRs for agronomic use. This study has three major parts: 1) mineralogical and chemical properties of PRs, 2) mineralogical, physical, and chemical properties of acid soils that influence phosphorus sorption, and 3) influence of soil properties on the available phosphorus of soil incubated with PRs with different phosphate minerals, and mono-calciumphosphate (MCP) (water soluble P fertilizer). Eighteen acid soils and three Thai phosphate rocks together with the reference North Carolina phosphate rock (NCR-PR) and MCP were employed in this study.

The soils were very strongly acid (pH 3.5 to 5.8) and having quite high exchangeable acidity. They had low available P (< 20 mg P kg^{-1} extracted by Bray II solution), and low exchangeable Ca (≤ 3 cmol kg^{-1}). There were two levels of phosphorus sorption maximum in these soils of which the first one was high ranging from 217 to 385 µg g^{-1} and the second was low ranging from 4 to 164 µg g^{-1}, depending on the amounts of clay and oxides of Fe and Al that they contained. All soils had kaolinite as the dominant mineral of their clay fraction. Other minerals found in some soils influencing P sorption were illite, hematite, goethite, and gibbsite. Most soils were found suitable for applying PRs.

Three Thai PRs have different phosphate minerals. Ratchaburi PR (Rat-PR) contains hydroxyapatite, Kanchanaburi PR (Kan-PR) contains hydroxyapatite and crandallite, and Roi-Et PR (Roi-PR) contains variscite and crandallite, while the reference NCR-PR contains francolite. The types of phosphate minerals were verified by X-rays diffraction and scanning electron microscope techniques, which the results showed that francolite in NCR-PR was close to the ideal apatite with an a-value of 9.336 Å, hydroxyapatite in Rat-PR and Kan-PR was close to ideal hydroxyapatite with the a-values of 9.428 and 9.406 Å, respectively. The dissolution kinetics of PRs in 2% formic acid (2%FA), 2% citric acid (2%CA), neutral ammonium citrate (NAC), and DI-water were determined. The dissolution rates of phosphate from PRs in 2%FA, 2%CA, NAC, and DI-water were NCR-PR > Rat-PR > Kan-PR > Roi-PR. Roi-PR was very poorly soluble and unsuitable for direct application.

Bicarbonate extractable P from incubated soil/ PR mixtures (ΔP_{BC}) is an indicator of PR dissolution. The results clearly showed that all PRs and MCP treatments provided the highest amounts of available P at 14 days of soil incubation. The highest ΔP_{BC} was for NCR-PR followed by Rat-PR, Kan-PR, and Roi-PR. The main factor affecting the increases of available P was the type of phosphate mineral in PR. The influence of soil properties on available P was complex and could not be predicted using only a single soil property. Many properties of soils affected PR dissolution and the availability of released P including the ability of soils to provide hydrogen ions, the capacity of soils to adsorb P, and the initial amount of available P in original soils. In addition, NCR-PR and Rat-PR increased the available P level at the end of 112 days soil incubation, and therefore, suitable for long term application.

Student's signature Thesis Advisor's signature ___ / ___ / ___

ACKNOWLEDGMENTS

I would like to express my deep and sincere gratitude to my supervisor, Associate Professor Anchalee Suddhiprakarn, for providing an opportunity to study under her supervision. Her constant support, warm encouragement and guidance were useful and valuable for this work.

I am sincerely grateful to Professor Irb Kheoruenromne for his advice and valuable criticism for this work. His detailed and constructive comments are very important for supporting throughout this entire work.

I would like to sincerely thank to Emeritus Professor Bob Gilkes, School of Earth and Environment, University of Western Australia for his kind encouragement, enormously suggestion, and excellent guidance for laboratory analyses.

I greatly acknowledge Centre of Microscopy, Characterization and Analysis (CMCA), University of Western Australia for providing SEM-EDS instruments. I would like to thank Dr. Janet Muhling for her assistance to identify the type of phosphate mineral in phosphate rock samples. And also thanks to Mr. Michael Smirk from University of Western Australia for assisting with the laboratory analyses.

For the officials from Office of Science for Land Development, Land Development Department, I would like to sincerely thank to Dr. Wanpen Wiriyakitnateekul, for her sincerely guidance and encouragement during my study, and Dr. Siwaporn Siltecho for her assistance in soil physical analysis and her fellowship, and also thank to my colleagues for their facilitation in laboratory analysis. I would like to thanks to the stuff at Department of Soil Science, Kasetsart University for their help.

The Center for Advanced Studied for Agricultural and Food, Institute for Advanced Studies, Kasetsart University under the Higher Education Research Promotion and National Research University Project of Thailand; Capacity Building of Kasetsart University Students on Internationalization Program; and also the Kasetsart University Research and Development Institute (KURDI) are grateful for financial support in this research.

Above all, I am very grateful to my dearest sisters, my brother and all members of my family for everything of their supports, encouragement and help during my study.

Chanida Charanworapan

March 2013

TABLE OF CONTENTS

Page

TABLE OF CONTENTS i

LIST OF TABLES ii

LIST OF FIGURES vii

INTRODUCTION 1

OBJECTIVES 3

LITERATURE REVIEW 4

MATERIALS AND METHODS 18

- Materials 18
- Methods 21

RESULTS AND DISCUSSION 31

CONCLUSIONS AND RECOMMENDATION 122

- Conclusions 122
- Recommendation 123

LITERATURE CITED 124

APPENDICES 147

- Appendix A Table 148
- Appendix B Figure 192

CURRICULUM VITAE 194

LIST OF TABLES

Table		Page
1	Proposed classification of PR for direct application by solubility and expected initial response	11
2	Solubility data for selected phosphate rock samples	12
3	Total P_2O_5, NAC-soluble P_2O_5, and CO_3:PO_4 ratio of apatite in various phosphate rocks	13
4	Current legislation of phosphate rock for direct application	15
5	Phosphate rocks (PRs) deposited in Thailand	16
6	Characteristics of phosphate rock samples	20
7	Physical properties of soils	32
8	Chemical properties of soils	34
9	Correlation matrix (r) for soil properties	35
10	The amounts of phosphorus sorption and extractable Fe, Al, and Mn	40
11	Mineralogy of the clay fraction of soils	46
12	Mineralogy of the silt fraction of soils	47
13	Mineralogy of the sand fraction of soils	48
14	The unit-cell dimensions of apatite, crandallite, and variscite in phosphate rock samples and literature values	52
15	The total element composition of phosphate rock samples	57
16	The percentage calcium carbonate equivalence (%CCE) and the percentage solubility of P in phosphate rock samples in standard AOAC extractants	60
17	The slope of the linear regression line and coefficient of determination (r^2) of the linear relationships between ΔP_{BC} and incubation time for 0 to 14 days	67
18	Bic-P, ΔP_{BC}, the percentage increase in Bic-P and available P_{BC} level at 14 days of soil incubation	69

LIST OF TABLES (Continued)

Table **Page**

19 Bic-P, ΔP_{BC}, the percentage increase in Bic-P and available P_{BC} level at 112 days of soil incubation 88

20 The changed pH_{H_2O} at 14 and 112 days of incubation, and the ΔpH_{H_2O} at 112 days relative to 0 day 100

21 The changed pH_{CaCl_2} at 14 and 112 days of incubation, and the ΔpH_{CaCl_2} at 112 days relative to 0 day 105

22 The changed EC at 14 and 112 days of incubation, and the ΔEC at 112 days relative to 0 day 110

23 Correlation coefficient (r) of log transformed data of ΔP_{BC} and soil properties at 14 days of soil incubation significant at $P < 0.05$ (n=18) 114

Appendix Table

A1 The variation of changed P_{BC} for Nb-soil incubated with PR and MCP treatments from 0 to 112 days by Duncan's multiple range test 149

A2 The variation of changed P_{BC} for Ak-soil incubated with PR and MCP treatments from 0 to 112 days by Duncan's multiple range test 150

A3 The variation of changed P_{BC} for Kc-soil incubated with PR and MCP treatments from 0 to 112 days by Duncan's multiple range test 151

A4 The variation of changed P_{BC} for Klt-soil incubated with PR and MCP treatments from 0 to 112 days by Duncan's multiple range test 152

A5 The variation of changed P_{BC} for Nat-soil incubated with PR and MCP treatments from 0 to 112 days by Duncan's multiple range test 153

A6 The variation of changed P_{BC} for Tg-soil incubated with PR and MCP treatments from 0 to 112 days by Duncan's multiple range test 154

LIST OF TABLES (Continued)

Appendix Table **Page**

A7 The variation of changed P_{BC} for Hp-soil incubated with PR and MCP treatments from 0 to 112 days by Duncan's multiple range test 155

A8 The variation of changed P_{BC} for Koi-soil incubated with PR and MCP treatments from 0 to 112 days by Duncan's multiple range test 156

A9 The variation of changed P_{BC} for Knk-soil incubated with PR and MCP treatments from 0 to 112 days by Duncan's multiple range test 157

A10 The variation of changed pH_{H_2O} for Nb-soil incubated at 0 to 112 days by Duncan's multiple range test 158

A11 The variation of changed pH_{H_2O} for Ak-soil incubated at 0 to 112 days by Duncan's multiple range test 159

A12 The variation of changed pH_{H_2O} for Kc-soil incubated at 0 to 112 days by Duncan's multiple range test 160

A13 The variation of changed pH_{H_2O} for Klt-soil incubated at 0 to 112 days by Duncan's multiple range test 161

A14 The variation of changed pH_{H_2O} for Nat-soil incubated at 0 to 112 days by Duncan's multiple range test 162

A15 The variation of changed pH_{H_2O} for Tg-soil incubated at 0 to 112 days by Duncan's multiple range test 163

A16 The variation of changed pH_{H_2O} for Hp-soil incubated at 0 to 112 days by Duncan's multiple range test 164

A17 The variation of changed pH_{H_2O} for Koi-soil incubated at 0 to 112 days by Duncan's multiple range test 165

A18 The variation of changed pH_{H_2O} for Knk-soil incubated at 0 to 112 days by Duncan's multiple range test 166

A19 The variation of changed pH_{CaCl_2} for Nb-soil incubated at 0 to 112 days by Duncan's multiple range test 167

LIST OF TABLES (Continued)

Appendix Table **Page**

A20 The variation of changed pH_{CaCl_2} for Ak-soil incubated at 0 to 112 days by Duncan's multiple range test 168

A21 The variation of changed pH_{CaCl_2} for Kc-soil incubated at 0 to 112 days by Duncan's multiple range test 169

A22 The variation of changed pH_{CaCl_2} for Klt-soil incubated at 0 to 112 days by Duncan's multiple range test 170

A23 The variation of changed pH_{CaCl_2} for Nat-soil incubated at 0 to 112 days by Duncan's multiple range test 171

A24 The variation of changed pH_{CaCl_2} for Tg-soil incubated at 0 to 112 days by Duncan's multiple range test 172

A25 The variation of changed pH_{CaCl_2} for Hp-soil incubated at 0 to 112 days by Duncan's multiple range test 173

A26 The variation of changed pH_{CaCl_2} for Koi-soil incubated at 0 to 112 days by Duncan's multiple range test 174

A27 The variation of changed pH_{CaCl_2} for Knk-soil incubated at 0 to 112 days by Duncan's multiple range test 175

A28 The variation of changed EC for Nb-soil incubated at 0 to 112 days by Duncan's multiple range test 176

A29 The variation of changed EC for Ak-soil incubated at 0 to 112 days by Duncan's multiple range test 177

A30 The variation of changed EC for Kc-soil incubated at 0 to 112 days by Duncan's multiple range test 178

A31 The variation of changed EC for Klt-soil incubated at 0 to 112 days by Duncan's multiple range test 179

A32 The variation of changed EC for Nat-soil incubated at 0 to 112 days by Duncan's multiple range test 180

A33 The variation of changed EC for Tg-soil incubated at 0 to 112 days by Duncan's multiple range test 181

LIST OF TABLES (Continued)

Appendix Table **Page**

A34 The variation of changed EC for Hp-soil incubated at 0 to 112 days by Duncan’s multiple range test 182

A35 The variation of changed EC for Koi-soil incubated at 0 to 112 days by Duncan’s multiple range test 183

A36 The variation of changed EC for Knk-soil incubated at 0 to 112 days by Duncan’s multiple range test 184

A37 The stepwise equations relating soil properties to ΔP_{BC} for soil incubation for 14 days 185

A38 Soil pH (soil : water = 1:1) classes 190

A39 Available phosphorus (Bray II) classes 190

A40 Cation exchange capacity (CEC) classes 190

A41 Extractable acidity (EA) classes 191

LIST OF FIGURES

Figure **Page**

1 Location of soil and phosphate rock sampling sites 19

2 Plots of C/S versus C for all soils. Phosphorus sorption maximum (Smax) of soils studied 39

3 Plots sorbed P (S, µg g^{-1}) versus Log C (log transformed data of final P conc., µg mL^{-1}), current phosphorus buffer capacity (PBCc) derived from the slope (m) of the linear equation of $S = a + m\log_{10}C$ 41

4 The correlation of determination (r^2) between P sorption isotherm and P desorption isotherm of all soils studied 43

5 XRD of powdered phosphate rock samples 50

6 BSE and element maps for NCR-PR (a) and a ternary graph for major elements based on point analyses (b) 51

7 BSE and element maps for Rat-PR (a) and ternary graphs for major elements (b and c) indicating that microcrystalline apatite is often included within various minerals 54

8 BSE and element maps for Kan-PR (a) and a ternary graph for major elements obtained by point analyses (b) 55

9 BSE and element maps for Roi-PR in (a) and (b) and ternary graphs for major elements corresponding to the point analyses in (c) and (d) 56

10 The kinetics of dissolution of NCR-, Rat-, Kan-, and Roi-PR in chemical extractants (A = 2%FA, B = 2%CA, C = NAC, D = AAC) plotted as log % of total-P Al and Ca dissolved versus log time 61

11 The kinetics of dissolution of NCR-, Rat-, Kan-, and Roi-PR in chemical extractants (A = 2%FA, B = 2%CA, C = NAC, D = AAC) plotted as % of total Al/total P dissolved versus log time illustrating the noncongruent dissolution of these phosphate rocks 62

LIST OF FIGURES (Continued)

Figure **Page**

12 Plots of ΔP_{BC} versus time for Nb-soil incubated with NCR-PR (A), Rat-PR (B), Kan-PR (C), Roi-PR (D), and MCP (E) for 0 to 14 days and 14 to 112 days 66

13 Plots of ΔP_{BC} versus time for Ak-soil incubated with NCR-PR (A), Rat-PR (B), Kan-PR (C), Roi-PR (D), and MCP (E) for 0 to 14 days and 14 to 112 days 72

14 Plots of ΔP_{BC} versus time for Kc-soil incubated with NCR-PR (A), Rat-PR (B), Kan-PR (C), Roi-PR (D), and MCP (E) for 0 to 14 days and 14 to 112 days 74

15 Plots of ΔP_{BC} versus time for Klt-soil incubated with NCR-PR (A), Rat-PR (B), Kan-PR (C), Roi-PR (D), and MCP (E) for 0 to 14 days and 14 to 112 days 76

16 Plots of ΔP_{BC} versus time for Nat-soil incubated with NCR-PR (A), Rat-PR (B), Kan-PR (C), Roi-PR (D), and MCP (E) for 0 to 14 days and 14 to 112 days 78

17 Plots of ΔP_{BC} versus time for Tg-soil incubated with NCR-PR (A), Rat-PR (B), Kan-PR (C), Roi-PR (D), and MCP (E) for 0 to 14 days and 14 to 112 days 79

18 Plots of ΔP_{BC} versus time for Hp-soil incubated with NCR-PR (A), Rat-PR (B), Kan-PR (C), Roi-PR (D), and MCP (E) for 0 to 14 days and 14 to 112 days 81

19 Plots of ΔP_{BC} versus time for Koi-soil incubated with NCR-PR (A), Rat-PR (B), Kan-PR (C), Roi-PR (D), and MCP (E) for 0 to 14 days and 14 to 112 days 83

20 Plots of ΔP_{BC} versus time for Knk-soil incubated with NCR-PR (A), Rat-PR (B), Kan-PR (C), Roi-PR (D), and MCP (E) for 0 to 14 days and 14 to 112 days 85

21 Relationships between pH_{CaCl_2} and pH_{H_2O} for soils incubated with PRs and MCP from 0 to 112 days 109

Appendix Figure

B1 Isotherm for P sorption of all soils studied 193

AVAILABLE PHOSPHORUS (BICARBONATE P) IN ACID SOIL AMENDED WITH PHOSPHATE ROCKS

INTRODUCTION

Thailand has extensive areas of acid soils, Ultisols and Oxisols. Ultisols are the most extensive soils which typically quite acidic. They occupy the area approximately 44% of the country (Moncharoen *et al*., 1987). Both Ultisols and Oxisols exhibit phosphorus deficiency which is a major limiting for plant growth. The problem of phosphorus deficiency is caused by both low available P level and high P fixation capacity (Ponnamperuma, 1977). Unavailable P can occur in the form of P sorbed by kaolinite and Al- and Fe-oxides and hydroxides. Conversion of available adsorbed forms to unavailable forms occurs through multidentate bonding of phosphate ions on the surface of Al- and Fe-hydroxides together with kaolinite (Hingston *et al*., 1974; Bachik and Baert, 1981; Smeck, 1985).

Phosphate rocks (PRs) are an alternative mineral fertilizers and have been used extensively for perennial crops in Asia, especially for rubber and oil palm in Malaysia and Thailand (Chien and Menon, 1995). PRs possibly support appropriate levels available P for long-term crops (Rajan *et al*., 1994) and may be more efficient than soluble fertilizers in term of plant recovery of applied phosphate (Yeates and Clarke, 1993). The PRs are suitable for applying to the highly weathered soils in the humid tropics and they increase in effectiveness in these soils (Sale and Mokwunye, 1993). The agronomic effectiveness of PR depends on the properties of both PR and soil, and also on the crop species (FAO, 2004; Chien *et al*., 2009). The mineral composition and particle size of PR affect its dissolution. Chien and Black (1976) proposed that the apatite in PR varies greatly in solubility in soil. Hughes and Gilkes (1986) and Syers *et al*. (1986) proposed that the main factor affecting solubility of PRs is the type of phosphate mineral viz francolite (e.g. North Carolina phosphate rock, NCR-PR) is considered to be a high reactivity PR. Hoare (1980), Stumm and Morgan (1996), and Francisco *et al*. (2008) showed that crandallite and variscite have low reactivity in soils and consequently they are unsuitable for agronomic use. McClellan and Gremillion (1980) categorized PRs into three groups: apatite group minerals (Ca-P minerals), crandallite and millisite (Ca-Fe-Al-P minerals), and variscite, wavellite and strengite (Fe-Al-P minerals), which differ greatly in their solubility in reagents and soils.

The soil properties which generally are conducive to PR dissolution include the ability of soil to provide sufficiently hydrogen ions (measured as soil pH, soil pH buffering capacity, and titratable acidity) (Hughes and Gilkes, 1986; Babare *et al*., 1997), capacity of soil for P adsorption (Chien *et al*., 1980; Babare *et al*., 1997), and soil moisture content (Bolland, 1994). For determining the extent of PR dissolution in soil, Kanabo and Gilkes (1988) suggested that the measurement of delta exchangeable Ca of soil incubated with PR is a direct method of measuring the dissolution of calcium phosphates and measurement of the bicarbonate extractable P (P_{BC}) of soil incubated with PR is an indicator of the increase in available P due to PR dissolution.

There is no adequate information about the effectiveness of Thai phosphate rock in acid soils and effectiveness is likely to vary considerably considering the different phosphate mineral types in Thai PRs. Therefore, a study of PR properties as well as soil properties is necessary. The details of PR properties such as their mineralogy and dissolution in reagents and soils in the short and long term will indicate their suitability for use in agriculture. The increase in available phosphate for soil incubated with PRs will show the influence of soil properties on PR dissolution and retention of dissolved P by soil constituents. In this study, the three Thai PRs studied are bat guano from Ratchaburi (Rat-PR) and Kanchanaburi (Kan-PR), and phosphatic sandstone from Roi-Et (Roi-PR). A reference North Carolina Phosphate Rock (NCR-PR) and reagent grade monocalcium phosphate are included in the research.

OBJECTIVES

1. To investigate the mineralogical and chemical properties of phosphate rocks especially their solubility in various chemical extractants and compare their short-term and long-term dissolution to establish their potential as direct application fertilizers

2. To investigate the mineralogical physical and chemical properties of some Thai acid soils that may be suitable for fertilizing with PR.

3. To evaluate the influence of soil and PR properties on the extractable phosphate in soils incubated with phosphate rocks.

Hypothesis

Phosphate Rocks (PRs) are an alternative mineral fertilizer for P-deficient acid soils. The appropriate use of PRs in agriculture must consider the type of phosphate minerals in PRs, the dissolution of PRs in acid soils and associated changes in available P.

LITERATURE REVIEW

1. Acid Soils

Acid soils occupy over 50% of the area in the Tropics. Most of them are Ultisols and Oxisols. In Southeast Asia, acidic upland soils, Ultisols and Oxisols, occupy at least 38% of the land area (FAO-UNESCO, 1979; IBSRAM, 1985). In Thailand, acid soils are also extensive especially Ultisols which are quite extensive. They occupy the areas approximately 44% of the total area or approximately 228,089 square kilometers. They are acidic (pH 5.5 and lower in general), highly leached and well-developed soils. Oxisols occur in the lower part of the Northeast Plateau and in the Southeast Coast region. Their extent is rather limited in Thailand as they occupy approximately 0.26% of total land area (Moncharoen *et al*., 1987).

Ultisols are often more acid than Oxisols and usually contain appreciable amounts of silicate clay minerals (mainly kaolinite). In general, Ultisols have ECEC values higher than Oxisols but they also exhibit considerable variable charge (Sumner and Noble, 2003). Wada *et al*. (1990) found that the low effective CEC of the Thai Ultisols was due primarily to the low constant negative charge, which can be related to clay mineralogy, soil texture or both. These soils contained fine-grained kaolin as the major clay mineral species, and some were very low in clay. In the B horizons, clay CEC was 5.7 ± 2.2 cmol kg^{-1}. The higher constant charge of 10.8 ± 7.4 cmol kg^{-1} of clay in the A horizons may indicate the contribution of humus.

Oxisols are the most intensely weathered soils but not necessarily the most acidic soils because in the final stages of weathering, soil pH increases due to the high point of zero charge (>pH 7) of Fe and Al oxides. They have very low basic cation status, very low effective cation exchange capacity (ECEC), and low available phosphorus, but usually have good physical properties (Sumner and Noble, 2003). Von Uexküll and Bosshart (1989) reported that Oxisols were poor in nutrients, especially Ca, Mg, K and P. Phosphorus fixation was generally more severe in

Oxisols than in Ultisols. The CEC was less than 16 cmol kg^{-1} of clay, of which normally less than 10 cmol kg^{-1} soil may be due to the low permanent charge.

2. Phosphorus Deficiency in Acid Soils

There are many interacting factors that contribute to nutritional limitations in tropical acid soils. One of the most important factors is phosphorus deficiency or low availability of phosphorus (Sanchez, 1976; Foy, 1984; Lopes *et al*., 1985; Owusu-Bennoah *et al*., 2002). Chairatna *et al*. (1986) screened 14 acid soils from southern Thailand and found that all of them were P deficient. This result is similar to the conclusion of Lopes *et al*. (1985) that showed over 90% of the acid soils of tropical America had the problem of phosphorus deficiency.

Phosphorus deficiency in tropical acid soils is due to phosphorus fixation and consequent immobility. Phosphorus fixation is often high in Oxisols and Ultisols because they are most likely to have P-fixing clay and sesquioxide minerals (amorphous and crystalline hydrous oxides of Fe and Al), and low pH, all of which are conductive to P fixation (Fox *et al*., 1971; Fox, 1988). According to Wada *et al*. (1990), Ultisols and Oxisols which achieved an Olsen's soil test P value of 10 mg kg^{-1} (0-15 cm depth) required only about 40 kg P ha^{-1} for the Ultisols but more than 260 kg P ha^{-1} (more than six times as much) for the Oxisols. Therefore, Oxisols had more P-fixation than Ultisols. Ultisols are normally deficient in phosphorus due to the inherent low phosphorus and high phosphorus fixation therefore P from applied phosphorus is rapidly fixed into a highly insoluble form (Ponnamperuma, 1977). To increase crop production, these soils are fertilized with water soluble P fertilizers such as triple super phosphate, however, these fertilizers are expensive. Thus, the use of less expensive P fertilizers such as phosphate rocks may be a possible alternative practice.

Asomaning *et al*. (2006) reported that Ultisols of the semi-deciduous forest zone of Ghana needed phosphorus fertilizer. Instead of expensive superphosphate they used using Gafsa rock phosphate (GRP) and 50% partially acidulated phosphate rock (PAPR) as alternative P sources which were reactive enough to provide plant available P to satisfy the early P requirement for maize growth. Similarly, Hilman *et al*. (2006) reported that the local phosphate rock, which may be low grade and had 30-100 % of dissolution capacity, could be applied to Indonesian acid Ultisols and Oxisols (pH in water 4.1-5.7) instead of water soluble phosphate fertilizers, TSP and SP-36. This was because the chemical fertilizers in acid soils were inefficient and expensive due to available phosphorus being affected by phosphorus fixation.

3. Influence of Soil Properties on the Agronomic Effectiveness of Phosphate Rock

Many researchers have identified important soil properties influence to the agronomic effectiveness of phosphate rocks (PRs). Hughes and Gilkes (1986), Wright *et al*. (1992) and Babare *et al*. (1997) proposed that the ability of soil to provide hydrogen ions (low soil pH, high pH buffering capacity, and high titratable acidity) stimulated PR dissolution. Khawawneh and Doll (1978) proposed that soil pH had the most influence on PR dissolution, when the pH decreased from 6.5 to 3.9 the dissolution of North Carolina PR (NCR-PR) increased from 29.3 to 83.5 %. On the other hand, when pH decreased from 6.5 to 3.9 the bicarbonate extractable P of PR fertilized soil decreased from 38 to 5 % (Bolan and Hedley, 1990).

Mackay and Syers (1986) proposed that soil with low concentrations of Ca and P in soil solution had a high capacity to dissolve PR which is compatible with the study of Khawawneh and Doll (1978) that showed that PR dissolution was depressed with a high Ca concentration in soil solution. Thus acid soils (Ultisols and Oxisols) which have a low CEC (< 10 cmol kg^{-1}), low soil pH (< 5.0), high contents of Fe- and Al-oxides, high exchangeable Al, high P sorption capacity were suitable for applying PR (Sanchez, 1976; Sale and Mokwunye, 1993).

Chien and Menon (1995) proposed that P sorption capacity was one of the most important soil factors which influenced PR effectiveness. PR release to plants consists of two important steps which are the initial dissolution of PR in soil and the subsequent availability of the dissolved P to plants (Gregg *et al.*, 1987). The initial dissolution of PR in soil increased with an increase in phosphate (P) sorption capacity of soil (Kanabo and Gilkes, 1987a), however, the subsequent availability of dissolved P to plants (the agronomic effectiveness) decreased with an increase in P sorption capacity (Harris, 1985).

The amount of P sorbed is influenced by solution P concentration. At high saturation of the sorption complex, the concentration of P maintained in solution is high. Sorption describes the removal of phosphate ions from solution by soil components (Barrow, 1990). Some soil components that affect P sorption processes are clay type and content, soil pH, organic matter (OM), calcium carbonate, and Fe and Al oxides (Brennan *et al*., 1994; Börling *et al*., 2001; Burt *et al*., 2002). Clay content is important for P sorption due to phosphate being sorbed by Al and/or Fe hydrous oxides on the surface of clay-size particles. The phosphate ion replaces O, water or OH surface ions to make a single bond of chemisorption which makes P less available (Reddy *et al.*, 1980; Mozzafari and Sims, 1994). Sample *et al.* (1980) found that hydrous Fe and Al oxides retained P through ligand exchange and precipitation reactions.

Wada *et al.* (1990) found that phosphate showed a strong affinity for Al and Fe. Phosphate was adsorbed by replacing H_2O and OH groups coordinated to Al and Fe atoms (ligand exchange). These Al(Fe)-H_2O and –OH groups were present as “broken bonds” on mineral surfaces or complexed with humus. Chemically adverse upland soils generally had great P sorption capacities, because their clay mineralogy was dominated by oxides and hydroxides of Fe and Al or allophane and imogolite, and because their humus was complexed with Al and Fe.

Agbenin (2003) proposed that phosphate sorbed was linearly related to Fe_d (r^2=0.71), Al_d (r^2=0.69) and Al_o (r^2=0.52). Dithionite-extractable Fe and Al (Fe_d and Al_d) and oxalate-extractable Al (Al_o) increased with soil depth, while oxalate-extractable Fe (Fe_o) decreased from the surface up to 20 cm depth, and thereafter remained constant with depth.

Many researchers have reported that the simple Langmuir equation can be used to calculate parameters that are indices of the capacity for and the intensity of P sorption by the soil (Nair *et al.*, 1984; Nair *et al.*, 1998; Sharpley *et al.*, 2008). The Langmuir sorption isotherm is plotted as equilibrium solution P concentration (C, mg P L^{-1}) against P sorbed (S, mg P kg $soil^{-1}$) and the linear Langmuir equation is shown as follow;

$$C/S = (1/bSmax) + (C/Smax)$$

This equation is used to calculate P sorption maximum (Smax, mg P kg $soil^{-1}$) and a constant relating the binding energy of P to soil (b, L mg P^{-1}).

Bolland *et al.* (2001) proposed that the influence of soil properties on PR dissolution was a consequence of complex interactions of PR with soil which could not be predicted by a single soil property. They suggested that soil moisture retention, P sorption capacity, the capacity of soil to retain Ca (estimated by CEC and % clay), and soil organic matter content affected PR dissolution. They developed a stepwise multiple linear regression for log transformed data to describe the dissolution of North Carolina PR which was:

$$\text{Log \% NCR-PR dissolution} = 1.23 - [0.010\ \text{pH (Ca)}] + [0.20\ \log \text{OC (\%)}] + [0.32\ \log \text{CEC (cmol kg}^{-1})]$$

($r^2 = 0.44$, $P = 0.039^*$, with pH (Ca) accounting for 94% of the variation)

Desorption is a reverse reaction of sorption and describes the release of sorbed P into solution. It is well established that P is not reversibly sorbed by soil components, that is, the sorption and desorption isotherms are not coincidental. The desorption isotherm is displaced to the left of the sorption isotherm; i.e., during the desorption phase, a lower solution P concentration is maintained for a given quantity of sorbed P (Syers and Ru-Kun, 1990). Desorbed P has been positively related to plant growth and P uptake (Raven and Hosmer, 1994).

Li *et al*. (2007) found that the P desorption showed linear or power relationship with P sorption by acidic purple soils. The P desorption was the most from sand fractions and the least from clay fractions, and P desorption rate was positively correlated with Al but not with Fe extracted by acidified ammonium oxalate. Therefore the Al-P was more active than Fe-P in P desorption. Moreover, this is supported by the lower binding energy of P with Al compounds than with Fe, yet the greater sorption capacity of Al (compared with that of Fe; Parfitt, 1989). The P desorption percentage was significantly correlated with soil test P and the degree of P saturation (r=0.78** and 0.82**), but negatively correlated with P sorption capacity (r=-0.66**) (Li *et al*., 2007).

4. Phosphate Rock

4.1 Characterization of Phosphate Rocks

Phosphate rock (PR) is an alternative P source for acid soils. Its chemical composition varies according to the source and mineralogy, PR that most suitable for direct application phosphate rock (DAPR) must have more than 5.9% P_2O_5 soluble in neutral ammonium citrate (Hammond and Leon, 1983). Chemical grade phosphate rock should contain at least 24% P_2O_5, less than 3% Fe_2O_3 and have a CaO to P_2O_5 ratio between 3.3:1 and 3.6:1 (Holmes *et al*., 1982).

The phosphate compounds in PR depend on the origin of the PR deposit and particularly its geological history. The mineral apatite generally has widely difference in chemical and crystallographic characteristics and physical properties. About 80 % of world PR production is derived from deposits of sedimentary marine origin, some 17% is derived from igneous rocks and their weathering derivatives, and the remainder comes from residual sedimentary and guano-type deposits (FAO, 2004).

Phosphate deposits can be classified into three types (Cook, 1984; Cook *et al.*, 1990). The most economically significant are marine sedimentary deposits of phosphorite which are typically argillaceous to sandy sediments containing stratified concentrations of calcium phosphate, mainly as apatite, and P_2O_5 may reach exceptional concentrations of 20 to 30% (54 to 80% apatite) (McConnell, 1938; Altschuler, 1973). Other deposit types are igneous rocks and ancient guano accumulations (Johns, 1962; Johns, 1976; Cook, 1984). Igneous deposits are formed in association with alkaline intrusive plutonic rocks such as carbonatites or in alkaline intrusive igneous complexes. These deposits usually contain varieties of fluorapatite, which are unreactive and least suitable for direct application (FAO, 2004). These PRs are may not be mined for their P but for a wide range of other economically important minerals and rare minor elements that occur in them (Cook *et al.*, 1990). Guano deposits are commonly cave deposits and insular deposits. Cave deposits are small P deposits, primarily formed through the accumulation of bat droppings. Insular deposits are more important than cave deposits but are also of small extent comprising 10-15% of total PR production for the Asia-Pacific region. They are of two types, on low coral islands as a result of the leaching of fresh guano from birds to form thin accumulations (usually cemented caps and crusts) and the high island deposits which show abundant evidence of post-depositional phosphatization of the underlying bedrock (usually coralline limestone) (Cook *et al.*, 1990).

4.2 Evaluation of Phosphate Rock for Direct Application

The methods for evaluating PRs for direct application use chemical extractants to provide an empirical solubility test. Conventional extraction methods include the use of the same organic acids that are found in the soil after microbial metabolism and organic matter decomposition, and in root exudates that assist roots to absorption phosphate (Amberger, 1978). The three solutions commonly used to measure the solubility (reactivity) of direct application phosphate rock (DAPR) are neutral ammonium citrate (NAC), 2% citric acid (CA) and 2% formic acid (FA) (Chien and Hammond, 1978; Hammond and Day, 1992; Gholizadeh *et al.*, 2009). The methods used to measure the solubility of PR relate to procedures used to analyze conventional water- and citrate-soluble phosphate fertilizers (Hammond *et al.*, 1986). Diamond (1979) proposed a threefold classification system (low, medium and high reactivity) according to NAC, 2% CA and 2% FA solubilities for classifying PRs for direct application (Table 1).

Table 1 Proposed classification of PR for direct application by solubility and expected initial response.

Rock potential	Solubility (%P_2O_5)		
	NAC	2% CA	2% FA
High	>5.4	>9.4	>13.0
Medium	3.2-4.5	6.7-8.4	7.0-10.8
Low	<2.7	<6.0	<5.8

NAC = neutral ammonium citrate, CA = citric acid, FA = formic acid
Source: Diamond (1979)

The chemical properties that influence the reactivity of PR are phosphate mineral(s) and the presence of accessory materials, especially calcium carbonate. Increasing the substitution of carbonate for phosphate in the crystal structure of apatite generally increases the reactivity of PR. This substitution results in decreasing the unit cell dimensions and also in weakening of apatite crystal structure (Chien and Hammond, 1978). The NAC solubility of francolites with a maximum known amount of CO_3 substitution ($CaO/P_2O_5 \cong 1.67$) is about 7% P_2O_5. This value decreases with decreasing CO_3 substitution to about 1-2% P_2O_5 for sedimentary francolites with very little CO_3 substitution ($CaO/P_2O_5 \cong 1.33$). PRs containing carbonate-apatite with low fluorine contents and OH-substitution may have solubilities in various extraction media as high as the most highly substituted francolites. NAC solubilities of igneous apatites are generally about 1-2% P_2O_5 or about the same as sedimentary francolites with little carbonate substitution (FAO, 2004). The solubility in NAC, 2%CA and 2%FA for some PRs listed in order of decreasing CO_3 substitution shown in Table 2.

Table 2 Solubility data for selected phosphate rock samples.

PR Sample	Type	Total P_2O_5 (%)	Apatite CO_3 subst. (%)	Solubility ($\%P_2O_5$)			
				NAC (%wt.)		2% CA	2% FA
				1st extract	2nd extract		
North Carolina (USA)	Sedimentary	29.8	6.4	7.1	6.6	15.8	25.7
Gafsa (Tunisia)	Sedimentary	29.2	5.8	6.6	6.8	11.9	18.6
Central Florida (USA)	Sedimentary	32.5	3.2	3.0	3.2	8.5	8.2
Tennessee (USA)	Sedimentary	30.0	1.6	2.5	2.7	8.7	6.9
Araxa (Brazil)	Igneous	37.1	0	1.7	1.7	3.5	3.9

Source: FAO (2004)

Rajan *et al*. (1996) reported that total P_2O_5 content of PR had no relationship with its chemical reactivity and agronomic effectiveness. As more CO_3 substitution for PO_4 in an apatite structure resulted in a lower total P_2O_5 content and higher chemical reactivity, a very high total P_2O_5 content suggested that the apatite in the PR had very low CO_3 substitution in the apatite structure and low chemical reactivity. FAO (2004) presented data on some PRs that varied widely in the CO_3:PO_4 ratio of apatite, total P_2O_5 content, and solubility in NAC solution. The solubility was related closely to the CO_3:PO_4 ratio of apatite but not to the total P_2O_5 content (Table 3).

In addition to the solubility test of PR by using chemical extractants, the additional simple procedure for measuring the kinetics of PR dissolution over time is also proposed. The advantage of this procedure is that it removes all the dissolved P and Ca, and no particles precipitate on the surface of grains preventing further PR dissolution. Plots of dissolution kinetics show that here are two steps in the dissolution process, the first is a zone of fast dissolution which can be related to the short-term efficiency and the second is a zone of slow dissolution which relates to long-term effect (Truong and Fayard, 1995). This conclusion is supported by the study of Gholizadeh *et al*. (2009) they also suggested that 2% FA extractant was preferable for the dissolution kinetic studies. This method is more time consuming than a single extraction; however, it provides more information on PR dissolution over time (FAO, 2004).

Table 3 Total P_2O_5, NAC-soluble P_2O_5, and CO_3:PO_4 ratio of apatite in various phosphate rocks.

PR source[1/]	CO_3:PO_4	Total P_2O_5 (% of rock)	NAC-P_2O_5[2/]
North Carolina, USA	0.26	30.0	7.6
Arad, Israel	0.20	32.4	7.1
El-Hassa, Jordan	0.16	31.3	5.8
Hahotoe, Togo	0.11	36.8	3.9
Idaho, USA	0.08	32.3	3.5
Kaiyang, China	0.05	17.6	3.4
Araxa, Brazil	<0.01	36.1	2.8
Dorowa, Zimbabwe	<0.01	33.1	1.9
Sukulu hills, Uganda	<0.01	41.0	1.6

Remark: [1/] Ground to minus 100-mesh (-0.15 mm) size

[2/] NAC, second extraction

Source: FAO (2004)

Truong and Fayard (1995) calculated the dissolution rate constant (r) of PR in solution using a parabolic rate law. They assumed that the dissolution was controlled by the surface area (A), the solute concentration next to the surface was equal to the bulk solution concentration, and the dissolution kinetics was zero-order. Thus the dissolution rate (r) is; $r = dC/dt = KA$

The dissolution rate (r) is proportional to the surface area (A) of the mineral. Thus, for a surface-controlled reaction the relationship between time and concentration (C) should be linear (Robarge, 1999) as

$$C = Co + kt$$

Where C is concentration of phosphate that varied with time (t), Co is a concentration constant of phosphate and k is designate constant to determine the change in concentration of phosphate with time.

The solubility of PR also depends on the particle size because it will increase with decreasing particle size (Chien and Friesen, 1992; Chien, 1993, 1995). Rajan *et al*. (1992) also reported that the increase in chemically extractable P with grinding of PRs related positively to the reactivity of the PRs. Grinding provides fresh particle surface, increases geometric surface area, and increases solubility level. The suitable particle size of PR is -100 mesh (149µm) which gives desirable dissolution and decreases the grinding cost (FAO, 2004).

The direct application of PRs in many countries is controlled using legislation. This legislation provides guidelines for quality control of direct application phosphate rock (DAPR). Most legislation includes three main specifications: total P_2O_5 content of PR, chemical properties (solubility), and physical properties (particle size), that are shown in Table 4.

4.3 Phosphate Rock in Thailand

Sheldon (1984) reported that there are many occurencies of guano-derived phosphate rock in Thailand such as Mae Tha (36% P_2O_5) and Ban Mae Pa Phai (35% P_2O_5) in Lam Phun, Sap Sombun (20-25% P_2O_5) and Khao Cha-Ngok (20-25% P_2O_5) in Phetchabun, Khao Rang Kai (30% P_2O_5) in Chinat, Ban Na Kan (12-34% P_2O_5) in Khanchanaburi, and Khao Phak Ma (20-34% P_2O_5) in Ratchaburi. Most deposits were less than 25,000 metric tons, but Mae Tha and Ban Na Kan deposits contained an estimated 50,000 and 100,000 metric tons of phosphate rock respectively. The major mineral in these Thai deposits was hydroxyapatite with minor fluorine. The Khao Rang Kai deposit, phosphate rock contained 73% apatite and 12% robertsite, a hydrous calcium manganese phosphate mineral (IFDC, 1983). Another type of phosphate rock that is found in Thailand is the aluminum phosphate mineral variscite at Ban Lao Kham, west of Roi-Et in the Khorat Plateau. Variscite is an extreme weathering product of phosphorite, the determined phosphate mineral was a ferroan variscite with a high refractive index. The P_2O_5 of the main phosphate rock varied between 18 and 27%, but some cores contained 6 to 14%.

Table 4 Current legislation of phosphate rock for direct application.

Country	Specifications of DAPR
The Council of the European Communities (EC)[1/]	1) Minimum 25% total P_2O_5 2) At least 55% of total P_2O_5 soluble in 2% formic acid 3) At least 90% through 0.063 mm (250 Tyler mesh) and 99% through 0.125 mm (115 Tyler mesh) in particle size distribution
Department of Standards of Malaysia[2/]	1) Minimum 28% total P_2O_5 2) At least 7.5% P_2O_5 (weight basis) soluble in 2% citric acid 3) At least 90% less than 0.500 mm (32 mesh) in particle size distribution
The Brazilian Ministry of Agriculture[3/]	1) Minimum 28% total P_2O_5 2) At least 9% P_2O_5 (weight basis) soluble in 2% citric acid 3) 100% less than 4 mesh (4.8 mm) and 80% less than 7 mesh (2.8 mm) with a tolerance of 15% for particles larger than 4.8 mm 4) Calcium content of 30-35%
The India Fertilizer (Control) Order[3/]	1) Minimum 18% total P_2O_5 2) 90% less than 100 mesh (0.15 mm) and the remaining 10% must be less than 60 mesh (0.25 mm) * There is no minimum solubility requirement of PR in legislation

Source : [1/] Office Journal of the European Communities (1976)

[2/] Malaysian Standard (1998)

[3/] FAO (2004)

Sapattavanija and Ratanajarurak (n.d.) reported on phosphate rocks (PRs) in the West, North, Northeast and the Southern parts of Thailand. The five important PRs deposited in Thailand are shown in Table 5. There are four types of phosphates in Thailand i.e. biogenic phosphate, sedimentary phosphate, Al containing phosphate and nodule phosphate.

Table 5 Phosphate Rocks (PRs) deposited in Thailand.

Province	Part of Thailand	Type of PR	Total P (%P)	Resources (1,000 tones)
Kanchanaburi	Western	Guano	5.6-14.8	100-150
Roi-et	Northeast	Al containing phosphate	7.8-11.8	74
Lamphoon	Northern	Guano	15.7	57
Phetchaboon	Central	Guano	8.7-15.2	27
Phatdalung	Southern	Guano	10.9-15.7	20

Source: Sapattavanija and Ratanajarurak (n.d.)

4.4 Determination of Phosphate Rocks and Phosphorus Fertilizer Rate

The concept of soil analysis in Thailand is to understand the fertility level of the soils and categorize them into low, medium or high. The fertilizer recommendation of Department of Agriculture (DOA) and Land Development Department (LDD) depend on soil fertility level and crop type. Soil fertility level identifies by the quantities of nitrogen, phosphorus, and potassium.

LDD has recommended the varying the rate of phosphate rock application for acid sulfate soils from 200 to 300 kg PR rai^{-1} (1250 to 1875 kg PR ha^{-1}) based on empirical results. For acid soils, it has recommended the suitable rate of PR is 400 kg PR rai^{-1} when the PR has 3% of P_2O_5. Yampracha (2006) predicted the direct application rate of Kanchanaburi PR (KPR), which was calculated from the P critical level determined using TSP, was 2,542 kg PR ha^{-1} (about 407 kg PR rai^{-1}) applied to some acid sulfate soil of Thailand. The rate assumes an average P solubility in phosphate rock of Thailand of approximately 1.31-1.74 %P of rock, which is extracted by neutral ammonium citrate. The properties of phosphate rock materials and extent of P deficiency in acid sulfate soils are, however, widely different. The decision on the rate of phosphate rock application needs to be based on soil P tests (Perrott and Wise, 2000), the rate of dissolution of phosphate rock, and its availability to plants (Sidibé-Diarra *et al.*, 2004).

The mono-calcium phosphate (MCP) rate used in the present research is based on fertilizer recommendations of DOA (2005) based on soil sample analysis and plant types. For perennial plants (para rubber), the analysis of soil samples (Bray II method) identified three categories of available phosphorus as low, medium, and high, for which the available phosphorus contents (Bray II) were <11, 11-30, and >30 mg P kg^{-1}, respectively. And the phosphorus recommendation rates were 8, 4, and 4 kg P_2O_5 rai^{-1} or 18, 9, and 9 kg MCP rai^{-1} respectively.

MATERIALS AND METHODS

This study consists of three experiments:

Experiment 1. Study of the physical, chemical, and mineralogical characteristics of acid soils for both of top-soil and sub-soil.

Experiment 2. Study of the chemical composition, dissolution kinetics, and mineralogical composition of phosphate rocks.

Experiment 3. Study of the increase of available phosphate of acid soils amended with phosphate rocks and monocalcium phosphate using an incubation method.

Materials

1. **Soil Samples Collection**

Eighteen soil profiles were investigated, the soils are Ultisols and Oxisols, top- (0-15cm) and sub-soil (15-100 cm) were collected. The soils are from high annual rainfall areas (> 1,500 mm), Southeast Coast of Thailand (Figure 1). They included one series formed on basalt (Nong Bon series, Nb), three series formed on shale/limestone (Ao Luk, Ak; Khlong Chak, Kc; and Khlong Teng, Klt), one series formed on sandstone (Nathawi, Nat), and four series formed on granite (Thung Wa, Tg; Huai Pong, Hp; Khok Kloi, Koi; and Khlong Nokkra Thung, Knk). Most of soil samples had low soil pH (< 5.5), low available P, low OC, and had wide range of clay content (6 to 77 % clay) (Sirichuaychoo *et al*., 2004). Most of them were planted to perennial plants (para rubber) that normally used phosphate rocks (PRs) as an alternative phosphorus fertilizer. Some profiles were from the natural grassland.

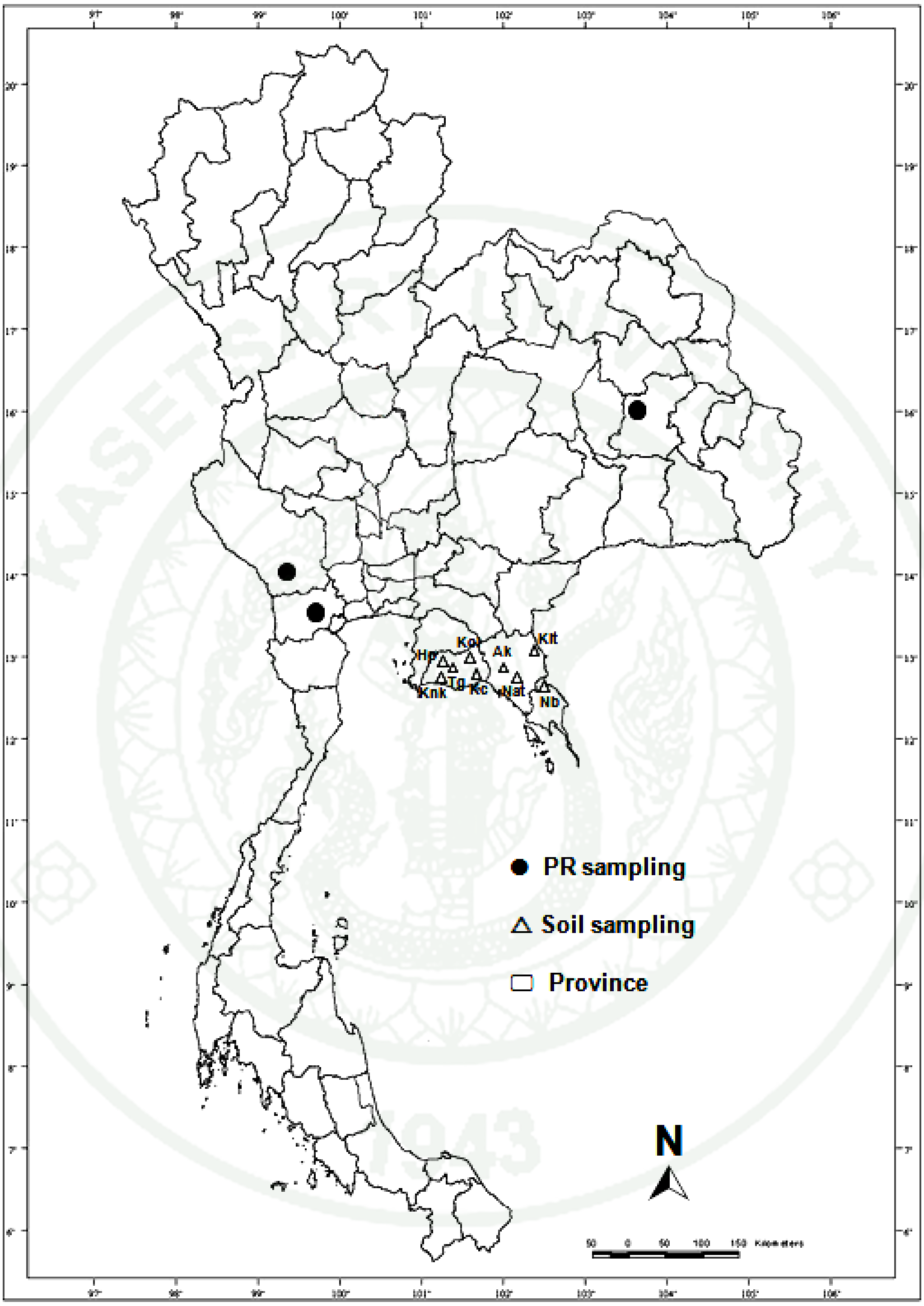


Figure 1 Locations of soil and phosphate rock sampling sites.
(Nb = Nong Bon; Ak = Ao Luk; Kc = Khlong Chak; Klt = Khlong Teng; Nat = Nathawi; Tg = Thung Wa; Hp = Huai Pong; Koi = Khok Kloi; Knk = Khlong Nokkra Thung)

2. Phosphorus Sources

Three Thai phosphate rocks (PRs) Rat-, Kan-, and Roi-PR were used in this study together with the references North Carolina Phosphate Rock (NCR-PR) and mono-calcium phosphate (MCP). Rat- and Kan-PR were collected from Khao Phak Ma, Ratchaburi province (23^{o} 32’N, 99^{o} 38’E), and Khao Noi, Kanchanaburi province (14^{o} 3’N, 99^{o} 15’E) in the west of Thailand (Figure 1). Roi-PR was collected from Ban Lao Kham, Roi-Et province (16^{o} 5’N, 103^{o} 32’E) in the northeast of Thailand. The PR samples differed in the phosphate minerals and the percentage of total P_2O_5. NCR-PR contained the highest total P_2O_5, Rat- and Kan-PR contained the equal amounts of total P_2O_5, and Roi-PR contained the lowest of total P_2O_5 (Table 6).

Table 6 Characteristics of phosphate rock samples.

Province	Resource	Gross weight (ton)	P_2O_5 (%)	Type
Ratchaburi[1/]	Khao Phak Ma	3,000	20-34	Apatite
Roi Et[2/]	Ban Lao Kham	74,000	18-27	Variscite
Kanchanaburi[3/]	Khao Noi	-	20-30	Crandallite
North Carolina[4/]	-	-	46	Francolite

Source: [1/] Japakasetre (1980)

[2/] Sheldon (1984)

[3/] New concession area under survey (Concession by Department of Primary Industries and Mines, Ministry of Industry, Thailand)

[4/] Hughes and Gilkes (1994)

Methods

1. Bulk Soil Samples

The acid soil samples were air-dried and ground to pass through a 2-mm sieve and used to analyze soils as follow:.

1.1 Particle Size Analysis by Pipette Method (Kilmer and Alexander, 1949; Day, 1965)

Particle size analysis determined the percentages of sand (0.5-0.02 mm), silt (0.02-0.002 mm) and clay (<2 μm). There were three main steps in this analysis: (a) pretreatment to remove organic carbon by adding hydrogen peroxide (b) dispersion of the soil by stirring and shaking using sodium hexametaphosphate as a dispersing agent and (c) fractionation into particle sizes by sedimentation and pipette sampling.

1.2 Soil Water Retention at Field Capacity (Klute and Dirksen, 1986)

Dried soil soil was put in a rubber ring with 5 cm diameter and 1 cm thickness and was saturated with tap water for 24 hours, soil water content at the field capacity (FC) was measured equilibrating soil moisture for 24 hours at 1/3 bar (33 kPa) on a ceramic plate. The percentage moisture content at field capacity was calculated as follow:

% moisture (by weight) = (weight of water) / (weight of dried soil at 105 ^{o}C)

1.3 Soil Reaction (pH)

Soil reaction (pH) was measured in deionized water (H_2O) by 1:1 soil:H_2O ratio and in 1M KCl (KCl) by 1:1 soil:KCl ratio (Natural Resources Conservation Service, 1996).

1.4 Organic Carbon (OC)

Organic carbon (OC) was determined by Walkley-Black Titration (Walkley and Black, 1934). This involved wet combustion of organic carbon with a mixture of potassium dichromate and sulphuric acid. After reaction the residual dichromate was titrated against ferrous sulphate.

1.5 Extractable Phosphorus by Bray II and Bicarbonate Extractants (P_{BII}, P_{BC})

For Bray II extractable P, the soil samples were extracted with Bray II solution (0.1M HCl in 0.03M NH_4F) by using 1:10 soil to solution ratio. The modified Bray II method was prepared in the same way as Bray I (Bray and Kurtz, 1945) that used the fluoride for enhancing P release from aluminum phosphates by decreasing Al activity in solution through the formation of various Al-F complexes. Extractable P in these extracts was determined by a colorimetric method (Ascorbic acid method; Murphy and Riley, 1962).

For bicarbonate extractable P, 1 g of soil was extracted with 0.5M $NaHCO_3$, pH 8.5, for 30 minutes at room temperature (Olsen *et al*., 1954). The phosphorus in the filtrate was analyzed by a colorimetric method (Ascorbic acid method; Murphy and Riley, 1962).

1.6 Phosphorus Sorption Maximum (Smax), the Constant Relating the Binding Energy (b), Current Phosphorus Buffer Capacity (PBCc), and Phosphorus Desorption Isotherm

One gram soil was extracted in 20 mL of 0.01M $CaCl_2$ containing standard P (7 to 10 P doses at intervals ranging from 0 to 1500 mg P kg^{-1} soil) and few drops of toluene (Nair *et al*., 1984; Graetz and Nair, 2000). The suspension was shaken for 24 h at 25±1 ^{o}C, and the soluble reactive P in the filtrate was analyzed by the flow injection analysis (FIA) (QuickChem® 8500 Series 2 FIA Lachat). The soluble reactive P (an equilibrium solution P concentration, C) was plotted as a curve against the P sorbed (S) to give a P-sorption isotherm. The linear Langmuir sorption isotherm of C/S against S was plotted and Smax (mg P kg^{-1} soil) and a constant relating the binding energy of P to soil (b, L mg^{-1} P) were calculated (Nair *et al.*, 1998). Moreover, the linear equation of S, which S is plotted against log C, is "$S = a + mLog_{10}C$". The slope (m) from this equation called a current PBC (PBCc) (Babare *et al.*, 1997). The PBCc was the ability of soil to sorb the freshly P added (beside a P already sorbed by soil) at a current P status (Holford, 1979; Babare *et al.*, 1997; Sale *et al.*, 1997).

The phosphorus desorption isotherm is analyzed after the supernatant removed. Each sample tube with the wet soil is weighed for finding the residual solution weight, and then the P entrapped in the residual solution is calculated.

Then 20 mL of 0.01M $CaCl_2$ with few drops of toluene is added to the tubes for extracting the desorped P. The same procedures used in the sorption were duplicated for the P desorption and also calculated the P desorption isotherm (Raven and Hossner, 1993; Li *et al.*, 2007).

1.7 Cation Exchange Capacity (CEC)

CEC of soil was determined by displacing exchangeable cations with a saturating salt solution and CEC was taken to be equivalent to the sum of exchangeable cations present in the leachate. In this study, the CEC determination followed the procedure of Chapman (1965). Ten gram of soil samples was saturated with 50 mL 1M NH_4OAc at pH 7 to remove exchangeable bases and allowed to equilibrate overnight. The filtrate was saved for analysis for Ca, Mg, Na and K (% Base saturation), and the soil was washed with 1M NH_4OAc, and 95% of ethyl alcohol. Then, the soil was washed with 10% NaCl for replacement of exchange NH_4^+ ions. The filtrate was distilled for entrapping NH_3 into 2% H_3BO_3 followed by titration with 0.01M HCl using bromocresol green-methyl red indicator. The volume of HCl was used for calculating the CEC as cmol kg^{-1}.

1.8 Effective Cation Exchange Capacity (ECEC)

Effective cation exchange capacity (ECEC) was calculated from the sum of basic ions (Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}) and acidic ions (Al^{3+} and H^{+}) which were extracted with 1M KCl and the extract titrated to pH 8.0 (Rayment and Higginson, 1992).

1.9 Exchangeable Acidity (EA)

Exchangeable acidity (EA) included all acidity generated by replacement of hydrogen and aluminum ions in soils from permanent and pH-dependent exchange sites. The soil samples were extracted with barium chloride-triethanolamine ($BaCl_2$-TEA) buffer solution at pH 8.2 (Thomas, 1982). The weight 5 g of soil samples was extracted by 15 mL of buffer $BaCl_2$-TEA solution at pH 8.2 (0.025M $BaCl_2 \cdot H_2O$ and 0.2M triethanolamine) and leaved 30 minutes for equilibrating. The filtrant was washed by the buffer solution and the replacing solution (0.25M $BaCl_2 \cdot H_2O$ and 0.4 mL of buffer solution in 1L). The mixed indicator of bromocresol green and methyl red in 95% ethyl alcohol was used. The filtrate was titrated against 0.2M HCl with the volume of titrated HCl being used to calculate the exchangeable acidity.

1.10 Exchangeable Al (Ex.Al)

Exchangeable Al was determined by extracting 10 g of soil with 15 mL of 1M KCl then left 30 minutes for equilibrating (Bertsch and Bloom, 1996). The filtrate developed color by addition of 2 mL of 1% thioglycolic acid and 10 mL of aluminon reagent, and exchangeable Al content was analyzed by UV-VIS spectrophotometer.

1.11 Dithionite-Citrate-Bicarbonate (DCB) Extractable Fe (Fe_d) , Al (Al_d), and Mn (Mn_d)

DCB analysis removes finely divided hematite, goethite, lepidocrocite, ferrihydrite and non-crystalline Fe-oxide minerals. The method extracts virtually no Fe or Al from most crystalline silicate minerals, and thus provides an estimated of “free oxide” (i.e. non-silicate Fe, Al, and Mn) in soils.

An accurately-weighed amount of 1.00 g of air-dried soil sample (< 0.5 mm) was added to 40 mL of 0.3M Na-citrate solution and 5 mL of 1M $NaHCO_3$ solution, and boiled at 75 - 80 ^{o}C in a water bath. One gram of Na-dithionite powder was added to the soil suspension. The soil suspension was stirred constantly for 2 minutes and occasionally during next 5 minutes. Addition of Na-dithionite was repeated 2 times. The soil suspension was centrifuged for 15 minutes at 2000 rpm. Clear supernatant was used for analyzing Fe, Al and Mn by atomic absorption spectrophotometer (AAS), standard solutions of these elements were prepared in a matrix of extracting solution (Mehra and Jackson, 1960).

1.12 Oxalate Extractable Fe (Fe_o), Al (Al_o) and Mn (Mn_o)

The oxalate procedure is used to estimate non-crystalline and poorly crystalline Fe and Al oxides in soils. In principle, the sample is shaken with a complex acidic ammonium oxalate solution and the active or poorly crystalline compounds of iron are dissolved and determined by AAS technique.

One gram of soil sample (< 0.5 mm) was added by 50 mL of 0.2M ammonium oxalate and shaken for 4 hours in darkness (McKeague and Day, 1966). Three drops of Superfloc were added while swirling the soil suspension constantly. The soil suspension was centrifuged and clear supernatant was analyzed for Fe, Al and Mn by AAS technique.

1.13 Mineralogical Analysis by X-ray Diffraction (XRD) for Clay, Silt, and Sand Fraction

X-ray diffraction analysis was used to identify the crystalline mineral components of clay fraction. The clay fraction from sedimentation was pretreated using 4 treatments (Brindley and Brown, 1980). The layers of clay fraction on ceramic plates were saturated with Mg^{2+}, Mg^{2+} and 10% glycerol, and were saturated with K^+, K^+ and 550 ^oC heated. The minerals were determined by using a Philips PW3719 diffractometer (CuKα, 50 kV, 20 mA) and scanned from 3 to 35^o 2θ at a step size of 0.02^o 2θ. Relative proportions of various minerals were calculated by comparing the XRD peak intensity with the intensity for standard minerals (Klug and Alexander, 1974; Brindley and Brown, 1980; Whittig and Allardice, 1986).

The mineralogical composition of silt and sand fractions was determined by random powder X-ray diffraction (XRD) (Brindley and Brown, 1980) using Philips PW3719 diffractometer (CuKα, 50 kV, 20 mA). The whole silt and sand samples were ground into very fine powder (< 10 μm) and scanned from 3 to 35^o 2θ at a step size of 0.02^o 2θ. Relative proportions of various minerals were calculated by comparing the XRD peak intensity with the intensity for standard minerals, and quartz reflection, normally presented in all samples, was an internal reference for reducing the peak shifts error (Klug and Alexander, 1974).

2. Phosphate Rock Samples

All phosphate rock (PR) samples were ground to 100 mesh (<149 μm) a size which gives desirable dissolution and decreased grinding cost (FAO, 2004).

2.1 Extractable Phosphorus by Deionized Water (H_2O), 2% Citric Acid (2% CA), 2% Formic Acid (2% FA), Neutral Ammonium Citrate (NAC), and Petermann Alkaline Ammonium Citrate (AAC).

The PR sample:solution ration was 1:100 and suspensions were shaken at room temperature for H_2O and 2% CA, and at 65 ^oC for NAC and AAC (AOAC, 1975). For NAC extraction, there were two times of sequential extraction for which the sequential second extraction was used to determine available P after removing the free carbonate interference in the first extraction (Chien, 1993; Smalberger *et al*., 2006). For 2% FA, the PR samples were extracted at a soil:solution ratio 1:100 and shaken at room temperature (Chien, 1993). After extraction all of filtrates were developed color by Vanadomolybdate method (Olsen and Sommers, 1982) and the extractable P was measured by the UV-VIS spectrophotometer technique.

2.2 The Dissolution Kinetics of Phosphate Rocks

To study the kinetics of long term dissolution of PR overtime, one gram of PR sample was put on a Whatman filter paper grade 42 and one drop/ second of all extractants (2%FA, 2%CA, NAC, and AAC) was dripped to pass through the PR samples. All extracted solution was kept for 20, 40, 60, 100, 140, 200, 260, 380, 500 and 620 minutes according to the procedure of Truong and Fayard (1995). This procedure removes all dissolved P and Ca from digests, so that there is no precipitation on PR surfaces which prevents PR dissolution. The extracted P for all extractants was analysed by the Vanadomolybdate method (Olsen and Sommers, 1982) using a UV-VIS spectrophotometry technique.

2.3 Calcium Carbonate Equivalent (CCE)

The calcium carbonate equivalence (CCE) of PR samples was determined by AOAC method 955.01 modified to an endpoint at pH 5 as suggested by Sikora (2002). One gram of PR sample was digested in 50 mL of 0.5N HCl, cooled, and back-titrated with 0.25N NaOH to pH 5.

2.4 Total Major Element Analysis

Total major element compositions of PR samples were determined on pelleted samples using a Philips PW1480 XRF spectrometer (Jones, 1987). Pelleted samples were produced with a boric acid back and edge designed to fit into Philips sample holders (PW 1480). A teaspoon of boric acid (fine powder of B.P. grade) was poured into the sample holder to encase the sample and element composition of sample was compared with certified reference materials.

2.5 Minor Elements Analysis

Minor elements were determined by inductively coupled plasma-optical emission spectrometry (ICP-OES) (Perkin Elmer Optima 5300DV) of aqua regia digests (0.25 g of very fine powder of whole PRs was digested in 2 mL conc. HNO_3 and 5 mL conc. HCl at 130 ^{o}C for 1 h). Supernatant was analyzed by ICP-OES together with a certified international reference material.

2.6 Mineral Composition of Phosphate Rocks

The mineralogical composition of PR was determined by powder X-ray diffraction (XRD) (Brindley and Brown, 1980; Środoń, 2006) using a Philips PW3719 diffractometer (CuKα, 50kV, 20mA). The whole rock samples were ground into very fine powder (<10 μm) and scanned from 3 to 70^{o} 2θ at a step size of 0.01^{o} 2θ. PDF files (International Center for Diffraction Data, 2011) were matched to XRD-patterns of PR samples to identify minerals. The unit-cell values of minerals were calculated using the XPowder program Ver.2010.01.20PRO (Díaz-Hernández *et al.*, 2011; Matin-Ramos, 2004).

2.7 Chemical Composition of Minerals in Phosphate Rocks

A scanning electron microscope coupled with electron dispersive X-ray spectrometry (SEM-EDS) was used to examine polished thin section with carbon coat of PR samples and determine the chemical composition of minerals in PRs. The JEOL6400 SEM with ISIS6400 EDS system was used to provide backscattered electron images (BSE) and element maps. Spot analyses of each material type were obtained to assist with the identification of minerals (van-Straaten, 2002).

3. Soil Incubation Study

NCR-, Rat-, Kan-, and Roi-PR, together with water soluble phosphate (mono-calcium phosphate; MCP) were thoroughly mixed with soil samples and incubated in a closed system from 0 day to 3, 7, 14, 28, 56 and 112 days. A few drops of toluene were added for inhibiting microorganism activity. First weight of soils for incubation was 250g per pot. At 0 day (after thoroughly mix soils and PRs), the 20g of air-dried soils were sampled for chemical analysis. Soils were incubated at field soil water capacity (FC). Water required for adjusting each dry soil to moist soil at FC was calculated. The 230 g of dry soils remaining was received the calculated amount of water. These moist soils were incubated in the humid condition close to the FC of each soil until the end of the experiment (112 days). Whole soil weight (weight of moist soil at FC and container) was recorded and 20 g of moist soil at FC was removed at every time of soil sampling (totally 7 times of sampling throughout the experiment). Soil moisture was checked every few day by weighing the whole soil and re-adjusting to the required weight to retain the soil at FC.

The rates of PRs (Rat-, Kan-, and Roi-PR) for incubation were based on the suggestion of Land Development Department (LDD); the lowest and the highest rates were 100 and 400 kg rai^{-1} (625 and 2,500 kg ha^{-1}) or 80 and 321 mg per 250 g soil. NCR-PR had 1.7 times more extractable P (2% CA) than Rat-PR (the representative Thai PR). The rates of NCR-PR were therefore less than for Thai PR for which the rates were 46 mg for low rate and 184 mg for high rate incubated with 250 g soil. The amounts of MCP for soil incubation were based on the recommendation for P fertilizer for para rubber of the Department of Agriculture (DOA). Low and high P-fertilizer level were 25 and 50 kg P_2O_5 ha^{-1} which corresponds to 44 and 88 kg MPC ha^{-1} or 5.7 and 11.4 mg MCP per 250 g soil.

Three replications of soil incubation were done and means of analyses are presented in subsequent text. The soil properties analyzed were pH of 1:5 soil:H_2O and of 1:5 soil:0.01M $CaCl_2$ (pH_{H_2O}, pH_{CaCl_2}) (Conyers and Davey, 1988), EC of incubated soil (EC), and delta bicarbonate extractable P (ΔP_{BC}). The delta bicarbonate extractable P (ΔP_{BC}) was a suitable indicator for predicting the effect on available P of dissolution of PR, (Kanabo and Gilkes, 1988; Babare *et al*., 1997). Statistical data were calculated by Statsoft: STATISTICA6 version 6.31.100.1190. Duncan's multiple range test was used for comparing the difference of each treatments.

RESUTLS AND DISCUSSION

Soil Properties

1. Physical Properties

Soil particle size and soil water retention at field capacity were measured.

The particle size analysis shows that the soil texture has a wide range from sand to clay (Table 7). The clay content of soil developed from basalt ranges from 360 to 380 g kg^{-1} (Nb-top and Nb-sub) which have a clay loam textural class, those on shale/ limestone have a clay content range from 200 to 600 g kg^{-1} ranging from sandy clay loam to clay (Ak-top, Ak-sub, Kc-top, Kc-sub, Klt-top, and Klt-sub), those on sandstone have a clay content range from 370 to 450 g kg^{-1} ranging from clay loam to clay (Nat-top and Nat-sub), and those on granite have clay content range from 20 to 430 g kg^{-1} ranging from sand to clay (Tg-top, Tg-sub, Hp-top, Hp-sub, Koi-top, Koi-sub, Knk-top, and Knk-sub). Normally, soils formed on sand stone and granite are coarse textured (Buol *et al*., 1980), but Nat-top, Nat-sub, and Koi-sub have a finer texture. That may be due to soil management or more diverse parent materials.

The silt and sand contents of soil developed from basalt range from 340 to 350 g kg^{-1} and 270 to 300 g kg^{-1}, respectively, those on shale/ limestone have silt and sand contents range from 180 to 370 g kg^{-1} and 170 to 540 g kg^{-1}, respectively, those on sand stone have silt and sand contents range from 280 to 320 g kg^{-1} and 270 to 310 g kg^{-1}, respectively, and those on granite have silt and sand contents range from 90 to 220 g kg^{-1} and 390 to 880 g kg^{-1}, respectively.

The influence of soil particle size on phosphorus sorption and extractable phosphorus was discussed by Scalenghe *et al.* (2007). They found that the total P and extractable P (resin-bicarbonate extraction) were much higher in the clay fraction than in silt and sand fractions which had similar amounts of total P. They concluded that the high P retention of clay fraction was due to high organic carbon and dithionite extractable Fe (Fe_d)

Table 7 Physical properties of soils.

Soil series	Annual rainfall[1/] (mm)	Particle size (g kg^{-1}) Sand	Silt	Clay	Texture	FC %
Basalt						
Nong Bon-top (Nb-top)	2,000-3,400	300	340	360	CL	34
Nong Bon-sub (Nb-sub)		270	350	380	CL	35
Shale/limestone						
Ao Luk-top (Ak-top)	> 1,500	210	260	530	C	32
Ao Luk-sub (Ak-sub)		170	230	600	C	31
Khlong Chak-top (Kc-top)	2,000-6,000	530	190	280	SCL	21
Khlong Chak-sub (Kc-sub)		390	180	430	C	23
Khlong Teng-top (Klt-top)	> 2,000	420	370	210	L	22
Khlong Teng-sub (Klt-sub)		540	260	200	SCL	21
Sandstone						
Nathawi-top (Nat-top)	1,800-3,000	310	320	370	CL	25
Nathawi-sub (Nat-sub)		270	280	450	C	23
Granite						
Thung Wa-top (Tg-top)	1,800-3,000	760	190	50	LS	16
Thung Wa-sub (Tg-sub)		660	210	130	SL	16
Huai Pong-top (Hp-top)	1,300-1,800	680	160	160	SL	12
Huai Pong-sub (Hp-sub)		510	160	330	SCL	17
Khok Kloi-top (Koi-top)	> 2,000	590	220	190	SL	16
Khok Kloi-sub (Koi-sub)		390	180	430	C	22
Khlong Nokkra Thung-top (Knk-top)	> 2,000	880	90	30	S	7
Khlong Nokkra Thung-sub (Knk-sub)		850	130	20	LS	7

Remark: C = clay, CL = clay loam, SCL = sandy clay loam, L = loam, LS = loamy sand, SL = sandy loam, S = sand; FC = soil water retention at field capacity

Source: [1/] Sirichuaychoo *et al*. (2004)

Soil water retention at field capacity (% FC) has a wide range of values (Table 7) rangeing from 21 to 35% for soils developed from basalt and shale/limestone and from 7 to 25% for soils developed from sandstone and granite.

2. Chemical Properties

2.1 Soil Reaction (pH)

All soil samples are acidic with pH in water ranging from 3.5 to 5.8 and pH in 1M KCl ranging from 3.1 to 4.5 (Table 8). The pH in 1M KCl is lower than pH in water indicating that negative charge prevails. Most of soils have similar pH for top-soil and sub-soil which is strongly acid ($3.5 \leq pH_{H_2O} \leq 5.1$). The soils are therefore suitable for PR use, because they likely to have sufficient soil acidity to promote PR dissolution (Di *et al.*, 1994; Bolland *et al.*, 2001; Chien, 2003). Bolan and Hedley (1990) found that the soil pH had the most influence on PR dissolution, when soil pH decreased from 6.5 to 3.9 the dissolution of North Carolina PR (NCR-PR) increased from 29.3 to 83.5 %.

The relationships of pH_{H_2O} and pH_{KCl} with soil properties are shown by the r-value in Table 9. pH_{H_2O} is correlated with sand, and pH_{KCl} and has negative relationship with phosphorus sorption maximum (Smax), current phosphorus buffer capacity (PBCc), clay, field capacity (FC), and exchangeable acidity (EA). The r-value ranges from 0.50 to 0.85 at $P < 0.05$.

2.2 Exchangeable Acidity (EA)

Exchangeable acidity (EA) ranges from 2 to 25 cmol kg^{-1} (Table 8), the higher clay content soils have higher exchangeable acidity. Therefore, the Nb-, Ak-, Kc-, Klt-, and Nat-soils have EA values of 17 to 25 cmol kg^{-1} which are higher than for Tg-, Hp-, Koi-, and Knk-soils at 2 to 15 cmol kg^{-1}.

Table 8 Chemical properties of the soils.

Soil	pH (1:1)		P_{BII}[1/]	P_{BC}[1/]	OC[2/]	EA[3/]	CEC[4/]	ECEC[5/]	Exchangeable cations				
series	H_2O	KCl	mg kg^{-1}		g kg^{-1}				Ca	Mg	Na	K	Al[6/]
						←			cmol kg^{-1}				→
Nb-top	4.2	3.4	9	5	13	23	13	24	1.0	0.1	0.04	0.12	19
Nb-sub	4.3	3.5	3	4	5	17	9	19	1.5	0.1	0.07	0.04	1.6
Ak-top	4.1	3.5	3	4	19	25	15	26	0.3	0.3	0.03	0.27	2.1
Ak-sub	4.3	3.7	1	3	10	21	12	21	0.1	0.03	0.03	0.04	1.3
Kc-top	4.3	3.5	10	5	17	20	10	21	0.6	0.2	0.06	0.08	5.4
Kc-sub	4.4	3.5	3	4	9	18	9	18	0.02	0.04	0.06	0.04	12
Klt-top	5.0	4.1	4	5	22	17	17	23	3.0	2.3	0.03	0.26	1.4
Klt-sub	5.0	3.4	1	3	2	16	16	25	2.4	6.7	0.19	0.05	0.8
Nat-top	4.7	3.6	8	4	19	22	17	23	0.1	0.3	0.02	0.08	12
Nat-sub	4.1	3.4	2	3	8	17	13	18	0.3	0.2	0.03	0.07	16
Tg-top	5.4	4.3	4	4	7	8	4	9	0.6	0.2	0.03	0.13	0.4
Tg-sub	4.1	3.6	1	3	2	8	6	9	0.7	0.2	0.04	0.05	2.3
Hp-top	4.8	4.2	17	7	12	9	6	11	1.0	0.6	0.05	0.21	0.5
Hp-sub	3.5	3.1	3	3	3	12	7	13	0.6	0.5	0.03	0.13	2.6
Koi-top	4.2	3.7	6	3	14	13	7	14	0.7	0.3	0.05	0.06	1.3
Koi-sub	4.0	3.4	1	3	6	15	8	15	0.3	0.04	0.03	0.02	12
Knk-top	5.5	4.1	2	3	3	5	3	5	0.1	0.05	0.03	0.04	0.8
Knk-sub	5.8	4.5	1	3	1	2	2	2	0.02	0.03	0.02	0.02	0.8

[1/] P_{BII} = available P extracted by Bray II solution, P_{BC} = available P extracted by sodium bicarbonate solution; [2/] OC = organic carbon content; [3/] EA =exchangeable acidity extracted by buffer $BaCl_2$-TEA solution at pH 8.2; [4/] CEC = cation exchange capacity; [5/] ECEC = effective-CEC calculated from sum of basic- (Ca^{2+}, Mg^{2+}, Na^+, and K^+) and acidic-cations (Al^{3+}, H^+); [6/] EA = exchangeable-Al extracted by 1M KCl

Table 9 Correlation matrix (r) for soil properties (see Tables 7, 8 and 10 for details and units) (n = 18).

Bold letter indicates significant relationship at $P < 0.05$

	Smax	b	PBCc	Sand	Silt	Clay	FC	pH_{H2O}	pH_{KCl}	P_{BII}	P_{BC}	CEC	Ex.Ca	Ex.Al	OC	Fe_d	Al_d	Mn_d	Fe_o	Al_o	Mn_o	EA
Smax	1.00																					
b	0.46	1.00																				
PBCc	**0.95**	0.24	1.00																			
Sand	**-0.87**	-0.35	**-0.87**	1.00																		
Silt	**0.56**	0.26	**0.57**	**-0.70**	1.00																	
Clay	**0.84**	0.33	**0.85**	**-0.95**	0.43	1.00																
FC	**0.86**	0.51	**0.83**	**-0.92**	**0.77**	**0.82**	1.00															
pH_{H2O}	**-0.50**	-0.24	**-0.53**	**0.65**	-0.25	**-0.70**	**-0.54**	1.00														
pH_{KCl}	**-0.51**	-0.25	**-0.56**	**0.64**	-0.32	**-0.66**	**-0.57**	**0.85**	1.00													
P_{BII}	-0.06	-0.06	-0.03	0.07	0.05	-0.12	-0.02	-0.02	0.14	1.00												
P_{BC}	0.33	0.09	0.35	-0.29	0.20	0.27	0.28	-0.27	-0.03	**0.79**	1.00											
CEC	**0.52**	0.07	**0.59**	**-0.76**	**0.80**	**0.60**	**0.70**	-0.30	**-0.48**	0.02	0.09	1.00										
Ex.Ca	-0.18	0.21	-0.23	-0.05	**0.55**	-0.19	0.15	0.11	0.01	0.08	-0.15	0.44	1.00									
Ex.Al	**0.53**	-0.24	**0.67**	**-0.49**	0.34	**0.47**	0.41	-0.38	**-0.49**	0.09	0.37	0.37	-0.26	1.00								
OC	0.26	-0.22	0.36	-0.44	**0.50**	0.33	0.41	-0.16	-0.02	**0.50**	**0.54**	**0.59**	0.19	0.18	1.00							
Fe_d	**0.71**	0.52	**0.60**	**-0.74**	**0.50**	**0.71**	**0.83**	-0.32	-0.28	-0.15	0.11	**0.47**	0.10	0.06	0.27	1.00						
Al_d	**0.82**	0.54	**0.73**	**-0.81**	**0.61**	**0.75**	**0.91**	-0.36	-0.37	-0.07	0.21	**0.57**	0.11	0.22	0.33	**0.97**	1.00					
Mn_d	0.28	0.10	0.29	**-0.59**	0.43	**0.55**	**0.53**	-0.24	-0.11	0.08	0.11	**0.62**	0.28	-0.16	**0.62**	**0.68**	**0.60**	1.00				
Fe_o	**0.54**	0.20	**0.53**	**-0.71**	**0.51**	**0.66**	**0.74**	-0.24	-0.20	-0.03	0.15	**0.65**	0.13	0.05	**0.62**	**0.86**	**0.84**	**0.87**	1.00			
Al_o	**0.77**	0.25	**0.74**	**-0.77**	**0.52**	**0.73**	**0.77**	-0.32	-0.41	0.16	0.44	**0.67**	-0.08	**0.47**	**0.60**	**0.63**	**0.73**	0.45	**0.70**	1.00		
Mn_o	0.18	0.03	0.21	**-0.49**	0.45	0.42	0.45	-0.08	0.02	0.24	0.23	**0.64**	0.36	-0.17	**0.73**	**0.57**	**0.51**	**0.96**	**0.83**	**0.47**	1.00	
EA	**0.77**	0.22	**0.82**	**-0.90**	**0.67**	**0.84**	**0.89**	**-0.56**	**-0.62**	0.12	0.34	**0.83**	0.09	**0.48**	**0.65**	**0.69**	**0.79**	**0.62**	**0.79**	**0.88**	**0.59**	1.00

The correlation between EA and soil properties is shown by the r-values in Table 9. The EA has high positive correlation with Smax, PBCc, silt, clay, FC, cation exchange capacity (CEC), exchangeable Al (Ex.Al), organic carbon (OC), dithionite extractable Fe and Al (Fe_d and Al_d), and oxalate extractable Fe and Al (Fe_o and Al_o) with r-value ranges from 0.48 to 0.89 at $P < 0.05$.

2.3 Cation Exchange Capacity (CEC) and Effective Cation Exchange Capacity (ECEC)

The cation exchange capacity (CEC) of soil samples varies widely from 2 to 17 cmol kg^{-1} (Table 8). This range is compatible with the range of CEC of the tropical acid soils, 3 to 20 cmol kg^{-1}, reported by Sanchez (1976). Only Knk-sub has a very low CEC (2 cmol kg^{-1}) due to the very low clay content. Most of the soils in this study, however, have rather low values of CEC (≤ 10 cmol kg^{-1}) and very low exchangeable cation contents Ca^{2+} ranges from 0.02 to 3.0 cmol kg^{-1}, Mg^{2+} ranges from 0.03 to 6.7 cmol kg^{-1}, Na^{+} ranges from 0.02 to 0.19 cmol kg^{-1}, and K^{+} ranges from 0.02 to 0.27 cmol kg^{-1}. The exchangeable Al (Ex.Al) varies widely from 0.5 to 19 cmol kg^{-1} for which the higher values of Ex.Al are for Nb-top, Nat-top, and Nat-sub being 19, 12, and 16 cmol kg^{-1}, respectively. Normally, Ultisols and Oxisols have low CEC with value less than 16 cmol kg^{-1} of clay of which less than 10 cmol $kg^{-1}$of soil may be due to permanent charge. These soils are commonly low in Ca, Mg and K (Von Uexküll and Bosshart, 1989).

The CEC has positive relationships with the amounts of Smax, PBCc, silt, clay, FC, OC, Fe_d Al_d and Mn_d, Fe_o Al_o and Mn_o, and EA for which the r-value ranges from 0.47 to 0.83 at $P < 0.05$ (Table 9). Exchangeable Ca (Ex.Ca) has a positive correlation only with the silt content (r = 0.55). The Ex.Al has positive correlations with the amount of Smax, PBCc, clay, Al_o, and EA for which the r-values range from 0.47 to 0.67 at $P < 0.05$.

For effective cation exchange capacity (ECEC), low values of ECEC of soils are comparable with values reported by Wada *et al.* (1990). They found that the low ECEC of Thai Ultisols was due primarily to the low constant negative charge, which can be related to clay mineralogy and soil texture.

2.4 Organic Carbon (OC)

The organic carbon content of soil samples varied widely from 1 to 22 g kg^{-1} (Table 8). The amount of OC in top-soil ranges from 3 to 22 g kg^{-1} which are higher than sub-soil, values ranging from 1 to 10 g kg^{-1}.

OC is positively correlated with the amount of silt, P_{BII}, P_{BC}, CEC, Mn_d, Fe_o, Al_o, Mn_o, and EA with the r-value ranging from 0.5 to 0.73 at $P < 0.05$ (Table 9).

2.5 Extractable Phosphorus by Bray II and Bicarbonate Extractants (P_{BII}, P_{BC})

The soil samples have low amounts of available phosphorus ranging from 1 to 17 mg P kg^{-1} extracted by Bray II solution and from 3 to 7 mg P kg^{-1} for sodium bicarbonate solution (Table 8). Samples with less than 20 mg P kg^{-1} extracted by Bray II solution and less than 10 mg P kg^{-1} extracted by sodium bicarbonate solution (Marx *et al*, 1999) are considered to be P-defficient. The highest levels of available P is for Hp-top (17 mg P kg^{-1}) may be due to the fertilization of the surface soil of this para rubber area.

The P_{BII} and P_{BC} have correlation only to the amounts of OC which r-value is 0.50 and 0.54 at $P < 0.05$ (Table 9), however OC has more correlation with soil properties as already mentioned.

2.6 Phosphorus Sorption Maximum (Smax), the Constant Relating the Binding Energy (b), Current Phosphorus Buffer Capacity (PBCc), and Phosphorus Desorption Isotherm

Phosphorus sorption isotherm of soil samples (S; µg g^{-1}) is well fit to Langmuir equation and the calculated phosphorus sorption maximum (Smax) from this equation gives high r^2 as 0.91 to 0.99 (Figure 2). The amount of Smax varies widely from 4 to 385 µg g^{-1} (Table 10) depending on the content and mineralogy of clay, silt, and sand fraction. The high amounts of Smax are found in Nb-, Ak-, Kc-, and Nat-soils as 217 to 385 µg g^{-1}.

The low amounts of Smax are found in Klt-, Tg-, Hp-, Koi-, and Knk-soils as 4 to 164 µg g^{-1}. Most of Smax contents in this study are compatible with the study of Wiriyakitnateekul (2005) who found that Smax of Thai Ultisols and Oxisols range from 35 to 1,111 µg g^{-1} with a median value of 370 µg g^{-1}. However, small portion of soil samples in this study (e.g. Tg-top, Hp-top, Knk-top, and Knk-sub) have Smax less than this report (4 to 10 µg g^{-1}) due to the less content of clay they have.

Smax is highly correlated with PBCc, silt, clay, FC, CEC, Ex.Al, Fe_d, Al_d, Fe_o, Al_o, and EA r-values rangeing from 0.52 to 0.95 at $P < 0.05$ (Table 9). However, the Smax has a negative relationship with sand, pH_{H_2O}, and pH_{KCl} with the r-value rangeing from 0.50 to 0.87 at $P < 0.05$. Brennan *et al.* (1994) proposed that clay type and content, soil pH, organic matter, and oxides of Fe and Al influenced P sorption capacity. Reddy *et al.* (1980) found that clay content was strongly related to P sorption. Sample *et al.* (1980) found that oxides of Fe and Al retained P through ligand exchange and precipitation reactions. Consequently Smax of sub-soils, which have higher clay contents, are generally higher than in top-soils.

The constant (b) indicating the binding energy of P to soil calculated from Langmuir equation ranges from 2 to 26 mL µg P^{-1} (Figure 2). The b of top-soil ranges from 2 to 10 mL µg P^{-1} and is lower than for sub-soil where it ranges from 2 to 26 mL µg P^{-1} (Table 10). The b of sub-soils of Nb, Ak, Kc, and Klt are much higher than for associated top-soil. There is no relationship between soil properties and b.

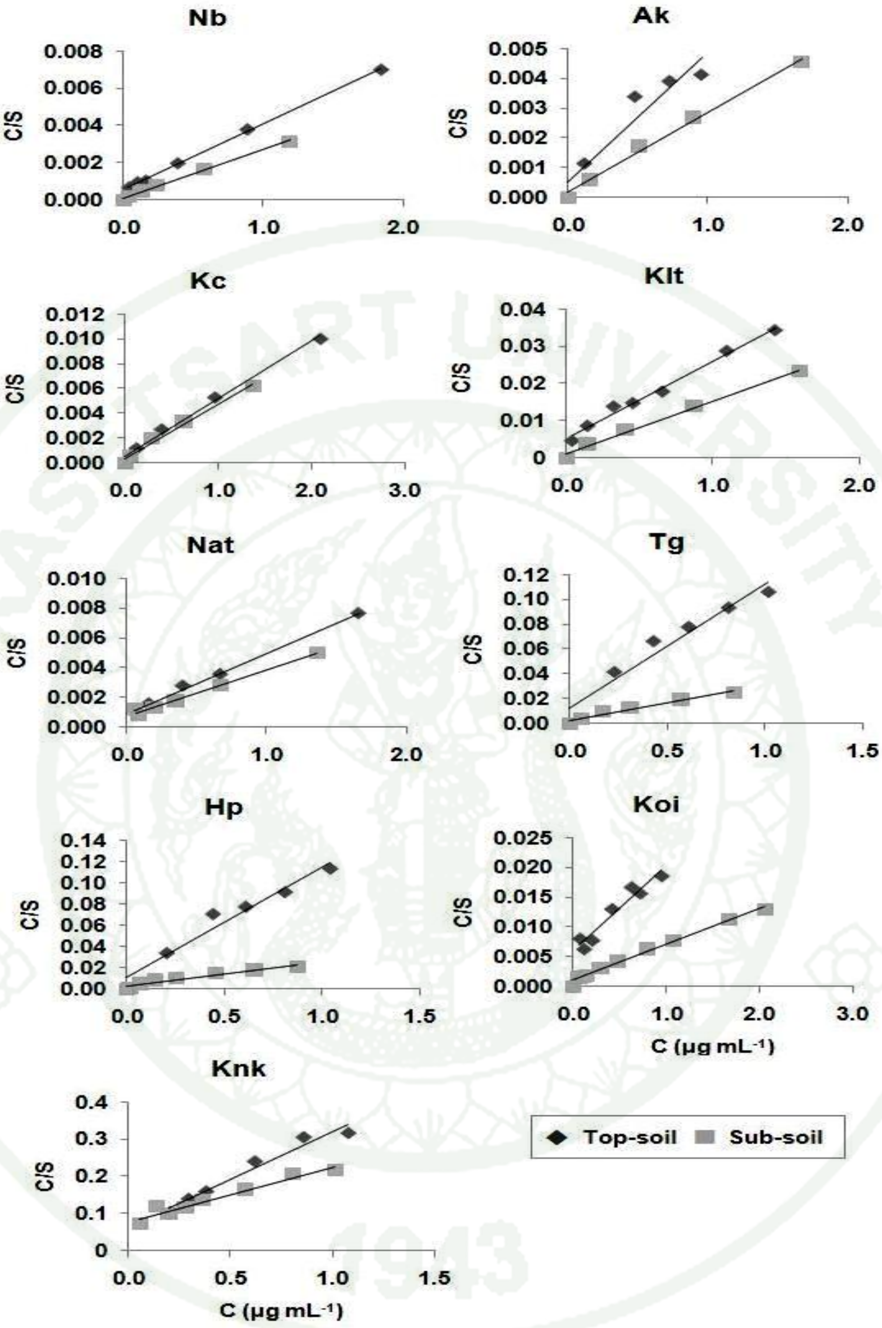


Figure 2 Plots of C/S versus C for all soils. Phosphorus sorption maximum (Smax) of soils studied; where C = final P conc. (µg mL^{-1}), S = sorbed P (µg g^{-1}), Smax = 1/ slope (µg g^{-1}), and constant (b) relating the binding energy = slope/ y-intercept (L mg P^{-1}).

(Isotherms for P sorption of all soil studied are in Appendix Figure 1)

Table 10 The amounts of phosphorus sorption and extractable Fe, Al, and Mn.

Soil	Horizon	Smax[1/]	b[2/]	PBCc[3/]	Fe$_d$[4/]	Al$_d$[4/]	Mn$_d$[4/]	Fe$_o$[5/]	Al$_o$[5/]	Mn$_o$[5/]
		µg g^{-1}	mL µg P^{-1}	mL g^{-1}	g kg^{-1}					
Nb	top	286	6	126	72	7.7	0.26	5.2	2.4	0.24
	sub	385	26	117	78	8.0	0.14	2.8	1.9	0.09
Ak	top	227	9	128	83	7.4	0.74	9.5	2.2	0.69
	sub	370	14	114	116	8.9	0.66	8.4	2.7	0.53
Kc	top	217	8	89	23	3.3	0.14	3.1	2.5	0.15
	sub	227	11	89	32	4.1	0.14	3.4	2.7	0.14
Klt	top	48	4	22	36	3.4	0.60	5.7	1.4	0.63
	sub	71	12	30	31	3.2	0.26	2.6	1.2	0.29
Nat	top	250	4	114	7.5	2.4	0.24	3.1	3.4	0.31
	sub	323	4	163	9.1	2.3	0.10	0.5	0.8	0.03
Tg	top	10	8	6	2.2	0.23	0.04	0.9	0.3	0.06
	sub	35	10	17	3.9	0.45	0.01	0.3	0.1	0.00
Hp	top	10	10	5	1.9	0.31	0.32	0.7	0.5	0.41
	sub	44	8	18	1.6	0.39	0.24	0.2	0.2	0.06
Koi	top	70	2	34	19	1.3	0.23	2.1	0.8	0.26
	sub	164	6	75	28	2.2	0.16	1.9	1.6	0.13
Knk	top	4	4	3	0.3	0.1	0.03	0.01	0.04	0.01
	sub	7	2	3	0.2	0.1	0.00	0.01	0.03	0.00

[1/] Smax = P sorption maximum; [2/] b = constant indicating the binding energy of P to soil; [3/] PBCc = current P buffer capacity; [4/] Fe$_d$, Mn$_d$, Al$_d$ = dithionite extratable Fe, Al, and Mn; [5/] Fe$_o$, Al$_o$, Mn$_o$ = oxalate extractable Fe, Al, and Mn.

Current phosphorus buffer capacity (PBCc) is indicated by the slope (m) of the linear equation as $S = a + m\text{Log}_{10}C$ (Figure 3). PBCc indicates the ability of soil to buffer against a change in solution P concentration (Holford, 1979) and the ability of soil to sorb the freshly added P (beside a P already sorbed by soil) at a current P status (Babare *et al.*, 1997; Sale *et al.*, 1997).

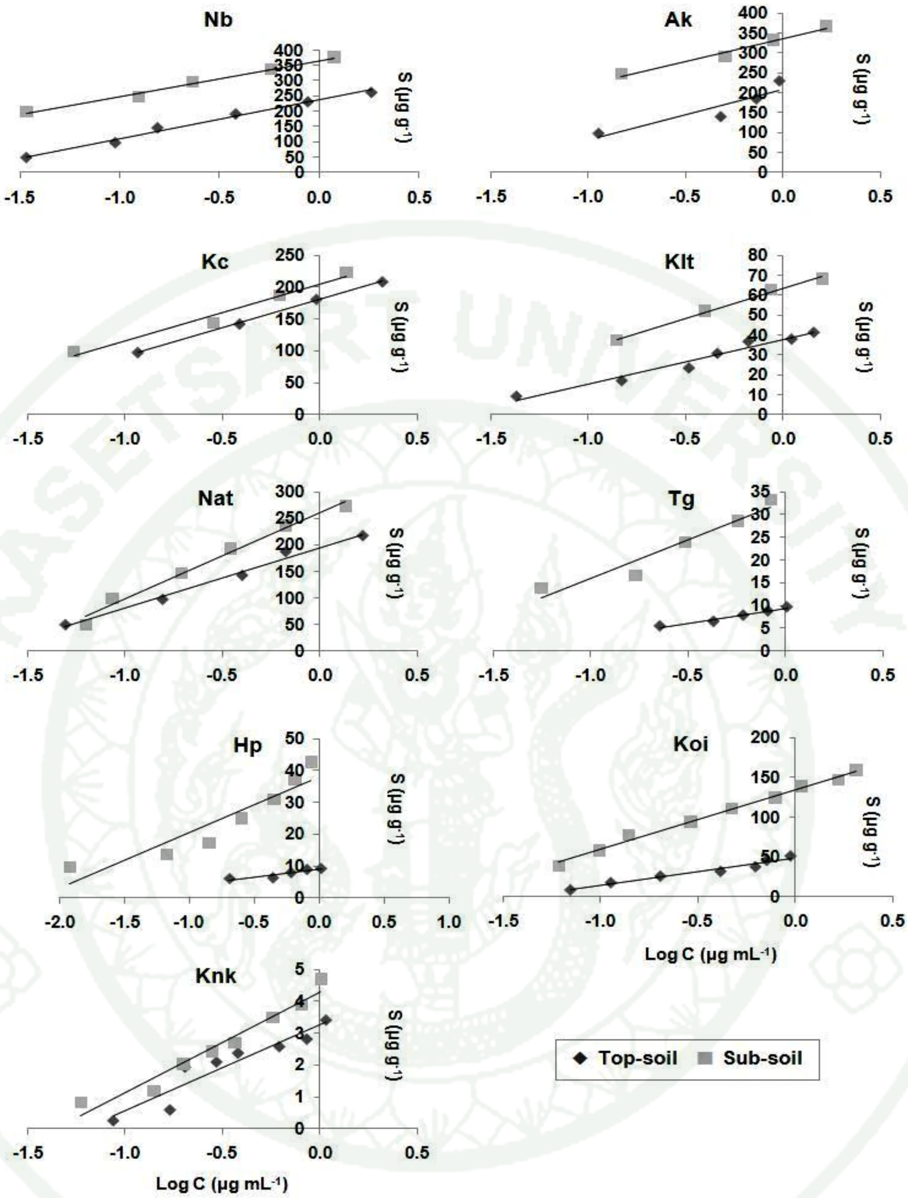


Figure 3 Plots sorbed P (S, µg g^{-1}) versus Log C (log transformed data of final P conc., µg mL^{-1}), current phosphorus buffer capacity (PBCc) derived from the slope (m) of the linear equation of $S = a + m\log_{10}C$.

The PBCc widely varies from 3 to 163 mL g^{-1} (Table 10). The high values of PBCc are for Nb-, Ak-, Kc-, and Nat-soil ranging from 89 to 163 mL g^{-1}. The low values of PBCc are for Klt-, Tg-, Hp-, Koi-, and Knk-soil rangeing from 3 to 75 mL g^{-1}. PBCc tends to be high for soils with a high clay content such as sub-soils of Nat, Tg, Hp, Koi, and Knk which also have higher PBCc than their top-soils.

The PBCc is highly correlated with the amounts of Smax, silt, clay, FC, CEC, Ex.Al, Fe_d, Al_d, Fe_o, Al_o, and EA with r-values ranging from 0.53 to 0.95 at $P < 0.05$ (Table 9). PBCc has a negative relationship with sand, pH_{H_2O}, and pH_{KCl} with r-values ranging from 0.53 to 0.87 at $P < 0.05$. This result is consistent with findings of Babare *et al.* (1997) whose experiments showed that PBCc had close positive relationship with titratable acidity (or exchangeable acidity). PBCc and titratable acidity together accounted for 72 % of the variance in phosphate rock dissolution.

P desorption can provide the information on P availability (Raven and Hossner, 1993; Raven and Hossner, 1994). Ruan and Gilkes (1996) found the linear correlation between P sorption and desorption. They proposed that the rapid P desorbed (within first minute of contact) directly reflected to the initial amount of P sorbed and followed by the slow desorption up to 20 h. This study found that the soils with high P sorption maximum (Smax) have high correlation between P sorption isotherm (S) and P desorption isotherm as shown in Figure 4. Nb-, Ak-, Kc-, and Nat-soils which have high Smax ranging from 217 to 385 µg g^{-1} have high correlation between P sorption and desorption isotherm with r^2 of top-soils ranging from 0.76 to 0.93 and of sub-soils ranging from 0.70 to 0.87.

2.7 Dithionite-Citrate-Bicarbonate (DCB) Extractable Fe Al and Mn (Fe_d, Al_d, and Mn_d) and Oxalate Extractable Fe Al and Mn (Fe_o, Al_o, and Mn_o)

2.7.1 Extractable Fe

Crystalline iron oxides (Fe_d) are estimated by dithionite citrate bicarbonate (DCB) and amorphous or poorly crystalline iron oxides (Fe_o) are estimated by ammonium oxalate. The amounts of Fe_d and Fe_o are shown in Table 10 which shows that the Fe_d is much higher than the Fe_o indicating that crystalline oxides of Fe are dominant. The range of Fe_d is from 0.2 to 116 g kg^{-1} which is more variable than the range of Fe_o, from 0.01 to 9.5 g kg^{-1}. Three levels of Fe_d (low, medium, and

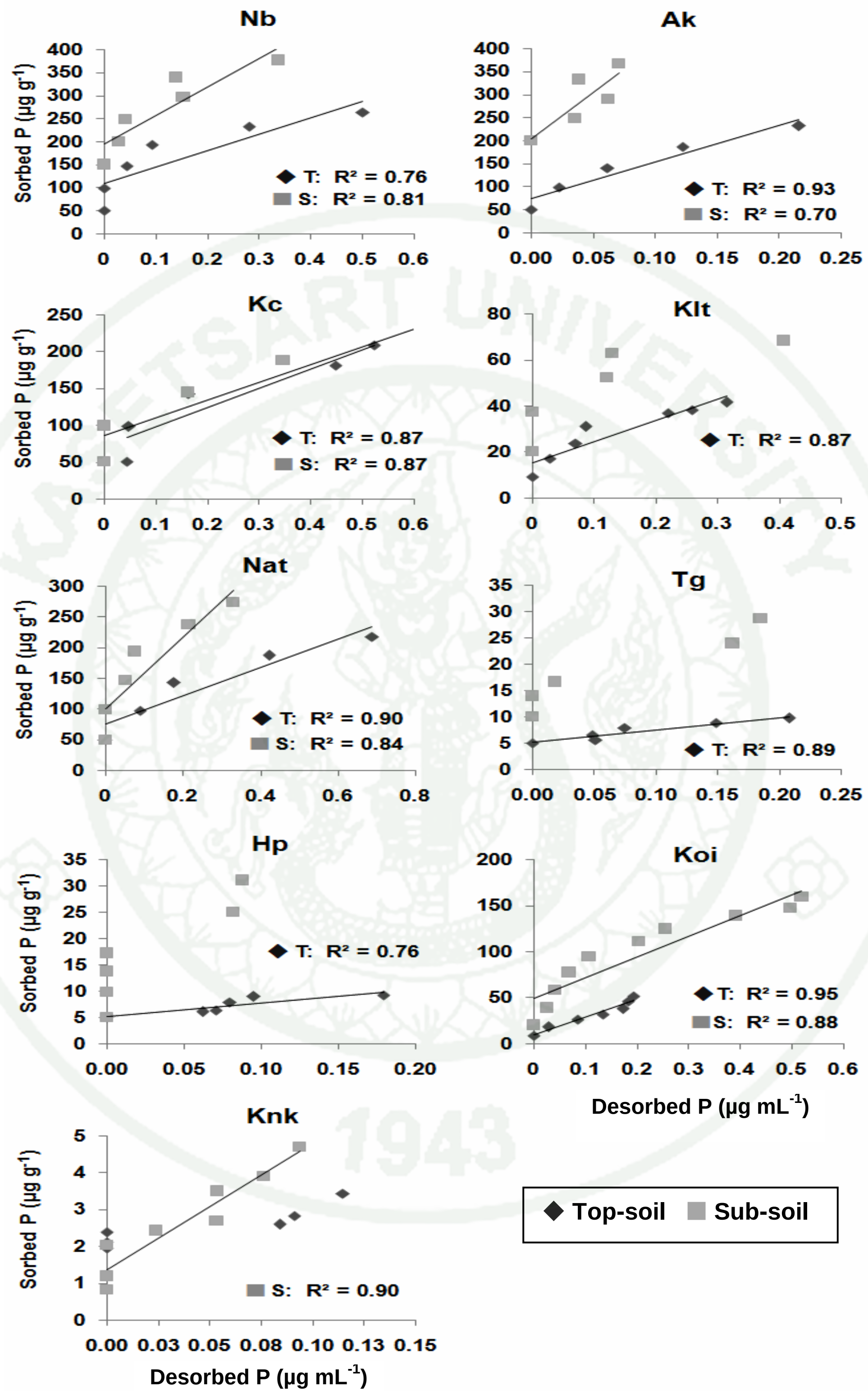


Figure 4 The correlation of determination (r^2) between P sorption isotherm and P desorption isotherm of all soils studied.

high) exist in these soils. The high level of Fe_d ranging from 72 to 116 g kg^{-1} is found in Nb- and Ak-soil. The medium level of Fe_d ranging from 19 to 36 g kg^{-1} is found in Kc-, Klt-, and Koi-soil. And the low level of Fe_d ranging from 0.2 to 9.1 g kg^{-1} is found in Nat-, Tg-, Hp-, and Knk-soil.

Fe_d has high positive correlations with the amounts of Smax, PBCc, silt, clay, FC, CEC, Al_d, Mn_d, Fe_o, Al_o, Mn_o, and EA with r-value ranging from 0.47 to 0.97 at $P < 0.05$ (Table 9). Fe_d has a negative relationship with sand (r = 0.74; $P < 0.05$). Fe_o has highly significant positive relationships with the amounts of Smax, PBCc, silt, clay, FC, CEC, OC, Fe_d, Al_d, Mn_d, Al_o, Mn_o, and EA for which r-value range from 0.51 to 0.87 at $P < 0.05$. Fe_o has an inverse relationship with sand (r = 0.71; at $P < 0.05$).

2.7.2 Extractable Al

The amounts of DCB extractable Al (Al_d) and oxalate extractable Al (Al_o) are similar. The range of Al_d is from 0.1 to 8.9 g kg^{-1} and of Al_o is from 0.03 to 3.4 g kg^{-1} (Table 10). The amounts of Al_d and Al_o are highly correlated with Smax, PBCc, silt, clay, FC, CEC, Fe_d, Fe_o and EA with the r-value ranging from 0.52 to 0.97 at $P < 0.05$ (Table 9).

2.7.3 Extractable Mn

The amounts of DCB extractable Mn (Mn_d) and oxalate extractable Mn (Mn_o) are equal. The range of Mn_d is from 0.00 to 0.74 g kg^{-1} and of Mn_o is from 0.00 to 0.69 g kg^{-1} (Table 10). The amounts of Mn_d and Mn_o have positive relationships with the contents of clay, CEC, OC, Fe_d, Al_d, Fe_o, Al_o, and EA with r-values ranging from 0.47 to 0.96 (Table 9). There is no relationship between either Mn_d or Mn_o, and phosphorus sorption by soils (Smax, and PBCc).

3. Mineralogical Properties

3.1 Mineralogy of the Clay Fraction

Kaolinite is abundant in all soil samples which being the dominant mineral of the clay fraction (Table 11). Illite is moderate in Klt- and Tg-soil, little in Nb-soil, and trace in Ak-, Kc-, Nat-, Hp-, Koi-, and Knk-soil. Hematite is trace in Nb-, Ak-, Kc-, Klt-, Nat-, Tg-, and Koi-soil. Goethite is little in Nb-soil, and trace in Ak-, Kc-, Klt-, Nat-, and Koi-soil. Gibbsite is little in Klt-soil, and trace in Nb-, Kc-, and Nat-soil. There are many published data demonstrate that minerals in the clay fraction strongly influence P sorption with goethite, hematite, gibbsite, and amorphous Fe and Al oxides being particularly important (Lin and Cox, 1989; Singh and Gilkes, 1991; Fontes and Weed, 1996; Owusu-Bennoah *et al.*, 1997). Variations in the abundance of goethite and hematite influenced the amounts of P sorption by Amazonian soils (Singh *et al.*, 1983). In addition, various amounts of accessory minerals including hydroxyl-Al interlayered vermiculite, quartz, and feldspar are presented in the soils.

3.2 Mineralogy of Silt Fraction

Quartz is abundant in all soil samples where it is the dominant mineral of the silt fraction (Table 12). It is ubiquitous and highly resistant mineral in soils (Stiles *et al.*, 2003). Kaolinite is found in most of soils, except only Tg-, and Knk-soil. Kaolinite is little in Nb-, Ak-, and Nat-soil, and trace in Kc-, Klt-, Hp-, and Koi-soil. Trace of hematite is found in Nb-, Ak-, Kc-soil, and sub-soil of Klt and Koi. Little of goethite is found in Nb- and Ak-soil, and trace of goethite is found in sub-soil of Klt and Koi. Gibbsite is trace in Nb- and Nat-soil. Illite is trace in Klt-, Nat- and Tg-soil. In addition, little to trace amounts of accessory minerals including feldspar, hydroxyl Al interlayered vermiculite, anatase, talc, and magnetite are presented in the soils. Schaefer (2001) proposed that the clay minerals included in the silt fraction are the consequence of aggregation by iron oxides forming the stable silt size aggregates.

Table 11 Mineralogy of the clay fraction of soils.

Soil	Horizon	Kao	Ill	Hem	Goe	Gib	Qtz	HIV	Fel
Nb	top	3	1	tr	1	tr	tr	tr	tr
	sub	3	1	tr	1	tr	tr	tr	tr
Ak	top	4	tr	tr	tr	-	-	-	-
	sub	4	tr	tr	tr	-	-	-	-
Kc	top	4	tr	tr	tr	tr	tr	tr	tr
	sub	4	tr	tr	tr	tr	tr	tr	tr
Klt	top	2	2	tr	tr	1	1	tr	tr
	sub	2	2	tr	tr	1	1	tr	tr
Nat	top	4	tr	tr	tr	tr	tr	tr	tr
	sub	4	tr	tr	tr	tr	tr	tr	tr
Tg	top	3	2	tr	-	-	tr	-	tr
	sub	3	2	tr	-	-	tr	-	tr
Hp	top	4	tr	-	-	-	tr	-	tr
	sub	4	tr	-	-	-	tr	-	tr
Koi	top	4	tr	tr	tr	-	tr	tr	tr
	sub	4	tr	tr	tr	-	tr	tr	tr
Knk	top	4	tr	-	-	-	1	-	tr
	sub	4	tr	-	-	-	1	-	tr

4 = > 60%; 3 = 40-60%; 2 = 20-40%; 1 = 5-20%; tr = <5%; Kao = Kaolinite; Ill = Illite; Hem = Hematite; Goe = Goethite; Gib = Gibbsite; Qtz = Quartz; HIV = Hydroxyl Al interlayered vermiculiet; Fel = Feldspar.

Table 12 Mineralogy of the silt fraction of soils.

Soil	Horizon	Qtz	Kao	Fel	Hem	Goe	Gib	Ill	HIV	Ana	Talc	Mag
Nb	top	3	1	tr	tr	1	tr	-	-	tr	tr	tr
	sub	3	1	tr	tr	1	tr	-	-	tr	-	tr
Ak	top	3	1	tr	tr	1	-	-	-	-	-	-
	sub	3	1	tr	tr	1	-	-	-	-	-	-
Kc	top	4	tr	tr	tr	-	-	-	-	tr	-	tr
	sub	4	tr	tr	tr	-	-	-	-	tr	-	tr
Klt	top	4	tr	tr	-	-	-	tr	tr	tr	-	-
	sub	4	tr	tr	tr	tr	-	tr	tr	tr	-	-
Nat	top	3	1	1	-	-	tr	tr	-	-	-	tr
	sub	3	1	1	-	-	tr	tr	-	-	-	tr
Tg	top	4	-	tr	-	-	-	tr	-	-	tr	-
	sub	4	-	tr	-	-	-	tr	-	-	-	-
Hp	top	4	tr	tr	-	-	-	-	-	tr	-	-
	sub	4	tr	tr	-	-	-	-	-	tr	-	-
Koi	top	4	tr	tr	-	-	-	-	-	tr	-	-
	sub	4	tr	tr	tr	tr	-	-	-	tr	-	-
Knk	top	4	-	tr	-	-	-	-	-	tr	-	-
	sub	4	-	tr	-	-	-	-	-	tr	-	-

4 = > 60%; 3 = 40-60%; 2 = 20-40%; 1 = 5-20%; tr = < 5%; Qtz = Quartz; Kao = Kaolinite; Fel = Feldspar; Hem = Hematite; Goe = Goethite; Gib = Gibbsite; Ill = Illite; HIV = Hydroxyl Al interlayered vermiculite; Ana = Anatase; Talc = Talc; Mag = Magnetite/maghemite.

3.3 Mineralogy of Sand Fraction

In the sand fraction, quartz is dominant as same as in silt fraction (Table 13). In addition, hematite is trace in Ak-soil and sub soil of Koi, goethite is trace in Nb- and Ak-soil, gibbsite is trace in Nb- and Nat-soil. And trace of feldspar and anatase is presented in the sand fraction of most of soils. Sand fraction in soils is sometimes coated with organic matter and amorphous minerals such as Fe rich amorphous alumino-silicates minerals (Al/Si/Fe minerals) (Fuller *et al.*, 1996; Penn

Table 13 Mineralogy of the sand fraction of soils.

Soil	Horizon	Qtz	Fel	Hem	Goe	Gib	Ana
Nb	top	4	tr	-	tr	tr	-
	sub	4	-	-	tr	tr	-
Ak	top	4	tr	tr	tr	-	
	sub	4	tr	tr	tr	-	-
Kc	top	4	tr	-	-	-	-
	sub	4	tr	-	-	-	-
Klt	top	4	tr	-	-	-	-
	sub	4	tr	-	-	-	tr
Nat	top	4	tr	-	-	tr	-
	sub	4	tr	-	-	tr	-
Tg	top	4	tr	-	-	-	-
	sub	4	tr	-	-	-	-
Hp	top	4	tr	-	-	-	-
	sub	4	-	-	-	-	tr
Koi	top	4	-	-	-	-	-
	sub	4	tr	tr	-	-	tr
Knk	top	4	-	-	-	-	-
	sub	4	-	-	-	-	-

4 = > 60%; 3 = 40-60%; 2 = 20-40%; 1 = 5-20%; Q = Quartz; F = Feldspar; H = Hematite; Go = Goethite; Gi = Gibbsite; A = Anatase.

et al., 2001). Therefore, the sand fraction can readily retain P from soil solution, and sand may play an important role in P retention (Arai and Livi, 2013).

4. Summary

All soil samples are acidic with low pH and quite high EA. They contain low available P (< 20 mg kg^{-1} of P_{BII}, and < 10 mg kg^{-1} of P_{BC}), and low exchangeable Ca (≤ 3 cmol kg^{-1}). OC of top-soil is higher than sub-soil with top-soils containing low to medium OC and sub-soils containing low OC (≤ 10 g kg^{-1}).Phosphorus sorption maximum (Smax) of Nb-, Ak-, Kc-, and Nat-soil are high (217 to 385 μg g^{-1}) and of Klt-, Tg-, Hp-, Koi-, and Knk-soil are low (4 to 164 μg g^{-1}) depending on the amounts of clay and oxides of Fe and Al they contain. All soils contain much kaolinite as it is the dominant mineral of clay fraction. The other minerals influencing P sorption are illite, hematite, goethite, and gibbsite which are present in some soils such as Nb-, Ak-, Kc-, Klt-, Nat-, Tg-, and Koi-soil. All soil properties indicate that the soisl are suitable for PR use.

Phosphate Rock Properties

1. Mineralogical Properties

ThreeThai phosphate rocks (PRs) of Rat-, Kan-, and Roi-PR were used in this study together with the reference North Carolina Phosphate Rock (NCR-PR).

1.1 North Carolina Phosphate Rock (NCR-PR)

The XRD-pattern of NCR-PR (Figure 5(a)) exhibits many peaks for apatite which is the main mineral and for the accessory mineral quartz. The apatite peaks match closely data for carbonate-hydroxyapatite (PDF 01-073-7334).

The elemental composition of NCR-PR derived by SEM-EDS is of 36% P_2O_5 and 61% CaO (Figure 6). Ideal hydroxyapatite $Ca_{10}(PO_4)_6(OH)_2$ contains 42% P_2O_5 and 56% CaO values, which are close to the observed values but would not be expected to coincide as the apatite also exhibits carbonate substitution for phosphate. The unit-cell a-value of apatite in NCR-PR is 9.336 ± 0.007 Å and c-value is 6.889 ± 0.008 which are compatible with the published values for carbonate apatite or francolite (McClellan and Gremillion, 1980; Elliott *et al.*, 2002) shown in Table 14.

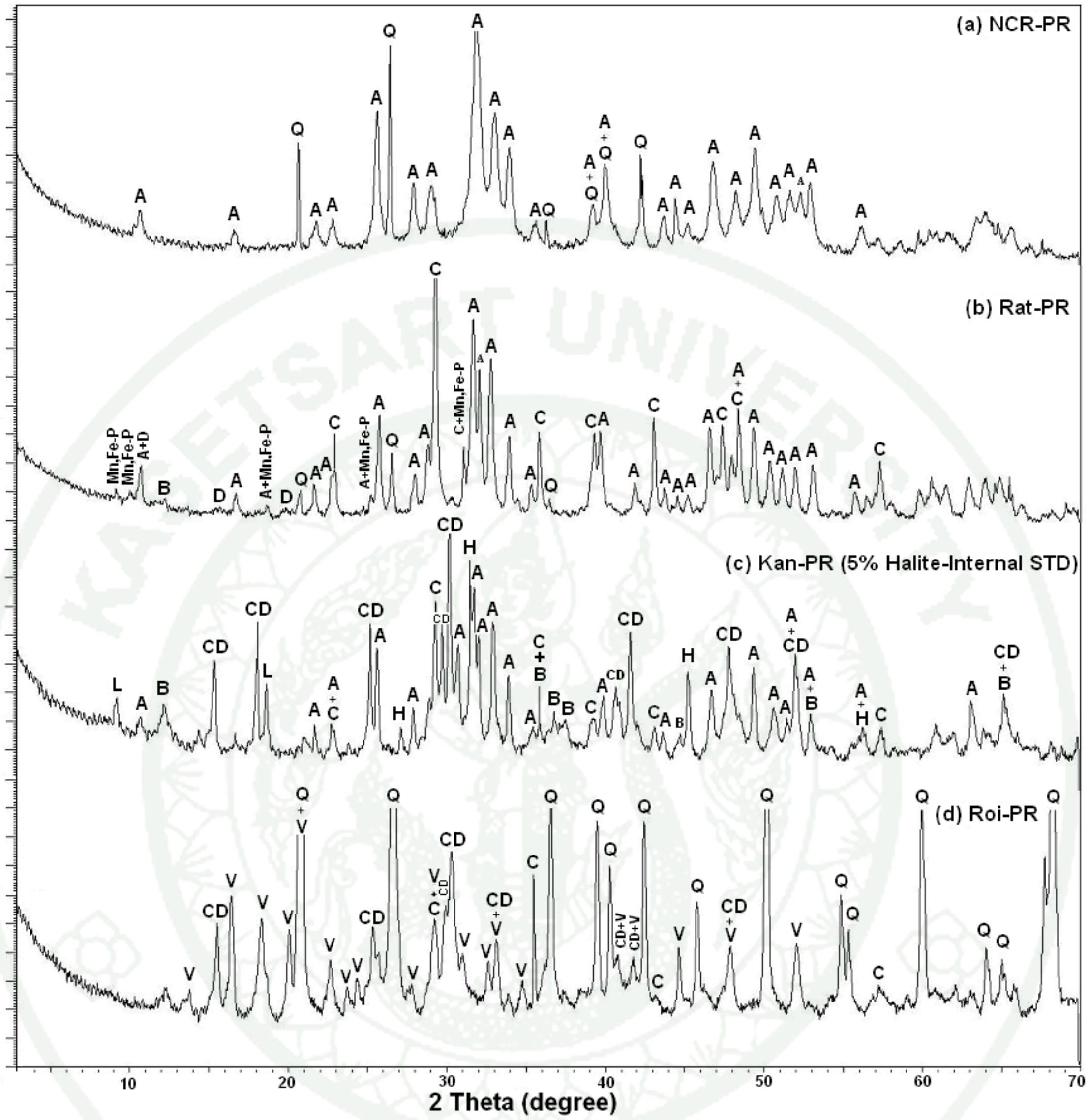


Figure 5 XRD of powdered phosphate rock samples (Key to minerals: A = apatite, Q = quartz, D = diadochite, B = birnessite, C = calcite, L = lithiophorite, CD = crandallite, H = halite, V = variscite, Mn,Fe-P = Mn, Fe phosphate mineral).

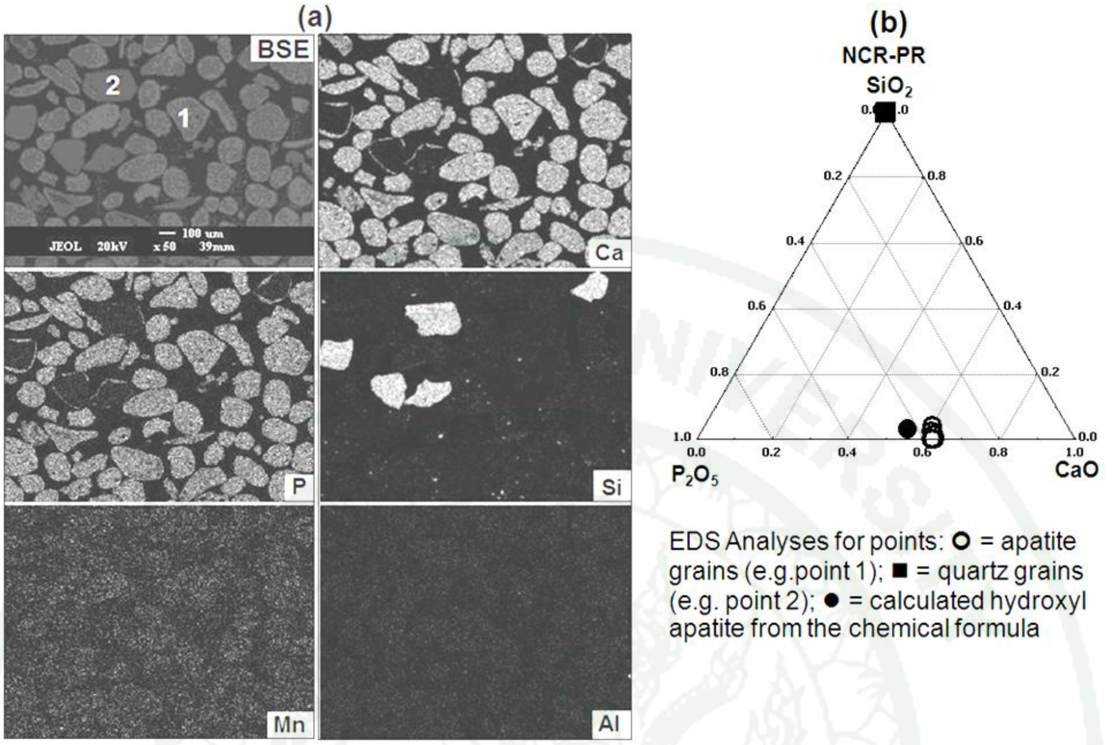


Figure 6 BSE and element maps for NCR-PR (a) and a ternary graph for major elements based on point analyses (b).

1.2 Ratchaburi Phosphate Rock (Rat-PR), Kanchanaburi Phosphate Rock (Kan-PR), and Roi-Et Phosphate Rock (Roi-PR)

XRD patterns for Rat-, Kan-, and Roi-PR are shown in Figures 5(b), 5(c), and 5(d), respectively. Rat- and Kan-PR contain apatite and calcite as the main minerals. Apatites in Rat- and Kan-PR have a-values of 9.428 ± 0.002 Å and 9.406 ± 0.008 Å, and c-values of 6.882 ± 0.002 Å and 6.888 ± 0.008 Å. They are likely to be hydroxyapatite, which has a- and c-values of 9.418 to 9.437 Å and 6.881 to 6.888 Å (Elliott, 1994; Ivanova *et al.*, 2001; Markovic *et al.*, 2004) (Table 14).

The a-value for apatite in Kan-PR is slightly less than published values, possibly due to other isomorphous substitutions in the apatite structure. Fluorine is a common element in apatite in sedimentary phosphate rock and influences both unit-cell dimensions the physical and chemical properties of apatite. The substitution of F^-

for OH^- contracts the a-value with no change to the c-value. Crystallinity and stability are increased by F substitution (Sivakumar and Manjubala, 2001). Apatites with a-values between 9.370 and 9.420 Å belong to a series between fluor- and hydroxy-apatite (McClellan and Gremillion, 1980; van-Straaten, 2002) and the a-value of Kan-PR is comparable with this range.

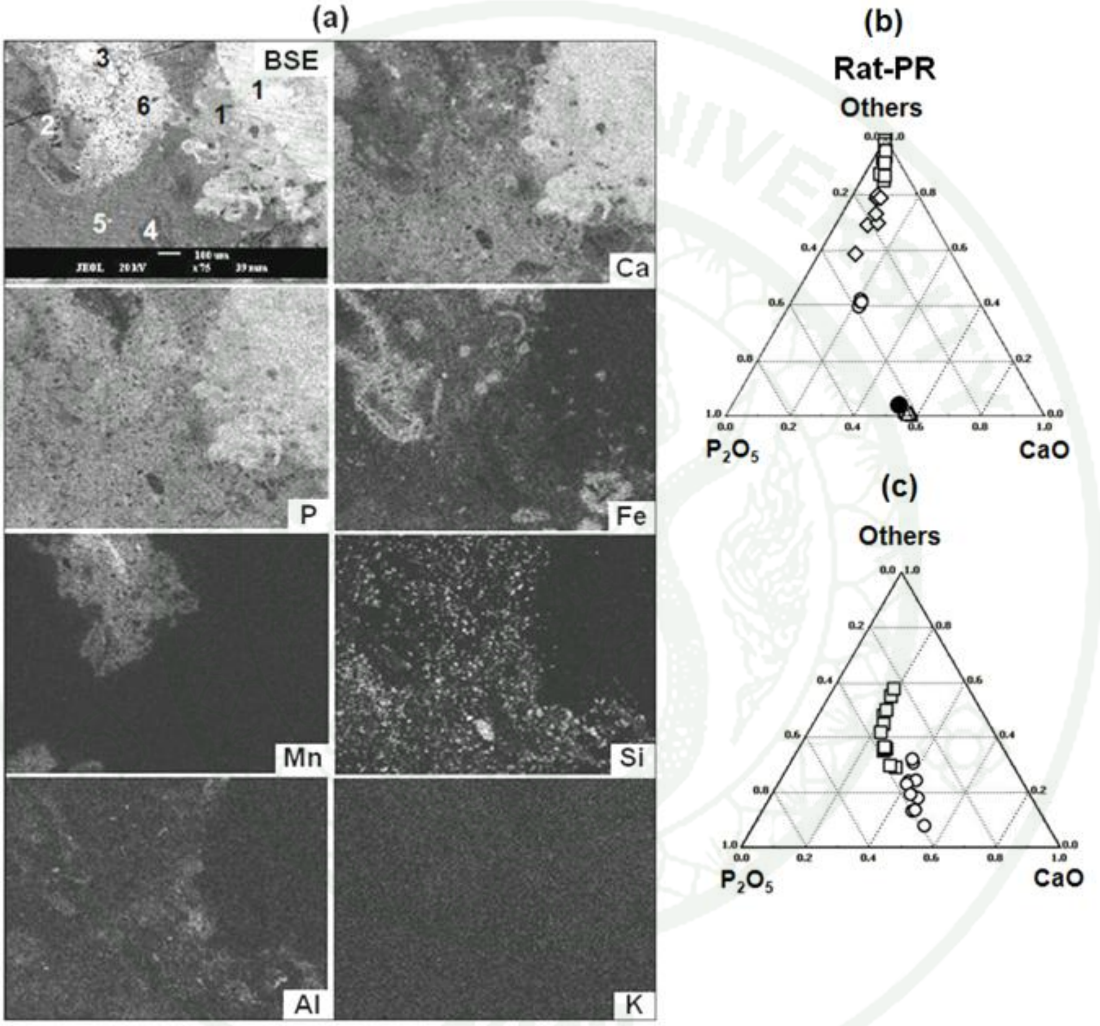
Table 14 The unit-cell dimensions of apatite, crandallite, and variscite in phosphate rock samples and literature values.

Mineral type	Reference	a (Å)	c (Å)
Variscite	1	9.823	8.562
	2	9.822	8.561
	3	9.898	8.589
	4	9.826±0.009	8.573±0.010
Crandallite	5a	7.017	16.252
	5b	7.013	16.196
	6	7.005	16.192
	7	7.003	16.166
	8	7.007	16.216
	9	7.014±0.005	16.182±0.007
	10	7.025±0.005	16.191±0.009
Natural apatite	11	9.322 to 9. 409	6.876 to 6.901
Francolite-apatite	12	9.341	6.924
Carbonate-apatite	13	9.322 to 9.376	6.877 to 6.900
	14	9.336±0.007	6.889±0.008
Hydroxyapatite	15	9.418	6.881
	16	9.437	6.888
	17	9.424	6.885
	18	9.428±0.002	6.882±0.002
	19	9.406±0.008	6.888±0.008

[1]Onac *et al.* (2004); [2]Kniep *et al.* (1977); [3]Salvador and Fayos (1972); [4]Roi-PR (this study); [5a,b]Blanchard (1972), [a]Utah-crandallite, [b]Florida-crandallite; [6]Blount (1974); [7]Radoslovich (1969); [8]Gilkes and Palmer (1983); [9]Kan-PR (this study); [10]Roi-PR (this study); [11]McClellan and Lehr (1969); [12]Elliott *et al.* (2002); [13]McClellan and Gremillion (1980); [14]NCR-PR (this study); [15]Elliott (1994); [16]Ivanova *et al.* (2001); [17]Markovic *et al.* (2004); [18]Rat-PR (this study); [19]Kan-PR (this study).

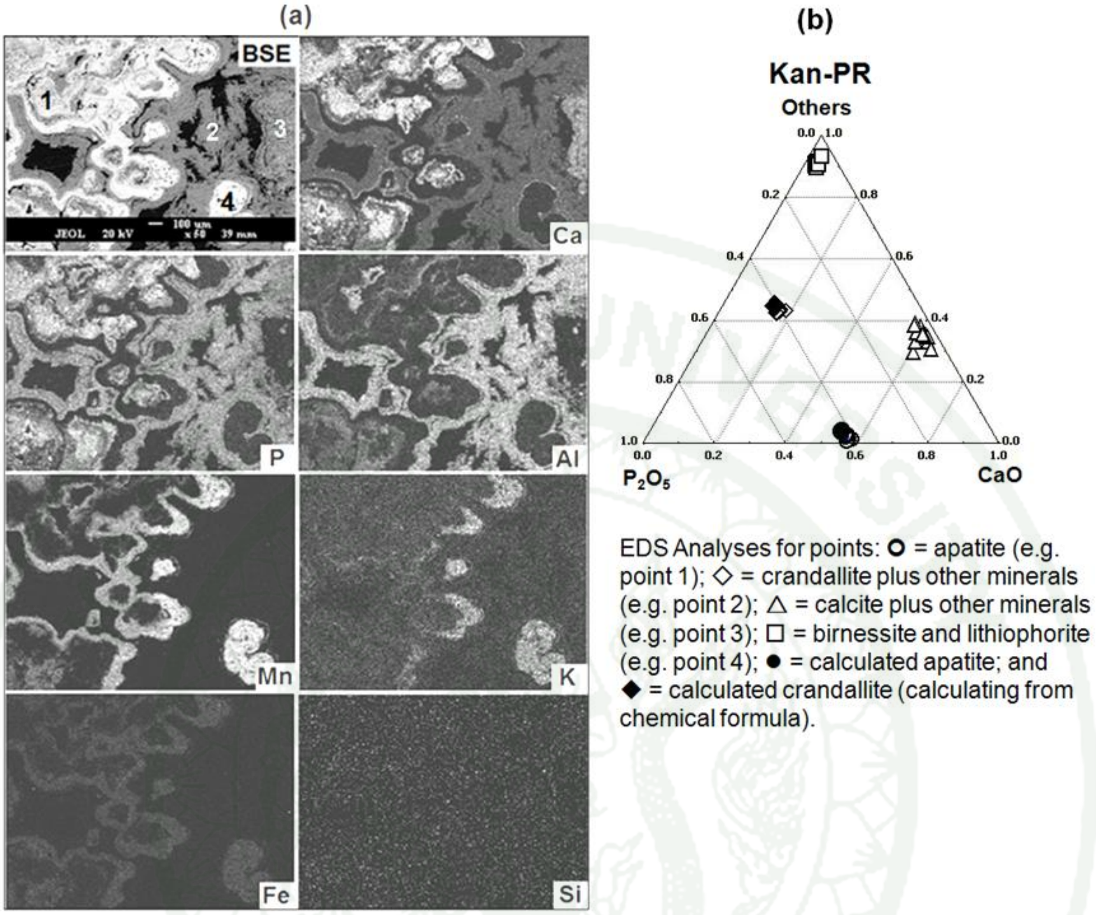
In EDS analyses of apatite grains in Rat-PR and Kan-PR (Figure 7 and 8), the phosphorus and calcium concentrations in many particles are close to the composition of ideal apatite. The results for Rat- and Kan-PR are shown in ternary graphs in Figure7 and 8. Discrete calcite is also seen in the BSE/EDS-images for Kan-PR. EDS analyses of areas in Rat-PR indicate that calcite is dispersed through particles containing other minerals. Calcite commonly occurs in carbonate-cemented phosphorites and is abundant in sedimentary phosphate rocks (McClellan and Gremillion, 1980). In addition to apatite, Kan-PR contains abundant crandallite ($CaAl_3(PO_4)_2(OH)_5•H_2O$). The chemical composition of this crandallite is close to ideal crandallite as shown in the ternary graph (Figure 8). Crandallite in Kan-PR has an a-value of 7.014 ± 0.005 Å and c-value of 16.182 ± 0.007 Å. These values are comparable with published a-values of 7.003 to 7.017 Å and c-values of 16.166 to 16.252 Å (Radoslovich, 1969; Blanchard, 1972; Blount, 1974; Gilkes and Palmer, 1983). Rat-PR also includes diadochite [$Fe_2(PO_4)(SO_4)(OH)•5H_2O$], an unnamed phosphate mineral rich in iron (Fe) and manganese (Mn) and birnessite [$(Ca,Na)0.5Mn_2O_4•1.5H_2O$]. Kan-PR contains birnessite and lithiophorite [$(Al,Li)MnO_3(OH)_2$].

In Roi-PR, the main mineral is quartz with variscite and crandallite as secondary minerals, and a little calcite mixed with variscite. Crandallite in Roi-PR, , contains a lower and more varied concentration of CaO (from 7 to 17%) than crandallite in Kan-PR (from 16 to 19%). Crandallite in Roi-PR also includes from 2 to 6% BaO. Therefore, the spot analyses for crandallite in Roi-PR shown in the ternary graph (Figure 9) are shifted from ideal crandallite composition. Crandallite in Roi-PR has an a-value of 7.025 ± 0.005 Å and c-value as 16.191 ± 0.009 Å. This a-value is slightly higher than the published a-values for crandallite (7.003 to 7.017 Å) shown in Table 14 (Radoslovich, 1969; Blanchard, 1972; Blount, 1974; Gilkes and Palmer, 1983), which may be a consequence of the substitution of the larger Ba ion for the smaller Ca ion as reported by Blanchard (1972) and Norrish (1968). Ba substituting for Ca will increase the stability of crandallite reducing its solubility (Dill, 2001). Variscite ($AlPO_4•2H_2O$) in Roi-PR contains 58% P_2O_5 and 41% Al_2O_3 (Figure 9). The unit-cell a- and c-values of variscite are 9.826 ± 0.009 Å and 8.573 ± 0.010 Å which are comparable with a- and c-values published by Salvador and Fayos (1972), Kniep *et al.* (1977), and Onac *et al.* (2004) (Table 14). The XRD pattern of Roi-PR also shows the presence of a little calcite.



EDS Analyses for points: (b): △ = apatite (e.g. point 1; bright and light gray); ○ = diadochite with minor apatite (e.g. point 2); ◇ = birnessite with minor apatite (e.g. point 3); □ = quartz (e.g. point 4); and ● = calculated apatite from chemical formula. (c): ○ = apatite included in a Fe mineral (e.g. point 5), and □ = and apatite included in Mn and Fe minerals (e.g. point 6).

Figrue 7 BSE and element maps for Rat-PR (a) and ternary graphs for major elements (b and c) indicating that microcrystalline apatite is often included within various minerals.



EDS Analyses for points: ○ = apatite (e.g. point 1); ◇ = crandallite plus other minerals (e.g. point 2); △ = calcite plus other minerals (e.g. point 3); ☐ = birnessite and lithiophorite (e.g. point 4); ● = calculated apatite; and ◆ = calculated crandallite (calculating from chemical formula).

Figure 8 BSE and element maps for Kan-PR (a) and a ternary graph for major elements obtained by point analyses (b).

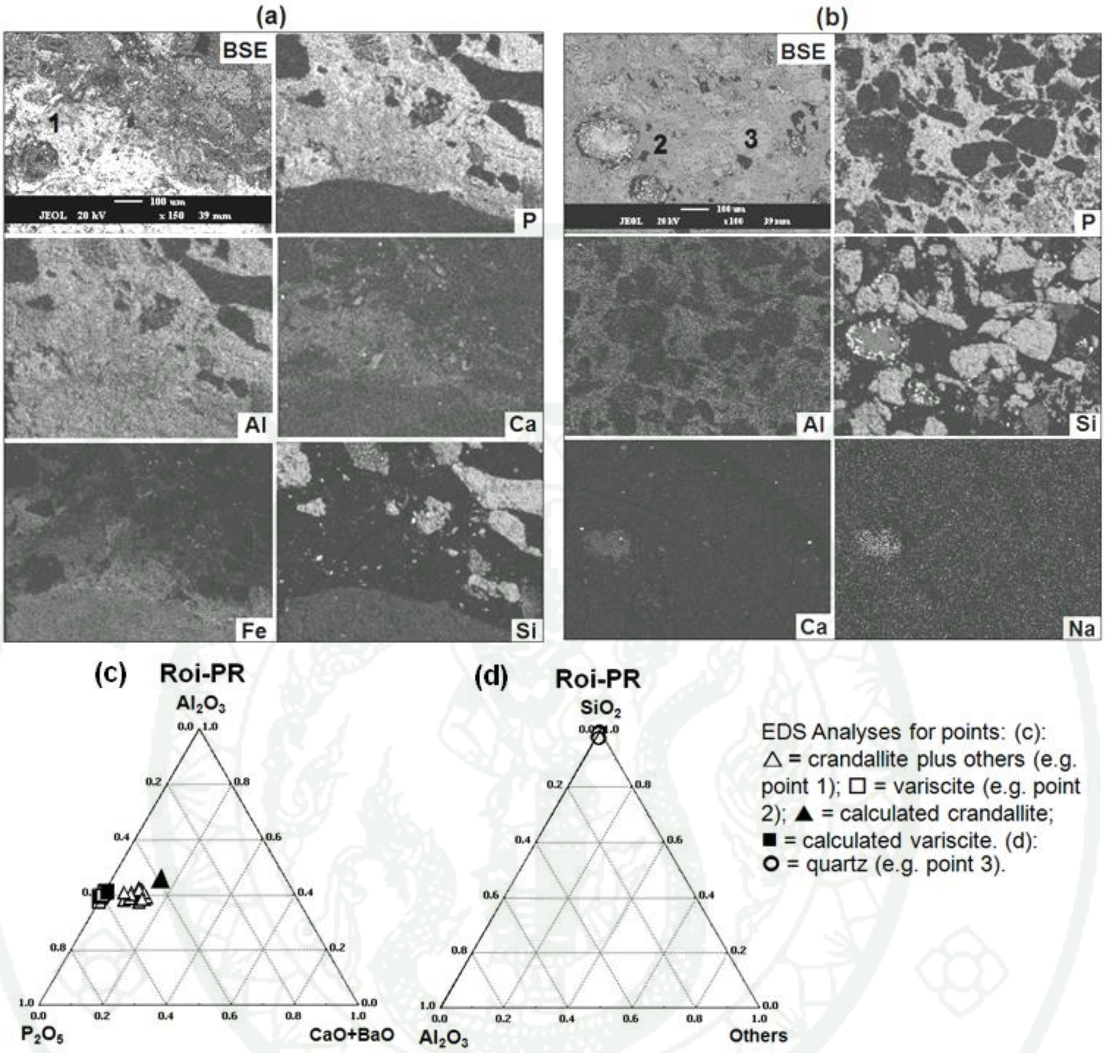


Figure 9 BSE and element maps for Roi-PR in (a) and (b) and ternary graphs for major elements corresponding to the point analyses in (c) and (d).

2. Chemical Properties

2.1 Total Element in Phosphate Rocks

Elemental analyses are shown in Table 15. NCR-PR contains the highest total-P (204 g kg^{-1}) and the other PRs (Rat-, Kan- and Roi-PR) contain similar much lower concentrations of total-P (104, 97, and 103 g kg^{-1}, respectively). Rat-PR has the

Table 15 The total element composition of phosphate rock samples.

PR	P	K	Ca	Mg	Al	Fe	Si	Ti	S	Na	Mn	Zn	Cu	Ba	Pb	Cd	Cr	Sr	As	Mo
	← g kg^{-1} →											← mg kg^{-1} →								
NCR	204	1.5	251	2.8	2	4	21	1.2	8.4	7	0.02	280	26	-	-	33	114	-	13	14
Rat	104	0.3	382	0.4	4	4	16	0.4	0.5	0.9	8	2160	267	284	14	11	7	175	6	2
Kan	97	2.9	199	3	69	12	20	2.4	0.6	0.5	11	3515	653	463	40	24	29	1330	25	17
Roi	103	0.6	18	0.2	60	17	246	1.1	0.1	0.8	0.2	57	30	4509	18	0.2	28	1989	3	1

highest total calcium (382 g kg^{-1}) with values descending for NCR-PR (251 g kg^{-1}) > Kan-PR (199 g kg^{-1}) > Roi-PR (18 g kg^{-1}). Roi-PR has the highest total Si (246 g kg^{-1}), which is largely present as quartz (the main mineral in Roi-PR), and the other PRs (NCR-, Rat-, and Kan-PR) contain similar smaller amounts of Si (21, 16, and 20 g kg^{-1}, respectively).

The chemical analyses are consistent with the mineralogical composition of the PRs with NCR-PR having high contents of P and Ca as it consists of apatite with a lesser content of Si as quartz. Rat-, Kan-, and Roi-PR have smaller amounts of P than NCR-PR. They have larger amounts of minor elements (Fe, Al, Mn, and Si) and trace elements (Zn, Cu, Ba, Pb, Cd, Cr, Sr, and As) than does NCR-PR and several of these elements are commonly accommodated within the crandallite structure (Blanchard, 1972; Gnandi and Tobschall, 1999). Kan-PR (contains crandallite) and Roi-PR (contains variscite and crandallite) have higher amounts of iron (Fe) (12 and 17 g kg^{-1}) and aluminum (Al) (69 and 60 g kg^{-1}), and Rat- and Kan-PR have moderate amounts of manganese (Mn) (8 and 11 g kg^{-1}) as birnessite. Roi-PR contains the highest amount of Ba (4,509 mg kg^{-1}) which is due to substitution of Ba for Ca in crandallite.

The three Thai PRs contain considerable amounts of some minor elements, e.g., Cd, Cr, Pb, and As depending on the type of phosphate mineral (Viisimaa *et al.,* 1991; Kpomblekou and Tabatabai, 1994; Sabiha *et al.,* 2009). Published ranges of minor elements in PRs of various origins and mineral types include As 3-24 mg kg^{-1}, Cd 0.1-92 mg kg^{-1}, Cr 1-637 mg kg^{-1}, Pb 1-89 mg kg^{-1}, and Sr nil-4100 mg kg^{-1} (van-Kauwenberg, 1997; Kharikov and Smetana, 2000; Sattouf, 2007; Javied *et al.,* 2009).

In this study, As (3-25 mg kg^{-1}), Cd (0.2-33 mg kg^{-1}), Cr (7-114 mg kg^{-1}), Pb (14-40 mg kg^{-1}), and Sr (175-1989 mg kg^{-1}) are present in similar ranges to the published ranges. However, Rat- and Kan-PR contain high amounts of Zn (2,160 and 3,515 mg kg^{-1}) which is consistent with the data of Truong and Zapata (2002) which found that PR samples from Ratchaburi and Petchaburi in Thailand were rich in Zn and Mn. The high amount of Zn in Rat- and Kan-PR may be due to the limestone containing these phosphates being mineralized with some Thai limestones e.g. Ratchaburi and Kanchaburi containing sphalerite ((Zn, Fe)S) (Shawe, 1984).

2.2 The Solubility of Phosphate Rocks in Various Extractants

The solubility of P in PR samples in various standard AOAC extractants (2%FA, 2%CA, NAC, AAC, and DI) is shown in Table 16. The solubility of PRs differs depending on mineralogy and the nature and strength of the extractants. NCR-PR has the highest solubility in all extractants except for AAC, and Rat-, Kan-, and Roi-PR have relatively low solubilities. For NAC extractant, the soluble P in NCR-, Rat-, and Kan-PR in first and second extractions is relatively constant except for Roi-PR where the P dissolved in a second extraction increased from 0.7% to 1.3%. This represents the influence of calcite that suppresses the solubility of apatite (Chien and Hammond, 1978; Chien, 1993; Smalberger *et al.*, 2006). Sikora (2002) proposed that gangue calcite was completely dissolved in the first extraction and the apatite would dissolve in subsequent extractions. The calcite in Rat- and Kan-PR, however, did not suppress the solubility of these phosphate rocks.

Roi-PR has most P soluble in AAC extractant (pH 9.35) with little P being soluble for NCR-PR, Rat-PR, and Kan-PR. Roi-PR differs from other PRs, because it includes variscite which is more soluble under basic conditions (pH 9.0) (Roncal-Herrero and Oelkers, 2011). The extraction results clearly show that apatite-containing PRs (NCR-, Rat-, and Kan-PR) and the non-apatite PR (Roi-PR) have quite different dissolution behaviors.

2.3 The Long Term Dissolution Kinetics of Phosphate Rocks

The long term dissolution kinetics of PRs are shown in Figure 10. The data are expressed on a log of % of total element dissolved versus log time basis. The proportions of total-P, total-Ca, and total-Al extracted depend on the nature of the extractants which for P and Ca is 2%FA > 2%CA > NAC. For Al the dissolution in

AAC is higher than in NAC. The dissolution of P, from Roi-PR, in AAC is similar to that from Rat- and Kan-PR, because, variscite is relatively soluble in alkaline solution (Rocal-Herrero and Oelkers, 2011). Roi-PR shows a quite different dissolution behavior to the other three PRs due to the different and apatite-free mineralogy of this type of PR. NCR-PR, Rat-PR, and Kan-PR showed similar dissolution behaviors for P and Ca reflecting the similar apatitic mineralogies of these PRs. Much of the total P and Ca in these PRs had dissolved in formic acid after 620 minutes with progressively less dissolution in CA > NAC > AAC.

Table 16 The percentage calcium carbonate equivalence (%CCE) and the percentage solubility of P in phosphate rock samples in standard AOAC extractants.

PR	CCE[1/]	% of total P					
	%	FA[2/]	CA[3/]	NAC_{E1}[3/]	NAC_{E2}[3/]	AAC[3/]	DI[3/]
NCR	62	93	53	26	21	1.4	0.13
Rat	73	40	19	1.4	1.5	0.6	0.09
Kan	50	18	15	0.6	0.6	0.5	0.07
Roi	13	5	0.6	0.7	1.3	32	0.04
Mean	-	39	21	7.1	6.0	8.7	0.08

[1/]CCE = calcium carbonate equivalent with endpoint at pH 5 (Sikora, 2002); [2/]FA = 2% formic acid (Chien, 1993); [3/]CA = 2% citric acid, NAC_{E1} and NAC_{E2} = 1st and 2nd extraction with neutral ammonium citrate, AAC = Petermann alkaline ammonium citrate, and DI = deionized water (AOAC, 1975).

The congruency of PR dissolution (plotted as % of total Al/%total P dissolved versus log time) shown in Figure 11 varies with extraction time due to the mixed mineralogies of the PRs (Rajan *et al.*, 1996; FAO, 2004). Therefore, plots for NCR-, Rat-, and Kan-PR (apatite containing) clearly differ from Roi-PR (non-apatite). Clearly as extractant pH increases relatively more Al is dissolved from

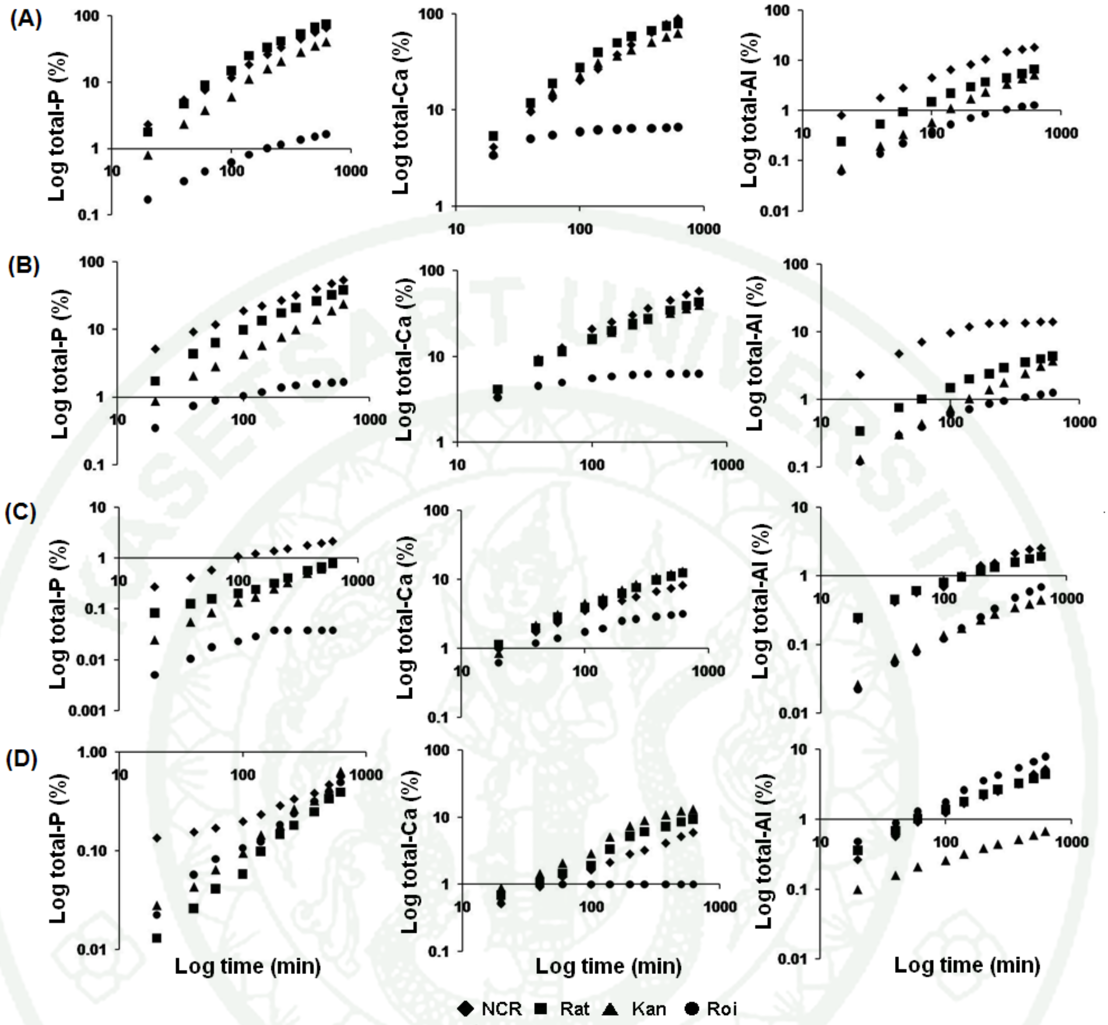


Figure 10 The kinetics of dissolution of NCR-, Rat-, Kan-, and Roi-PR in chemical extractants (A = 2%FA, B = 2%CA, C = NAC, D = AAC) plotted as log % of total-P Al and Ca dissolved versus log time.

crandallite and variscite but dissolution is slow resulting in a steady increase with time in % total Al/%total P.

The gradual dissolution of phosphate minerals and calcite in all PR samples is confirmed by XRD-patterns of residues after long term dissolution (Figure 11). All calcite in Rat- and Kan-PR had dissolved in acidic extractants (2%FA and 2%CA) and much less had dissolved in neutral and basic extractants (NAC and AAC). Calcite reflections in the Roi-PR XRD pattern overlap with variscite reflections so that it is uncertain that all calcite had dissolved. Dissolution of apatite in NCR-, Rat-, and Kan-PR was greater in 2%FA than in 2%CA and apatite was much less soluble under neutral and basic conditions. Crandallite and variscite were poorly soluble under both acidic and basic conditions as indicated by XRD patterns of residues being little different from those of the original materials.

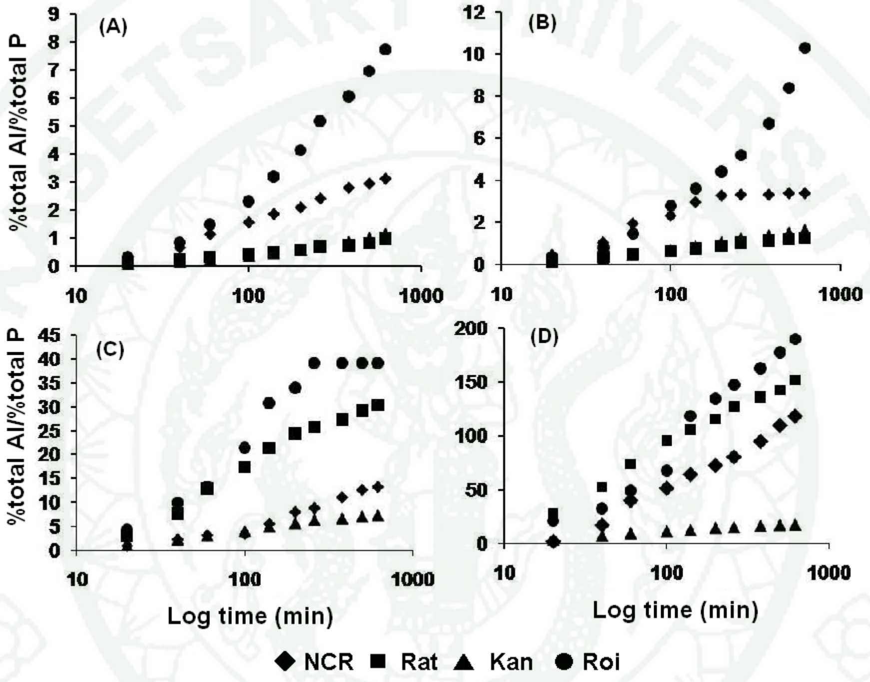


Figure 11 The kinetics of dissolution of NCR-, Rat-, Kan-, and Roi-PR in chemical extractants (A = 2%FA, B = 2%CA, C = NAC, D = AAC) plotted as % of total Al/total P dissolved versus log time illustrating the noncongruent dissolution of these phosphate rocks.

These results are consistent with observations of Hughes and Gilkes (1986) and Syers *et al.* (1986) who proposed that the main factor affecting solubility of PRs is the type of phosphate mineral. Hoare (1980), Stumm and Morgan (1996), and Francisco *et al.* (2008) proposed that crandallite and variscite have low reactivity in citrate reagents and soils and that they are unsuitable for agronomic use. Rocal-Herrero and Oelkers (2011) reported that the solubility of variscite increased at pH 9.0 and Stumm and Morgan (1996) proposed that the lowest solubility of variscite at 25°C occurred for 3 < pH < 6. The present study found that dissolution of Roi-PR (variscite) in AAC was higher than in the other extractants.

3. Summary

NCR-PR contains apatite which has 36% P_2O_5 and 61% CaO, which is close to values for ideal hydroxyapatite. It has an a-value as 9.336 Å and c-value as 6.889 Å which correspond to francolite. Rat- and Kan-PR include apatite and calcite as the main minerals. Apatites in Rat- and Kan-PR have a-values as 9.428 Å and 9.406 Å, and c-value as 6.882 Å and 6.888 Å, respectively. Their phosphorus and calcium concentrations are close to ideal hydroxyapatite. In addition to apatite, Kan-PR contains abundant crandallite which has a chemical composition close to ideal crandallite, and an a-value of 7.014 Å and c-value of 16.182 Å corresponding to ideal crandallite.

Roi-PR includes quartz as the main mineral, with variscite and crandallite as secondary minerals, and a little calcite mixed with the variscite. Crandallite in Roi-PR, has a lower and more varied content of CaO (from 7 to 17%) than for crandallite from Kan-PR (from 16 to 19%), and includes BaO at concentrations ranging from 2 to 6%. Roi-PR crandallite has an a-value as 7.025 Å and c-value as 16.191 Å, the a-value is slightly higher than published a-values of crandallite. This increasing of a-value may occur from the substitution of the larger Ba for the smaller Ca. Variscite in Roi-PR has average concentrations of P_2O_5 and Al_2O_3 of 58% and 41% which correspond to ideal variscite. It has a- and c-values of 9.826 Å and 8.573 Å, respectively. It also contains a little calcite mixed with variscite.

NCR-PR has the highest solubility in all of extractants (2%FA, 2%CA, and NAC) apart from AAC. Rat-, Kan-, and Roi-PR are less soluble. Roi-PR is most soluble in AAC extractant (pH 9.35) with little P being soluble in AAC for NCR-, Rat-, and Kan-PR. The kinetics of long term dissolution curves show that the P in NCR-PR with francolite as the main mineral is more soluble than for Rat-PR, Kan-PR, and Roi-PR, which contains P in hydroxyapatite, and variously crandallite and variscite. NCR-PR has a much higher reactivity than Rat-, Kan-, and Roi-PR and is therefore more suitable for agronomic use. Rat- and Kan-PR are less suitable and Roi-PR is unsuitable for agronomic use. Some consideration should be given to the elevated concentration of minor elements in the Thai PRs. Some elements will provide essential micronutrients to plants (Mn, Zn, Cu) but others are potentially toxic (Pb, Ca, As) if the PRs are applied at very high rates.

Soil Incubation

Delta bicarbonate extractable P (ΔP_{BC}) for soils incubated for 0 to 112 days are presented together with the changed pH (by DI-water and 0.01M $CaCl_2$ extractions) (pH_{H_2O} and pH_{CaCl_2}) and the changed EC. The data of P_{BC}, pH_{H_2O} and pH_{CaCl_2}, and EC were measured at 0, 3, 7, 14, 28, 56, and 112 days. The increases P_{BC} (ΔP_{BC}) of soils incubated at 3 to 112 days are compared with the P_{BC} at 0 day for eliminating the over extraction of P from PRs and MCP. The changed pH and EC of incubated soil from 3 to 112 days was studied, and the delta of pH (ΔpH_{H_2O} and ΔpH_{CaCl_2}) and EC (ΔEC) for 112 days are compared with the pH (pH_{H_2O} and pH_{CaCl_2}) and EC at 0 day. Moreover, the soils incubated at field capacity without PRs and MCP, called control, are analyzed for finding the influence of soils, themselves, to ΔP_{BC} of incubated soils.

1. Delta Bicarbonate Extractable P (ΔP_{BC}) of Soils Incubated for 0 to 112 Days

1.1 Delta Bicarbonate Extractable P (ΔP_{BC}) for 0 to 14 days

The results of soils incubated with NCR-PR (francolite), Rat-PR (hydroxyapatite), Kan-PR (hydroxyapatite included with crandallite), Roi-PR (variscite included with crandallite), and MCP (water soluble P) from 0 to 112 days are more or less complicated depending on the types of soils and the types and rates of P fertilizers. ΔP_{BC} for all treatments (all PRs and MCP treatments at low (L) and high (H) rate), continuously increases from 0 to about 14 days and then gradually decreases until sensibly constant over 14 to 112 days. The soil incubation curves for all treatments are shown in Figures 12 to 20. The increased availability of P is indicated by the slope of the linear regression line (Table 17), which the higher slope means the higher availability of P increased. The increase of the ΔP_{BC} with increasing time is indicated by the coefficient of determination (r^2) of plots of ΔP_{BC} against time (Table 17).

At 14 days of soil incubation with Nb-soil, the ΔP_{BC} for all treatments (all PRs and MCP treatments at low and high rate) increase with increasing time and the highest ΔP_{BC} values are at 14 days (Figure 12). The slopes of NCR- and Rat-PR treatments are higher than Kan- and Roi-PR, and MCP treatments (Table 17). The slopes are 0.23 to 0.25 for LNCR (r^2 0.89 – 0.97), 0.47 to 0.65 for HNCR (r^2 = 0.74 – 0.86), 0.17 to 0.28 for LRat (r^2 = 0.79 – 0.89), 0.55 to 0.82 for HRat (r^2 = 0.82 – 0.88), 0.14 to 0.16 for LKan (r^2 = 0.97 – 1.00), 0.30 to 0.42 for HKan (r^2 = 0.96 – 0.98), 0.13 to 0.17 for LRoi (r^2 = 1.00), 0.11 to 0.19 for HRoi (r^2 = 0.96 to 1.00), 0.10 to 0.17 for LMCP (r^2 = 0.91 - 0.97), and 0.09 to 0.25 for HMCP (r^2 = 0.73 – 0.94). Therefore, the increased availability of P from NCR- and Rat-PR treatments is clearly higher than from Kan-PR treatments, especially at high rates, and from Roi-PR and MCP treatments are clearly low.

The available P_{BC} values of each treatment at 14 day are 7 to 9 mg $kg^{-1}$for LNCR and 12 to 17 mg kg^{-1} for HNCR, 7 to 10 mg $kg^{-1}$for LRat and 13 to 19 mg kg^{-1} for HRat, 6 to 8 mg kg^{-1} for LKan and 10 to 11 mg kg^{-1} for HKan, 6 to 8 mg kg^{-1} for LRoi and HRoi, and 6 to 8 mg kg^{-1} for LMCP and 6 to 9 mg kg^{-1} for HMCP (Table 18). The increase in P_{BC} by percentage (% increased P_{BC}) of each treatment are 65 to 103% for LNCR and 176 to 178% for HNCR, 65 to 76% for LRat and 182 to 227% for HRat, 37 to 52% for LKan and 73 to 152% for HKan, 45 to 46% for LRoi and 38 to 50% for HRoi, and 37 to 42% for LMCP and 24 to 74% for HMCP (Table 18). The increase in Bic-P for NCR-PR in Nb-soil is similar to that for Rat-PR. Their increases in Bic-P are higher than for Kan-PR, while increases for Roi-PR and MCP are low. The ΔP_{BC} for NCR-, Rat-, and Kan-PR at high rate are clearly higher than at low rate, however, this result is not found for Roi-PR, and MCP. Therefore, NCR- and Rat-PR are more suitable for use on Nb-soil more than is Kan-PR, while Roi-PR and MCP are unsuitable.

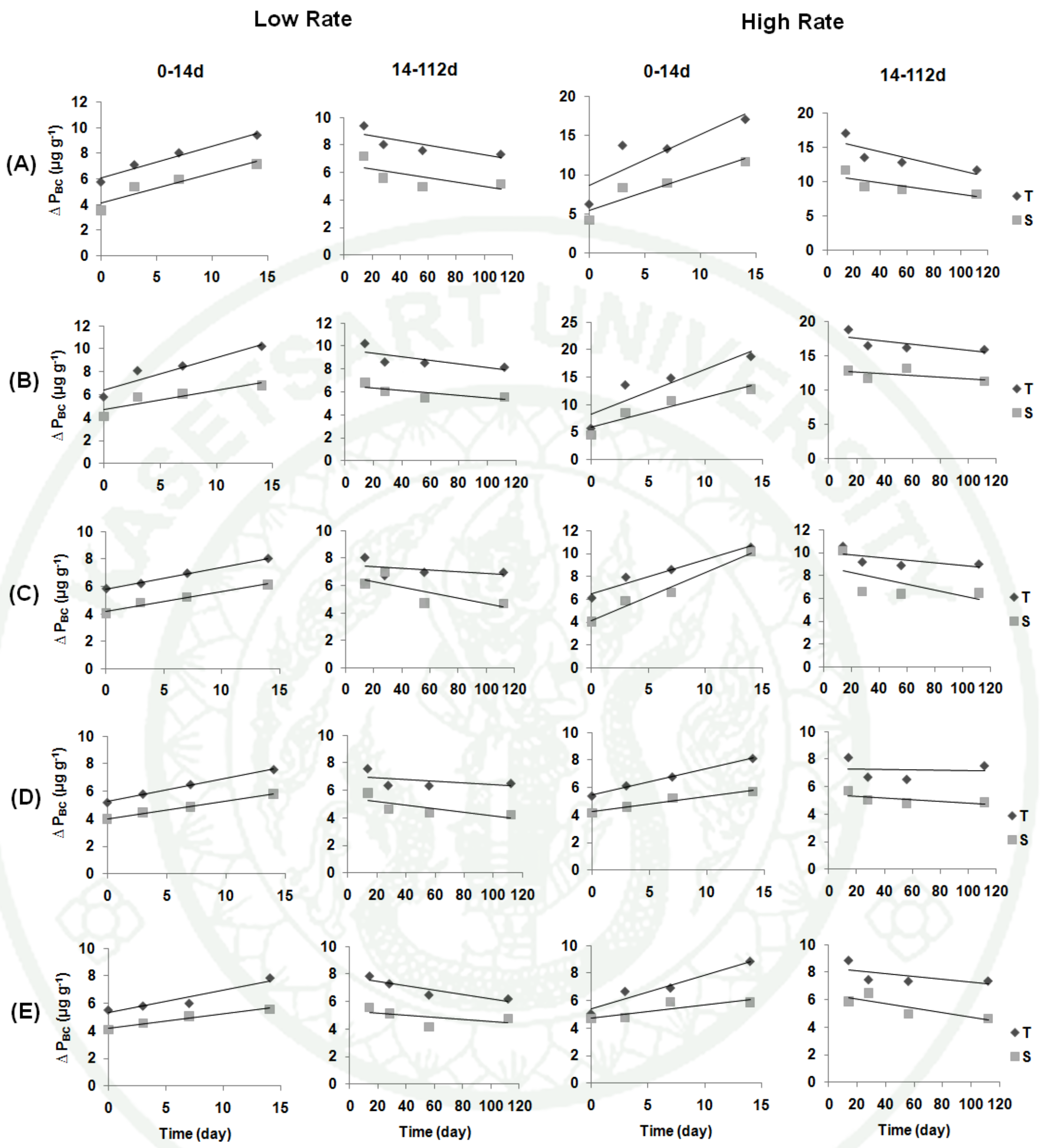


Figure 12 Plots of ΔP_{BC} versus time for Nb-soil incubated with NCR-PR (A), Rat-PR (B), Kan-PR (C), Roi-PR (D), and MCP (E) for 0 to 14 days and 14 to 112 days. (T = top-soil; S = sub-soil)

Table 17 The slope of the linear regression line and coefficient of determination (r^2) of the linear relationships between ΔP_{BC} and incubation time for 0 to 14 days.

Soil	Horizon	LNCR		HNCR		LRat		HRat		LKan		HKan	
		slope	r^2	slope	r^2	slope	r^2	slope	r^2	slope	r^2	slope	r^2
Nb	top	0.25	0.97	0.65	0.74	0.28	0.89	0.82	0.82	0.16	1.00	0.30	0.96
	sub	0.23	0.89	0.47	0.86	0.17	0.79	0.55	0.88	0.14	0.97	0.42	0.98
Ak	top	0.10	0.52	0.26	0.42	0.06	0.27	0.24	0.71	0.06	0.42	0.10	0.49
	sub	0.07	0.61	0.25	0.66	0.10	0.44	0.26	0.66	0.06	0.50	0.12	0.52
Kc	top	0.26	0.89	0.83	0.77	0.24	0.88	0.61	0.93	0.06	0.80	0.23	0.94
	sub	0.24	0.85	0.82	0.54	0.31	0.77	0.78	0.81	0.11	0.91	0.34	0.85
Klt	top	0.23	0.95	0.62	0.90	0.19	0.99	0.34	1.00	0.13	0.88	0.21	0.93
	sub	0.17	0.85	0.44	0.73	0.16	0.81	0.20	0.79	0.08	0.95	0.17	0.88
Nat	top	0.29	0.87	0.88	0.87	0.29	0.81	0.79	0.88	0.12	0.96	0.23	0.79
	sub	0.17	0.79	0.69	0.76	0.19	0.62	0.92	0.76	0.09	0.92	0.29	0.86
Tg	top	0.24	0.93	0.41	0.96	0.12	0.97	0.09	0.89	0.06	0.66	0.08	0.95
	sub	0.27	0.75	0.76	0.67	0.24	0.76	0.11	0.41	0.05	0.54	0.10	0.63
Hp	top	0.55	0.97	1.3	0.93	0.43	0.99	0.39	0.87	0.16	0.89	0.29	0.84
	sub	0.37	0.85	1.7	0.69	0.33	0.79	0.48	0.76	0.13	0.76	0.34	0.82
Koi	top	0.30	0.81	0.90	0.76	0.34	0.91	0.38	0.82	0.12	0.91	0.20	0.88
	sub	0.15	0.68	0.81	0.62	0.23	0.75	0.91	0.73	0.08	0.80	0.30	0.74
Knk	top	0.25	0.84	0.30	0.82	0.08	0.70	0.07	0.89	0.09	0.66	0.12	0.96
	sub	0.24	0.86	0.24	0.80	0.07	0.67	0.02	0.02	0.08	0.80	0.05	0.67

Table 17 (Continued).

Soil	Horizon	LRoi		HRoi		LMCP		HMCP	
		slope	r^2	slope	r^2	slope	r^2	slope	r^2
Nb	top	0.17	1.00	0.19	1.00	0.17	0.91	0.25	0.94
	sub	0.13	1.00	0.11	0.96	0.10	0.97	0.09	0.73
Ak	top	0.003	0.003	0.001	0.0001	-0.03	-0.53	-0.02	-0.22
	sub	-0.004	-0.008	0.014	0.06	-0.001	-0.09	-0.003	-0.02
Kc	top	0.09	0.99	0.09	0.32	0.05	0.64	0.14	0.76
	sub	0.07	0.83	0.05	0.96	-0.06	-0.46	0.01	0.30
Klt	top	0.07	0.94	0.07	0.90	0.12	0.91	0.02	0.04
	sub	0.06	0.91	0.04	0.93	0.02	0.02	-0.07	-0.16
Nat	top	0.10	0.85	0.11	0.95	0.10	0.97	0.20	0.98
	sub	0.06	0.75	0.04	0.65	0.06	0.75	0.10	0.75
Tg	top	0.06	0.88	0.06	0.76	0.11	0.90	-0.03	-0.01
	sub	0.001	0.002	0.06	0.91	0.04	0.44	-0.02	-0.30
Hp	top	0.11	0.93	0.24	0.88	0.09	0.40	-0.08	-0.02
	sub	0.03	0.71	0.04	0.50	0.03	0.21	-0.08	-0.07
Koi	top	0.01	0.32	0.06	0.55	0.08	0.68	-0.01	-0.03
	sub	0.04	0.37	0.04	0.32	0.04	0.19	0.09	0.44
Knk	top	0.04	0.56	0.06	0.79	0.16	0.93	0.10	0.26
	sub	0.06	0.73	0.04	0.96	0.21	0.85	0.23	0.61

Remark: Plots of ΔP_{BC} versus time of soil incubation shown in Figure 12 for Nb-soil, Figure 13 for Ak-soil, Figure 14 for Kc-soil, Figure 15 for Klt-soil, Figure 16 for Nat-soil, Figure 17 for Tg-soil, Figure 18 for Hp-soil, Figure 19 for Koi-soil, and Figure 20 for Knk-soil.

Table 18 Bic-P, ΔP_{BC}, the percentage increase in Bic-P and available P_{BC} level at 14 days of soil incubation.

Soil series		Low$^{1/}$	$P_{BC}$$^{2/}$	$\Delta P_{BC}$$^{3/}$	Avai.$P_{BC}$$^{4/}$	%increased	High$^{1/}$	$P_{BC}$$^{2/}$	$\Delta P_{BC}$$^{3/}$	Avai.$P_{BC}$$^{4/}$	%increased
			$\longleftarrow$	mg kg^{-1}	$\longrightarrow$	$P_{BC}$$^{5/}$		$\longleftarrow$	mg kg^{-1}	$\longrightarrow$	$P_{BC}$$^{5/}$
Nb	top	NCR	5.7	3.7	9 (L)	65	NCR	6.2	10.9	17 (M)	176
	sub		3.5	3.6	7 (L)	103		4.2	7.5	12 (M)	178
	top	Rat	5.8	4.4	10 (M)	76	Rat	5.7	13.0	19 (M)	227
	sub		4.1	2.7	7 (L)	65		4.5	8.3	13 (M)	182
	top	Kan	5.9	2.2	8 (L)	37	Kan	6.1	4.5	11 (M)	73
	sub		4.1	2.1	6 (L)	52		4.0	6.1	10 (M)	152
	top	Roi	5.2	2.4	8 (L)	45	Roi	5.4	2.7	8 (L)	50
	sub		4.0	1.8	6 (L)	46		4.2	1.6	6 (L)	38
	top	MCP	5.5	2.3	8 (L)	42	MCP	5.1	3.8	9 (L)	74
	sub		4.1	1.5	6 (L)	37		4.7	1.1	6 (L)	24
Ak	top	NCR	3.8	1.8	6 (L)	47	NCR	4.0	4.8	9 (L)	119
	sub		3.4	1.3	5 (L)	38		3.4	4.2	8 (L)	125
	top	Rat	4.0	1.6	6 (L)	39	Rat	5.1	3.7	9 (L)	73
	sub		2.8	1.9	5 (L)	68		3.5	4.3	8 (L)	122
	top	Kan	3.4	1.3	5 (L)	39	Kan	3.9	1.9	6 (L)	50
	sub		2.8	1.3	4 (L)	45		3.0	2.2	5 (L)	72
	top	Roi	3.7	0.7	4 (L)	19	Roi	3.9	1.2	5 (L)	30
	sub		3.6	0.4	4 (L)	12		3.7	0.7	4 (L)	20
	top	MCP	4.3	0.2	5 (L)	4	MCP	4.6	0.3	5 (L)	7
	sub		3.7	0.0	4 (L)	0		4.2	0.0	4 (L)	0
Kc	top	NCR	5.1	4.2	9 (L)	81	NCR	5.5	13.5	19 (M)	245
	sub		4.2	3.8	8 (L)	90		4.3	14.3	19 (M)	337
	top	Rat	5.3	3.8	9 (L)	73	Rat	6.7	9.4	16 (M)	140
	sub		4.0	5.1	9 (L)	127		5.2	12.3	18 (M)	235
	top	Kan	4.9	1.0	6 (L)	21	Kan	5.1	3.5	9 (L)	68
	sub		3.9	1.6	5 (L)	41		3.9	5.3	9 (L)	135
	top	Roi	4.8	1.2	6 (L)	25	Roi	5.0	1.3	6 (L)	25
	sub		4.0	0.9	5 (L)	22		4.5	0.7	5 (L)	16
	top	MCP	5.4	0.8	6 (L)	15	MCP	6.2	1.9	8 (L)	31
	sub		5.1	0.0	5 (L)	0		5.7	0.0	6 (L)	1
Klt	top	NCR	5.2	3.6	9 (L)	68	NCR	5.5	9.6	15 (M)	173
	sub		3.3	2.6	6 (L)	78		3.7	7.1	11 (M)	190
	top	Rat	5.2	2.7	8 (L)	52	Rat	5.8	4.7	11 (M)	82
	sub		3.6	2.5	6 (L)	70		4.1	3.1	7 (L)	76
	top	Kan	5.4	1.8	7 (L)	33	Kan	5.6	2.8	8 (L)	51
	sub		3.6	1.1	5 (L)	31		3.8	2.6	6 (L)	69
	top	Roi	5.2	0.9	6 (L)	17	Roi	5.3	1.0	6 (L)	19
	sub		3.6	0.8	4 (L)	21		4.0	0.5	5 (L)	12
	top	MCP	4.8	1.8	7 (L)	37	MCP	6.9	0.0	7 (L)	0
	sub		4.6	0.0	5 (L)	0		6.3	0.0	6 (L)	0

Table 18 (Continued).

Soil		Low$^{1/}$	$P_{BC}^{2/}$	$\Delta P_{BC}^{3/}$	Avai.$P_{BC}^{4/}$	%increased	High$^{1/}$	$P_{BC}^{2/}$	$\Delta P_{BC}^{3/}$	Avai.$P_{BC}^{4/}$	%increased
series			$\longleftarrow$	mg kg^{-1}	$\longrightarrow$	$P_{BC}^{5/}$		$\longleftarrow$	mg kg^{-1}	$\longrightarrow$	$P_{BC}^{5/}$
Nat	top	NCR	4.0	4.6	9 (L)	113	NCR	4.9	13.7	19 (M)	282
	sub		3.2	2.7	6 (L)	86		3.4	10.9	14 (M)	321
	top	Rat	4.2	4.6	9 (L)	108	Rat	4.8	12.4	17 (M)	261
	sub		3.3	3.1	6 (L)	93		3.9	14.9	19 (M)	387
	top	Kan	4.4	1.7	6 (L)	38	Kan	4.1	3.8	8 (L)	93
	sub		3.3	1.3	5 (L)	40		3.4	4.6	8 (L)	135
	top	Roi	4.0	1.4	5 (L)	35	Roi	4.3	1.7	6 (L)	40
	sub		3.2	0.9	4 (L)	30		3.8	0.7	5 (L)	19
	top	MCP	4.3	1.4	6 (L)	32	MCP	4.6	2.8	7 (L)	62
	sub		3.3	1.0	4 (L)	32		4.2	1.4	6 (L)	34
Tg	top	NCR	4.0	3.7	8 (L)	91	NCR	4.1	6.2	10 (M)	149
	sub		3.2	4.4	8 (L)	136		3.5	12.9	16 (M)	371
	top	Rat	4.0	1.8	6 (L)	44	Rat	4.2	1.3	6 (L)	30
	sub		3.2	3.7	7 (L)	116		3.7	2.0	6 (L)	55
	top	Kan	3.8	1.0	5 (L)	26	Kan	4.4	1.0	5 (L)	23
	sub		3.3	0.7	4 (L)	21		3.4	1.7	5 (L)	48
	top	Roi	4.0	1.0	5 (L)	24	Roi	4.3	0.9	5 (L)	21
	sub		3.5	0.1	4 (L)	2		3.9	0.7	5 (L)	17
	top	MCP	3.9	1.6	6 (L)	42	MCP	9.8	0.0	10 (L)	0
	sub		3.5	0.4	4 (L)	11		7.0	0.0	7 (L)	0
Hp	top	NCR	7.9	8.1	16 (M)	103	NCR	8.2	20.1	28 (H)	246
	sub		3.9	5.8	10 (M)	149		4.0	28.6	33 (H)	713
	top	Rat	7.8	5.9	14 (M)	76	Rat	8.3	5.8	14 (M)	70
	sub		3.6	5.4	9 (L)	151		4.1	7.7	12 (M)	187
	top	Kan	8.1	2.1	10 (M)	26	Kan	8.6	3.7	12 (M)	43
	sub		3.1	2.0	5 (L)	63		3.2	5.4	9 (L)	170
	top	Roi	7.6	1.4	9 (L)	19	Roi	8.1	3.2	11 (M)	39
	sub		3.5	0.5	4 (L)	14		3.7	0.7	4 (L)	17
	top	MCP	9.1	0.9	10 (M)	10	MCP	16.7	0.0	17 (L)	0
	sub		3.6	0.1	4 (L)	4		8.9	0.0	9 (L)	0
Koi	top	NCR	4.0	4.9	9 (L)	122	NCR	4.3	14.6	19 (M)	343
	sub		3.3	2.6	6 (L)	78		3.5	14.2	18 (M)	403
	top	Rat	4.1	5.2	9 (L)	127	Rat	4.4	6.1	11 (M)	139
	sub		3.6	3.8	7 (L)	106		4.0	15.0	19 (M)	379
	top	Kan	3.8	1.8	6 (L)	46	Kan	3.9	3.0	7 (L)	77
	sub		3.1	1.2	4 (L)	41		3.4	4.7	8 (L)	139
	top	Roi	4.6	0.2	5 (L)	5	Roi	4.3	1.1	5 (L)	27
	sub		3.1	0.9	4 (L)	29		3.5	1.0	5 (L)	29
	top	MCP	4.2	0.9	5 (L)	22	MCP	5.5	0.0	6 (L)	0
	sub		3.6	0.2	4 (L)	5		4.6	0.8	5 (L)	18

Table 18 (Continued).

Soil series		Low[1/]	P_{BC}[2/]	ΔP_{BC}[3/]	Avai.P_{BC}[4/]	%increased P_{BC}[5/]	High[1/]	P_{BC}[2/]	ΔP_{BC}[3/]	Avai.P_{BC}[4/]	%increased P_{BC}[5/]
			←	mg kg^{-1}	→			←	mg kg^{-1}	→	
Knk	top	NCR	2.9	3.8	7 (L)	129	NCR	3.1	4.9	8 (L)	160
	sub		3.0	3.8	7 (L)	126		3.2	3.8	7 (L)	118
	top	Rat	3.1	1.2	4 (L)	38	Rat	3.6	1.0	5 (L)	28
	sub		3.0	1.2	4 (L)	39		3.3	1.0	4 (L)	29
	top	Kan	2.7	1.3	4 (L)	49	Kan	3.1	1.8	5 (L)	56
	sub		3.1	1.2	4 (L)	40		3.3	0.9	4 (L)	26
	top	Roi	3.4	0.7	4 (L)	21	Roi	3.8	0.9	5 (L)	23
	sub		3.1	1.0	4 (L)	32		4.2	0.6	5 (L)	14
	top	MCP	3.5	2.4	6 (L)	69	MCP	7.2	1.3	9 (L)	18
	sub		3.0	3.0	6 (L)	101		3.6	3.2	7 (L)	90

[1/] Low = low rate of PRs and MCP treatments, High = high rate of PRs and MCP treatments; [2/] P_{BC} = bicarbonate extractable P at 0 day (control); [3/] ΔP_{BC} = increased P_{BC} at 14 days of PRs and MCP treatments; [4/] Avai.P_{BC} = the extracted P_{BC} at 14 days with available P_{BC} level in parenthesis, where L (low) is < 10; M (medium) is 10-20; H (high) is 20-40 (mg kg^{-1}) (Marx *et al.*, 1999); [5/] % increased P_{BC} = the percentage of ΔP_{BC} by calculation (% increased P_{BC} = $(\Delta P_{BC}/P_{BC}) \times 100$).

For Ak-soil, the values of ΔP_{BC} for NCR-, Rat-, and Kan-PR treatments increase with increasing time, while ΔP_{BC} of Roi-PR and MCP are relatively constant (Figure 13). The highest ΔP_{BC} for NCR-, Rat-, and Kan-PR treatments are at 14 days. The slopes of NCR-, Rat-, and Kan-PR at low rate are similar, and clearly higher than for Roi-PR, and MCP. At high rate, the slopes of NCR- and Rat-PR are similar and higher than for Kan-PR, Roi-PR, and MCP (Table 17). The slopes are 0.07 to 0.10 for LNCR (r^2 = 0.52 – 0.61) and 0.25 to 0.26 for HNCR (r^2 = 0.42 – 0.66), 0.06 to 0.10 for LRat (r^2 = 0.27 – 0.44) and 0.24 to 0.26 for HRat (r^2 = 0.66 – 0.71), 0.06 for LKan (r^2 = 0.42 – 0.50) and 0.10 to 0.12 for HKan (r^2 = 0.49 – 0.52), -0.004 to 0.003 for LRoi (r^2 = -0.008 – 0.003) and 0.001 to 0.014 for HRoi (r^2 = 0.0001 – 0.06), and -0.001 to -0.03 for LMCP (r^2 = -0.09 – -0.53) and -0.003 to -0.02 for HMCP (r^2 = -0.02 – -0.22).

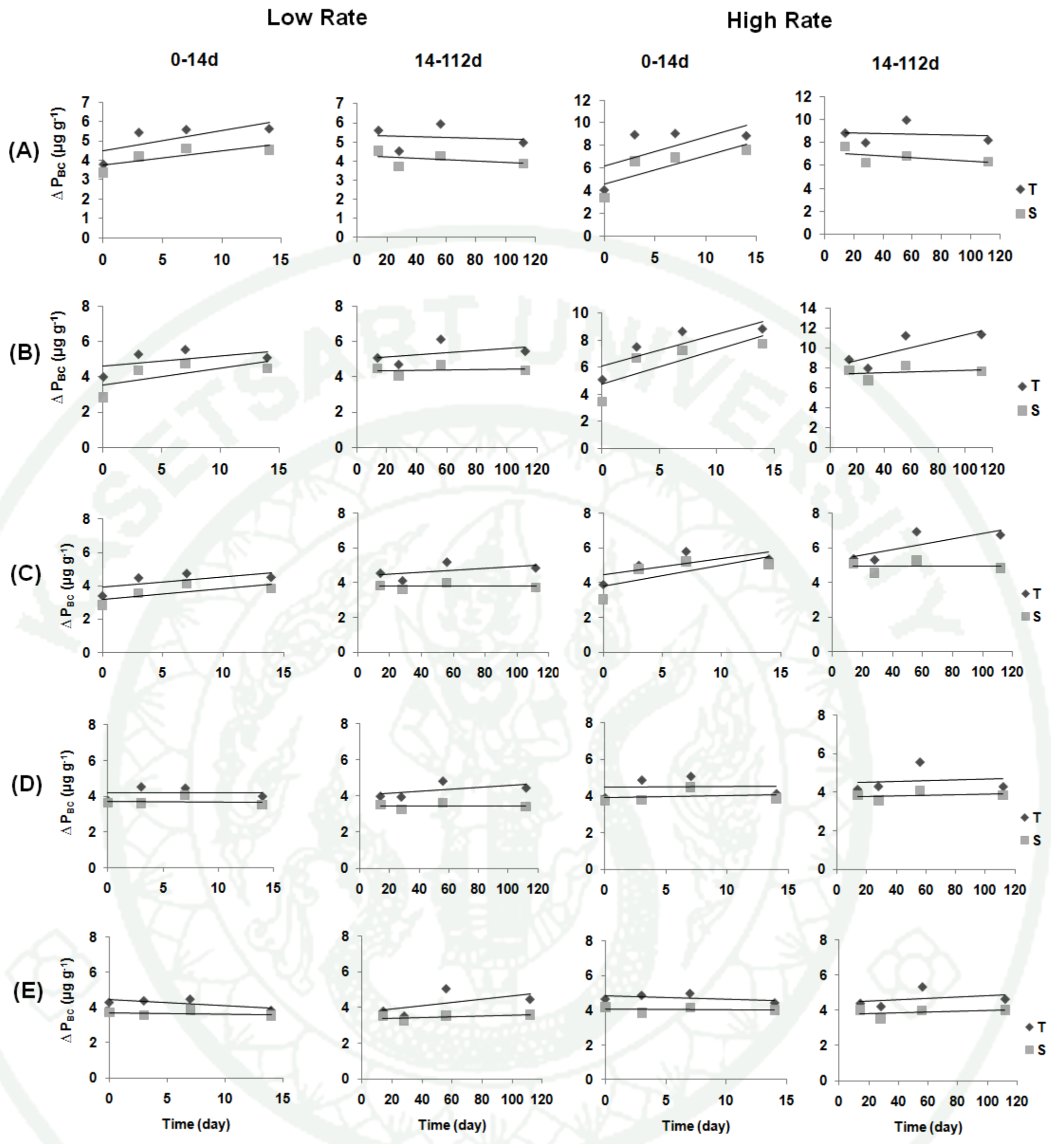


Figure 13 Plots of ΔP_{BC} versus time for Ak-soil incubated with NCR-PR (A), Rat-PR (B), Kan-PR (C), Roi-PR (D), and MCP (E) at 0 to 14 days and 14 to 112 days.

The available P_{BC} values at 14 day of each treatment are 5 to 6 mg kg^{-1}for LNCR and LRat and 8 to 9 mg kg^{-1} for HNCR and HRat, 4 to 5 mg kg^{-1} for LKan and 5 to 6 mg kg^{-1} for HKan, and 4 to 5 mg kg^{-1} for LRoi HRoi LMCP and HMCP (Table 18). The % increases in P_{BC} for each treatments are 38 to 47% for LNCR and 119 to 125% for HNCR, 39 to 68% for LRat and 73 to 122% for HRat, 39 to 45% for LKan and 50 to 72% for HKan, 12 to 19% for LRoi and 20 to 30% for HRoi, and 0 to 7%

for LMCP and HMCP (Table 18). The increases in Bic-P forNCR-, Rat-, and Kan-PR at low rate are similar, and clearly higher than for Roi-PR and MCP. At high rate, however, values of ΔP_{BC} for NCR- and Rat-PR are similar and higher than for Kan-PR, Roi-PR and MCP. In addition, the values of ΔP_{BC} for NCR-, and Rat-PR at high rate are clearly higher than at low rate. Therefore, NCR- and Rat-PR are more suitable for use on Ak-soil more than is Kan-PR, while Roi-PR and MCP are unsuitable. P fixation in Ak-soil is clearly higher than in Nb-soil, since the % increase in P_{BC} for all treatments for Ak-soil is less than for Nb-soil including MCP treatments for which most of the added soluble P had been fixed and was not recovered as Bic-P.

For Kc-soil, the values of ΔP_{BC} for NCR-, and Rat-PR treatments increase with increasing time, while ΔP_{BC} of Kan– and Roi-PR, and MCP are relatively constant (Figure 14). The highest ΔP_{BC} of all treatments are at 14 days. The slopes of NCR- and Rat-PR at low rate are similar and higher than Kan-PR, Roi-PR, and MCP. At high rate, the slopes of NCR-PR are higher than Rat-PR. However, they are clearly higher than for Kan-PR, Roi-PR, and MCP (Table 17). The slopes are 0.24 to 0.26 for LNCR (r^2 = 0.85 – 0.89) and 0.82 to 0.83 for HNCR (r^2 = 0.54 – 0.77), 0.24 to 0.31 for LRat (r^2 = 0.77 – 0.88) and 0.61 to 0.78 for HRat (r^2 = 0.81 – 0.93), 0.06 to 0.11 for LKan (r^2 = 0.80 – 0.91) and 0.23 to 0.34 for HKan (r^2 = 0.85 – 0.94), 0.07 to 0.09 for LRoi (r^2 = 0.83 – 0.99) and 0.05 to 0.09 for HRoi (r^2 = 0.32 – 0.96), and -0.06 to 0.05 for LMCP (r^2 = -0.46 – 0.64) and 0.01 to 0.14 for HMCP (r^2 = 0.30 – 0.76).

The available P_{BC} values at 14 day of each treatment are 8 to 9 mg kg^{-1} for LNCR and LRat and 16 to 19 mg kg^{-1} for HNCR and HRat, 5 to 6 mg kg^{-1} for LKan and 9 mg kg^{-1} for HKan, 5 to 6 mg kg^{-1} for LRoi HRoi and LMCP, and 6 to 8 mg kg^{-1} for HMCP (Table 18). The % increases in P_{BC} for each treatment are 81 to 90% for LNCR and 245 to 337% for HNCR, 73 to 127% for LRat and 140 to 235% for HRat, 21 to 41% for LKan and 68 to 135% for HKan, 16 to 25% for LRoi and HRoi, and 0 to 15% for LMCP and 1 to31% for HMCP (Table 18). The increase in Bic-P for NCR-PR in Kc-soil is similar to that for Rat-PR. Their increases in Bic-P

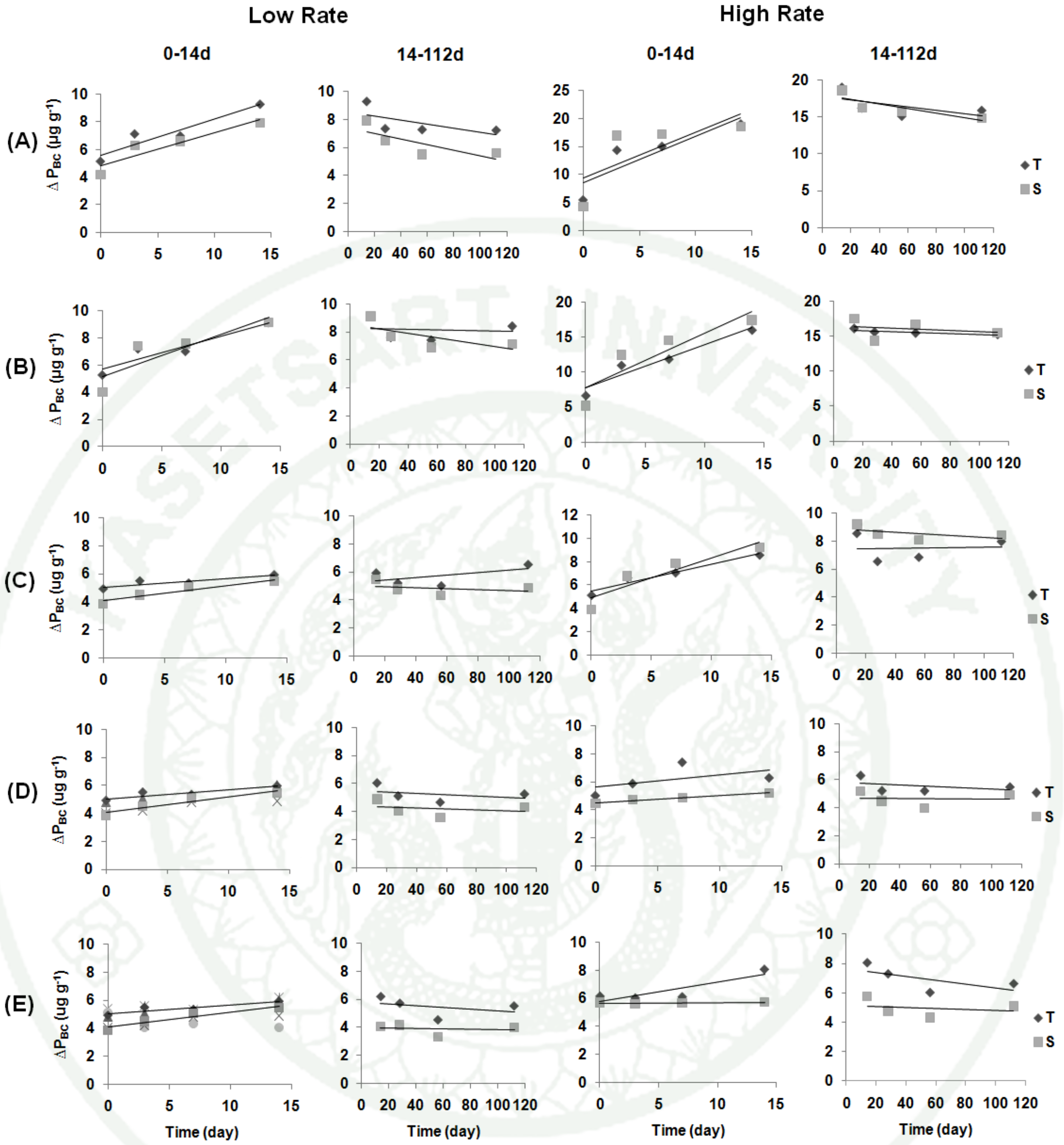


Figure 14 Plots of ΔP_{BC} versus time for Kc-soil incubated with NCR-PR (A), Rat-PR (B), Kan-PR (C), Roi-PR (D), and MCP (E) at 0 to 14 days and 14 to 112 days.

are higher than for Kan-PR, while the increases for Roi-PR and MCP are relatively constant. The ΔP_{BC} for NCR-, Rat-, and Kan-PR at high rate are clearly higher than at low rate, however, this result is not found for Roi-PR and MCP. Therefore, NCR- and Rat-PR are more suitable for use on Kc-soil more than is Kan-PR, while Roi-PR and MCP are unsuitable.

For Klt-soil, the values of ΔP_{BC} for NCR-, Rat-, and Kan-PR treatments increase with increasing time, while ΔP_{BC} of Roi-PR, and MCP are relatively constant (Figure 15). The highest ΔP_{BC} of NCR-, Rat-, and Kan-PR treatments are at 14 days. The slopes of NCR-PR treatments are higher than Rat-PR, while the slopes of Rat-PR are higher than Kan-PR, Roi-PR, and MCP treatments (Table 17). The slopes are 0.17 to 0.23 for LNCR (r^2 = 0.85 – 0.95) and 0.44 to 0.62 for HNCR (r^2 = 0.73 – 0.90), 0.16 to 0.19 for LRat (r^2 = 0.81 – 0.99) and 0.20 to 0.34 for HRat (r^2 = 0.79 – 1.00), 0.08 to 0.13 for LKan (r^2 = 0.88 – 0.95) and 0.17 to 0.21 for HKan (r^2 = 0.88 – 0.93), 0.06 to 0.07 for LRoi (r^2 = 0.91 – 0.94) and 0.04 to 0.07 for HRoi (r^2 = 0.90 – 0.93), 0.02 to 0.12 for LMCP (r^2 = 0.02 – 0.91) and -0.07 to 0.02 for HMCP (r^2 = -0.16 – 0.04).

The available P_{BC} values at 14 day of each treatment are 6 to 9 mg $kg^{-1}$for LNCR and 11 to 15 mg $kg^{-1}$for HNCR, 6 to 8 mg $kg^{-1}$for LRat and 7 to 11 mg $kg^{-1}$for HRat, 5 to 7 mg kg^{-1} for LKan and 6 to 8 mg $kg^{-1}$for HKan, 4 to 6 mg $kg^{-1}$for LRoi and HRoi, and 5 to 7 mg kg^{-1} for LMCP and HMCP (Table 18). The % increases in P_{BC} for each treatment are 68 to 78% for LNCR and 173 to 190% for HNCR, 52 to 70% for LRat and 76 to 82% for HRat, 31 to 33% for LKan and 51 to 69% for HKan, 12 to 21% for LRoi and HRoi, and 0 to 37% for LMCP and no increased amount of available P_{BC} for HMCP (Table 18). The increase in Bic-P for NCR-PR in Klt-soil is higher than Rat- and Kan-PR, while the increases for Roi-PR and MCP are low. The ΔP_{BC} for NCR-, Rat-, and Kan-PR at high rate are clearly higher than at low rate, however, this result is not found for Roi-PR and MCP. Therefore, NCR- and Rat-PR are more suitable for use on Klt-soil more than is Kan-PR, while Roi-PR and MCP are unsuitable.

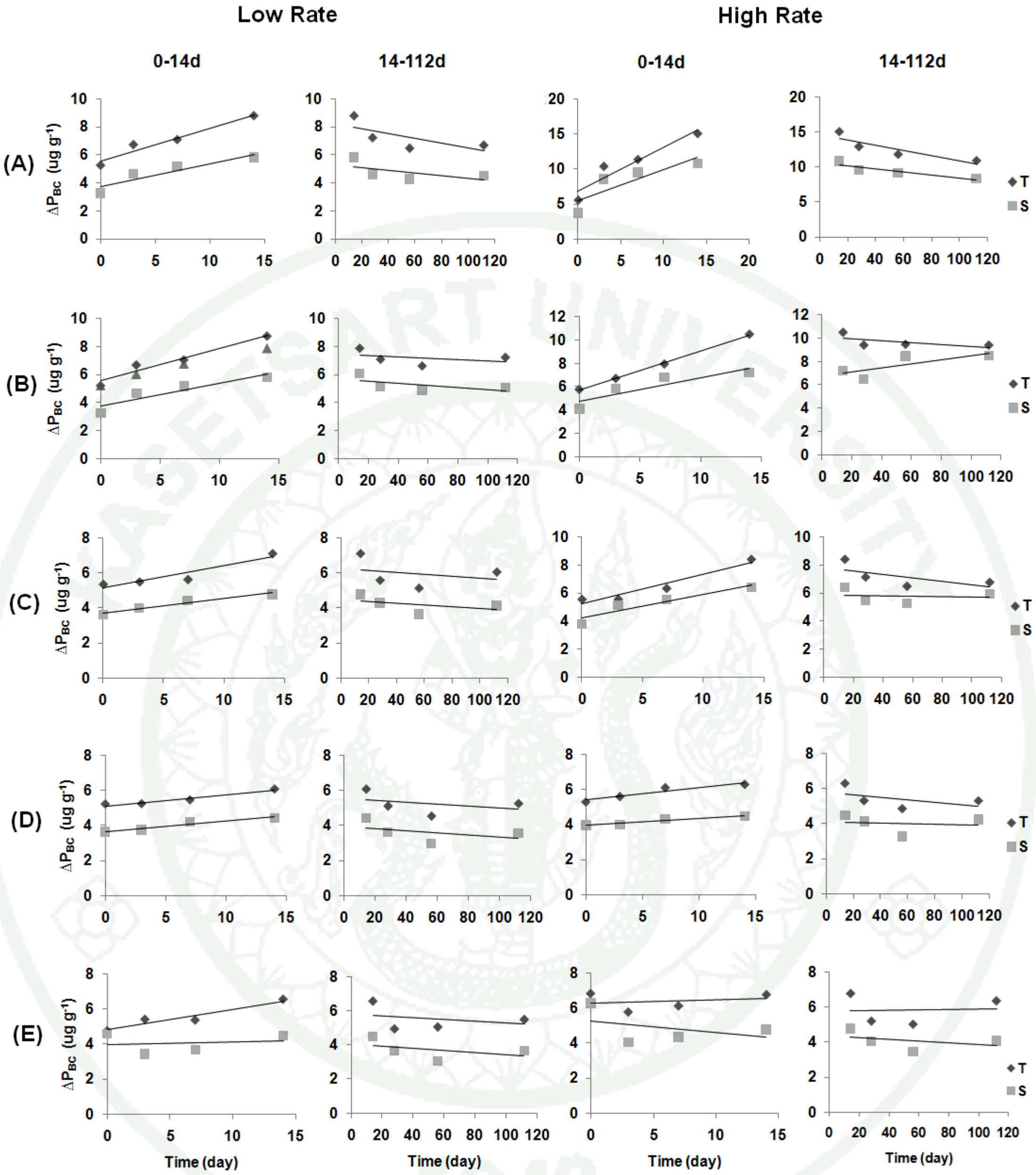


Figure 15 Plots of ΔP_{BC} versus time for Klt-soil incubated with NCR-PR (A), Rat-PR (B), Kan-PR (C), Roi-PR (D), and MCP (E) at 0 to 14 days and 14 to 112days.

For Nat-soil, the values of ΔP_{BC} for PRs and MCP treatments increase with increasing time (Figure 16). The highest ΔP_{BC} of PRs and MCP treatments are at 14 days. The slopes of NCR- and Rat-PR treatments are similar and clearly higher than Kan-PR, Roi-PR, and MCP (Table 17). The slopes are 0.17 to 0.29 for LNCR ($r^2 = 0.79 – 0.87$) and 0.69 to 0.88 for HNCR ($r^2 = 0.76 – 0.87$), 0.19 to 0.29 for LRat ($r^2 = 0.62 – 0.81$) and 0.79 to 0.92 for HRat ($r^2 = 0.76 – 0.88$), 0.09 to 0.12 for LKan ($r^2 = 0.92 – 0.96$) and 0.23 to 0.29 for HKan ($r^2 = 0.79 – 0.86$), 0.06 to 0.10 for LRoi ($r^2 = 0.75 – 0.85$) and 0.04 to 0.11 for HRoi ($r^2 = 0.65 – 0.95$), 0.06 to 0.10 for LMCP ($r^2 = 0.75 – 0.97$) and 0.10 to 0.20 for HMCP ($r^2 = 0.75 – 0.98$).

The available P_{BC} values at 14 day of each treatment are 6 to 9 mg $kg^{-1}$for LNCR and LRat, and 14 to 19 mg $kg^{-1}$for HNCR and HRat, 5 to 6 mg $kg^{-1}$for LKan and 8 mg $kg^{-1}$for HKan, 4 to 5 mg kg^{-1} for LRoi and 5 to 6 mg kg^{-1} for HRoi, and 4 to 6 mg kg^{-1} for LMCP and 6 to 7 mg kg^{-1} for HMCP (Table 18). The % increases in P_{BC} for each treatment are 86 to 113% for LNCR and 282 to 321% for HNCR, 93 to 108% for LRat and 261 to 387% for HRat, 38 to 40% for LKan and 93 to 135% for HKan, 30 to 35% for LRoi and 19 to 40% for HRoi, and 32% for LMCP and 34 to 62% for HMCP (Table 18). The increase in Bic-P for NCR-PR in Nat-soil is similar to that for Rat-PR. Their increases in Bic-P are higher than for Kan-PR, Roi-PR and MCP. The increase in Bic-P for Kan-PR at low rate is similar to that for Roi-PR and MCP, while the increase for Kan-PR at high rate is higher than for Roi-PR and MCP. The ΔP_{BC} for NCR-, Rat-, and Kan-PR at high rate are clearly higher than at low rate, however, this result is not found for Roi-PR, and MCP. Therefore, NCR- and Rat-PR are more suitable for use on Nat-soil more than in Kan-PR, while Roi-PR and MCP are unsuitable.

For Tg-soil, the values of ΔP_{BC} for NCR-, Rat-, and Kan-PR treatments increase with increasing time, while ΔP_{BC} of Roi-PR, and MCP are relatively constant (Figure 17). The highest ΔP_{BC} of PRs and MCP treatments are at 14 days. The slopes of NCR-PR treatments are higher than Rat-PRan-PR, Roi-PR, and MCP (Table 17). The slope of Rat-PR at low rate is higher than of Kan-PR, while at high rate, the slope

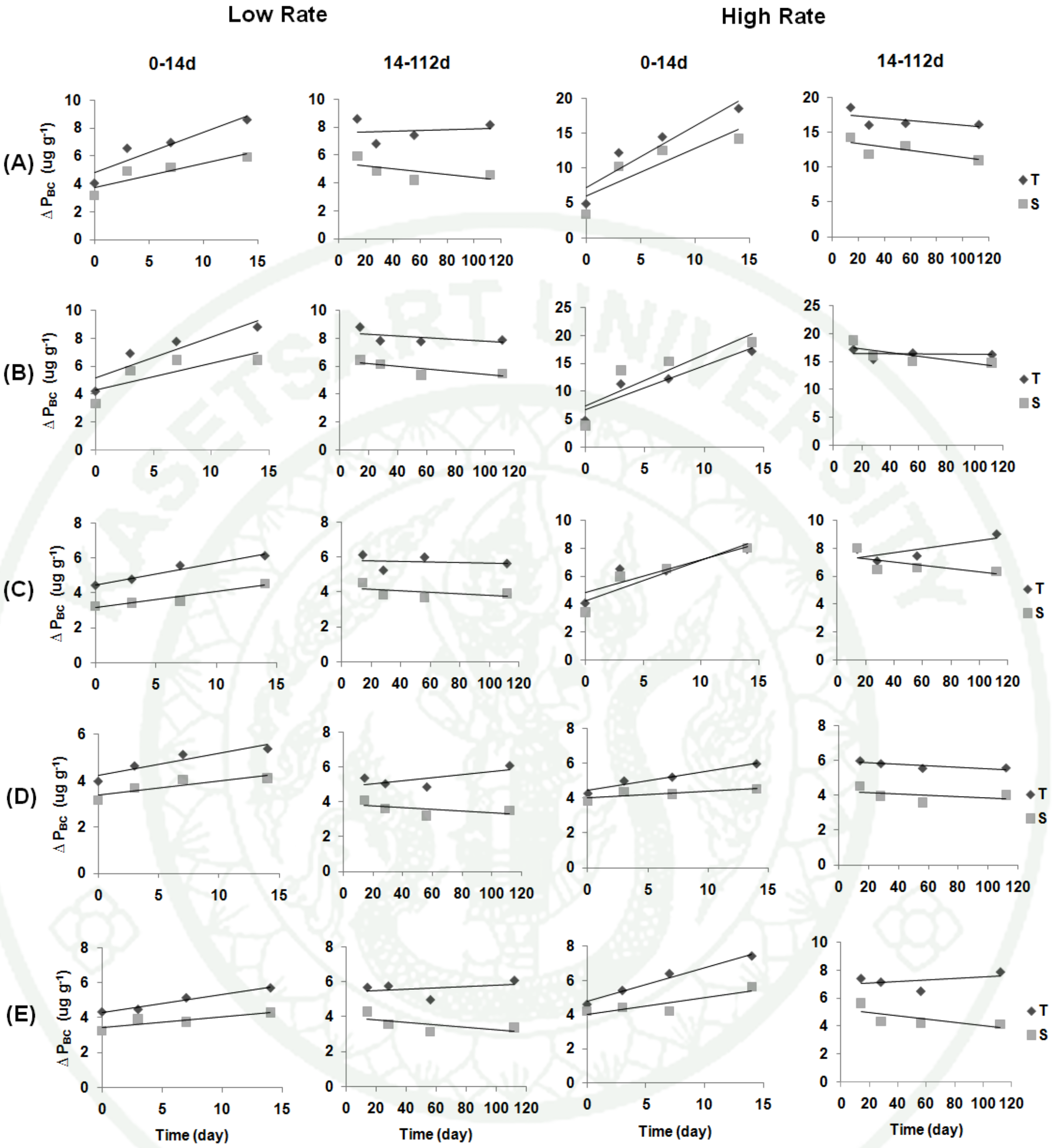


Figure 16 Plots of ΔP_{BC} versus time for Nat-soil incubated with NCR-PR (A), Rat-PR (B), Kan-PR (C), Roi-PR (D), and MCP (E) at 0 to 14 days and 14 to 112 days.

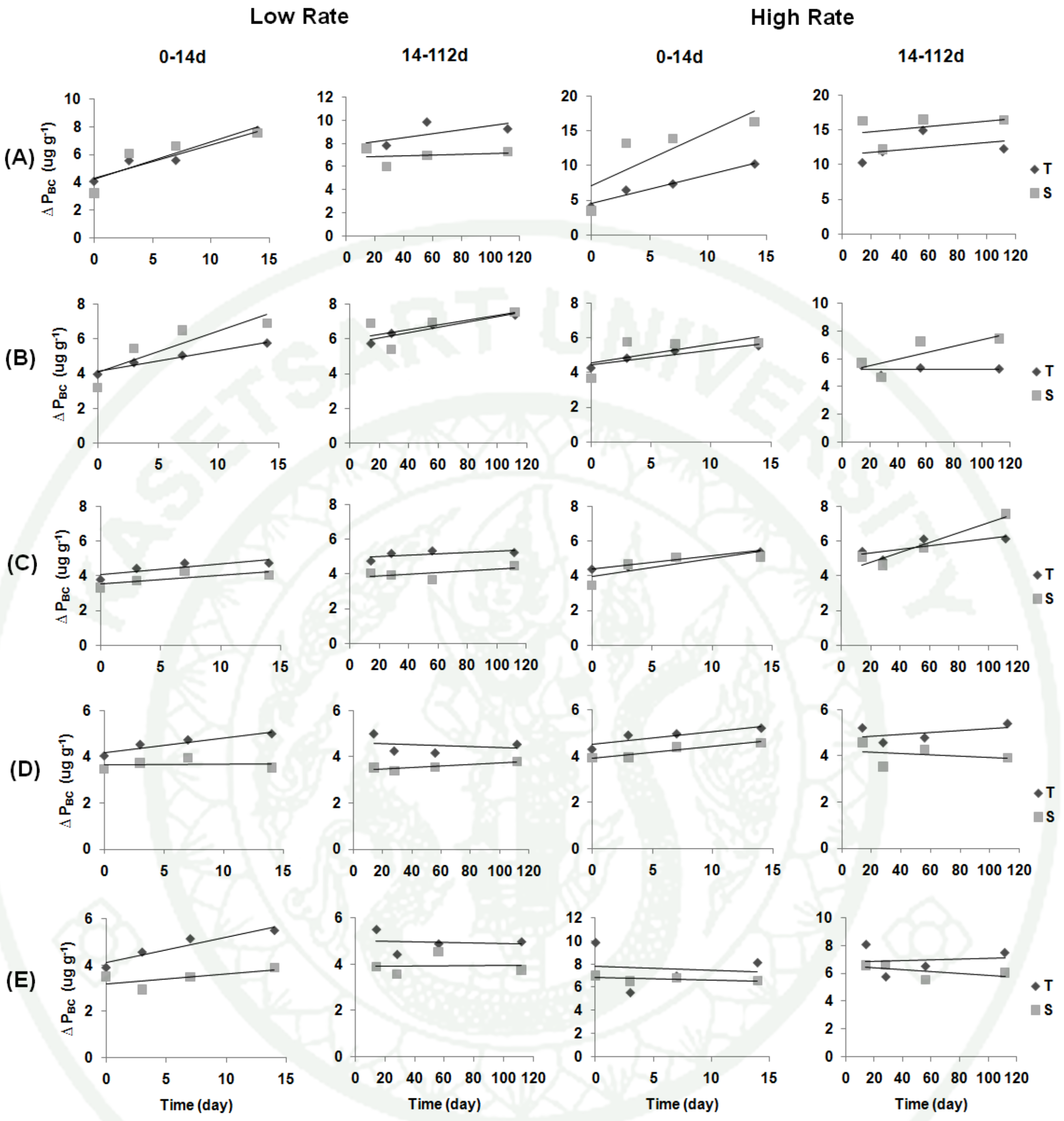


Figure 17 Plots of ΔP_{BC} versus time for Tg-soil incubated with NCR-PR (A), Rat-PR (B), Kan-PR (C), Roi-PR (D), and MCP (E) at 0 to 14 days and 14 to 112 days.

of Rat-PR is similar to that for Kan-PR. The slopes are 0.24 to 0.27 for LNCR (r^2 = 0.75 – 0.93) and 0.41 to 0.76 for HNCR (r^2 = 0.67 – 0.96), 0.12 to 0.24 for LRat (r^2 = 0.76 – 0.97) and 0.09 to 0.11 for HRat (r^2 = 0.41 – 0.89), 0.05 to 0.06 for LKan (r^2 = 0.54 – 0.66) and 0.08 to 0.10 for HKan (r^2 = 0.63 – 0.95), 0.001 to 0.06 for LRoi (r^2 =

0.002 to 0.88) and 0.06 for HRoi (r^2 = 0.76 – 0.91), and 0.04 to 0.11 for LMCP (r^2 = 0.44 – 0.90) and -0.02 – -0.03 for HMCP (r^2 = -0.01 – -0.30).

The available P_{BC} values at 14 day of each treatment are 8 mg kg^{-1} for LNCR and 10 to 16 mg kg^{-1} for HNCR, 6 to 7 mg kg^{-1} for LRat and HRat, 4 to 5 mg kg^{-1} for LKan and HKan, 4 to 5 mg kg^{-1} for LRoi and HRoi, and 4 to 6 mg kg^{-1} for LMCP and 7 to 10 mg kg^{-1} for HMCP (Table 18). The % increases in P_{BC} for each treatment are 91 to 136% for LNCR and 149 to 371% for HNCR, 44 to 116% for LRat and 30 to 55% for HRat, 21 to 26% for LKan and 23 to 48% for HKan, 2 to 4% for LRoi and 17 to 21% for HRoi, and 11 to 42% for LMCP and no increased amount of the available P_{BC} for HMCP (Table 18). The increase in Bic-P for NCR-PR in Tg-soil is higher than Rat-, Kan-, and Roi-PR, while the increase for MCP is low and found only at low rate. The ΔP_{BC} for NCR at high rate are clearly higher than at low rate, however, this result is not found for Rat-PR, Kan-PR, Roi-PR, and MCP. Therefore, NCR-PR is more suitable for use on Tg-soil more than Rat-PR, while Kan-PR, Roi-PR, and MCP are unsuitable.

For Hp-soil, the values of ΔP_{BC} for NCR-, Rat-, and Kan-PR treatments increase with increasing time, while ΔP_{BC} of Roi-PR are low and of MCP are relatively constant (Figure 18). The highest ΔP_{BC} of NCR-, Rat-, and Kan-PR treatments are at 14 days. The slopes of NCR-PR treatments are higher than Rat-PR, however, they are clearly higher than for Kan-PR, Roi-PR, and MCP (Table 17). The slopes are 0.37 to 0.55 for LNCR (r^2 = 0.85 – 0.97) and 1.3 to 1.7 for HNCR (r^2 = 0.69 – 0.93), 0.33 to 0.43 for LRat (r^2 = 0.79 – 0.99) and 0.39 to 0.48 for HRat (r^2 = 0.76 – 0.87), 0.13 to 0.16 for LKan (r^2 = 0.76 – 0.89) and 0.29 to 0.34 for HKan (r^2 = 0.82 – 0.84), 0.03 to 0.11 for LRoi (r^2 = 0.71 to 0.93) and 0.04 to 0.24 for HRoi (r^2 = 0.50 – 0.88), and 0.03 to 0.09 for LMCP (r^2 = 0.21 – 0.40) and -0.08 for HMCP (r^2 = -0.02 – -0.07).

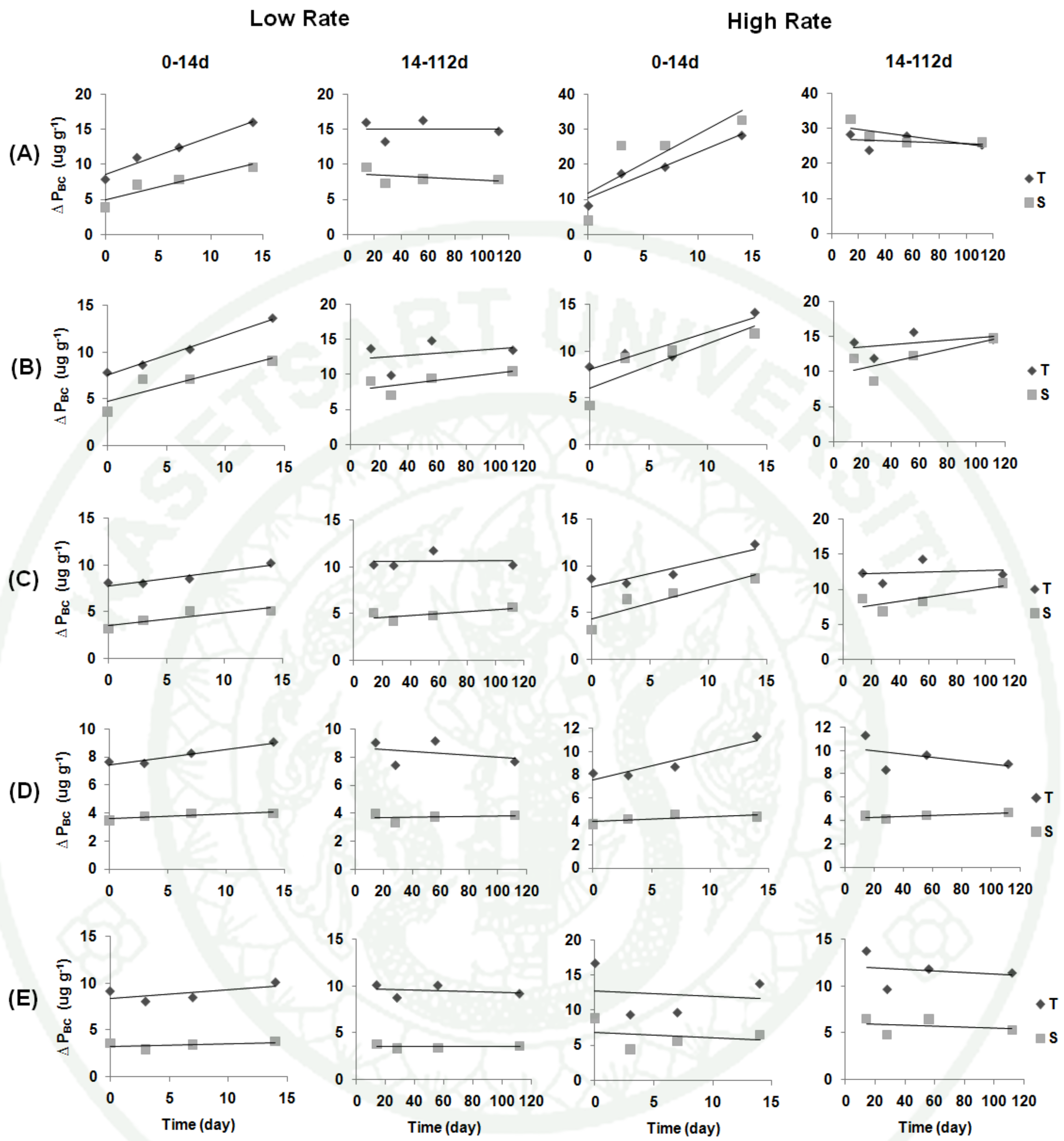


Figure 18 Plots of ΔP_{BC} versus time for Hp-soil incubated with NCR-PR (A), Rat-PR (B), Kan-PR (C), Roi-PR (D), and MCP (E) at 0 to 14 days and 14 to 112 days.

The available P_{BC} values at 14 day of each treatment are 10 to 16 mg kg^{-1} for LNCR and 28 to 33 mg kg^{-1} for HNCR, 9 to 14 mg kg^{-1} for LRat and 12 to 14 mg kg^{-1} for HRat, 5 to 10 mg kg^{-1} for LKan and 9 to 12 mg kg^{-1} for HKan, 4 to 9 mg kg^{-1} for LRoi and 4 to 11 mg kg^{-1} for HRoi, and 4 to 10 mg kg^{-1} for LMCP and 9 to 17 mg kg^{-1} for HMCP (Table 18). The % increases in P_{BC} for each treatment are 103 to

149% for LNCR and 246 to 713% for HNCR, 76 to 151% for LRat and 70 to 187% for HRat, 26 to 63% for LKan and 43 to 170% for HKan, 14 to 19% for LRoi and 17 to 39% for HRoi, and 4 to 10% for LMCP and no increased amount of the available P_{BC} for HMCP (Table 18). The increase in Bic-P for NCR-PR in Hp-soil is higher than Rat-, Kan-, and Roi-PR, while the increase for MCP is low and found only at low rate. The ΔP_{BC} for NCR at high rate are clearly higher than at low rate, however, this result is not found for Rat-PR, Kan-PR, Roi-PR, and MCP. Therefore, NCR-PR is more suitable for use on Hp-soil more than Rat-PR, while Kan-PR, Roi-PR, and MCP are unsuitable.

For Koi-soil, the values of ΔP_{BC} for NCR-, Rat-, and Kan-PR treatments increase with increasing time, while ΔP_{BC} of Roi-PR and MCP are low and relatively constant (Figure 19). The highest ΔP_{BC} of NCR-, Rat-, and Kan-PR treatments are at 14 days. The slopes of NCR-PR treatments are higher than Rat-PR, however, they are clearly higher than for Kan-PR, Roi-PR, and MCP (Table 17). The slopes are 0.15 to 0.30 for LNCR (r^2 = 0.68 – 0.81) and 0.81 to 0.90 for HNCR (r^2 = 0.62 – 0.76), 0.23 to 0.34 for LRat (r^2 = 0.75 – 0.91) and 0.38 to 0.91 for HRat (r^2 = 0.73 – 0.82), 0.08 to 0.12 for LKan (r^2 = 0.80 – 0.91) and 0.20 to 0.30 for HKan (r^2 = 0.74 – 0.88), 0.01 to 0.04 for LRoi (r^2 = 0.32 to 0.37) and 0.04 to 0.06 for HRoi (r^2 = 0.32 – 0.55), and 0.04 to 0.08 for LMCP (r^2 = 0.19 – 0.68) and -0.01 to 0.09 for HMCP (r^2 = -0.03 – 0.44).

The available P_{BC} values at 14 day of each treatment are 6 to 9 mg kg^{-1} for LNCR and 18 to 19 mg kg^{-1} for HNCR, 7 to 9 mg kg^{-1} for LRat and 11 to 19 mg kg^{-1} for HRat, 4 to 6 mg kg^{-1} for LKan and 7 to 8 mg kg^{-1} for HKan, 4 to 5 mg kg^{-1} for LRoi and HRoi, and 4 to 5 mg kg^{-1} for LMCP and 5 to 6 mg kg^{-1} for HMCP (Table 18). The % increases in P_{BC} for each treatment are 78 to 122% for LNCR and 343 to 403% for HNCR, 106 to 127% for LRat and 139 to 379% for HRat, 41 to 46% for LKan and 77 to 139% for HKan, 5 to 29% for LRoi and 27 to 29% for HRoi, and 5 to 22% for LMCP and 0 to 18% for HMCP (Table 18). The increase in Bic-P for NCR-PR at low rate in Koi-soil is similar to that for Rat-PR, while the increase at high rate is clearly higher than Rat-PR. However, their increases in Bic-P are higher than for

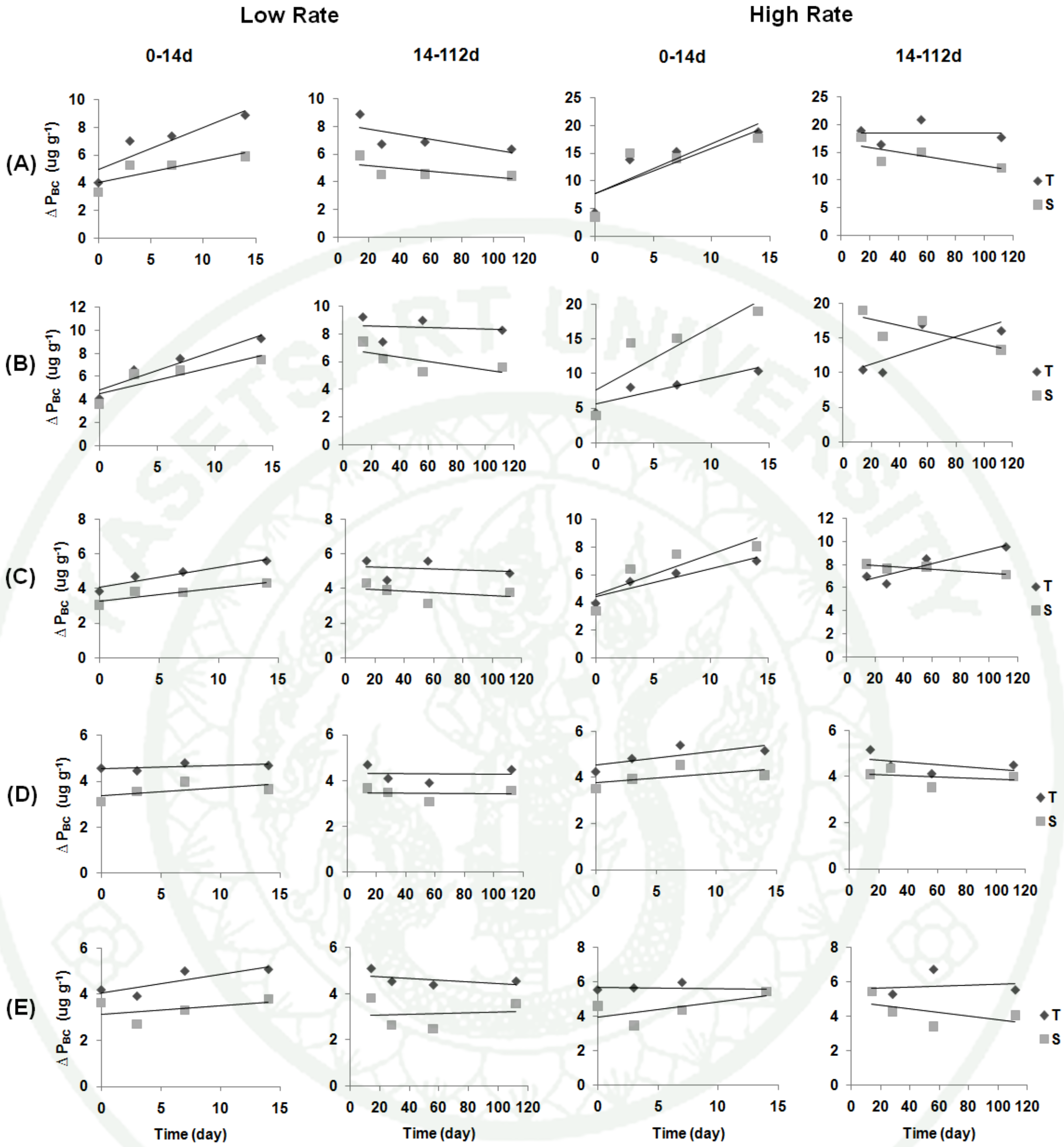


Figure 19 Plots of ΔP_{BC} versus time for Koi-soil incubated with NCR-PR (A), Rat-PR (B), Kan-PR (C), Roi-PR (D), and MCP (E) at 0 to 14 days and 14 to 112 days.

Kan-PR, Roi-PR and MCP. The increases in Bic-P for Kan-PR are higher than for Roi-PR and MCP. The ΔP_{BC} for NCR-, Rat-, and Kan-PR at high rate are clearly higher than at low rate, however, this result is not found for Roi-PR, and MCP. Therefore, NCR- and Rat-PR are more suitable for use on Koi-soil more than in Kan-PR, while Roi-PR and MCP are unsuitable.

For Knk-soil, the values of ΔP_{BC} for NCR-PR, Rat-PR, Kan-PR, and MCP increase with increasing time, while ΔP_{BC} of Roi-PR are low and relatively constant (Figure 20). The highest ΔP_{BC} of NCR-PR, Rat-PR, Kan-PR, and MCP treatments are at 14 days. The slopes of NCR-PR treatments are higher than Rat-PR,, Kan-PR, Roi-PR, and MCP, while the slopes of Rat-PR are similar to Kan-PR and lower than MCP (Table 17). The slopes are 0.24 to 0.25 for LNCR (r^2 = 0.84 – 0.86) and 0.24 to 0.30 for HNCR (r^2 = 0.80 – 0.82), 0.07 to 0.08 for LRat (r^2 = 0.67 – 0.70) and 0.02 to 0.07 for HRat (r^2 = 0.02 – 0.89), 0.08 to 0.09 for LKan (r^2 = 0.66 – 0.80) and 0.05 to 0.12 for HKan (r^2 = 0.67 – 0.96), 0.04 to 0.06 for LRoi (r^2 = 0.56 to 0.73) and 0.04 to 0.06 for HRoi (r^2 = 0.79 – 0.96), and 0.16 to 0.21 for LMCP (r^2 = 0.85 – 0.93) and 0.10 to 0.23 for HMCP (r^2 = 0.26 – 0.61).

The available P_{BC} values at 14 day of each treatment are 7 to 8 mg kg^{-1} for LNCR and HNCR, 4 to 5 mg kg^{-1} for LRat and HRat, 4 to 5 mg kg^{-1} for LKan and HKan, 4 to 5 mg kg^{-1} for LRoi and HRoi, and 6 mg kg^{-1} for LMCP and 7 to 9 mg kg^{-1} for HMCP (Table 18). The % increases in P_{BC} for each treatment are 126 to 129% for LNCR and 118 to 160% for HNCR, 38 to 39% for LRat and 28 to 29% for HRat, 40 to 49% for LKan and 26 to 56% for HKan, 21 to 32% for LRoi and 14 to 23% for HRoi, and 69 to 101% for LMCP and 18 to 90 for HMCP (Table 18). The increase in Bic-P for NCR-PR in Knk-soil is higher than MCP, while the increase for MCP is higher than for Rat-, Kan-, and Roi-PR. The ΔP_{BC} for NCR at high rate is similar to at low rate, this result is found for Rat-PR, Kan-PR, Roi-PR, and MCP. Therefore, NCR-PR and MCP at low rate is more suitable for use on Knk-soil more than Rat-, Kan-, and Roi-PR.

The results of all soils incubation at 14 days clearly show that NCR-PR (francolite) has the highest reactivity and most suitable for all soils. Rat-PR (hydroxyapatite) has higher reactivity than Kan-PR (hydroxyapatite included with crandallite) and Roi-PR (variscite included with crandallite). Its reactivity is similar to NCR-PR in many soils, except only in soils developed on granite which the texture is sand, loamy sand, and sandy loam viz Tg-, Hp-, Koi-, and expecially Knk-soil (the sandy soil). Kan-PR has higher reactivity than Roi-PR, however, its reactivity is more

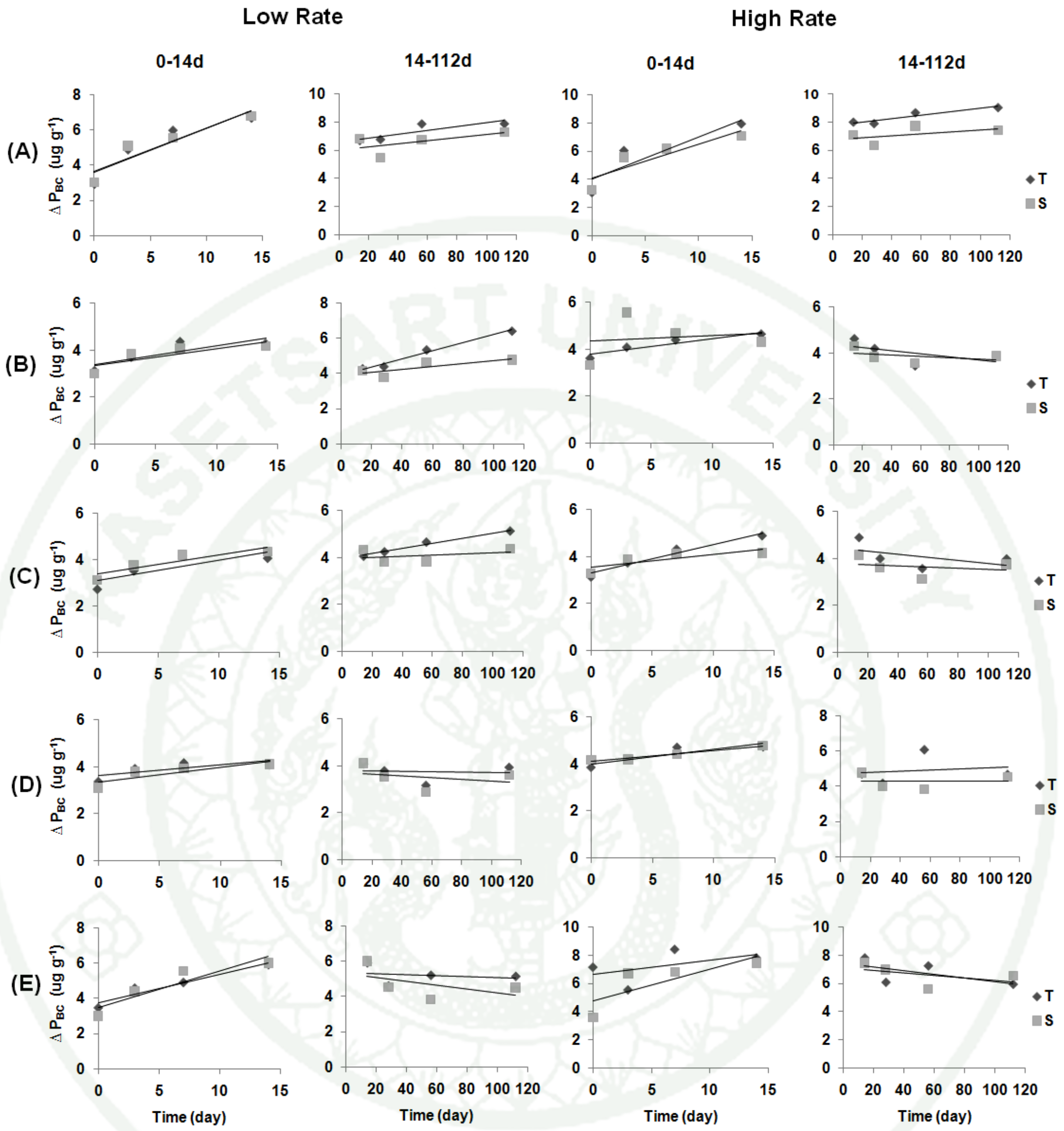


Figure 20 Plots of ΔP_{BC} versus time for Knk-soil incubated with NCR-PR (A), Rat-PR (B), Kan-PR (C), Roi-PR (D), and MCP (E) at 0 to 14 days and 14 to 112 days.

lower than NCR-PR and Rat-PR caused by the different type of phosphate mineral. Roi-PR has the lowest reactivity caused by the lowest solubility of variscite and crandallite. Therefore, the main factor which influences to the reactivity of PR is the type of phosphate mineral. This result is compatible with many researches such as Chien and Black, 1976; Hughes and Gilkes, 1986; Syers *et al*., 1986; Stumm and

Morgan, 1996; Francisco *et al*., 2008; Chien *et al*., 2009. For MCP, it is a highly water-soluble P fertilizer which the soluble P in soil solution is rapidly fixed by P fixation process (Sample *et al*., 1980; Hedley *et al*., 1982; and Chien, 2004).

MCP is fixed in most of the soils, except only in Knk-subsoil (the sandy soil) which their properties are low contents of clay, P sorption capacity, exchangeable acidity, OC, Fe_d, Al_d,Fe_o,and Al_o, and their reaction are moderately acid (pH 5.5 to 5.8). Therefore, MCP is suitable only for Knk-soil. In addition, this study shows that the high rate of MCP cannot increase their reactivity when it applied to acid tropical soils consistent with the study of Prochnow *et al*. (2006). And the effectiveness of MCP is highest at 14 days after being applied to the soils and then it continuously decreased at 14 to 112 days consistent with the study of Di *et al*. (1994) who found that the highest effectiveness of MCP was at 8 days and then continuously decreased for long time incubation (8 to 111 days).

The reactivity of PRs and MCP treatments for Ak-soil is less than for the other soils, because P fixation in Ak-soil is higher than the other soils. The chemical properties of Ak-soil include the high contents of clay, hematite, goethite, Fe_d, Al_d, and Fe_o, and their reaction are extremely acid, these properties are suitable for P fixation process (Reddy *et al*., 1980; Sample *et al*., 1980; Mozzafari and Sims, 1994).

1.2 Delta Bicarbonate Extractable P (ΔP_{BC}) for 14 to 112 Days

At 14 to 112 days of soil incubation, the delta bicarbonate extractable P (ΔP_{BC}) of all soils gradually decreases until sensibly constant comparing with the ΔP_{BC} for 0 to 14 days.

For Nb-soil, the values of ΔP_{BC} of all treatments (all PRs and MCP treatments at low and high rate) gradually decrease from 14 to 112 days until constant (Figure 12). The available P_{BC} of each treatment at 112 days are 5 to 7 mg kg^{-1} for LNCR and 8 to 12 mg kg^{-1} for HNCR, 6 to 8 mg kg^{-1} for LRat and 11 to 16 mg kg^{-1} for HRat, 5 to 7 mg kg^{-1} for LKan and 6 to 9 mg kg^{-1} for HKan, 4 to 7 mg kg^{-1} for

LRoi and 5 to 8 mg kg^{-1} for HRoi, and 5 to 6 mg kg^{-1} for LMCP and 5 to 7 mg kg^{-1} for HMCP (Table 19). The % increases in P_{BC} for each treatment are 27 to 46% for LNCR and 89 to 95% for HNCR, 35 to 40% for LRat and 147 to 176% for HRat, 16 to 19% for LKan and 48 to 60% for HKan, 6 to 25% for LRoi and 17 to 39% for HRoi, and 12 to 17% for LMCP and 0 to 45% for HMCP (Table 19). The increases Bic-P for NCR-, Rat-, and Kan-PR at low rate are similar and higher than for Roi-PR, and MCP, however, at high rate the increase of Rat-PR is higher than NCR-PR. These increases in Bic-P are the long term effectiveness of NCR- and Rat-PR which can increase the low available P level of original soil to medium level of incubated soil (Table 19). For Kan-PR, Roi-PR, and MCP treatments, the available P_{BC} and the % increases in P_{BC} at 112 days are clearly lower than NCR- and Rat-PR, which show that they are unsuitable for Nb-soil.

For Ak-soil, the values of ΔP_{BC} of almost all treatments gradually decrease from 14 to 112 days, except only for HRat and HKan (Rat- and Kan-PR treatment at high rate) that ΔP_{BC} are increased at 112 day (Figure 13). The available P_{BC} of each treatment at 112 days are 4 to 5 mg kg^{-1} for LNCR and 6 to 8 mg kg^{-1} for HNCR, 4 to 6 mg kg^{-1} for LRat and 6 to 11 mg kg^{-1} for HRat, 4 to 5 mg kg^{-1} for LKan and 5 to 7 mg kg^{-1} for HKan, 4 mg kg^{-1} for LRoi and HRoi, and 4 to 5 mg kg^{-1} for LMCP and HMCP (Table 19). The % increases in P_{BC} for each treatment are 15 to 31% for LNCR and 86 to 103% for HNCR, 37 to 54% for LRat and 119 to 122% for HRat, 31 to 42% for LKan and 60 to 75% for HKan, and 0 to 19% for LRoi and 3 to 10% for HRoi (Table 19). Most of MCP treatments are not found the increasing of P_{BC}, except only LMCP for Ak-top (Ak top-soil), the % increase is 5. The increases Bic-P for NCR-, Rat-, and Kan-PR at low rate are similar and clearly higher than for Roi-PR, and MCP. The increases Bic-P for Rat-PR at high rate are higher than NCR- and Kan-PR. The increases of Roi-PR at high rate are very low, while for MCP treatments are not found the increase. In addition, the values of ΔP_{BC} for NCR-, Rat-, and Kan-PR at high rate are clearly higher than at low rate. These increases of Bic-P are the long term effectiveness of NCR-, Rat-, and Kan-PR. The ΔP_{BC} of HRat and HKan treatments at 112 day are slightly higher than that at 14 day may be due to the

Table 19 Bic-P, ΔP_{BC}, the percentage increase in Bic-P and available P_{BC} level at 112 days of soil incubation.

Soil		Low$^{1/}$	$P_{BC}$$^{2/}$	$\Delta P_{BC}$$^{3/}$	Avai.$P_{BC}$$^{4/}$	%increased	High$^{1/}$	$P_{BC}$$^{2/}$	$\Delta P_{BC}$$^{3/}$	Avai.$P_{BC}$$^{4/}$	%increased
series			←	mg kg^{-1}	→	$P_{BC}$$^{5/}$		←	mg kg^{-1}	→	$P_{BC}$$^{5/}$
Nb	top	NCR	5.7	1.6	7 (L)	27	NCR	6.2	5.5	12 (M)	89
	sub		3.5	1.6	5 (L)	46		4.2	4.0	8 (L)	95
	top	Rat	5.8	2.3	8 (L)	40	Rat	5.7	10.1	16 (M)	176
	sub		4.1	1.4	6 (L)	35		4.5	6.7	11 (M)	147
	top	Kan	5.9	1.1	7 (L)	19	Kan	6.1	2.9	9 (L)	48
	sub		4.1	0.6	5 (L)	16		4.0	2.4	6 (L)	60
	top	Roi	5.2	1.3	7 (L)	25	Roi	5.4	2.1	8 (L)	39
	sub		4.0	0.2	4 (L)	6		4.2	0.7	5 (L)	17
	top	MCP	5.5	0.7	6 (L)	12	MCP	5.1	2.3	7 (L)	45
	sub		4.1	0.7	5 (L)	17		4.7	0.0	5 (L)	0
Ak	top	NCR	3.8	1.2	5 (L)	31	NCR	4.0	4.2	8 (L)	103
	sub		3.4	0.5	4 (L)	15		3.4	2.9	6 (L)	86
	top	Rat	4.0	1.5	6 (L)	37	Rat	5.1	6.2	11 (M)	122
	sub		2.8	1.5	4 (L)	54		3.5	4.1	8 (L)	119
	top	Kan	3.4	1.4	5 (L)	42	Kan	3.9	2.9	7 (L)	75
	sub		2.8	0.9	4 (L)	31		3.0	1.8	5 (L)	60
	top	Roi	3.7	0.7	4 (L)	19	Roi	3.9	0.4	4 (L)	10
	sub		3.6	0.0	4 (L)	0		3.7	0.1	4 (L)	3
	top	MCP	4.3	0.2	5 (L)	5	MCP	4.6	0.0	5 (L)	0
	sub		3.7	0.0	4 (L)	0		4.2	0.0	4 (L)	0
Kc	top	NCR	5.1	2.1	7 (L)	41	NCR	5.5	10.4	16 (M)	188
	sub		4.2	1.4	6 (L)	34		4.3	10.6	15 (M)	248
	top	Rat	5.3	3.1	8 (L)	60	Rat	6.7	8.6	15 (M)	128
	sub		4.0	3.1	7 (L)	77		5.2	10.3	16 (M)	197
	top	Kan	4.9	1.6	7 (L)	33	Kan	5.1	2.9	8 (L)	56
	sub		3.9	1.0	5 (L)	26		3.9	4.5	8 (L)	115
	top	Roi	4.8	0.4	5 (L)	9	Roi	5.0	0.5	6 (L)	9
	sub		4.0	0.3	4 (L)	7		4.5	0.5	5 (L)	11
	top	MCP	5.4	0.1	6 (L)	3	MCP	6.2	0.4	7 (L)	7
	sub		5.1	0.0	5 (L)	0		5.7	0.0	6 (L)	0
Klt	top	NCR	5.2	1.5	7 (L)	28	NCR	5.5	5.4	11 (M)	97
	sub		3.3	1.2	5 (L)	38		3.7	4.6	8 (L)	124
	top	Rat	5.2	2.0	7 (L)	39	Rat	5.8	3.6	9 (L)	63
	sub		3.6	1.5	5 (L)	42		4.1	4.4	9 (L)	107
	top	Kan	5.4	0.7	6 (L)	13	Kan	5.6	1.2	7 (L)	21
	sub		3.6	0.5	4 (L)	14		3.8	2.1	6 (L)	57
	top	Roi	5.2	0.1	5 (L)	1	Roi	5.3	0.0	5 (L)	0
	sub		3.6	0.0	4 (L)	0		4.0	0.3	4 (L)	7
	top	MCP	4.8	0.7	6 (L)	15	MCP	6.9	0	7 (L)	0
	sub		4.6	0.0	5 (L)	0		6.3	0	6 (L)	0

Table 19 (Continued).

Soil		Low$^{1/}$	$P_{BC}{}^{2/}$	$\Delta P_{BC}{}^{3/}$	Avai.$P_{BC}{}^{4/}$	%increased	High$^{1/}$	$P_{BC}{}^{2/}$	$\Delta P_{BC}{}^{3/}$	Avai.$P_{BC}{}^{4/}$	%increased
series			$\longleftarrow$	mg kg^{-1}	$\longrightarrow$	$P_{BC}{}^{5/}$		$\longleftarrow$	mg kg^{-1}	$\longrightarrow$	$P_{BC}{}^{5/}$
Nat	top	NCR	4.0	4.1	8 (L)	103	NCR	4.9	11.2	16 (M)	232
	sub		3.2	1.4	5 (L)	44		3.4	7.6	11 (M)	225
	top	Rat	4.2	3.7	8 (L)	87	Rat	4.8	11.5	16 (M)	241
	sub		3.3	2.1	5 (L)	64		3.9	10.9	15 (M)	283
	top	Kan	4.4	1.2	6 (L)	27	Kan	4.1	4.9	9 (L)	120
	sub		3.3	0.7	4 (L)	20		3.4	2.9	6 (L)	85
	top	Roi	4.0	2.1	6 (L)	54	Roi	4.3	1.3	6 (L)	30
	sub		3.2	0.4	4 (L)	11		3.8	0.2	4 (L)	5
	top	MCP	4.3	1.8	6 (L)	41	MCP	4.6	3.3	8 (L)	72
	sub		3.3	0.1	3 (L)	4		4.2	0.0	4 (L)	0
Tg	top	NCR	4.0	5.2	9 (L)	130	NCR	4.1	8.2	12 (M)	198
	sub		3.2	4.1	7 (L)	126		3.5	13.0	17 (M)	374
	top	Rat	4.0	3.4	7 (L)	86	Rat	4.2	1.0	5 (L)	24
	sub		3.2	4.4	8 (L)	136		3.7	3.8	8 (L)	102
	top	Kan	3.8	1.5	5 (L)	39	Kan	4.4	1.8	6 (L)	39
	sub		3.3	1.2	5 (L)	35		3.4	4.1	8 (L)	40
	top	Roi	4.0	0.5	5 (L)	13	Roi	4.3	1.1	5 (L)	120
	sub		3.5	0.3	4 (L)	9		3.9	0.0	4 (L)	0
	top	MCP	3.9	1.1	5 (L)	28	MCP	9.8	0.0	10 (L)	0
	sub		3.5	0.2	4 (L)	7		7.0	0.0	7 (L)	0
Hp	top	NCR	7.9	6.8	15 (M)	87	NCR	8.2	17.0	25 (H)	208
	sub		3.9	4.0	8 (L)	103		4.0	22.0	26 (H)	550
	top	Rat	7.8	5.7	14 (M)	73	Rat	8.3	6.2	15 (M)	75
	sub		3.6	6.9	11 (M)	190		4.1	10.6	15 (M)	257
	top	Kan	8.1	2.1	10 (M)	25	Kan	8.6	3.5	12 (M)	41
	sub		3.1	2.5	6 (L)	81		3.2	7.7	11 (M)	239
	top	Roi	7.6	0.1	8 (L)	1	Roi	8.1	0.7	9 (L)	9
	sub		3.5	0.4	4 (L)	11		3.7	0.9	5 (L)	25
	top	MCP	9.1	0.0	9 (L)	0	MCP	16.7	0.0	17 (L)	0
	sub		3.6	0.0	4 (L)	0		8.9	0.0	9 (L)	0
Koi	top	NCR	4.0	2.4	6 (L)	59	NCR	4.3	13.4	18 (M)	315
	sub		3.3	1.1	4 (L)	33		3.5	8.6	12 (M)	245
	top	Rat	4.1	4.2	8 (L)	103	Rat	4.4	11.7	16 (M)	268
	sub		3.6	2.0	6 (L)	55		4.0	9.3	13 (M)	235
	top	Kan	3.8	1.0	5 (L)	27	Kan	3.9	5.6	10 (L)	143
	sub		3.1	0.7	4 (L)	24		3.4	3.8	7 (L)	112
	top	Roi	4.6	0.0	5 (L)	0	Roi	4.3	0.2	5 (L)	5
	sub		3.1	0.5	4 (L)	15		3.5	0.5	4 (L)	14
	top	MCP	4.6	0.3	5 (L)	8	MCP	5.5	0.0	6 (L)	0
	sub		3.6	0.0	4 (L)	0		4.6	0.0	5 (L)	0

Table 19 (Continued).

Soil		Low[1/]	P_{BC}[2/]	ΔP_{BC}[3/]	Avai.P_{BC}[4/]	%increased	High[1/]	P_{BC}[2/]	ΔP_{BC}[3/]	Avai.P_{BC}[4/]	%increased
series			←	mg kg^{-1}	→	P_{BC}[5/]		←	mg kg^{-1}	→	P_{BC}[5/]
Knk	top	NCR	2.9	5.0	8 (L)	171	NCR	3.1	6.0	9 (L)	194
	sub		3.0	4.3	7 (L)	142		3.2	4.2	7 (L)	128
	top	Rat	3.1	3.3	6 (L)	107	Rat	3.6	0.2	4 (L)	7
	sub		3.0	1.8	5 (L)	59		3.3	0.5	4 (L)	16
	top	Kan	2.7	2.4	5 (L)	87	Kan	3.1	0.8	4 (L)	27
	sub		3.1	1.3	4 (L)	41		3.3	0.5	4 (L)	14
	top	Roi	3.4	0.6	4 (L)	17	Roi	3.8	0.8	5 (L)	22
	sub		3.1	0.5	4 (L)	16		4.2	0.4	5 (L)	9
	top	MCP	3.5	1.7	5 (L)	47	MCP	7.2	0.0	7 (L)	0
	sub		3.0	1.5	5 (L)	50		3.6	3.0	7 (L)	83

[1/] Low = low rate of PRs and MCP treatments, High = high rate of PRs and MCP treatments; [2/] P_{BC} = bicarbonate extractable P at 0 day (control); [3/] ΔP_{BC} = increased P_{BC} at 112 days of PRs and MCP treatments; [4/] Avai.P_{BC} = the extracted P_{BC} at 112 days with available P_{BC} level in parenthesis, where L (low) is < 10; M (medium) is 10-20; H (high) is 20-40 (mg kg^{-1}) (Marx *et al.*, 1999); [5/] % increased P_{BC} = the percentage of ΔP_{BC} by calculation (% increased P_{BC} = $(\Delta P_{BC}/P_{BC})$ x 100).

dissolution of calcite included in Rat- and Kan-PR effects to the increasing of phosphate dissolution as same as the study of Gholizadeh *et al.* (2009). This result shows that NCR- and Rat-PR are suitable for Ak-soil more than Kan-PR, while Roi-PR and MCP are unsuitable.

For Kc-soil, the values of ΔP_{BC} of almost all treatments gradually decrease from 14 to 112 days, except only for HKan (Kan-PR treatment at high rate) that ΔP_{BC} are almost constant at 112 days (Figure 14). The available P_{BC} of each treatment at 112 days are 7 to 6 mg kg^{-1} for LNCR and 15 to 16 mg kg^{-1} for HNCR, 7 to 8 mg kg^{-1} for LRat and 15 to 16 mg kg^{-1} for HRat, 5 to 7 mg kg^{-1} for LKan and 8 mg kg^{-1} for HKan, 4 to 5 mg kg^{-1} for LRoi and 5 to 6 mg kg^{-1} for HRoi, and 5 to 6 mg kg^{-1} for LMCP and 6 to 7 mg kg^{-1} for HMCP (Table 19). The % increases in P_{BC} for each treatment are 34 to 41% for LNCR and 188 to 248% for HNCR, 60 to 77% for LRat and 128 to 197% for HRat, 26 to 33% for LKan and 56 to 115% for HKan, and 7 to 9% for LRoi and 9 to 11% for HRoi (Table 19). MCP for Kc-sub (Kc sub-soil) at low and high rate are not found the increasing of P_{BC}, the increase is found for Kc-top (Kc top-soil) as 3% at low rate and 7% at high rate. The increases Bic-P for NCR-, and Rat-PR at low and high rate are similar and clearly higher than for Kan-PR, Roi-PR, and MCP. In addition, the values of ΔP_{BC} for NCR-, and Rat-PR at high rate are clearly higher than at low rate. These increases of Bic-P are the long term effectiveness of NCR- and Rat-PR which can increase the low available P level of original soil to medium level of incubated soil (Table 19). Therefore, NCR- and Rat-PR are suitable for Kc-soil. For Kan-PR treatments, they may be useful for long term effectiveness, although they cannot increase the available P level of original soils from low to medium, they can increase the Bic-P from 3 to 7mg kg^{-1} of original soil to 8 mg kg^{-1} of incubated soil (Table 19). For Roi-PR, and MCP treatments, the available P_{BC} and the % increased P_{BC} at 112 days are clearly lower than NCR-, Rat-, and Kan-PR, it shows that they are unsuitable for Kc-soil.

For Klt-soil, the values of ΔP_{BC} at low rate of all treatments gradually decrease from 14 to 112 days, at high rate, the value of ΔP_{BC} of Rat-PR for Klt-sub increases while for the others treatments gradually decrease (Figure 15). The available P_{BC} of each treatment at 112 days are 5 to 7 mg kg^{-1} for LNCR and 8 to 11 mg kg^{-1} for HNCR, 5 to 7 mg kg^{-1} for LRat and 9 mg kg^{-1} for HRat, 4 to 6 mg kg^{-1} for LKan and 6 to 7 mg kg^{-1} for HKan, 4 to 5 mg kg^{-1} for LRoi and HRoi, and 5 to 6 mg kg^{-1} for LMCP and 6 to 7 mg kg^{-1} for HMCP (Table 19). The % increases in P_{BC} for each treatment are 28 to 38% for LNCR and 97 to 124% for HNCR, 39 to 42% for LRat and 63 to 107% for HRat, and 13 to 14% for LKan and 21 to 57% for HKan, however, the increases for Roi-PR and MCP are less (Table 19). The increases Bic-P for NCR-, and Rat-PR at low and high rate are similar and clearly higher than for Kan-PR, Roi-PR, and MCP. In addition, the values of ΔP_{BC} for NCR-, and Rat-PR at high rate are clearly higher than at low rate. These increases of Bic-P are the long term effectiveness of NCR- and Rat-PR, although they cannot increase the available P level of original soils from low to medium, they can increase the P_{BC} from 5 to 7 mg kg^{-1} of original soil to 8 to 11 mg kg^{-1} of incubated soil (Table 19). Therefore, NCR- and Rat-PR are suitable for Klt-soil, while Kan-PR, Roi-PR, and MCP are unsuitable.

For Nat-soil, the values of ΔP_{BC} at low and high rate of all treatments gradually decrease from 14 to 112 days, except only the ΔP_{BC} for LRoi and HKan of top-soil slightly increase from those at 14 day (Figure 16). The available P_{BC} of each treatment at 112 days are 5 to 8 mg kg^{-1} for LNCR and 11 to 16 mg kg^{-1} for HNCR, 5 to 8 mg kg^{-1} for LRat and 15 to 16 mg kg^{-1} for HRat, 4 to 6 mg kg^{-1} for LKan and 6 to 9 mg kg^{-1} for HKan, 4 to 6 mg kg^{-1} for LRoi and HRoi, and 3 to 6 mg kg^{-1} for LMCP and 4 to 8 mg kg^{-1} for HMCP (Table 19). The % increases in P_{BC} for each treatment are 44 to 103% for LNCR and 225 to 232% for HNCR, 64 to 87% for LRat and 241 to 283% for HRat, and 20 to 27% for LKan and 85 to 120% for HKan, 11 to 54% for LRoi and 5 to 30% for HRoi, and 4 to 41% for LMCP and 72% for top-soil of HMCP. For sub-soil of HMCP is not found the increased P_{BC} (Table 19). The increases Bic-P for NCR-, and Rat-PR at low and high rate are similar and clearly higher than for Kan-PR, Roi-PR, and MCP. In addition, the values of ΔP_{BC} for NCR-, and Rat-PR at high rate are clearly higher than at low rate. These increases of Bic-P are the long term effectiveness of NCR- and Rat-PR which can increase the low available P level of original soil to medium level of incubated soil (Table 19). Therefore, NCR- and Rat-PR are suitable for Nat-soil, while Kan-PR, Roi-PR, and MCP are unsuitable.

For Tg-soil, the values of ΔP_{BC} of NCR-, Rat-, and Kan-PR treatments are not constant from 14 to 112 days (Figure 17). In top-soil, the increases of ΔP_{BC} are found for NCR-RP at low and high rate, Rat-PR at low rate, Kan-PR at low and high rate, and the decrease of ΔP_{BC} is found for Rat-PR at high rate. In sub-soil, the increases of ΔP_{BC} are found for NCR-PR at high rate, Rat-PR at low and high rate, and Kan-PR at low rate, and the decreases of ΔP_{BC} are found for NCR-PR at low rate, and Kan-PR at low rate. For Roi-PR and MCP treatments, the values of ΔP_{BC} gradually decrease from 14 to 112 days. The available P_{BC} of each treatment at 112 days are 7 to 9 mg kg^{-1} for LNCR and 12 to 17 mg kg^{-1} for HNCR, 7 to 8 mg kg^{-1} for LRat and 5 to 8 mg kg^{-1} for HRat, 5 mg kg^{-1} for LKan and 6 to 8 mg kg^{-1} for HKan, 4 to 5 mg kg^{-1} for LRoi and HRoi, and 4 to 5 mg kg^{-1} for LMCP and 7 to 10 mg kg^{-1} for HMCP (Table 19). The % increases in P_{BC} for each treatment are 126 to 130% for LNCR and 198 to 374% for HNCR, 86 to 136% for LRat and 24 to 102% for HRat, and 35 to 40% for LKan and HKan, 9 to 13% for LRoi and 0 to 120% for HRoi, and 7 to 28% for LMCP and the increase for HMCP are not found (Table 19). The increases Bic-P for NCR-PR at low rate are similar to Rat-PR and clearly higher than Kan-PR, Roi-PR, and MCP. At high rate, the increases Bic-P for NCR-PR are higher than Rat-PR, Kan-PR, Roi-PR, and MCP. These increases Bic-P are the long term effectiveness of NCR-, Rat-, and Kan-PR. Only NCR-PR at high rate can increase the low available P level of original soils to medium level of incubated soil, while Rat- and Kan-PR at high rate and NCR-, Rat-, and Kan-PR at low rate can increase the P_{BC} from 3 to 4 mg kg^{-1} of original soil to 5 to 9 mg kg^{-1} of incubated soil (Table 19). Therefore, NCR- and Rat-PR are suitable for Tg-soil more than Kan-PR, while Roi-PR and MCP are unsuitable.

For Hp-soil, the values of ΔP_{BC} for NCR-, Rat-, and Kan-PR treatments are not constant from 14 to 112 days (Figure 18). In top-soil, the increases of ΔP_{BC} is found for Rat-PR at high rate and the decrease of ΔP_{BC} are found for NCR-PR at low and high rate, Rat-PR at low rate, Kan-PR at low and high rate. In sub-soil, the increases of ΔP_{BC} are found for Rat-PR at low and high rate, and Kan-PR at low and high rate. For Roi-PR and MCP treatments, the values of ΔP_{BC} gradually decrease from 14 to 112 days. The available P_{BC} of each treatment at 112 days are 8 to 15 mg kg^{-1} for LNCR and 25 to 26 mg kg^{-1} for HNCR, 11 to 14 mg kg^{-1} for LRat and 15 mg kg^{-1} for HRat, 6 to 10 mg kg^{-1} for LKan and 11 to 12 mg kg^{-1} for HKan, 4 to 8 mg kg^{-1} for LRoi and 5 to 9 mg kg^{-1} for HRoi, and 4 to 9 mg kg^{-1} for LMCP and 9 to 17 mg kg^{-1} for HMCP (Table 19). The % increases in P_{BC} for each treatment are 87 to 103% for LNCR and 208 to 550% for HNCR, 73 to 190% for LRat and 75 to 257% for HRat, and 25 to 81% for LKan and 41 to 239% for HKan, 1 to 11% for LRoi and 9 to 25% for HRoi, and the increase for MCP at low and high rate are not found (Table 19). The increases Bic-P for NCR-PR at low rate are similar to Rat-PR and clearly higher than Kan-PR, Roi-PR, and MCP. At high rate, the increases Bic-P for NCR-PR are higher than Rat- and Kan-PR, while the increases of Rat- and Kan-PR are similar. The increases of NCR-, Rat-, and Kan-PR are clearly higher than Roi-PR, and MCP. The ΔP_{BC} for NCR-, Rat-, and Kan-PR at high rate are clearly higher than at low rate. At high rate, NCR-PR can increase the medium available P level of original soils to high level of incubated soil, while Rat- and Kan-PR can increase the P_{BC} from 3 to 9 mg kg^{-1} of original soil to 11 to 15 mg kg^{-1} of incubated soil (Table 19). Therefore, NCR-, Rat-, and Kan-PR are suitable for Hp-soil, while Roi-PR and MCP are unsuitable.

For Koi-soil, the values of ΔP_{BC} at low rate for NCR-, Rat-, and Kan-PR treatments gradually decrease from 14 to 112 days, and the values of ΔP_{BC} at high rate of Rat- and Kan-PR slightly increase, while the values for others treatments gradually decrease from 14 to 112 days (Figure 19). The available P_{BC} of each treatment at 112 days are 4 to 6 mg kg^{-1} for LNCR and 12 to 18 mg kg^{-1} for HNCR, 6 to 8 mg kg^{-1} for LRat and 13 to 16 mg kg^{-1} for HRat, 4 to 5 mg kg^{-1} for LKan and 7 to 10 mg kg^{-1} for HKan, 4 to 5 mg kg^{-1} for LRoi and HRoi, and 4 to 5 mg kg^{-1} for LMCP and 5 to 6 mg kg^{-1} for HMCP (Table 19). The % increases in P_{BC} for each treatment are 33 to 59% for LNCR and 245 to 315% for HNCR, 55 to 103% for LRat and 235 to 268% for HRat, and 24 to 27% for LKan and 112 to 143% for HKan, 0 to 15% for LRoi and 5 to 14% for HRoi, and the increase for MCP treatments is found only at low rate of top-soil as 8% and the others are not found (Table 19). The increases Bic-P for NCR-PR at low and high rate are similar to Rat-PR and clearly higher than Kan-PR, Roi-PR, and MCP. The ΔP_{BC} for NCR-, Rat-, and Kan-PR at high rate are clearly higher than at low rate. At high rate, NCR- and Rat-PR can increase the low available P level of original soils to medium level of incubated soil, while Kan-PR can increase the P_{BC} from 3 to 4 mg kg^{-1} of original soil to 7 to 10 mg kg^{-1} of incubated soil (Table 19). Therefore, NCR- and Rat-PR are suitable for Koi-soil more than Kan-PR, while Roi-PR and MCP are unsuitable.

For Knk-soil, the values of ΔP_{BC} at low rate for NCR-, Rat-, and Kan-PR, and at high rate of NCR-PR gradually increase from 14 to 112 days, while those of Rat- and Kan-PR at high rate gradually decrease from 14 to 112 days (Figure 20). The values of ΔP_{BC} of Roi-PR and MCP treatments gradually decrease from 14 to 112 days. The available P_{BC} of each treatment at 112 days are 7 to 8 mg kg^{-1} for LNCR and 7 to 9 mg kg^{-1} for HNCR, 5 to 6 mg kg^{-1} for LRat and 4 mg kg^{-1} for HRat, 4 to 5 mg kg^{-1} for LKan and 4 mg kg^{-1} for HKan, 4 mg kg^{-1} for LRoi and 5 mg kg^{-1} for HRoi, and 5 mg kg^{-1} for LMCP and 7 mg kg^{-1} for HMCP (Table 19). The % increases in P_{BC} for each treatment are 142 to 171% for LNCR and 128 to 194% for HNCR, 59 to

107% for LRat and 7 to 16% for HRat, and 41 to 87% for LKan and 14 to 27% for HKan, 16 to 17% for LRoi and 9 to 22% for HRoi, and 47 to 50% for LMCP while the increase for HMCP is found only in sub-soil as 83% and in top-soil is not found (Table 19). The increases Bic-P for NCR-PR at low and high rate are higher than Rat-PR, Kan-PR, Roi-PR, and MCP, and those for Rat- and Kan-PR at low rate are similar and higher than Roi-PR and MCP. The ΔP_{BC} for NCR-PR at low and high rate are similar, while those for Rat- and Kan-PR at high rate are lower than at low rate. NCR-PR at high rate can increase the P_{BC} from 3 mg kg^{-1} of original soil to 7 to 9 mg kg^{-1} of incubated soil, MCP at low rate can increase the P_{BC} from 3 to 4 mg kg^{-1} of original soil to 5 mg kg^{-1} of incubated soil, while the increases P_{BC} for Rat- and Kan-PR are low (Table 19). Therefore, NCR-PR is suitable for Knk-soil more than Rat- and Kan-PR, while Roi-PR is unsuitable. In addition, MCP at low rate has high effectiveness for Knk-soil more than the other soils.

At 14 to 112 days of soil incubation, the ΔP_{BC} for all soils are fluctuated from the ΔP_{BC} at 14 days, however, most of them are lower than the ΔP_{BC} at 14 days. The ΔP_{BC} at 112 days of all soils for all treatments are used to predict the long term effectiveness of PRs and MCP. The results clearly show that the ΔP_{BC} at 112 days of all soils incubated with NCR- and Rat-PR are higher than P_{BC} of original soils, especially at high application rate, except only Rat-PR at high rate for Knk-soil (sandy soil). The ΔP_{BC} at 112 days of Kan-PR are higher than Roi-PR and MCP, however they are clearly lower than NCR- and Rat-PR. Therefore, the long term effectiveness of NCR-PR is higher than of Rat-PR and clearly higher than Kan-PR, Roi-PR and MCP. Roi-PR and MCP are unsuitable for all soils, since the low reactivity of Roi-PR and the high P fixation of MCP, however this study found that MCP at low rate has high effectiveness for Knk-soil more than the other soils.

1.3 The Differences of ΔP_{BC} of Soil Incubated with PR and MCP Treatments from 0 to 112 Days Calculate by Duncan's Multiple Range Test.

Duncan’s multiple range test of soil incubated from 0 to 112 days show the differences of Bic-P for PR and MCP treatments. The soils without P fertilizers are incubated at field soil water capacity for indentifying the influences of soils, themselves, to the changes of Bic-P and are called the control. All analytical data of Duncan’s multiple range test are shown in Appendix Table A1 to A9.

The differences of ΔP_{BC} of Nb-soil incubated with PR and MCP treatments are significantly different at $P < 0.01$ (Appendix Table A1). For Nb top-soil, the Bic-P (µg mL^{-1}) from PR and MCP treatments are 14.5a for HRat, 12.6b for HNCR, 8.6c for HKan, 6.8ef for HRoi, 7.1e for HMCP, and 6.1g for control. For Nb sub-soil, the Bic-P (µg mL^{-1}) from PR and MCP treatments are 10.4a for HRat, 8.5b for HNCR, 6.6c for HKan, 4.9fgh for HRoi, 5.3ef for HMCP, and 4.5h for control. Means of Bic-P of each time for top and sub soil of Nb-soil are not significant in statistic, however the highest of Bic-P trends to be at 14 days.

The differences of ΔP_{BC} of Ak-soil incubated with PR and MCP treatments are significantly different at $P < 0.01$ (Appendix Table A2). For Ak top-soil, the Bic-P (µg mL^{-1}) from PR and MCP treatments are 8.7a for HRat, 8.1b for HNCR, 5.6c for HKan, 4.6e for HRoi, 4.7e for HMCP, and 4.2g for control. Means of Bic-P of each time for Ak top-soil are significantly different at $P < 0.01$. Means of Bic-P (µg mL^{-1}) at 14 days is 5.3bc and the highest of Bic-P at 56 days are 6.5a. For Ak sub-soil, the Bic-P (µg mL^{-1}) from PR and MCP treatments are 6.8a for HRat, 6.3b for HNCR, 4.7c for HKan, 3.9e for HRoi, 4.0e for HMCP, and 3.4g for control. Means of Bic-P of each time for Ak sub-soil are significantly different at $P < 0.01$. Means of Bic-P (µg mL^{-1}) at 14 days is 4.7ab and the highest of Bic-P at 7 days is 4.9a.

The differences of ΔP_{BC} of Kc-soil incubated with PR and MCP treatments are significantly different at $P < 0.01$ (Appendix Table A3). For Kc top-soil, the Bic-P (µg mL^{-1}) from PR and MCP treatments are 14.5a for HNCR, 13.2b for HRat, 7.0cd for HKan, 6.6d for HMCP, 5.8e for HRoi, and 5.0f for control. Means of Bic-P of each time for Kc top-soil are significantly different at $P < 0.05$. Means of Bic-P (µg mL^{-1}) at 14 days is 9.1a. For Kc sub-soil, the Bic-P (µg mL^{-1}) from PR and MCP treatments are 14.8a for HNCR, 13.8b for HRat, 7.5c for HKan, 5.3e for HMCP, 4.7fg for HRoi, and 4.0g for control. Means of Bic-P of each time for Kc sub-soil are significantly different at $P < 0.01$. Means of Bic-P ($\mu g\ mL^{-1}$) at 14 days is 8.4a.

The differences of ΔP_{BC} of Klt-soil incubated with PR and MCP treatments are significantly different at $P < 0.01$ (Appendix Table A4). For Klt top-soil, the Bic-P ($\mu g\ mL^{-1}$) from PR and MCP treatments are 11.2a for HNCR, 8.4b for HRat, 6.6c for HKan, 6.0d for HMCP, 5.5ef for HRoi, and 5.2f for control. For Klt sub-soil, the Bic-P ($\mu g\ mL^{-1}$) from PR and MCP treatments are 8.5a for HNCR, 6.7b for HRat, 5.4c for HKan, 4.4de for HMCP, 4.1ef for HRoi, and 3.5g for control. Means of Bic-P of each time for top- and sub-soil of Klt-soil are not significant in statistic, however the highest of Bic-P trends to be at 14 days.

The differences of ΔP_{BC} of Nat-soil incubated with PR and MCP treatments are significantly different at $P < 0.01$ (Appendix Table A5). For Nat top-soil, the Bic-P ($\mu g\ mL^{-1}$) from PR and MCP treatments are 14.1a for HNCR, 13.4b for HRat, 6.9cd for HKan, 6.5d for HMCP, 5.4e for HRoi, and 4.9e for control. Means of Bic-P of each time for Nat top-soil are significantly different at $P < 0.01$. Means of Bic-P ($\mu g\ mL^{-1}$) at 14 days are 8.9a. For Nat sub-soil, the Bic-P ($\mu g\ mL^{-1}$) from PR and MCP treatments are 13.9a for HRat, 10.9b for HNCR, 6.2c for HKan, 4.5e for HMCP, 4.1ef for HRoi, and 3.5f for control. Means of Bic-P of each time for Nat sub-soil are significantly different at $P < 0.01$. Means of Bic-P ($\mu g\ mL^{-1}$) at 14 days are 7.3a.

The differences of ΔP_{BC} of Tg-soil incubated with PR and MCP treatments are significantly different at $P < 0.01$ (Appendix Table A6). For Tg top-soil, the Bic-P ($\mu g\ mL^{-1}$) from PR and MCP treatments are 9.6a for HNCR, 7.2b for HMCP, 5.7c for LRat, 5.2cd for HKan, 4.9de for HRoi, and 4.3f for control. Means of Bic-P of each time for Tg top-soil are significantly different at $P < 0.05$. Means of Bic-P ($\mu g\ mL^{-1}$) at 14 days are 6.2ab, and the highest value is 6.6a at 112 days. For Tg sub-soil, the Bic-P ($\mu g\ mL^{-1}$) from PR and MCP treatments are 13.2a for HNCR, 6.4b for HMCP, 6.0bc for LRat, 5.2d for HKan, 4.1e for HRoi, and 3.2f for control. Means of Bic-P of each time for Tg sub-soil are significantly different at $P < 0.01$. Means of Bic-P (μg mL^{-1}) at 14 days are 6.2ab, and the highest value is 6.5a at 112 days.

The differences of ΔP_{BC} of Hp-soil incubated with PR and MCP treatments are significantly different at $P < 0.01$ (Appendix Table A7). For Hp top-soil, the Bic-P (μg mL^{-1}) from PR and MCP treatments are 21.4a for HNCR, 12.0c for HRat, 11.8c for HMCP, 10.8d for HKan, 9.0e for HRoi, and 8.0f for control. Means of Bic-P of each time for Hp top-soil are significantly different at $P < 0.05$. Means of Bic-P (μg mL^{-1}) at 14 days are 13.4a. For Hp sub-soil, the Bic-P (μg mL^{-1}) from PR and MCP treatments are 23.8a for HNCR, 10.2b for HRat, 7.3c for HKan, 6.0d for HMCP, 4.3e for HRoi, and 3.0f for control. Means of Bic-P of each time for Hp sub-soil are significantly different at $P < 0.01$. Means of Bic-P (μg mL^{-1}) at 14 days are 9.0a.

The differences of ΔP_{BC} of Koi-soil incubated with PR and MCP treatments are significantly different at $P < 0.01$ (Appendix Table A8). For Koi top-soil, the Bic-P (μg mL^{-1}) from PR and MCP treatments are 15.3a for HNCR, 10.6b for HRat, 6.7c for HKan, 5.7d for HMCP, 4.7e for HRoi, and 4.1e for control. Means of Bic-P of each time for Koi top-soil are significantly different at $P < 0.01$. Means of Bic-P (μg mL^{-1}) at 14 days are 7.7ab, and the highest value is 8.2a at 56 days. For Koi sub-soil, the Bic-P (μg mL^{-1}) from PR and MCP treatments are 14.1a for HRat, 13.0b for HNCR, 6.9c for HKan, 4.2ef for HMCP, 4.0fg for HRoi, and 3.3h for control. Means of Bic-P of each time for Koi sub-soil are significantly different at $P < 0.01$. Means of Bic-P (μg mL^{-1}) at 14 days are 7.5a.

The differences of ΔP_{BC} of Knk-soil incubated with PR and MCP treatments are significantly different at $P < 0.01$ (Appendix Table A9). For Knk top-soil, the Bic-P (μg mL^{-1}) from PR and MCP treatments are 7.0a for HNCR, 6.9a for HMCP, 4.6c for HRoi, 4.0de for HRat, 4.1de for LKan, and 3.5e for control. For Knk sub-soil, the Bic-P (μg mL^{-1}) from PR and MCP treatments are 6.2a for HNCR, 6.2a for HMCP, 4.2dc for HRat, 4.3dc for HRoi, 3.9ef for LKan, and 3.3g for control. Means of Bic-P of each time for top and sub soil of Knk-soil are not significant in statistic, however the highest of Bic-P trends to be at 14 days.

Duncan’s multiple range test of soil incubated from 0 to 112 days clearly show that the Bic-P from NCR-PR is highest for all soils, and it is similar to Rat-PR for most of soil, except only for Tg- and Knk-soil which originating from granite and contained low clay content. The effectiveness of PRs is NCR- > Rat- > Kan. Roi-PR is low reactivity and unsuitable for agronomic use. Bic-P for MCP are significantly different for Tg- and Knk-soil, however they are only slight increase after 14 days of soil incubated, and after 14 to 112 days most P is fixed and insoluble in bicarbonate solution.

2. Changes of Soil pH in Soil Incubated with PRs and MCP

2.1 pH in DI-water (pH_{H_2O})

All soils incubated with PRs and MCP show the same trend variation of the changed pH_{H_2O} and the ΔpH_{H_2O} (Table 20). After 14 days of soil incubation, the changed pH_{H_2O} are close to the pH_{H_2O} of original soil (pH_{H_2O} at 0 day). At 112 days of incubation, the changed pH_{H_2O} is clearly lower than the pH_{H_2O} of original soil.

The soils incubated with low rate of NCR-PR retain the original soil pH_{H_2O} ranging from 4.5 to 6.1, the changed pH_{H_2O} at 14 days ranging from 4.4 to 6.2, and the changed pH_{H_2O} at 112 days ranging from 3.6 to 5.4 (Table 20). For low rate of NCR-PR, the ΔpH_{H_2O} at 112 days are less than the original soil pH_{H_2O} about 0.3 to 1.1 units. The soils incubated with high rate of NCR-PR have the original soils pH_{H_2O} ranging from 4.6 to 6.2, the changed pH_{H_2O} at 14 days ranging from 4.6 to 6.2, and the changed pH_{H_2O} at 112 days ranging from 3.7 to 5.6. For high rate of NCR-PR, the ΔpH_{H_2O} at 112 days are less than the original soil pH_{H_2O} about 0.3 to 1.1 units.

The soils incubated with low rate of Rat-PR have the original soils pH_{H_2O} ranging from 4.6 to 6.1, the changed pH_{H_2O} at 14 days ranging from 4.4 to 6.3, and the changed pH_{H_2O} at 112 days ranging from 3.4 to 5.4 (Table 20). For low rate of Rat-PR, the ΔpH_{H_2O} at 112 days are less than the original soil pH_{H_2O} about 0.3 to 1.2 units.

Table 20 The changed pH_{H_2O} at 14 and 112 days of incubation, and the ΔpH_{H_2O} at 112 days relative to 0 day.

Soil		pH_{H_2O}			ΔpH_{H_2O}	pH_{H_2O}			ΔpH_{H_2O}
		0 d	14 d	112 d	at 112 d$^{1/}$	0 d	14 d	112 d	at 112 d$^{1/}$
		Low rate of NCR-PR				*High rate of NCR-PR*			
Nb	top	4.5	4.4	3.9	-0.6	4.6	4.6	4.1	-0.5
	sub	5.1	5.2	4.6	-0.5	5.1	5.3	4.7	-0.4
Ak	top	4.7	5.1	3.6	-1.1	4.8	5.3	3.7	-1.1
	sub	5.0	5.2	4.4	-0.6	5.1	5.2	4.4	-0.7
Kc	top	4.8	4.6	4.2	-0.6	4.8	4.7	4.4	-0.4
	sub	5.2	5.2	4.4	-0.8	5.3	5.4	4.8	-0.6
Klt	top	5.7	5.1	4.8	-0.9	5.7	5.2	5.1	-0.7
	sub	6.1	5.9	5.4	-0.7	6.2	6.0	5.6	-0.5
Nat	top	4.9	4.4	4.1	-0.9	5.0	4.6	4.3	-0.7
	sub	5.1	5.2	4.3	-0.7	5.2	5.2	4.5	-0.7
Tg	top	5.6	5.2	4.6	-1.1	5.8	5.3	5.0	-0.7
	sub	5.2	5.5	4.5	-0.7	5.2	5.8	4.9	-0.3
Hp	top	5.3	4.7	4.4	-0.9	5.5	4.9	4.6	-0.9
	sub	4.5	4.9	4.2	-0.3	4.7	5.2	4.4	-0.3
Koi	top	5.1	5.5	3.9	-1.1	5.2	5.6	4.4	-0.8
	sub	5.1	5.3	4.5	-0.5	5.2	5.4	4.8	-0.4
Knk	top	5.9	5.7	4.9	-1.0	5.9	5.7	5.2	-0.7
	sub	5.8	6.2	5.4	-0.4	6.0	6.2	5.6	-0.4
		Low rate of Rat-PR				*Hig rate of Rat-PR*			
Nb	top	4.6	4.5	4.0	-0.6	4.8	4.6	4.3	-0.5
	sub	5.1	5.2	4.6	-0.5	5.3	5.3	4.8	-0.5
Ak	top	4.6	5.1	3.4	-1.2	4.8	5.4	3.8	-1.0
	sub	5.0	5.2	4.5	-0.5	5.2	5.3	4.7	-0.5
Kc	top	4.7	4.6	4.2	-0.6	5.1	4.8	4.6	-0.6
	sub	5.3	5.2	4.6	-0.7	5.4	5.5	5.1	-0.3
Klt	top	5.7	5.1	5.0	-0.7	5.8	5.4	5.2	-0.6
	sub	6.1	5.9	5.3	-0.8	6.3	6.1	5.7	-0.6
Nat	top	5.0	4.4	4.1	-0.8	5.3	4.7	4.4	-0.9
	sub	5.0	5.2	4.3	-0.7	5.1	5.2	4.7	-0.3
Tg	top	5.8	5.2	4.8	-1.0	6.0	5.7	5.5	-0.5
	sub	5.2	5.6	4.6	-0.6	5.7	6.0	5.4	-0.4
Hp	top	5.5	4.7	4.4	-1.1	5.7	5.2	4.9	-0.8
	sub	4.8	5.2	4.5	-0.3	5.5	5.6	5.1	-0.4
Koi	top	5.1	5.5	4.0	-1.1	5.5	5.7	4.7	-0.9
	sub	5.1	5.3	4.6	-0.6	5.5	5.6	5.1	-0.5
Knk	top	5.9	5.6	5.0	-0.9	6.2	6.5	6.2	-0.03
	sub	6.0	6.3	5.4	-0.7	6.8	7.0	6.7	-0.1

Table 20 (Continued).

Soil		pH_{H_2O}			ΔpH_{H_2O}	pH_{H_2O}			ΔpH_{H_2O}
		0 d	14 d	112 d	at 112 d[1/]	0 d	14 d	112 d	at 112 d[1/]
		Low rate of Kan-PR				*High rate of Kan-PR*			
Nb	top	4.5	4.5	4.0	-0.5	4.6	4.4	4.0	-0.6
	sub	5.0	5.3	4.6	-0.4	5.1	5.3	4.7	-0.4
Ak	top	4.7	5.2	3.6	-1.1	4.8	5.2	3.5	-1.2
	sub	5.0	5.2	4.5	-0.5	5.0	5.2	4.6	-0.3
Kc	top	4.7	4.6	4.1	-0.7	4.9	4.7	4.2	-0.7
	sub	5.2	5.3	4.3	-0.9	5.2	5.3	4.6	-0.6
Klt	top	5.7	5.0	4.8	-0.9	5.6	5.1	4.9	-0.7
	sub	6.1	5.9	5.4	-0.7	6.1	6.0	5.5	-0.6
Nat	top	5.0	4.4	4.1	-0.9	5.0	4.5	4.1	-0.8
	sub	5.0	5.2	4.4	-0.6	5.0	5.2	4.5	-0.5
Tg	top	5.7	5.2	4.8	-0.9	5.7	5.3	5.0	-0.7
	sub	5.1	5.6	4.5	-0.6	5.2	5.7	4.7	-0.5
Hp	top	5.2	4.7	4.4	-0.8	5.2	4.7	4.5	-0.8
	sub	4.7	5.2	4.4	-0.3	4.6	5.1	4.4	-0.2
Koi	top	5.1	5.6	4.0	-1.1	5.1	5.6	4.2	-1.0
	sub	5.1	5.3	4.6	-0.6	4.9	5.4	4.7	-0.2
Knk	top	5.8	5.8	4.8	-1.0	5.9	5.6	5.3	-0.6
	sub	5.8	6.4	5.4	-0.4	6.0	6.4	6.0	-0.03
		Low rate of Roi-PR				*High rate of Roi-PR*			
Nb	top	4.5	4.3	3.8	-0.7	4.5	4.4	3.9	-0.6
	sub	5.0	5.1	4.5	-0.5	5.0	5.1	4.5	-0.5
Ak	top	4.7	5.0	3.7	-1.0	4.6	5.1	3.6	-1.0
	sub	5.0	5.1	4.4	-0.6	5.0	5.1	4.4	-0.6
Kc	top	4.7	4.5	3.9	-0.8	4.6	4.5	3.9	-0.7
	sub	5.0	5.1	4.0	-1.0	5.1	5.2	4.1	-1.1
Klt	top	5.5	5.0	4.7	-0.8	5.5	5.0	4.7	-0.8
	sub	5.9	5.9	5.1	-0.8	5.9	5.8	5.2	-0.7
Nat	top	4.9	4.3	3.9	-1.0	4.9	4.3	4.0	-0.9
	sub	5.0	5.2	4.2	-0.8	5.0	5.2	4.1	-0.8
Tg	top	5.5	5.0	4.5	-1.0	5.5	5.1	4.4	-1.2
	sub	5.0	5.4	4.4	-0.6	5.0	5.4	4.3	-0.7
Hp	top	5.2	4.6	4.4	-0.9	5.3	4.8	4.3	-1.0
	sub	4.4	4.7	4.3	-0.1	4.5	4.9	4.3	-0.2
Koi	top	5.0	5.5	3.8	-1.2	5.0	5.5	3.8	-1.2
	sub	4.8	5.3	4.4	-0.4	5.0	5.2	4.3	-0.7
Knk	top	5.4	5.5	4.4	-1.0	5.6	5.6	4.3	-1.3
	sub	5.6	5.9	4.5	-1.1	5.6	5.9	4.6	-1.1

Table 20 (Continued).

Soil		pH_{H_2O}			ΔpH_{H_2O}	pH_{H_2O}			ΔpH_{H_2O}
		0 d	14 d	112 d	at 112 d[1/]	0 d	14 d	112 d	at 112 d[1/]
		Low rate of MCP				*High rate of MCP*			
Nb	top	4.5	4.4	4.0	-0.5	4.7	4.4	3.9	-0.8
	sub	5.0	5.2	4.5	-0.5	5.0	5.2	4.5	-0.5
Ak	top	4.6	5.2	3.7	-0.9	4.7	5.0	3.9	-0.8
	sub	4.9	5.3	4.8	-0.2	4.9	5.1	4.4	-0.5
Kc	top	4.7	4.5	3.9	-0.8	4.8	4.5	3.8	-1.0
	sub	5.1	5.2	4.1	-1.0	5.1	5.2	4.1	-1.0
Klt	top	5.7	5.0	4.7	-1.0	5.7	5.0	4.6	-1.1
	sub	6.0	5.9	5.3	-0.7	6.0	5.8	5.2	-0.8
Nat	top	5.0	4.4	4.0	-0.9	4.9	4.4	4.0	-1.0
	sub	5.0	5.2	4.2	-0.9	5.0	5.1	4.3	-0.8
Tg	top	5.6	5.1	4.7	-0.8	5.5	5.2	4.7	-0.8
	sub	5.0	5.4	4.4	-0.6	5.0	5.4	4.4	-0.6
Hp	top	5.3	4.7	4.2	-1.0	5.3	4.6	4.3	-1.0
	sub	4.3	4.8	4.3	-0.0	4.5	4.9	4.2	-0.3
Koi	top	5.0	5.5	3.8	-1.1	4.9	5.5	3.8	-1.2
	sub	5.1	5.3	4.4	-0.7	5.0	5.4	4.5	-0.5
Knk	top	5.6	5.6	4.4	-1.2	5.6	5.6	4.4	-1.1
	sub	5.6	6.0	4.7	-0.9	5.5	5.9	4.7	-0.9

[1/] ΔpH_{H_2O} at 112 d = the difference of pH_{H_2O} at 0 day and 112 days (pH_{H_2O} at 112 d - pH_{H_2O} at 0 d).

The soils incubated with high rate of Rat-PR, have the original soils pH_{H_2O} ranging from 4.8 to 6.8, the changed pH_{H_2O} at 14 days ranging from 4.6 to 7.0, and the changed pH_{H_2O} at 112 days ranging from 3.8 to 6.7. For high rate of Rat-PR, the ΔpH_{H_2O} at 112 days are less than the original soil pH_{H_2O} about 0.03 to 1.0 units.

The soils incubated with low rate of Kan-PR have the original soils pH_{H_2O} ranging from 4.5 to 6.1, the changed pH_{H_2O} at 14 days ranging from 4.4 to 6.4, and the changed pH_{H_2O} at 112 days ranging from 3.6 to 5.4 (Table 20). For low rate of Kan-PR, the ΔpH_{H_2O} at 112 days are less than the original soil pH_{H_2O} about 0.3 to 1.1 units. The soils incubated with high rate of Kan-PR, have the original soils pH_{H_2O} ranging from 4.6 to 6.1, the changed pH_{H_2O} at 14 days ranging from 4.4 to 6.4, and the changed pH_{H_2O} at 112 days ranging from 3.5 to 6.0. For high rate of Kan-PR, the ΔpH_{H_2O} at 112 days are less than the original soil pH_{H_2O} about 0.03 to 1.2 units.

The soils incubated with low rate of Roi-PR have the original soils pH_{H_2O} ranging from 4.4 to 5.9, the changed pH_{H_2O} at 14 days ranging from 4.3 to 5.9, and the changed pH_{H_2O} at 112 days ranging from 3.7 to 5.1 (Table 20). For low rate of Roi-PR, the ΔpH_{H_2O} at 112 days are less than the original soil pH_{H_2O} about 0.1 to 1.2 units. The soils incubated with high rate of Roi-PR, have the original soils pH_{H_2O} ranging from 4.5 to 5.9, the changed pH_{H_2O} at 14 days ranging from 4.3 to 5.9, and the changed pH_{H_2O} at 112 days ranging from 3.6 to 5.2. For high rate of Roi-PR, the ΔpH_{H_2O} at 112 days are less than the original soil pH_{H_2O} about 0.2 to 1.3 units.

The soils incubated with low rate of MCP have the original soils pH_{H_2O} ranging from 4.3 to 6.0, the changed pH_{H_2O} at 14 days ranging from 4.4 to 6.0, and the changed pH_{H_2O} at 112 days ranging from 3.7 to 5.3 (Table 20). For low rate of MCP, the ΔpH_{H_2O} at 112 days are less than the original soil pH_{H_2O} about 0.0 to 1.2 units. The soils incubated with high rate of MCP have the original soils pH_{H_2O} ranging from 4.5 to 6.0, the changed pH_{H_2O} at 14 days ranging from 4.4 to 5.9, and the changed pH_{H_2O} at 112 days ranging from 3.8 to 5.2. For high rate of MCP, the ΔpH_{H_2O} at 112 days are less than the original soil pH_{H_2O} about 0.3 to 1.2 units.

The results of soil incubation with PRs and MCP show that the changed pH_{H_2O} at 14 days are slightly fluctuated from the pH_{H_2O} of original soils, and it ranges from 4.3 to 6.4. This range of soil pH is suitable for orthophosphate in form of $H_2PO_4^-$ (Pierzynski *et al*., 2005). Bolan and Hedley (1990) proposed that the soil incubated with PR and MCP with pH ranged from 3.9 to 6.5 would have the bicarbonate extractable P increasing from 5 to 38%. Therefore, the highest of ΔP_{BC} in this study are shown at 14 days. At 112 days of soil incubation, the ΔpH_{H_2O} are clearly lower than the pH_{H_2O} of original soils about 0.03 to 1.3 units depending on the type of soil and the type of P fertilizer (PRs or MCP). Therefore, the ΔP_{BC} at 112 days give the lower ΔP_{BC} than the soils incubated at 14 day.

2.2 pH in 0.01M $CaCl_2$ (pH_{CaCl_2})

All incubated soils with PRs and MCP show the same trend variation of the changed pH_{CaCl_2} and the ΔpH_{CaCl_2} (Table 21). At 14 days of soil incubation, the changed pH_{CaCl_2} are close to the pH_{CaCl_2} of original soil (pH_{CaCl_2} at 0 day). At 112 days of soil incubation, the changed pH_{CaCl_2} are clearly lower than the pH_{CaCl_2} of original soil. The soil pH in 0.01M $CaCl_2$ is commonly lower than those obtained by DI-water about 0.5 to 1.0 pH unit (Conyers and Davey, 1988).

The soils incubated with low rate of NCR-PR have the original soils pH_{CaCl_2} ranging from 3.9 to 4.8, the changed pH_{CaCl_2} at 14 days ranging from 3.8 to 5.0, and the changed pH_{CaCl_2} at 112 days ranging from 3.3 to 4.5 (Table 21). For low rate of NCR-PR, the ΔpH_{CaCl_2} at 112 days are less than the original soil pH_{CaCl_2} about 0.2 to 0.9 units. The soils incubated with high rate of NCR-PR, have the original soils pH_{CaCl_2} ranging from 4.0 to 5.0, the changed pH_{CaCl_2} at 14 days ranging from 4.0 to 5.1, and the changed pH_{CaCl_2} at 112 days ranging from 3.4 to 4.7. For high rate of NCR-PR, the ΔpH_{CaCl_2} at 112 days are less than the original soil pH_{CaCl_2} about 0.1 to 0.9 units.

The soils incubated with low rate of Rat-PR have the original soils pH_{CaCl_2} ranging from 4.0 to 5.3, the changed pH_{CaCl_2} at 14 days ranging from 3.8 to 5.0, and the changed pH_{CaCl_2} at 112 days ranging from 3.3 to 4.8 (Table 21). For low rate of Rat-PR, the ΔpH_{CaCl_2} at 112 days are less than the original soil pH_{CaCl_2} about 0.2 to 1.2 units. The soils incubated with high rate of Rat-PR, have the original soils pH_{CaCl_2} ranging from 4.2 to 6.2, the changed pH_{CaCl_2} at 14 days ranging from 4.0 to 5.6, and the changed pH_{CaCl_2} at 112 days ranging from 3.5 to 5.8. For high rate of Rat-PR, the ΔpH_{CaCl_2} at 112 days are less than the original soil pH_{CaCl_2} about 0.0 to 1.2 units.

The soils incubated with low rate of Kan-PR have the original soils pH_{CaCl_2} ranging from 3.9 to 4.7, the changed pH_{CaCl_2} at 14 days ranging from 3.9 to 4.9, and the changed pH_{CaCl_2} at 112 days ranging from 3.4 to 4.4 (Table 21). For low rate of Kan-PR, the ΔpH_{CaCl_2} at 112 days are less than the original soil pH_{CaCl_2} about 0.0 to 0.6 units.

Table 21 The changed pH_{CaCl_2} at 14 and 112 days of incubation, and the ΔpH_{CaCl_2} at 112 days relative to 0 day.

Soil		pH_{CaCl_2}			ΔpH_{CaCl_2}	pH_{CaCl_2}			ΔpH_{CaCl_2}
		0 d	14 d	112 d	at 112 d$^{1/}$	0 d	14 d	112 d	at 112 d$^{1/}$
		Low rate of NCR-PR				*High rate of NCR-PR*			
Nb	top	3.9	3.8	3.5	-0.4	4.0	4.1	3.6	-0.4
	sub	4.1	4.0	3.9	-0.2	4.2	4.5	4.1	-0.1
Ak	top	4.0	4.1	3.3	-0.7	4.2	4.3	3.4	-0.8
	sub	4.2	4.3	3.9	-0.4	4.3	4.6	4.0	-0.3
Kc	top	4.1	3.9	3.7	-0.4	4.1	4.0	3.8	-0.3
	sub	4.1	4.2	3.8	-0.3	4.1	4.5	4.0	-0.1
Klt	top	4.7	4.5	4.2	-0.5	4.8	4.6	4.4	-0.4
	sub	4.7	5.0	4.4	-0.3	4.9	5.1	4.7	-0.2
Nat	top	4.1	3.9	3.7	-0.4	4.2	4.1	3.7	-0.4
	sub	4.0	4.0	3.7	-0.3	4.1	4.2	3.8	-0.3
Tg	top	4.8	4.3	4.1	-0.8	4.9	4.4	4.3	-0.5
	sub	4.2	4.3	3.7	-0.5	4.3	4.7	4.2	-0.1
Hp	top	4.7	3.9	3.8	-0.9	4.9	4.2	4.0	-0.9
	sub	4.2	4.2	3.6	-0.6	4.2	4.4	3.8	-0.4
Koi	top	4.1	4.0	3.6	-0.5	4.2	4.3	3.8	-0.5
	sub	4.2	4.0	3.7	-0.5	4.3	4.2	4.0	-0.3
Knk	top	4.8	4.7	4.3	-0.5	5.0	4.5	4.6	-0.4
	sub	4.8	4.7	4.5	-0.3	5.0	5.1	4.7	-0.3
		Low rate of Rat-PR				*High rate of Rat-PR*			
Nb	top	4.0	4.0	3.6	-0.4	4.2	4.0	3.7	-0.5
	sub	4.1	4.1	3.9	-0.2	4.4	4.5	4.3	-0.1
Ak	top	4.5	4.1	3.3	-1.2	4.5	4.4	3.5	-1.0
	sub	4.3	4.4	3.9	-0.4	4.7	4.8	4.5	-0.2
Kc	top	4.1	4.1	3.7	-0.4	4.3	4.3	3.9	-0.4
	sub	4.1	3.8	3.8	-0.3	4.5	4.4	4.2	-0.3
Klt	top	4.8	4.6	4.2	-0.6	5.1	4.8	4.5	-0.6
	sub	4.9	5.0	4.4	-0.5	5.5	5.2	4.9	-0.6
Nat	top	4.1	3.9	3.6	-0.5	4.4	4.1	3.8	-0.6
	sub	4.3	4.1	3.7	-0.6	4.6	4.3	4.0	-0.6
Tg	top	4.9	4.4	4.1	-0.8	5.5	4.9	5.0	-0.5
	sub	4.3	4.5	3.8	-0.5	4.9	5.1	4.6	-0.3
Hp	top	4.7	4.0	3.8	-0.9	5.4	4.5	4.2	-1.2
	sub	4.2	4.5	3.8	-0.4	4.8	4.9	4.4	-0.4
Koi	top	4.2	4.1	3.6	-0.6	4.7	4.7	3.9	-0.8
	sub	4.2	4.3	3.8	-0.4	4.5	4.5	4.5	0.0
Knk	top	5.3	4.6	4.5	-0.8	6.1	5.5	5.4	-0.7
	sub	5.1	4.9	4.8	-0.3	6.2	5.6	5.8	-0.4

Table 21 (Continued).

Soil		pH_{CaCl_2}			ΔpH_{CaCl_2}	pH_{CaCl_2}			ΔpH_{CaCl_2}
		0 d	14 d	112 d	at 112 d[1/]	0 d	14 d	112 d	at 112 d[1/]
		Low rate of Kan-PR				*High rate of Kan-PR*			
Nb	top	3.9	4.1	3.6	-0.3	3.9	4.1	3.6	-0.3
	sub	4.1	4.3	3.9	-0.2	4.3	4.1	4.1	-0.2
Ak	top	4.0	4.1	3.4	-0.6	4.1	4.1	3.4	-0.7
	sub	4.3	4.3	3.9	-0.4	4.3	4.8	4.0	-0.3
Kc	top	4.0	4.0	3.7	-0.3	4.0	4.1	3.7	-0.3
	sub	4.0	4.2	3.8	-0.2	4.1	4.2	3.9	-0.2
Klt	top	4.7	4.5	4.2	-0.5	4.8	4.6	4.3	-0.5
	sub	4.6	4.9	4.4	-0.2	4.7	5.1	4.6	-0.1
Nat	top	4.0	3.9	3.6	-0.4	4.1	3.9	3.7	-0.4
	sub	4.0	4.1	3.7	-0.3	4.0	4.0	3.7	-0.3
Tg	top	4.7	4.4	4.1	-0.6	4.8	4.5	4.4	-0.4
	sub	4.1	4.3	3.7	-0.4	4.2	4.7	3.9	-0.3
Hp	top	4.2	4.1	3.7	-0.5	4.6	4.1	3.9	-0.7
	sub	4.2	4.3	3.7	-0.5	4.3	4.4	3.8	-0.5
Koi	top	4.2	4.2	3.6	-0.6	4.3	4.3	3.7	-0.6
	sub	4.0	3.9	4.0	-0.0	4.1	4.2	3.9	-0.2
Knk	top	4.6	4.4	4.1	-0.5	4.8	4.7	4.6	-0.2
	sub	4.6	4.6	4.3	-0.3	5.0	5.3	5.2	0.2
		Low rate of Roi-PR				*High rate of Roi-PR*			
Nb	top	3.8	3.9	3.5	-0.3	3.9	3.9	3.5	-0.4
	sub	4.1	4.4	3.9	-0.2	4.1	4.4	3.8	-0.3
Ak	top	3.9	3.9	3.4	-0.5	4.0	4.0	3.5	-0.5
	sub	4.2	4.2	3.8	-0.4	4.2	4.2	3.8	-0.4
Kc	top	4.0	3.9	3.6	-0.4	4.0	4.3	3.6	-0.4
	sub	4.0	4.0	3.7	-0.3	4.3	4.1	3.7	-0.6
Klt	top	4.7	4.5	4.1	-0.6	4.8	4.5	4.1	-0.7
	sub	4.5	4.8	4.2	-0.3	4.5	4.8	4.2	-0.3
Nat	top	4.1	3.8	3.6	-0.5	4.0	3.9	3.5	-0.5
	sub	4.0	3.9	3.7	-0.3	4.2	4.0	3.6	-0.6
Tg	top	4.7	4.2	4.1	-0.6	4.7	4.3	3.9	-0.8
	sub	4.0	4.1	3.7	-0.3	4.0	4.1	3.5	-0.5
Hp	top	4.5	3.9	3.7	-0.8	4.5	4.1	3.7	-0.8
	sub	3.8	4.7	3.6	-0.2	4.0	4.2	3.7	-0.3
Koi	top	4.0	4.1	3.5	-0.5	4.1	4.0	3.5	-0.6
	sub	4.0	3.8	3.6	-0.4	4.0	3.9	3.7	-0.3
Knk	top	4.6	4.3	3.9	-0.7	4.3	4.2	4.0	-0.3
	sub	4.4	4.3	3.9	-0.5	4.4	4.3	4.0	-0.4

Table 21 (Continued).

Soil		pH_{CaCl_2}			ΔpH_{CaCl_2}	pH_{CaCl_2}			ΔpH_{CaCl_2}
		0 d	14 d	112 d	at 112 d[1/]	0 d	14 d	112 d	at 112 d[1/]
		Low rate of MCP-PR				*High rate of MCP*			
Nb	top	3.9	4.4	3.5	-0.4	3.8	4.0	3.5	-0.3
	sub	4.2	4.6	3.8	-0.4	4.1	4.1	3.9	-0.2
Ak	top	4.0	4.0	3.5	-0.5	3.9	3.9	3.5	-0.4
	sub	4.3	4.2	3.8	-0.5	4.2	4.2	3.8	-0.4
Kc	top	4.0	4.0	3.7	-0.3	4.1	3.8	3.6	-0.5
	sub	4.0	4.1	3.7	-0.3	4.0	4.1	3.7	-0.3
Klt	top	4.7	4.5	4.0	-0.7	4.7	4.6	4.1	-0.6
	sub	4.6	4.6	4.3	-0.3	4.6	4.8	4.3	-0.3
Nat	top	4.0	3.8	3.6	-0.4	4.0	3.9	3.6	-0.4
	sub	4.0	4.1	3.6	-0.4	4.0	4.0	3.7	-0.3
Tg	top	4.7	4.3	4.0	-0.7	4.7	4.4	4.1	-0.6
	sub	4.1	4.1	3.6	-0.5	4.0	4.0	3.6	-0.4
Hp	top	4.6	4.0	3.8	-0.8	4.6	3.9	3.7	-0.9
	sub	3.9	4.0	3.7	-0.2	4.1	4.3	3.6	-0.5
Koi	top	4.1	4.0	3.5	-0.6	4.1	4.0	3.5	-0.6
	sub	4.1	3.9	3.7	-0.4	4.1	4.0	3.7	-0.4
Knk	top	4.5	4.2	4.0	-0.5	4.5	4.5	4.0	-0.5
	sub	4.4	4.4	4.0	-0.4	4.3	4.6	4.0	-0.3

[1/] ΔpH_{CaCl_2} at 112 d = the difference of pH_{CaCl_2} at 0 day and 112 days (pH_{CaCl_2} 112 d- pH_{CaCl_2} 0 d).

The soils incubated with high rate of Kan-PR, have the original soils pH_{CaCl_2} ranging from 3.9 to 5.0, the changed pH_{CaCl_2} at 14 days ranging from 3.9 to 5.3, and the changed pH_{CaCl_2} at 112 days ranging from 3.4 to 5.2. For high rate of Kan-PR, the ΔpH_{CaCl_2} at 112 days are less than the original soil pH_{CaCl_2} about 0.1 to 0.7 units.

The soils incubated with low rate of Roi-PR have the original soils pH_{CaCl_2} ranging from 3.8 to 4.7, the changed pH_{CaCl_2} at 14 days ranging from 3.8 to 4.8, and the changed pH_{CaCl_2} at 112 days ranging from 3.4 to 4.2 (Table 21). For low rate of Roi-PR, the ΔpH_{CaCl_2} at 112 days are less than the original soil pH_{CaCl_2} about 0.2 to 0.8 units. The soils incubated with high rate of Roi-PR, have the original soils pH_{CaCl_2} ranging from 3.9 to 4.8, the changed pH_{CaCl_2} at 14 days ranging from 3.9 to 4.8, and the changed pH_{CaCl_2} at 112 days ranging from 3.5 to 4.2. For high rate of Roi-PR, the ΔpH_{CaCl_2} at 112 days are less than the original soil pH_{CaCl_2} about 0.3 to 0.8 units.

The soils incubated with low rate of MCP have the original soils pH_{CaCl_2} ranging from 3.9 to 4.7, the changed pH_{CaCl_2} at 14 days ranging from 3.8 to 4.6, and the changed pH_{CaCl_2} at 112 days ranging from 3.5 to 4.3 (Table 21). For low rate of MCP, the ΔpH_{CaCl_2} at 112 days are less than the original soil pH_{CaCl_2} about 0.2 to 0.8 units. The soils incubated with high rate of MCP, have the original soils pH_{CaCl_2} ranging from 3.8 to 4.7, the changed pH_{CaCl_2} at 14 days ranging from 3.8 to 4.8, and the changed pH_{CaCl_2} at 112 days ranging from 3.5 to 4.3. For high rate of MCP, the ΔpH_{CaCl_2} at 112 days are less than the original soil pH_{CaCl_2} about 0.2 to 0.9 units

The ΔpH_{CaCl_2} of soil incubated with PRs and MCP at 112 days are clearly lower than those of the original soil about 0.0 to 1.2 units. The differences of this soil pH_{CaCl_2} depend on the type of soil and of P fertilizers (PRs or MCP). The low pH_{CaCl_2} of soil incubated with PRs and MCP at 112 days can increase the PRs dissolution together increase the adsorption of dissolved P from PRs, similarly to the studies of Chien *et al*. (1980) and Bolan and Hedley (1990).

In addition, this study found that the changed pH_{CaCl_2} and the changed pH_{H_2O} of soil incubated with PRs and MCP at low and high rate have high correlation (Figure 21). The r^2 of changed pH_{CaCl2} and changed pH_{H_2O} of soil incubated for PRs and MCP treatments at low rate are 0.71 at 0 day, 0.37 at 14 days, and 0.87 at 112 days. The r^2 of changed pH_{CaCl_2} and changed pH_{H_2O} of soil incubated for PRs and MCP treatments at high rate are 0.75 at 0 day, 0.60 at 14 days, and 0.92 at 112 days. Therefore, the soil reaction by DI-water is more suitable than by 0.01M $CaCl_2$, because the analytical time is decreased and EC is measured together with the soil reaction by DI-water.

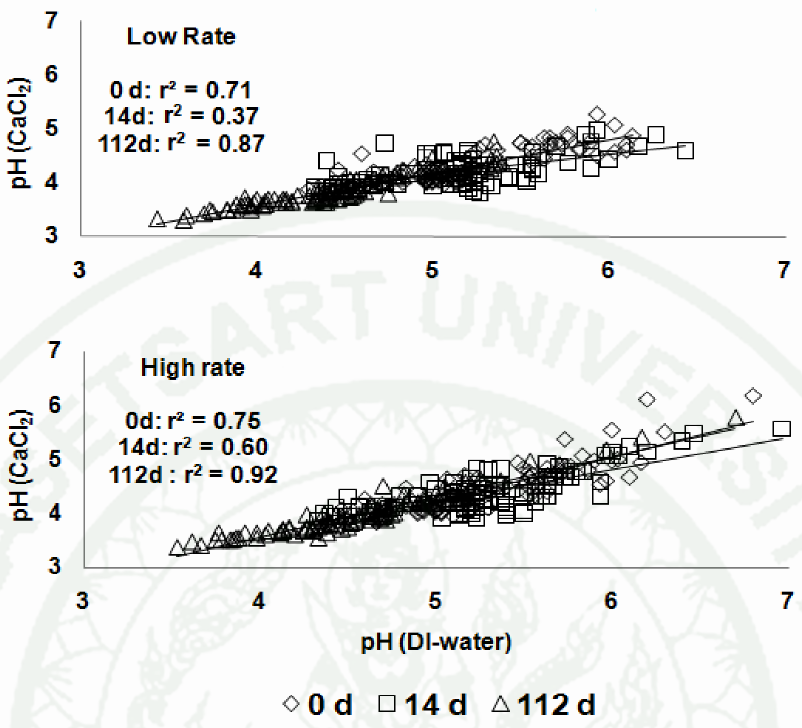


Figure 21 Relationships between pH_{CaCl_2} and pH_{H_2O} for soils incubated with PRs and MCP from 0 to 112 days.

3. The Variation of EC of Soils Incubated with PRs and MCP at 0 to 112 Days

The changed EC of soils incubation with PRs and MCP are slightly different from the original soils for both 14 and 112 days (Table 22). The changed EC is often higher in soils incubated for a long time as found in some results which changed EC at 112 days are higher than those at 14 days. The original soils have low EC ranging from 0.01 to 0.12 mS cm^{-1}. At 14 days, the changed EC is slightly higher than for the original soils, and it ranges from 0.02 to 0.11 mS cm^{-1} for low and high rates of PR and MCP treatments. The ΔEC of incubated soils at 112 days are from 0.01 to 0.36 mS cm^{-1} for low and high rates of PRs and MCP treatments. Therefore, the high rate of fertilizers (PRs and MCP) can slightly increase EC from the EC of original soils. However, the increasing rates of the changed EC are small, and the differences of the changed EC between 112 days and 0 day (original soils) are fluctuated (Table 22).

Table 22 The changed EC at 14 and 112 days of incubation, and the ΔEC at 112days relative to 0 day.

Soil		EC (mS cm^{-1})			ΔEC	EC (mS cm^{-1})			ΔEC
		0 d	14 d	112 d	at 112 d[1/]	0 d	14 d	112 d	at 112 d[1/]
		Low rate of NCR-PR				*High rate of NCR-PR*			
Nb	top	0.08	0.05	0.13	0.05	0.07	0.05	0.14	0.07
	sub	0.03	0.06	0.04	0.01	0.04	0.04	0.04	0.00
Ak	top	0.08	0.07	0.32	0.24	0.07	0.07	0.35	0.28
	sub	0.08	0.03	0.03	-0.05	0.07	0.03	0.05	-0.02
Kc	top	0.04	0.10	0.12	0.08	0.09	0.06	0.13	0.05
	sub	0.04	0.03	0.04	0.00	0.02	0.04	0.04	0.01
Klt	top	0.05	0.09	0.18	0.13	0.04	0.09	0.17	0.13
	sub	0.03	0.02	0.04	0.01	0.02	0.02	0.04	0.02
Nat	top	0.05	0.08	0.13	0.08	0.04	0.06	0.13	0.09
	sub	0.03	0.05	0.05	0.01	0.03	0.05	0.05	0.02
Tg	top	0.04	0.05	0.12	0.08	0.05	0.04	0.11	0.06
	sub	0.05	0.03	0.04	-0.01	0.05	0.02	0.05	0.00
Hp	top	0.10	0.08	0.16	0.06	0.11	0.10	0.18	0.07
	sub	0.05	0.04	0.07	0.02	0.08	0.04	0.11	0.02
Koi	top	0.03	0.04	0.13	0.10	0.04	0.03	0.14	0.10
	sub	0.04	0.05	0.03	-0.01	0.06	0.03	0.02	-0.04
Knk	top	0.10	0.03	0.05	-0.05	0.08	0.02	0.05	-0.03
	sub	0.02	0.02	0.02	0.00	0.02	0.02	0.03	0.01
		Low rate of Rat-PR				*High rate of Rat-PR*			
Nb	top	0.05	0.04	0.13	0.08	0.07	0.05	0.14	0.07
	sub	0.02	0.09	0.04	0.01	0.03	0.08	0.04	0.01
Ak	top	0.07	0.07	0.36	0.28	0.07	0.08	0.35	0.28
	sub	0.12	0.02	0.04	-0.08	0.09	0.03	0.05	-0.04
Kc	top	0.05	0.06	0.12	0.07	0.04	0.07	0.13	0.09
	sub	0.02	0.03	0.04	0.02	0.02	0.04	0.04	0.02
Klt	top	0.07	0.08	0.17	0.10	0.07	0.10	0.18	0.11
	sub	0.04	0.03	0.04	0.00	0.03	0.07	0.04	0.01
Nat	top	0.04	0.04	0.12	0.08	0.03	0.05	0.14	0.11
	sub	0.03	0.03	0.04	0.01	0.07	0.03	0.05	-0.02
Tg	top	0.03	0.05	0.10	0.06	0.07	0.04	0.07	0.00
	sub	0.05	0.04	0.04	-0.01	0.05	0.03	0.04	-0.01
Hp	top	0.09	0.09	0.16	0.08	0.10	0.09	0.15	0.05
	sub	0.08	0.03	0.08	0.00	0.09	0.04	0.08	-0.01
Koi	top	0.03	0.05	0.13	0.10	0.03	0.04	0.12	0.09
	sub	0.06	0.03	0.02	-0.04	0.04	0.02	0.02	-0.02
Knk	top	0.05	0.04	0.04	-0.01	0.04	0.03	0.05	0.01
	sub	0.03	0.03	0.02	-0.01	0.02	0.02	0.02	0.00

Table 22 (Continued).

Soil		EC (mS cm^{-1})			ΔEC	EC (mS cm^{-1})			ΔEC
		0 d	14 d	112 d	at 112 d[1/]	0 d	14 d	112 d	at 112 d[1/]
		Low rate of Kan-PR				*High rate of Kan-PR*			
Nb	top	0.10	0.06	0.30	0.20	0.10	0.06	0.36	0.26
	sub	0.07	0.03	0.03	-0.04	0.08	0.03	0.04	-0.04
Ak	top	0.10	0.06	0.30	0.20	0.10	0.06	0.36	0.26
	sub	0.07	0.03	0.03	-0.04	0.08	0.03	0.04	-0.04
Kc	top	0.04	0.05	0.12	0.08	0.06	0.05	0.13	0.07
	sub	0.04	0.03	0.03	-0.01	0.03	0.05	0.04	0.01
Klt	top	0.07	0.09	0.18	0.10	0.06	0.11	0.17	0.11
	sub	0.04	0.03	0.04	0.00	0.02	0.02	0.04	0.02
Nat	top	0.02	0.05	0.13	0.11	0.06	0.05	0.13	0.07
	sub	0.03	0.03	0.04	0.01	0.03	0.03	0.05	0.02
Tg	top	0.03	0.03	0.09	0.06	0.03	0.05	0.09	0.06
	sub	0.04	0.02	0.04	0.00	0.06	0.03	0.04	-0.02
Hp	top	0.07	0.11	0.15	0.08	0.08	0.09	0.16	0.08
	sub	0.04	0.03	0.07	0.03	0.08	0.04	0.08	0.00
Koi	top	0.05	0.03	0.13	0.08	0.03	0.03	0.12	0.09
	sub	0.05	0.02	0.03	-0.02	0.04	0.02	0.02	-0.02
Knk	top	0.03	0.03	0.05	0.02	0.02	0.04	0.04	0.02
	sub	0.02	0.03	0.01	0.00	0.01	0.02	0.02	0.01
		Low rate of Roi-PR				*High rate of Roi-PR*			
Nb	top	0.04	0.05	0.13	0.09	0.06	0.05	0.13	0.07
	sub	0.06	0.04	0.04	-0.02	0.03	0.04	0.03	0.00
Ak	top	0.08	0.06	0.21	0.13	0.06	0.06	0.24	0.17
	sub	0.07	0.03	0.03	-0.04	0.12	0.02	0.04	-0.08
Kc	top	0.06	0.07	0.12	0.06	0.04	0.05	0.13	0.09
	sub	0.02	0.04	0.04	0.02	0.04	0.04	0.04	0.00
Klt	top	0.05	0.07	0.17	0.12	0.05	0.07	0.18	0.13
	sub	0.02	0.03	0.04	0.02	0.02	0.03	0.04	0.02
Nat	top	0.08	0.04	0.12	0.04	0.04	0.08	0.12	0.08
	sub	0.02	0.04	0.04	0.02	0.04	0.02	0.06	0.02
Tg	top	0.03	0.04	0.11	0.08	0.03	0.04	0.10	0.07
	sub	0.07	0.02	0.03	-0.04	0.06	0.02	0.03	-0.03
Hp	top	0.07	0.07	0.15	0.08	0.09	0.07	0.15	0.06
	sub	0.07	0.04	0.05	-0.02	0.05	0.03	0.06	0.01
Koi	top	0.05	0.02	0.14	0.09	0.04	0.02	0.14	0.10
	sub	0.04	0.03	0.03	-0.01	0.04	0.03	0.02	-0.02
Knk	top	0.03	0.02	0.05	0.02	0.03	0.03	0.06	0.03
	sub	0.01	0.02	0.02	0.01	0.02	0.03	0.02	0.00

Table 22 (Continued).

Soil		EC (mS cm^{-1})			ΔEC	EC (mS cm^{-1})			ΔEC
		0 d	14 d	112 d	at 112 d[1]	0 d	14 d	112 d	at 112 d[1]
		Low rate of MCP				High rate of MCP			
Nb	top	0.05	0.08	0.13	0.08	0.06	0.05	0.13	0.07
	sub	0.03	0.04	0.04	0.01	0.02	0.07	0.04	0.02
Ak	top	0.09	0.06	0.23	0.14	0.10	0.06	0.24	0.14
	sub	0.07	0.02	0.02	-0.05	0.05	0.06	0.03	-0.02
Kc	top	0.08	0.05	0.13	0.05	0.03	0.11	0.13	0.10
	sub	0.02	0.02	0.04	0.02	0.02	0.05	0.04	0.02
Klt	top	0.06	0.08	0.17	0.11	0.07	0.09	0.18	0.11
	sub	0.02	0.02	0.05	0.03	0.02	0.05	0.04	0.02
Nat	top	0.05	0.05	0.13	0.08	0.03	0.05	0.13	0.10
	sub	0.05	0.05	0.05	0.00	0.05	0.02	0.05	0.00
Tg	top	0.03	0.04	0.09	0.06	0.03	0.04	0.09	0.06
	sub	0.07	0.02	0.04	-0.03	0.05	0.04	0.04	-0.01
Hp	top	0.07	0.08	0.15	0.08	0.09	0.09	0.16	0.07
	sub	0.04	0.04	0.06	0.02	0.08	0.03	0.06	-0.02
Koi	top	0.04	0.02	0.14	0.10	0.03	0.03	0.14	0.11
	sub	0.05	0.02	0.02	-0.03	0.08	0.04	0.02	-0.06
Knk	top	0.01	0.03	0.05	0.04	0.05	0.02	0.05	0.00
	sub	0.02	0.02	0.02	0.00	0.02	0.03	0.03	0.01

[1] ΔEC 112 d = the difference of EC at 0 day and 112 days (mS cm^{-1}) (EC at 112d – EC at 0d).

4. The Influence of Soil Properties to the Variation of P_{BC} (ΔP_{BC})

For evaluating the agronomic effectiveness of PRs and MCP, the change in available P (Bic-P, $P_{BC)}$ due to soils-PR incubation (ΔP_{BC}) is used as an indicator. It may increase as the PR dissolution increases (Bolan and Hedley, 1990; Babare *et al.*, 1997).

This study found that the highest ΔP_{BC} was at 14 days of soil-PR incubations. Therefore, examination of the relationships of soil properties to ΔP_{BC} at 14 days will indicate the influences of soil properties on available P.

4.1 The Correlation Coefficient (R) for Relationships between Soil properties and ΔP_{BC} at 14 Days

The correlation coefficient (r) for relationships of soil properties versus ΔP_{BC} are used to evaluate the influence of soil properties on the availability of P from of PRs with the significant differences at $P < 0.05$ (Table 23). The log-transformed data are more suitable for this study.

For NCR-PR treatments (francolite), the log ΔP_{BC} for low rate (LNCR-PR) correlates to log data of several original soils properties; current phosphorus buffer capacity (PBCc, r = -0.47), %sand (r = 0.65), Bray II P (P_{BII}, r = 0.62), dithionite extractable Fe and Al (Fe_d, r = -0.54, and Al_d, r = -0.50). ΔP_{BC} for high rates of NCR-PR treatments (HNCR-PR) correlate to log data of incubated soil properties consisting of pH_{CaCl_2} (r = -0.52), and original soils properties consisting of pH_{H_2O} (r = -0.58), pH_{KCl} (r = -0.48), and P_{BII} (r = 0.52).

For Rat- and Kan-PR treatments (hydroxyapatite, and hydroxyapatite included with crandallite), there are many parameters of original and incubated soil properties related to log ΔP_{BC} of incubated soils.

For LRat-PR treatments, log ΔP_{BC} correlate to log pH_{H_2O} (r = -0.50) and log pH_{CaCl_2} (r = -0.56) of incubated soil, and correlate to log data of original soils for pH_{H_2O} (r = -0.60), pH_{KCl} (r = -0.52), Bray II P (P_{BII}, r = 0.56), bicarbonate extractable P (P_{BC}, r = 0.61), and exchangeable Al (Ex.Al, r = 0.48). For HRat-PR treatment, the log ΔP_{BC} correlate to log data for pH_{H_2O} (r = -0.77), pH_{CaCl_2} (r = -0.85) of incubated soil, and correlate to log data of original soils consisting of phosphorus sorption maximum (Smax, r = 0.79), PBCc (r = 0.78), %sand (r = -0.59), %silt (r = 0.51), %clay (r = 0.84), percentage of soil water retention at field capacity (%FC, r = 0.67), pH_{H_2O} (r = -0.69), pH_{KCl} (r = -0.68), P_{BC} (r = 0.61), cation exchange capacity (CEC, r = 0.67), exchangeable Al (Ex.Al, r = 0.79), %OC (r = 0.56), dithionite extractable Fe Al and Mn (Fe_d, r = 0.59; Al_d, r = 0.68; Mn_d, r = 0.56), oxalate extractable Fe Al and Mn (Fe_o, r = 0.58; Al_o, r = 0.75; Mn_o, r = 0.54), and exchangeable acidity (EA, r = 0.75).

Table 23 Correlation coefficient (r) of log transformed data of ΔP_{BC} and soil properties at 14 days of soil incubation significant at $P < 0.05$. (n = 18).

Soil	Correlation of log ΔP_{BC} and the soil properties									
Properties	LNCR	HNCR	LRat	HRat	LKan	HKan	LRoi	HRoi	LMCP	HMCP
Incubated soils[1/]										
Log I(EC) (dS m^{-1})	0.24	0.37	0.13	0.17	0.39	0.17	0.08	**0.64**	0.10	-0.10
Log I(pH_{H_2O})	-0.28	-0.44	**-0.50**	**-0.77**	-0.41	**-0.55**	**-0.47**	**-0.72**	**0.58**	-0.27
Log I(pH_{CaCl_2})	-0.22	**-0.52**	**-0.56**	**-0.85**	-0.15	**-0.69**	-0.14	-0.40	**0.57**	0.06
Original soils[2/]										
Log Smax (µg g^{-1})	-0.46	0.15	0.35	**0.79**	0.19	**0.63**	0.16	0.17	-0.23	-0.05
Log b (mL $µg^{-1}$ P)	-0.19	0.04	0.13	0.16	0.001	0.32	0.08	0.14	-0.27	-0.04
Log PBCc (mL g^{-1})	**-0.47**	0.14	0.34	**0.78**	0.17	**0.61**	0.17	0.18	-0.23	-0.07
Log sand (%)	**0.65**	0.11	-0.08	**-0.59**	-0.27	-0.45	-0.19	-0.27	0.19	0.19
Log silt (%)	-0.26	0.06	0.25	**0.51**	0.29	0.37	0.22	0.28	0.07	0.02
Log clay (%)	-0.33	0.38	0.54	**0.84**	0.31	**0.74**	0.08	0.25	**-0.47**	-0.27
Log FC (%)	-0.45	0.12	0.32	**0.67**	0.24	**0.53**	0.21	0.29	-0.24	-0.18
Log pH_{H_2O}	0.08	**-0.58**	**-0.60**	**-0.69**	-0.18	**-0.67**	0.26	-0.08	**0.75**	0.28
Log pH_{KCl}	0.16	**-0.48**	**-0.52**	**-0.68**	-0.12	**-0.69**	0.08	0.08	**0.61**	0.14
Log P_{BII} (mg kg^{-1})	**0.62**	**0.52**	**0.56**	0.39	**0.50**	0.35	0.42	**0.85**	0.10	0.19
Log P_{BC} (mg kg^{-1})	0.34	0.45	**0.61**	**0.61**	**0.47**	**0.47**	0.32	**0.75**	0.05	0.15
Log CEC (cmol kg^{-1})	-0.36	0.22	0.38	**0.67**	0.23	**0.54**	0.18	0.20	-0.21	-0.17
Log EA (cmol kg^{-1})	-0.34	0.29	0.45	**0.75**	0.28	**0.64**	0.17	0.33	-0.30	-0.25
Log Ex.Ca (cmol kg^{-1})	0.17	0.27	0.25	0.12	0.14	0.21	-0.02	0.25	-0.14	-0.22
Log Ex.Mg (cmol kg^{-1})	0.21	0.26	0.22	-0.02	0.06	0.04	-0.05	-0.06	-0.12	-0.20
Log Ex.Na (cmol kg^{-1})	0.06	0.15	0.27	0.14	0.001	0.30	-0.12	-0.03	0.01	-0.21
Log Ex.K (cmol kg^{-1})	0.22	0.24	0.20	0.11	0.35	0.09	0.22	**0.47**	-0.14	-0.28
Log Ex.Al (cmol kg^{-1})	-0.10	0.41	**0.48**	**0.79**	0.14	**0.63**	0.23	0.13	-0.19	0.30
Log OC (%)	-0.05	0.27	0.40	**0.56**	0.37	0.37	0.23	**0.61**	-0.04	-0.16
Log Fe_d (g kg^{-1})	**-0.54**	0.01	0.24	**0.59**	0.19	**0.47**	0.11	0.25	-0.16	-0.29
LogAl_d (g kg^{-1})	**-0.50**	0.06	0.29	**0.68**	0.25	**0.57**	0.21	0.27	-0.14	-0.19
LogMn_d (g kg^{-1})	-0.25	0.20	0.32	**0.56**	**0.56**	**0.53**	0.28	0.44	-0.24	-0.35
LogFe_o (g kg^{-1})	-0.37	0.12	0.35	**0.58**	0.21	0.41	0.16	0.38	-0.15	-0.28
LogAl_o (g kg^{-1})	-0.34	0.18	0.41	**0.75**	0.31	**0.59**	0.34	0.41	-0.10	-0.13
LogMn_o (g kg^{-1})	-0.20	0.19	0.34	**0.54**	**0.51**	0.46	0.34	**0.49**	-0.14	-0.30

[1/] I(EC), I(pH_{H_2O}), I(pH_{CaCl_2}) = EC, pH_{H_2O}, pH_{CaCl_2} of soil incubated at 14 days; [2/] Chemical properties of the original soils (0 day); where Smax = P sorption maximum, b = constant relating the binding energy, PBCc = current phosphorus buffer capacity, pH_{H_2O} and pH_{KCl} = pH in DI-water and in 1M KCl, P_{BII} and P_{BC} = P extracted by Bray II solution and sodium bicarbonate solution, EA = extractable acidity; (**Bold letter** indicates significant level).

For LKan-PR treatments, log ΔP_{BC} correlates to log data of original soils consisting of P_{BII} (r = 0.50), P_{BC} (r = 0.47), Mn_d (r = 0.56), and Mn_o (r = 0.51). For HKan-PR treatments, log ΔP_{BC} correlate to log data of incubated soils consisting of pH_{H_2O} (r = -0.55), pH_{CaCl_2} (r = -0.69), and correlate to log data of original soils consisting of Smax (r = 0.63), PBCc (r = 0.61), %clay (r = 0.74), %FC (r = 0.53), pH_{H_2O} (r = -0.67), pH_{KCl} (r = -0.69), P_{BC} (r = 0.47), CEC (r = 0.54), Ex.Al (r =0.63), Fe_d (r = 0.47), Al_d (r = 0.57), Mn_d (r = 0.53), Al_o (r = 0.59), and EA (r = 0.64).

For Roi-PR and MCP treatments, only few soil properties correlate to ΔP_{BC}. For LRoi-PR treatments, log ΔP_{BC} correlates to log pH_{H_2O} (r = -0.47) of incubated soil. And HRoi-PR treatments, log ΔP_{BC} correlates to log data for incubated soils consisting of EC (r = 0.64), and pH_{H_2O} (r = -0.72), and correlates to log data of original soils consisting of P_{BII} (r = 0.85), P_{BC} (r = 0.75), exchangeable K (Ex.K, r = 0.47), %OC (r = 0.61), and Mn_o (r = 0.49).

For MCP treatments, the log ΔP_{BC} correlates to log pH_{H_2O} and pH_{CaCl_2} of incubated soils (r = 0.58 and 0.57, respectively), and correlates to log data of original soils consisting of %clay (r =-0.47), pH_{H_2O} (r = 0.75), pH_{KCl} (r = 0.61). For HMCP treatments, however, find there was no correlation of soil properties with ΔP_{BC} possibly due to strong P fixation occurring after applying MCP to the soils. Kanabo and Gilkes (1988) proposed that bicarbonate extractable P decreased with increasing the P retention capacity for acid soils with applied PR and water soluble P fertilizers, therefore, the delta bicarbonate extractable P (ΔP_{BC}) for soil receiving P fertilizers (both PR and P water fertilizer) was less than the P released by dissolution of the fertilizers.

This study showed that the correlations of ΔP_{BC} with soil properties are variable depending on the properties of each soil and the types and rates of P fertilizer (PRs and MCP). Consequently these results are consistent with the studied of Chien and Black (1976), Chien (1993), and Sale and Mokwunye (1993).

4.2 The Stepwise Linear Regression of Soils Properties versus ΔP_{BC} at 14 Days of Soil Incubation

For identifying the important soil properties determining ΔP_{BC}, stepwise linear regression for each treatment (PRs and MCP) were calculated. The log transformed data was most suitable for this study.

According to the results of the study, the relationship of ΔP_{BC} with soil properties is variable depending on treatments and rates of individual PRs and MCP. Therefore, the best fit equations for each treatment are shown. All stepwise equations for 14 days of soil incubation are shown in Appendix Table A37.

The best fit equation for low rate of NCR-PR is:

(1) $\log \Delta P_{BC} = -0.16 + 0.33 \log \%\text{sand} + 0.94 \log P_{BII} - 0.50 \log \%\text{OC}$ ($r^2 = 0.82$, $P = 0.00002$)

The equation shows that the ΔP_{BC} of LNCR-PR treatments positively correlate with the amounts of sand, P_{BII}, and negatively correlate with the amounts of OC of original soils ($r^2 = 0.89$).

The best fit equation for high rate of NCR-PR is:

(2) $\log \Delta P_{BC} = -4.19 - 0.20 \log pH_{H_2O} + 1.75 \log \%\text{sand} + 1.92 \log \%\text{clay} - 0.36 \log \text{Ex.Na}$ ($r^2 = 0.89$; $P = 0.000004$)

The equation shows that the ΔP_{BC} of HNCR-PR treatments positively correlate with the amounts of sand and clay, and negatively correlate with the values of soil pH_{H_2O} and exchangeable Na of original soils ($r^2 = 0.89$).

The best fit equation for low rate of Rat-PR is:

(3) $\log \Delta P_{BC} = -2.11 + 0.46 \log P_{BC} - 0.25 \log pH_{KCl} + 1.05 \log \%sand + 1.03 \log \%clay$ ($r^2 = 0.89$; $P = 0.000005$)

The equation shows that the ΔP_{BC} of LRat-PR treatments positively correlate with the amounts of P_{BC}, sand and clay, and negatively correlate with the values of soil pH_{KCl} of original soils ($r^2 = 0.89$).

The best fit equation for high rate of Rat-PR is:

(4) $\log \Delta P_{BC} = 7.14 - 0.68 \log I(pH_{CaCl_2}) - 0.36 \log pH_{KCl}$ ($r^2 = 0.83$; $P = 0.000002$)

The equation shows that the ΔP_{BC} of HRat-PR treatments negatively correlate with the values of pH_{CaCl_2} of soils incubated and the values of pH_{KCl} of original soils ($r^2 = 0.83$).

The best fit equation for low rate of Kan-PR is:

(5) $\log \Delta P_{BC} = -0.77 + 1.31 \log Mn_d - 1.00 \log Fe_o + 0.45 \log P_{BC} + 0.86 \log \%silt - 0.71 \log CEC$ ($r^2 = 0.82$; $P = 0.0003$)

The equation shows that the ΔP_{BC} of LKan-PR treatments positively correlate with the amounts of Mn_d, P_{BC}, and silt, and negatively correlate with the amounts of Fe_o and CEC of original soils ($r^2 = 0.83$).

The best fit equation for high rate of Kan-PR is:

(6) $\log \Delta P_{BC} = -1.49 + 1.25 \log \%clay + 0.59 \log \%sand - 1.20 \log Fe_o + 1.15 \log Al_o$ ($r^2 = 0.83$; $P = 0.00006$)

The equation shows that the ΔP_{BC} of HKan-PR treatments positively correlate with the amounts of clay, sand and Al_o, and negatively correlate with the amounts of Fe_o of original soils ($r^2 = 0.83$).

The best fit equation for low rate of Roi-PR is:

(7) $\log \Delta P_{BC} = 3.41 - 0.34 \log I(pH_{H_2O}) + 1.13 \log pH_{H_2O} + 1.02 \log Smax$
$+ 0.39 \log I(EC) - 0.51 \log \%OC + 0.45 \log P_{BII}$
$(r^2 = 0.72;\ P = 0.013)$

The equation shows that the ΔP_{BC} of LRoi-PR treatments positively correlate with the amounts of EC and negatively correlate with the values of pH_{H_2O} of incubated soils, and positively correlate with the amount of pH_{H_2O} Smax and P_{BII} and negatively correlate with the amounts of OC of original soils ($r^2 = 0.72$).

The best fit equation for high rate of Roi-PR is:

(8) $\log \Delta P_{BC} = 0.23 + 0.61 \log P_{BII} - 0.51 \text{ Log Ex.Mg} + 0.44 \log \text{Ex.Ca}$
$(r^2 = 0.80;\ P = 0.0002)$

The equation shows that the ΔP_{BC} of HRoi-PR treatments positively correlate with the amounts of P_{BII} and Ex.Ca, and negatively correlate with the amounts of Ex.Mg of original soils ($r^2 = 0.80$).

The best fit equation for low rate of MCP is:

(9) $\log \Delta P_{BC} = -7.50 + 0.61 \log pH_{H_2O} + 0.74 \log Smax - 0.72 \log \%Clay$
$+ 0.39 \log P_{BC} + 0.34 \log I(pH_{CaCl_2})$ $(r^2 = 0.84;\ P = 0.0002)$

The equation shows that the ΔP_{BC} of LMCP treatments positively correlate with the amounts of pH_{H_2O}, Smax and P_{BC}, and negatively correlate with the amounts of clay of original soils, and positively correlate with the amount of pH_{CaCl_2} of incubated soils ($r^2 = 0.84$).

The best fit equation for high rate of MCP is:

$$(10)\ \log \Delta P_{BC} = 4.22 - 0.37 \log b - 1.20 \log I(pH_{H_2O}) - 0.54 \log \%OC - 0.57 \log Ex.K + 0.35 \log pH_{H_2O} \quad (r^2 = 0.81;\ P = 0.0005)$$

The equation shows that the ΔP_{BC} of HMCP treatments positive correlate with the values of pH_{H_2O} and negatively correlate with the amounts of b, OC and exchangeable K of original soils, and negatively correlate with the values of pH_{H_2O} of incubated soils ($r^2 = 0.81$).

This study showed that the influence of soil properties to the amount of ΔP_{BC} from PRs and MCP treatments concerned with the three main soil factors. The first one is the influence of soil properties affecting the dissolution of PR including with the values of soil pH, CEC, exchangeable Al, and exchangeable acidity. The second is the influence of soil properties on P sorption capacity including values of Smax, PBCc, % Clay, dithionite extractable Fe Al and Mn (Fe_d, Al_d, and Mn_d), and oxalate extractable Fe Al and Mn (Fe_o, Al_o, and Mn_o). And the third is the influence of amount of P in the original soil (P_{BII} and P_{BC}). The stepwise equations indicated that there are no single soil property adequately to predict the agronomic effectiveness of PR and MCP fertilizers which is consistent with the studies of Hughes and Gilkes (1986), Wright *et al.* (1992), and Bolland *et al.* (2001). There are many publications about these three main factors influencing to P dissolution from PRs and MCP including those by Hughes and Gilkes (1986), Di *et al.* (1994); Chien and Menon (1995); Babare *et al.* (1997); Bolland *et al.* (2001), and Guo *et al.* (2011).

5. Summary

The acid soils incubated with monocalcium phosphate (MCP) and phosphate rocks (PRs) with different phosphate minerals; NCR-PR (francolite), Rat-PR (hydroxyapatite), Kan-PR (hydroxyapatite included with crandallite), and Roi-PR (variscite included with crandallite), clearly show diverse results for MCP, and PR dissolution and available P.

From 0 to 112 days of soil incubation, the results clearly show that ΔP_{BC} increased for all soils and all treatments (PRs and MCP in both of low and high rate) with increasing time and that the highest values of ΔP_{BC} are at about 14 days. The availability of P from NCR-PR from 0 to 14 days increased with increasing time in all soils and all treatments with r^2 of ΔP_{BC} versus time ranging from 0.42 to 0.97. The availability of P from Rat-PR from 0 to 14 days is similar to that for NCR-PR in soils with high clay content viz Nb-, Ak-, Kc-, Klt-, and Nat-soil (r^2 ranging from 0.27 to 1.00), and is lower than for NCR-PR for soils with high sand content viz Tg-, Hp-, Koi-, and especially Knk-soil (r^2 ranging from 0.02 to 0.99). ΔP_{BC} for Kan-PR is higher than for Roi-PR and MCP, however, it is lower than for NCR-PR and Rat-PR due to the different phosphate minerals. Roi-PR has the lowest ΔP_{BC} values due to the low solubility of variscite and crandallite. Therefore, the main factor which influences ΔP_{BC} is the type of phosphate mineral. P from MCP is quickly fixed in most of the soils, except for the Knk-soil (a sandy soil). Because the soil is moderately acid (pH 5.5 to 5.8) and has low values of clay content, P sorption capacity, exchangeable acidity, OC, and Fe and Al oxides. In general ΔP_{BC} is only higher for NCR-PR and Rat-PR applied at the high rate than in low rate.

At 112 days of soil incubation, ΔP_{BC} for all soils differ from ΔP_{BC} at 14 days, and mostly values are lower than the ΔP_{BC} at 14 days. The ΔP_{BC} at 112 days for all soils and all treatments may be used to predict the long term effectiveness of PRs and MCP. The results clearly show that ΔP_{BC} at 112 days of all soils incubated with NCR- and Rat-PR are higher than P_{BC} of original soils, especially at high application rates, except for Rat-PR incubated in Knk-soil (a sandy soil). The ΔP_{BC} at 112 days of Kan-

PR is also higher than Roi-PR and MCP, however it is clearly lower than NCR- and Rat-PR. Therefore, the long term effectiveness of NCR-PR is highest, followed by Rat- and Kan-PR. Roi-PR and MCP are unsuitable for all soils, due to the low reactivity of Roi-PR and the high P fixation of P from MCP.

The soil pH for soil incubated with PRs and MCP have the range of pH_{H_2O} from 4.3 to 6.4 which is suitable for PR dissolution .Values of ΔpH_{H_2O} at 112 days are about 0.03 to 1.3 units and are in the range of pH_{H_2O} from 3.4 to 6.7 which are lower than the range of pH_{H_2O} of original soils from 4.3 to 6.8. This study found that the values of pH_{H_2O} of soil incubated with PRs and MCP highly correlate to the values of pH_{CaCl_2} of soil incubated. Therefore the pH measurement by DI-water is more suitable for soil incubated than by 0.01M $CaCl_2$, because the analytical time is decreased and EC is measured together with the soil reaction by DI-water.

CONCLUSIONS AND RECOMMENDATION

Conclusions

Most of soils are suitable for direct use of PRs because they have low soil pH in water (pH < 5.0), which could provide sufficiently hydrogen ion for PR dissolution, and have high exchangeable acidity (EA) especially in soils with high clay content. They have low levels of available P (P_{BII} < 20 mg P kg^{-1}), low contents of OC (≤ 22 g kg^{-1}), low level of CEC (< 12 cmol kg^{-1}), and very low content of exchangeable Ca (≤ 3.0 cmol kg^{-1}). The values of P sorption maximum (Smax) are high (217 to 385 μg g^{-1}) in soils originating from basalt, shale/limestone, and sandstone (Nb-, Ak-, Kc-, and Nat-soil). Most of soil that have high values of Smax also have high increases in Bic-P, except Ak-soil which included high contents of hematite, and dithionite and oxalate extractable Fe (Fe_d and Fe_o) so dissolved P was fixed.

The solubility of PRs depends on the type of phosphate mineral of which NCR-PR (contained francolite) has the highest solubility in all of extractants (2%FA, 2%CA, and NAC) apart from AAC. Rat-PR (contained hydroxyapatite) is less soluble than NCR-PR, but higher soluble than Kan-PR (contained hydroxyapatite and crandallite). Roi-PR (contained variscite and crandallite) is most soluble in AAC extractant (pH 9.35) with little P being soluble in AAC for NCR-, Rat-, and Kan-PR. NCR-PR is more reactivity than Rat-, Kan-, and Roi-PR and is therefore more suitable for agronomic use. Rat- and Kan-PR are less suitable and Roi-PR is unsuitable for agronomic use.

The results of soil incubation with PRs and MCP from 0 to 112 days are very complicated. The effectiveness of PR and MCP treatments shown by the increase of bicarbonate extractable P (the agricultural effectiveness indicator) (ΔP_{BC}) are highest at 14 days of soil incubation while increasing P fixation occurred during 14 to 112, in which available P decreased. However, at 112 days of soil incubation P_{BC} of NCR-, Rat-, and Kan-PR treatments are still higher than P_{BC} of the original soils which clearly show that they could increase the available P level in long term with the effectiveness of NCR- > Rat- > Kan-PR. However, Roi-PR is unsuitable for agricultural use. MCP rapidly dissolved in soil solution and most P is immediately fixed by Fe and Al oxides, therefore, at 14 days of soil incubated there is only a slight increase in the ΔP_{BC} and after 14 to 112 days most P is fixed and insoluble in bicarbonate solution. The correlations of soil properties with the ΔP_{BC} (r-value) at 14 days of soil incubation are diverse depending on the properties of each soil and the types and rates of P fertilizer. These relationships are investigated by stepwise equations. The equations show that there are three main soil properties influencing ΔP_{BC} for PR and MCP treatments. The first one is the soil properties that provide hydrogen ions for PR dissolution including soil pH, CEC, exchangeable Al, and exchangeable acidity. The second is the influence of soil properties on P sorption capacity consisting of Smax, PBCc, clay, and dithionite and oxalate extractable Fe Al and Mn. And the third factor is the influence of amount of extractable P in the original soils (P_{BII} and P_{BC}). The stepwise equations indicated that there is no single soil property or simple combination of properties that will adequately predict the agronomic effectiveness of PR and MCP fertilizers.

Recommendation

To develop a comprehensive knowledge of the appropriate use of PRs in agriculture in Thailand, the author would like to extend the research on the agronomic effectiveness and the economics effect to apatitic PRs applied to various acidic soils for annual and perennial crops.

LITERATURE CITED

Altschuler, Z.S. 1973. The weathering of phosphate deposits-geochemical and environmental aspects, pp. 33-96. *In* E.J. Griffith, ed. **Environmental Phosphorus Handbook.** John Wiley & Sons, New York, London, USA.

Agbenin, J.O. 2003. Extractable iron and aluminum effects on phosphate sorption in a Savanna Alfisol. **Soil Sci. Soc. Am. J.** 67: 589-595.

Amberger, A. 1978. Experiences with soft rock phosphate for direct fertilizer application, pp. 349-356. *In* IFDC, ed. **Seminar on Phosphate Rock for Direct Application.** Muscle Shoals, Alabama, USA, IFDC.

AOAC. 1975. **Official Methods of Analysis**. 12th Ed. Association of Official Agricultural Chemists, Washington, D.C.

Arai, Y. and K.J. Livi. 2013. Underassessed phosphorus fixation mechanisms in soil sand fraction. **Geoderma** 192: 422-429.

Asomaning, S.K., M.K. Abekoe and E. Owusu-Bennoah. 2006. Phosphate rock dissolution and availability in some soils of semi-deciduous rainforest zone of Ghana. **West African Journal of Applied Ecology** 10: 209-219.

Babare, A.M., R.J. Gilkes and P.W.G. Sale. 1997. The effect of phosphate buffering capacity and other soil properties on North Carolina phosphate rock dissolution, availability of dissolved phosphorus and relative agronomic effectiveness. **Aust. J. Exp. Agr.** 37: 1037-1049.

Bachik, A.T. and L. Baert. 1981. Factors controlling phosphate fixation and release in selected soils and rubber cultivation. **J. Rubber Res. Inst. Malaysia** 29: 163-170.

Barrow, N.J. 1990. Relating chemical processes to management systems, pp. 199-209. *In* IRRI, ed. **Phosphorus Requirements for Sustainable Agriculture in Asia and Oceania.** Proceedings of a Symposium 6-10 March 1989. International Rice Research Institute.

Bertsch, P.M. and P.R. Bloom. 1996. Aluminium, pp. 517-550. *In* D.L. Sparks, ed. **Methods of Soil Analysis, Part 3 - Chemical Methods**. Madison, USA, Soil Science Society of America Book Series.

Blanchard, F.N. 1972. Physical and chemical data for crandallite from Alachua County, Florida. **Am. Mineral.** 57: 473-484.

Blount, A.M. 1974. The crystal structure of crandallite. **Am. Mineral.** 59: 41-47.

Bolan, N.S. and M.J. Hedley. 1990. Dissolution of phosphate rocks in soils. 2. Effect of pH on the dissolution and plant availability of phosphate rock in soil with pH dependent. **Fert. Res.** 24: 125-134.

Bolland, M.D.A. 1994. Effect of water supply on the response of wheat and triticale to applications of rock phosphate and superphosphate. **Fert. Res.** 39: 43-57.

Bolland, M.D.A, D.C. Lewis, R.J. Gilkes and L.J. Hamilton. 1997. Review of Australian phosphate rock research. **Aust. J. Exp. Agr.** 37: 845-859.

Bolland, M.D.A, R.J. Gilkes and R.F. Breunan. 2001. The influence of soil properties on the effectiveness of phosphate rock fertilizers. **Aust. J. Soil Res.** 39: 773-798.

Börling, K., E. Otabbong and E. Barberis. 2001. Phosphorus sorption in relation to soil properties in some cultivated Swedish soils. **Nutrient Cycling in Agro-ecosystem** 59: 39-46. doi: 10.1023/A: 1009888707349.

Bray, R.H. and L.T. Kurtz. 1945. Determination of total, organic, and available forms of phosphorus in soils. **Soil Sci.** 59: 39-45.

Brennan, R.F., M.D.A. Bolland, R.C. Jeffery and D.G. Allen. 1994. Phosphorus adsorption by a range of Western Australian soils related to soil properties. **Soil Sci. Plant Anal.** 25: 2785-2795.

Brindley, G.W. and G. Brown. 1980. **Crystal Structures of Clay Minerals and Their X-ray Identification**. Mineralogical Society, London.

Burt, R., M.D. Mays, E.C. Benham and M.A. Wilson. 2002. Phosphorus characterization and correlation with properties of selected benchmark soils of the United States. **Soil Sci. Plant Anal.** 33: 117-141. doi: 10.1081/CSS-120002382.

Buol, S.W., F.D. Hole and R.J. McCracken. 1980. **Soil Genesis and Classification**. The Iowa State Uni. Press, Ames, Iowa, USA.

Chairatna, N., N. Panapitakkul, C. Nualsri, W. Pantanahirun, R.L. Aitken and C.J. Asher. 1986. Soil fertility assessment in southern Thailand, pp. 887-888. *In* ISSS, ed. **Transactions of the 13th Congress of the International Society of Soil Science, 13-20 August 1986.** Hamburg, Germany.

Chapman, H.D. 1965. Cation-exchange capacity, pp. 891-901. *In* C.A. Black, ed. **Methods of Soil Analysis, Part 2.** American Society of Agronomy, Inc., Madison, Wisconsin, USA.

Chien, S.H. 1993. Solubility assessment for fertilizer containing phosphate rock. **Fert. Res.** 35: 93-99.

Chien, S.H. 1995. Chemical, mineralogical, and solubility characteristics of phosphate rock for direct application, pp. 49-58. *In* K. Dahanayke, S.J Van Kauwenbergh and D.T. Hellums, eds. **Direct Application of Phosphate Rock and Appropriate Technology Fertilizers in Asia: What Hinders Acceptance and Growth**. Kandy, Sri Lanka, Institute of Fundamental Studies, and Muscle Shoals, USA, IFDC.

Chien, S.H. 2003. Factors affecting the agronomic effectiveness of phosphate rock for direct application, pp. 50-62. *In* S.S.S. Rajan and S.H. Chien, eds. **Direct Application of Phosphate Rock and Related Technology**: Latest Development and Practical Experiences. Special publications IFDC-SP-37, IFDC, Muscle Shoals, AL.

Chien, S.H. 2004. Soil testing for phosphate rock application, pp. 59-68. *In* F. Zapata and R.N. Roy, ed. **Use of Phosphate Rocks for Sustainable Agriculture.** FAO Fertilizer and Plant Nutrition. Bull. No.13. Rome.

Chien, S.H. and C.A. Black. 1976. Free energy of formation of carbonate apatites in some phosphate rocks. **Soil Sci. Soc. Am. J.** 40: 234-239.

Chien, S.H. and D.K. Friesen. 1992. Phosphate rock for direct application, pp. 47-52. *In* F.J. Sikora, ed. **Future Directions for Agricultural Phosphorus Research.** Bull. Y-224. Muscle Shoals, USA, Valley Authority.

Chien, S.H., L.A. Leon and H.R. Tejeda. 1980. Dissolution of North Carolina phosphate rock in acid Colombian soils as related to soil properties. **Soil Sci. Soc. Am. J.** 44: 1267-1271.

Chien, S.H., L.I. Prochnow and H. Cantarella. 2009. Recent development of fertilizer production and use to improve nutrient efficiency and minimize environmental impacts. **Adv. Agron.** 102: 267-322.

Chien, S.H. and L.L. Hammond. 1978. A comparison of various laboratory methods for predicting the agronomic potential of phosphate rock for direct application. **Soil Sci. Soc. Am. J.** 42: 935-939.

Chien, S.H. and R.G. Menon. 1995. Factors affecting the agronomic effectiveness of phosphate rock for direct application. **Fert. Res.**, 41: 227-234.

Conyers, M.K. and B.G. Davey. 1988. Observations on some routine methods for soil pH determination. **Soil Sci.** 145: 29-36.

Cook, P.J. 1984. The spatial and temporal distribution of phosphate deposits – a review, pp. 242-274. *In* P.B. Moore and J.O. Nriagu, eds. **Phosphate Minerals.** Springer – Verlag, Berlin.

Cook, P.J., D.M. Banerjee and P.N. Southgate. 1990. The phosphorus resources of Asia and Oceania, pp. 98-114. *In* IRRI, ed. **Phosphorus Requirements for Sustainable Agriculture in Asia and Oceania.** Proceedings of a Symposium 6-10 March 1989. International Rice Research Institute.

Day, D.R. 1965. Particle fractionation and particle-size analysis, pp. 545-566. *In* C.A. Black, ed. **Methods of Soil Analysis, Part I: Physical and Mineralogical Methods.** Am. Soc. Monogr. No. 9, Madison, Wisconsin, USA.

Diamond, R.B. 1979. Views on marketing of phosphate rock for direct application, pp. 448-463. *In* IFDC, ed. **Proc. of Seminar on Phosphate Rock for Direct Application.** Special Publication SP-1. Muscle Shoals, USA, IFDC.

Díaz-Hernández, J.L., J.D. Martín-Ramos, and A. López-Galindo. 2011. Quantitative analysis of mineral phases in atmospheric dust deposited in the south-eastern Iberian Peninsula. **Atmos. Environ.** 45: 3015-3024.

Di, H.J., R. Harrison and A.S. Campbell. 1994. Assessment of methods for studying the dissolution of phosphate fertilizers of differing solubility in soil. II. Chemical extractions and comparison with isotopic exchange. **Fert. Res.** 38: 11-18.

Dill, H.G. 2001. A review of the geology of aluminium phosphates and sulphates of the alunite group minerals. **Earth-Sci. Rev.** 53: 35-93.

Elliott, J.C. 1994. **Structure and Chemistry of the Apatites and Other Calcium Orthophosphate.** Elsevier, Amsterdam, The Netherlands, New York.

Elliott, J.C., R.M. Wilson and S.E.P. Dowker. 2002. Apatite structures. JCPDS-International Center for Diffraction Data. **Adv. X-Ray Anal.** 45: 172-181.

Elzinga, E.J. and D.L. Sparks. 2007. Phosphate adsorption onto hematite: An in situ ATR-FTIR investigation of the effects of pH and loading level on the mode of phosphate surface complexation. **J. Colloid Interface Sci.** 308: 53-70.

FAO. 2004. **Use of Phosphate Rocks for Sustainable Agriculture.** FAO Fertilizer and Plant Nutrition. Bull. No.13. Rome.

FAO-UNESCO. 1979. **Soil Map of the World.** Vol. 10. South-East Asia. UNESCO, Paris, France.

Fontes, M.P.F. and S.B. Weed. 1996. Phosphate adsorption by clays from Brazilian Oxisols relationships with specific surface area and mineralogy. **Geoderma** 72: 37–51.

Fox, R.L. 1988. Phosphorus - a basic nutrient for soil improvement, pp. 57-63. *In* K.M. Pretty and S.F. Dowdle, eds. **Proceedings of an International Conference in the Management and Fertilization of Upland Soils in the Tropics and Subtropics.** Chinese Academy of Sciences and Ministry of Agriculture, Animal Husbandry and Fisheries.

Fox, R.L., S.M. Hasan and R.C. Jones. 1971. Phosphate and sulfate sorption by Latosols, pp. 857-864. *In* **Proceedings of an International Symposium on Soil Fertility Evaluation, Vol. 1.** New Delhi.

Foy, C.D. 1984. Physiological effects of hydrogen, aluminum and manganese toxicities in acid soil, pp. 57-97. *In* F. Adams, ed. **Soil Acidity and Liming.** 2nd ed. SSSA, Madison, WI, USA.

Francisco, E.A.B., S.H. Chien, L.I. Prochnow, E.R. Austin, M.C.M. Toledo and R.W. Taylor. 2008. Characterization and greenhouse evaluation of Brazilian calcined nonapatite phosphate rocks for upland and flooded rice. **Agro. J.** 100: 819-829.

Fuller, C.C., J.A. Davis, J.A. Coston and E. Dixon. 1996. Characterization of metal adsorption variability in a sand and gravel aquifer, Cape Cod, Massachusetts, U.S.A. **Journal of Contaminant Hydrology** 22, 165–187.

Gee, G.W. and J.W. Bauder. 1986. Particle-size analysis, pp. 383-411. *In*: A. Klute *et al.*, eds. **Methods of Soil Analysis, Part I.** American Society of Agronomy Monograph. No. 9. Medison, Wisconsin. USA.

Gholizadeh, A., M. Ardalan, M.M. Tehrani, H.M. Hosseini, and N. Karimian. 2009. Solubility test in some phosphate rocks and their potential for direct application in soil. **World Appl. Sci. J.** 6: 182-190.

Gilkes, R.J. and B. Palmer. 1983. Synthesis, properties, and dehydroxylation of members of the crandallite-goyazite series. **Mineralog. Mag.** 47: 221-227.

Gnandi, K. and H.J. Tobschall. 1999. Heavy metal release from phosphorite tailings into seawater: a simulated laboratory study. **Sci. Total Environ.** 236: 181-190.

Graetz, D.A. and V.D. Nair. 2000. Phosphorus sorption isotherm determination, pp. 35-38. *In* G.M. Pierzynski, ed. **Method of Phosphorus Analysis for Soils, Sediments, Residuals, and Waters.** Southern Cooperative Series Bulletin No. 396. A Publication of SERA-IEG 17.

Gregg, P.E.H., A.D. Mackay, R.W. Tillman and L.D. Currie. 1987. A summary of reactive phosphate rock research at Massey University, pp. 115-124. *In* R.E. White and L.D. Currie, eds. **The Use of Reactive Phosphate Rocks and Their Derivatives as Fertilizers.** Massey University, Palmerston North.

Guo, H.C., Q.C. Zhang, G.H. Wang and S.H. Chien. 2011. Phosphorus fractions of soils treated with phosphate rock and monocalcium phosphate after ryegrass growth. **Commun. Soil Sci. Plan.** 42: 93-99.

Hammond, L.L. and D.P. Day. 1992. Phosphate rock standardization and product quality, pp. 73-89. *In* A.T. Bachik and A. Bidin, eds. **Proceedings of Workshop on Phosphate Sources for Acid Soils in the Humid Tropics of Asia.** Malaysian Soil Science society.

Hammond, L.L. and L.A. Leon. 1983. Agronomic effectiveness of natural and altered phosphate rocks from Latin America, pp. 503-518. *In* IMPHOS, ed. **3rd International Congress on Phosphorus Compounds.** Brussels.

Hammond, L.L., S.H. Chien and A.U. Mokwunye. 1986. Agronomic value of unacidulated and partially acidulated phosphate rocks indigenous to the tropics. **Adv. Agron.** 40: 89-140.

Hedley, M.J., J.W.B. Stewart and B.S. Chauhan. 1982. Changes in inorganic and organic soil phosphorus fractions induced by cultivation practices and by laboratory incubations. **Soil Sci. Soc. Am. J.** 46: 970-976.

Hilman, Y., M.M. Hanafi, A.A. Rahim, A. Hashim and J.S. Adiningsih. 2006. Characteristics of phosphate rock materials from China Indonesia and Tunisia and their dissolution in Indonesia acid soils. **ID J. Agri. Sci.** 7: 43-50.

Hingston, F.J., A.M. Posner and J.P. Quirk. 1974. Anion adsorption by goethite and gibbsite. II. Desorption of anions from hydrous oxide surfaces. **J. Soil Sci**. 25: 16-26.

Hoare, J. 1980. Phosphate raw materials and fertilizers: Part II. A case history of marginal materials. pp. 121-128. *In* F.E. Khasawneh *et al*., ed. **The Role of Phosphorus in Agriculture.** ASA, CSSA, and SSSA, Madison, WI.

Holford, I.C.R. 1979. Evaluation of soil phosphate buffering indices. **Aust. J. Soil Res.** 17: 495-504.

Holmes, G.G., S.R. Lishmund and G.M. Oakes. 1982. A review of industrial minerals and rocks in New South Wales. **Geological Survey of New South Wales.** Bulletin 30.

Hughes, J.C. and R.J. Gilkes. 1986. The effect of soil properties and level of fertilizer application on the dissolution of Sechura rock phosphate in some soils from Brazil, Colombia, Australia, and Nigeria. **Aust. J. Soil Res.** 24: 219-227.

Hughes, J.C. and R.J. Gilkes. 1994. The dissolution of North Carolina phosphate rock in some south-western Australian soils. **Fert. Res.** 38: 249-253.

IBSRAM. 1985. **Report of the Inaugural Workshop and Proposal for Implementation of the Acid Tropical Soils Management Network** (Peru and Brazil, 1985). Bangkok: IBSRAM.

IFDC. 1983. **Characterization of a phosphate rock sample from Thailand.** International Fertilizer Development Center report.

Ivanova, T.I., O.V. Frank-Kamenetskaya, A.B. Kol'tsov and V.L. Ugolkov. 2001. Crystal structure of calcium-deficient carbonated hydroxyapatite. **J. Solid State Chem.** 160: 340-349.

Japakasetr, T. 1980. **Phosphate in Thai.** Thai Department of Mineral resources report.

Javied, S., T. Mehmood, M.M. Chaudhry, M. Tufail, N. Irfan. 2009. Heavy metal pollution from phosphate rock used for the production of fertilizer in Pakistan. **Microchem. J.** 91: 94-99.

Johns, R.K. 1962. South Australian rock phosphate deposits. **Mining Review, Adelaide** 114: 22-30.

Johns, R.K. 1976. Phosphate, South Australia, pp. 282-285. *In* C.L. Knight, ed. **Economic Geology of Australia and Papua New Guinea, Vol. 4, Industrial Minerals and Rocks.** Australasian Institute of Mining and Metallurgy. Monograph Series.

Jones, A.A. 1987. X-ray fluorescence spectrometry, pp. 85-121. *In* A.L. Page, ed. **Methods of Soil Analysis, Part II: Physical and Mineralogical Methods.** Am. Soc. Monogr. No. 9, Madison, Wisconsin, USA.

Kanabo, I.A.K. and R.J. Gilkes. 1987a. A comparison between plant response and chemical measurements of the dissolution of reactive phosphate rock in soils of different pH and phosphorus retention. **Aus. J. Soil Res.** 25: 451-460.

Kanabo, I.A.K. and R.J. Gilkes. 1987b. The role of soil pHin the dissolution of phosphate rock fertilizers. **Fert. Res.** 12: 165-179.

Kanabo, I.A.K. and R.J. Gilkes. 1988. The effect of the level of phosphate rock application on its dissolution in soil and on bicarbonate-soluble phosphorus. **Fert. Res.** 16: 67-85.

Kanchanaprasert, N. 1986. **A Study on Vital Diagnostic Features in Soil Development and Land Potential Evaluation of Alfisols and Inceptisols in Mae Klong Draniage Basin**. M.S. Thesis, Kasetsart University.

Kharikov, A.M. and V.V. Smetana. 2000. Heavy metals and radioactivity in phosphate fertilizers: Short term detrimental effects. *In* **IFA Technical Conference, New Orleans.** Louisiana, USA. October 1-4, 2000. http://ebookbrowse.com/2000-ifa-neworleans-kharikov-pdf-d108233655 (November, 2012).

Khawawneh, F.E. and E.C. Doll. 1978. The use of phosphate rock for direct application. **Adv. Agron.** 30: 195-206.

Kilmer, V.J. and L.T. Alexander. 1949. Method of making mechanical analysis of soils. **Soil Sci**. 68: 15-24.

Klug, H.P. and L.E. Alexander. 1974. **X–ray Diffraction Procedures for Polycrystalline and Amorphous Materials.** John Wiley and Sons Inc., New York, London.

Klute, A. and C. Dirksen. 1986. Water retention: Laboratory methods, pp. 635-662. *In* A. Klute *et al*., eds. **Methods of Soil Analysis. Part 1.** 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Kniep, R., D. Mootz and A. Vegas. 1977. Variscite. **Acta Cryst.** 33: 263-265.

Kpomblekou, K. and M.A. Tabatabai. 1994. Metal contents of phosphate rocks. Commum. **Soil Sci. Plant Analy.** 25: 2871-2882.

Kumar, V., R.J. Gilkes, T.M. Armitage and M.D.A. Bolland. 1994. Identification of residual P compounds in fertilized soil using density fractionation, scanning and transmission electron microscopy. **Fert. Res.** 37: 133-149.

Li, M., Y.L. Hou and B. Zhu. 2007. Phosphorus sorption-desorption by purple soils of China in relation to their properties. **Aust. J. Soil Res.** Vol. 45: 182-189.

Lins, I.D.G. and F.R. Cox. 1989. Effect of extractant and selected soil properties on predicting the correct phosphorus fertilization of soybean. **Soil Sci.** 53:813–816.

Lopes, A.S., T.J. Smyth and N. Curi. 1985. The need for a soil fertility reference base and nutrient dynamics studies, pp. 147-166. *In* **Management of Acid Tropical Soils for Sustainable Agriculture**. IBSRAM Proceedings No. 2. Bangkok: IBSRAM.

Mackay, A.D., J.K. Syers and P.E.H. Gregg. 1984. Ability of chemical extraction procedures to assess the agronomic effectiveness of phosphate rock materials. **N.Z.J. Agric. Res**. 27: 219-230.

Mackay, A.D. and J.K. Syers. 1986. Effect of phosphate, calcium, and pH on the dissolution of a phosphate rock in soil. **Fert. Res.** 10: 175-184.

Malaysian Standard. 1998. **Specification for Ground Phosphate Rock, Agricultural Grade (second revision).** MS46: 1998. Selangor DE, Malaysia, Department of Standards.

Markovic, M., B.O. Fowler and M.S. Tung. 2004. Preparation and comprehensive characterization of a calcium hydroxyapatite reference material. **J. Res. Natl. Tnst. Stand. Technol.** 109: 553-568.

Marx, E.S., J. Hart and R.G. Stevens. 1999. **Soil Test Interpretation Guide.** Oregon State University Extension Service. EC1478. https://ir.library.oregonstate.edu/jspui/bitstream/1957/14361/1/ec1478.pdf., search 10 Oct 12.

Matín-Rumos, J.D. 2004. **Using XPowder – a Software Package for Powder X-ray Diffraction Analysis.** D.L.GR-1001/04, ISBN 84-609-1497-6 Spain.

McClellan, G.H. and J.R. Lehr. 1969. Crystal chemical investigation of natural apatites. **Am Mineral.** 54: 1374-1391.

McClellan, G.H. and L.R. Gremillion. 1980. Evaluation of phosphatic raw materials, pp. 43-80. *In* **The Role of Phosphorus in Agriculture.** Published by ASA, CSSA, SSSA. Madison, Wisconsin, USA.

McConnell, D. 1938. A structural investigation of the isomorphism of the apatite group. **Am. Min.** 54: 1379-1391.

McKeague, J.A., J.E. Brydon and N.M. Miles. 1971. Differentiation of forms of extractable iron and aluminium in soils. **Soil Sci. Soc. Am. Proc.** 35: 33-38.

McKeague, J.A. and J.H. Day. 1966. Dithionite and oxalate-extractable Fe and Al as aids in differentiating various classes of soils. **Can. J. Soil Sci.** 46: 13-22.

Mehra, O.P. and M.L. Jackson. 1960. Iron oxide removal from soils and clays by dithionite-citrate system buffered with sodium carbonate. **Clays Clay Miner.** 7: 317-327.

Moncharoen L., T. Vearasilp and H. Eswaran. 1987. **Benchmark Soils of Thailand.** Land Development Department, Thailand, and Soil Management Support Services, USA.

Mozzafari, M. and J.T. Sims. 1994. Phosphorus availability and sorption in an Atlantic coastal plain watershed dominated by animal-based agriculture. **Soil Sci.** 157: 97-107.

Murphy, J. and J.P. Riley. 1962. A modified single solution method for the determination of phosphate in natural waters. **Anal. Chim. Acta** 27: 31-36.

Nair, P.S., T.J. Logan, A.N. Sharpley, L.E. Sommers, M.A. Tabatabai and T.L. Yuan. 1984. Interlaboratory comparison of a standardized phosphorus adsorption procedure. **J. Environ. Qual.** 13: 591-595.

Nair, V.D., D.A. Graetz and K.R. Reddy. 1998. Dairy manure influences on phosphorus retention capacity of Spodosols. **J. Environ. Qual.** 27: 522-527.

Natural Resources Conservation Service. 1996. **Soil Survey Laboratory Methods Manual.** Soil Survey Investigation Report No. 42, Version 3.0. USDA: Washington DC.

Noble, A.D., G.P. Gillman and S. Ruaysoongnern. 2000. A cation exchange index for assessing degradation of acid soil by further acidification under permanent agriculture in the tropics. **Eur. J. Soil Sci.** 51: 233-243.

Norrish, K. 1968. Some phosphate minerals in soils. **Trans. 9th Int. Soils Conf., Adelaide** 2: 713-723.

Official Journal of the European Communities. 1976. No. L24 of 30.1.76, p. 29. *In* F. Zapata and R.N. Roy, eds. **Use of Phosphate Rocks for Sustainable Agriculture.** FAO Fertilizer and Plant Nutrition Bull. No.13, Rome, Italy.

Olsen, S.R., C.V. Cole, F.S. Watanabe and L.A. Dean. 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. **U. S. Department of Agriculture Circular No. 939.** U.S. Government Printing Office, Washington D.C.

Olsen, S.R. and L.E. Sommers. 1982. Phosphorus, pp. 403-430. *In* A.L. Page, R.H. Miller and D.R. Keeney, eds. **Methods of Soil Analysis, Part 2, Chemical and Microbiological Properties.** Am. Soc. Agro., Madison, WI.

Onac, B.P., J. Kearns, S. C. Panzaru and R. Breban. 2004. Variscite ($AlPO_4.2H_2O$) from Cioclovina Cave (Sureneau Mountains, Romania): A tale of a missing phosphate. **Environmental Sustainability Publications.** Paper 855. http://scholarcommons.usf.edu/tles_publications/855 (October, 2012).

Owusu–Bennoah, E., C. Szilas, H.C.B. Hansen and O.K. Borggard. 1997. Phosphate sorption in relation to aluminum and iron oxides of Oxisols from Ghana. **Commun. Soil Sci. Plant Anal.** 28: 685–697.

Owusu–Bennoah, E., F. Zapata, and J.C. Fardeau. 2002. Comparison of greenhouse and P isotopic laboratory methods for evaluating the agronomic effectiveness of natural and modified rock phosphates in some acid soils of Ghana. **Nut. Cyc. Agroecosys.** 63: 1-12.

Parfitt, R.L. 1989. Phosphate reactions with natural allophone, ferrihydrite and goethite. **Eur. J. Soil Sci**. 40: 359-369. doi: 10.1111/j.1365-2389.1989.tb01280.x.

Penn, R.L., C. Zhu, H. Xu and D.R. Veblen. 2001. Iron oxide coatings on sand grains from the Atlantic coastal plain: high-resolution transmission electron microscopy characterization. **Geology** 29: 843–846.

Perrot, K. and R.G. Wise. 2000. Detemination of residual reactive phosphate rock in soil. Com. **Soil Sci. Plant Anal.** 31: 1809-1824.

Pierzynski, G.M., R.W. McDowell and J.T. Sims. 2005. Chemistry, cycling, and potential movement of inorganic phosphorus in soils. *In* J.T. Sims and A.N. Sharpley, eds. **Phosphorus: Agriculture and the Environment**. No. 46 in the series Agronomy, Am. Soc. Agro., Madison, WI., USA.

Ponnamperuma, F.N. 1977. **Screening Rice for Tolerance to Mineral Stress**. IRRI Res. Pap. Ser. 6.

Prochnow, L.I., J.F.S. Quispe, E.A.B. Francisco and G. Braga. 2006. Effectiveness of phosphate fertilizers of different water solubilities in relation to soil phosphorus adsorption. **Sci. Agric.** 63: 333-340.

Radoslovich, E.W. 1969. **Refinement of Cell Dimensions of Crandallite and Millisite Specimens.** CSIRO Australia, Div. Soils, Technical Memorandum 10.

Rajan, S.S.S., M.B. O’Connor and A.G. Sinclair. 1994. Partially acidulated phosphate rocks: Controlled release phosphorus fertilizers for more sustainable agriculture. **Fert. Res.** 37: 69-78.

Rajan, S.S.S., M.W Brown, M.K. Boyes and M.P. Upsdell. 1992. Extractable phosphorus to predict agronomic effectiveness of ground and unground phosphate rocks. **Fert. Res.** 32: 291-302.

Raven, K. P. and L.R.Hossner. 1993. Phosphorus desorption quantity-intensity in soils. **Soil Sci. Soc. Am. J.** 57: I501-1508.

Raven, K. P. and L.R. Hossner. 1994. Soil phosphorus desorption kinetics and its relationship with plant growth. **Soil Sci. Soc. Am. S. J.** 58: 416-423.

Rayment, G.E. and F.R. Higginson. 1992. Exchange acidity (hydrogen and aluminium) by 1M potassium chloride, pp. 177-178. *In*: G.E. Rayment and F.R. Higginson, ed. **Australian Laboratory Handbook of Soil and Water Chemical Methods.** Inkata Press, Melbourne, Sydney.

Reddy, K.R., M.R. Overcash, R. Khalel and P.W. Weterman. 1980. Phosphorus sorption-desorption of two soils utilized for disposal of animal wastes. **J. Environ. Qual.** 9: 86-92.

Robarge, W.P. 1999. Precipitation/dissolution reactions in soils, pp. 193-238. *In* D.L. Spark, ed. **Soil Physical Chemistry.** 2nd ed. CRC Press.

Roncal-Herrero, T. and E.H. Oelkers. 2011. Does variscite control phosphate availability in acidic natural waters? An experimental study of variscite dissolution. **Geochim. Cosmochim. Acta** 75: 416-426.

Ruan, H.D. and R.J. Gilkes. 1996. Kinetics of phosphate sorption and desorption by synthetic aluminous goethite before and after thermal transformation to hematite. **Clay Miner.** 31: 63-74.

Sabiha, J., T. Mehmood, M.M. Chaudhry, M. Tufail and N. Irfan. 2009. Heavy metal pollution from phosphate rock used for the production of fertilizer in Pakistan. **Microchem. J.** 91: 94-99.

Sale, P.W.G. and A.U. Mokwunye. 1993. Use of phosphate rocks in the tropics. **Fert. Res.** 35: 33-45.

Sale, P.W.G., P.G. Simpson, D.C. Lewis, R.J. Gilkes, M.D.A. Bolland, D.A. Ratkowsky, M.A. Gilbert, D.L. Garden, J.W.D. Cayley and D. Johnson. 1997. The agronomic effectiveness of reactive phosphate rocks. 1. Effect of the pasture environment. **Aust. J. Exp. Agr.** 37: 921-936.

Salvador, P.S. and J. Fayos. 1972. Some aspects of the structural relationship between "Messbach-Type" and "Lucin-Type" variscites. **Am. Mineral.** 57: 36-44.

Sampattavanija, S. and P. Ratanajarurak. n.d. **Phosphate.** Economic Geology Division, Department of Mineral Resources. Bangkok, Thailand (in Thai).

Sample, E.C., R.J. Soper, and G.J. Racz. 1980. Reactions of phosphate fertilizers in soils, pp. 263-310. *In* F.W. Khasawneh, ed. **The Role of Phosphorus in Agriculture.** American Society of Agronomy, Madison.

Sanchez, P.A. 1976. **Properties and Management of Soils in the Tropics**. John Wiley, New York.

Sattouf, M. 2007. **Identifying the Origin of Rock Phosphates and Phosphorus Fertilizers Using Isotope Ratio Techniques and Heavy Metal Patterns.** Landbauforschung Volkenrode - FAL Agricultural Research, Bundesallee50, 38116 Braunschweig, Germany.

Scalenghe, R., A.C. Edwards and E. Barberis. 2007. Phosphorus loss in overfertilized soils: The selective P partitioning and redistribution between particle size separates. **Eur. J. Agron.** 27: 72-80.

Schaefer, C.E.R. 2001. Brazilian latosols and their B horizon microstructure as long–term biotic constructs. **Aust. J. Soil Res.** 39: 909–926.

Sharpley, A.N., P.J.A. Kleinman and J.L. Weld. 2008. Environmental soil phosphorus indices, pp. 141-159. *In* M.R. Carter and E.G. Gregorich, eds. **Soil Sampling and Methods of Analysis**, 2nd eds. Canadian Society of Soil Science.

Shawe, D.R. 1984. **Geology and Mineral Deposits of Thailand.** Open-file report 84-403, Prepared on behalf of the Government of Thailand and the Agency for International Development, U.S. Department of State.

Sheldon, R.P. 1984. **Phosphate Resource Assessment and Exploration in Thailand.** Thai Department of Mineral Resources.

Shoji, S., M. Miyake and Y. Takeuchi. 1964. Comparison of methods of available soil phosphorus determination. II. Correlation between soil tests and “A” values. Res. Bull. **Hokkaido Natl. Agric. Exp. Stn.** 84: 32-39 (in Japanese with English summary).

Sidibé-Diarra, A., R.S. Yost, M. Doumbia, T. Attanandana, A. Bagayoko, A.B. Kouyate, R. Kablan and X. Wang. 2004. Proposed algorithm for estimating amounts of phosphate rock needed to meet crop phosphorus requirements in West African Soils. Com. **Soil Sci. Plant Anal.** 35: 385-397.

Sikora, F.J. 2002. Evaluating and quantifying the lime potential of phosphate rocks. **Nutr. Cycling in Agro-ecosystem** 63: 59-67.

Singh, B. and R.J. Gilkes. 1991. Phosphorus sorption in relation to soil properties for the major soils types of south–western Australia. **Aust. J. Soil Res.** 29: 603–618.

Singh, R.M., R.F. Moller and W.D.A. Ferreira. 1983. Characteristics of phosphorus adsorption in relation to selected soil properties of the human tropics of Amazonian, Brazil. **R. Bras. Ci. Solo** 7: 233–241.

Sirichuaychoo, W., N. Trisuwan, and R. Tawanron. 2004. **Characterization of Established Soil Series in the Peninsular and Southeast Coast Region of Thailand Reclassified According to Soil Taxonomy 2003**. Office of Soil Survey and Land Use Planning. Land Development Department. No. 523.

Sivakumar, M. and I. Manjubala. 2001. Preparation of hydroxyapatite/fluoroapatite-zirconia composites using Indian corals for biomedical applications. **Mater. Lett.** 50: 199-205.

Smalberger, S.A., U. Singh, S.H. Chien, J. Henao and P.W. Wilkens. 2006. Development and validation of a phosphate rock decision support system. **Agron. J.** 98: 471-483.

Smeck, N.E. 1985. Phosphorus dynamics in soils and landscapes. **Geoderma** 36: 185-191.

Soil Survey Staff. 1975. **Soil Taxonomy. A Basic System of Soil Classification for Making and Interpreting Soil Surveys**. USDA Agricultural Hand book.

Soil Survey Staff. 2006. **Key to Soil Taxonomy.** 10th ed. USDA and NRCS.

Środoń, J. 2006. Identification and quantitative analysis of clay minerals, pp. 765-787. *In* F. Bergaya, B.K.G. Theng, and G. Lagaly, eds. **Handbook of Clay Science**. Developments in Clay Science, Vol. 1, Elsevier Ltd.

Stiles, C.A., C.I. Mora and S.G. Driese. 2003. Pedogenic processes and domain boundaries in a Vertisol climosequence: from titanium and zirconium distribution and morphology. **Geoderma** 116: 279–299.

Stumm, W. and J.J. Morgan. 1996. **Aquatic Chemistry, Chemical Equilibria and Rates in Natural Water.** 3rd ed. John Wiley and Sons Inc., New York.

Sumner, M.E. and A.D. Noble. 2003. Soil acidification : The World Story, pp. 1-28. *In* Z. Rengel, ed. **Handbook of Soil Acidity.** Marcel Dekker, Inc. New York.

Syers, J.K., A.D. Mackay, M.W. Brown and L.D. Currie. 1986. Chemical and physical characteristics of phosphate rock materials of varying reactivity. **J. Sci. Food Agric.** 37: 1057-1064.

Syers, J.K. and L. Ru-Kun. 1990. Inorganic reactions influencing phosphorus cycling in soils, pp. 191-197. *In* IRRI, ed. **Phosphorus Requirements for Sustainable Agriculture in Asia and Oceania.** Proceedings of a Symposium 6-10 March 1989. International Rice Research Institute.

Thomas, G.W. 1982. Exchangeable cations, pp. 159-165. *In* A.L. Page, R.H. Miller and D.R. Keeney, eds. **Methods of Soil Analysis, Part 2. Chemical and Microbiological Porperties,** 2nd ed. Agronomy No. 9. ASA and SSSA. Inc., Madison, WI.

Truong, B. and C. Fayard. 1995. Small-scale fertilizer production units using raw and partially solubilized phosphate, pp. 181-191. *In* H. Gener and A.U. Mokwunye, eds. **Use of Phosphate Rock for Sustainable Agriculture in West Africa.** Miscellaneous Fertilizer Studies No. 11. Muscle Schoals, Alabama, USA, IFDC. Africa.

Truong, B. and F. Zapata. 2002. Standard characterization of phosphate rock samples from the FAO/IAEA phosphate project, pp. 9-23. *In* **Assessment of Soil Phosphorus Status and Management of Phosphatic Fertilizers to Optimize Crop Production.** IAEA-TECDOC-1272.

van-Kauwenberg, S.J. 1997. Cadmium and other minor elements in world resources of phosphate rock. *In* **Proceedings of the Fertilizer Society.** No. 400, London. 40 pp.

van-Straaten, P. 2002. **Rocks for Crops**: Agrominerals of sub-Saharan African. ICRAF, Nairobi, Kenya.

Viisimaa, L., M. Veiderma and H. Hödrejarw. 1991. Trace elements in phosphate rock and fertilisers. **Anal. Sci.** 7: 1161-1163.

Von Uexküll, H.R. and R.P. Bosshart. 1989. Management of acid upland soils in Asia, pp. 2-19. *In* E.T. Craswell and E. Pushparajah, eds. **Management of Acid Soils in the Humid Tropics of Asia.** Australian Centre for International Agricultural Research (ACIAR), Monograph No. 13.

Wada, K., L. Xue-Yuan and P.W. Moody. 1990. Chemistry of adverse upland soils, pp. 243-253. *In* IRRI, ed. **Phosphorus Requirements for Sustainable Agriculture in Asia and Ocenia.** Proceedings of Symposium 6-10 March 1989. International Rice Research Institute.

Walkley, A. and I.A. Black. 1934. An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. **Soil Sci.** 37: 29-38.

Whittig, L.D. and W.R. Allardice. 1986. X–ray diffraction technique, pp. 671–698. *In* A. Klute *et al*., eds. **Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods.** 2nd ed. Agronomy, No. 9. Amer. Soc. Agron. Inc., Madison, WI.

Wiriyakitnateekul, W. 2005. **The Properties of Clays in Red and Yellow Soils of Thailand**. Ph.D. Thesis, Kasetsart University.

Wright, R.J., V.C. Baligar and D.P. Belesky. 1992. Dissolution of North Carolina phosphate rock in soils of the Appalachian region. **Soil Sci.** 153: 25-36.

Yampracha, S. 2006. **Dissolution and Availability of Rock Phosphates for Rice Cultivation in Acid Sulfate Soils of Thailand.** Doctoral Thesis, Kasetsart University.

Yeates J.S. and M.F. Clarke. 1993. Developing alternatives to phosphate fertilizers of high water solubility. **Fert. Res.** 36: 141-150.

APPENDICES

Appendix A

Table

Appendix Table A1 The variation of changed P_{BC} for Nb-soil incubated with PR and MCP treatments from 0 to 112 days by Duncan's multiple range test.

Treatment[1/]	Changed P_{BC} by incubation time (μg mL^{-1})							Mean[3/]
	0d	3d	7d	14d	28d	56d	112d	*($P<0.01$)*
Nong Bon - topsoil (Nb-top)								
Control[2/]	5.4	5.6	6.6	7.0	6.7	5.8	5.9	6.1 g
LNCR	5.7	7.1	8.0	9.4	8.0	7.6	7.3	7.6 d
HNCR	6.2	13.7	13.3	17.1	13.5	12.8	11.7	12.6 b
LRat	5.8	8.1	8.5	10.2	8.6	8.5	8.1	8.3 c
HRat	5.7	13.6	14.8	18.8	16.4	16.1	15.8	14.5 a
LKan	5.9	6.2	7.0	8.0	6.7	7.0	7.0	6.8 ef
HKan	6.1	7.9	8.6	10.6	9.2	8.9	9.0	8.6 c
LRoi	5.2	5.8	6.5	7.6	6.4	6.4	6.5	6.3 fg
HRoi	5.4	6.2	6.8	8.1	6.7	6.5	7.5	6.8 ef
LMCP	5.5	5.8	6.0	7.9	7.3	6.5	6.2	6.5 fg
HMCP	5.1	6.7	6.9	8.8	7.5	7.3	7.4	7.1 e
Mean[3/]	5.6ns	7.9 ns	8.5ns	10.3ns	8.8ns	8.5ns	8.4ns	
Nong Bon - subsoil (Nb-sub)								
Control[2/]	3.9	4.5	4.7	5.2	4.7	4.2	4.5	4.5 h
LNCR	3.5	5.4	6.0	7.2	5.6	5.0	5.2	5.4 de
HNCR	4.2	8.4	8.9	11.6	9.3	8.8	8.2	8.5 b
LRat	4.1	5.8	6.1	6.8	6.0	5.5	5.6	5.7 d
HRat	4.5	8.6	10.7	12.8	11.7	13.2	11.2	10.4 a
LKan	4.1	4.8	5.2	6.1	7.0	4.7	4.7	5.2 fg
HKan	4.1	5.9	6.6	10.2	6.6	6.4	6.5	6.6 c
LRoi	4.0	4.5	4.9	5.8	4.7	4.3	4.2	4.6 gh
HRoi	4.2	4.6	5.3	5.7	5.0	4.8	4.9	4.9 fgh
LMCP	4.1	4.6	5.1	5.6	5.1	4.2	4.8	4.8 gh
HMCP	4.7	4.8	5.9	5.9	6.5	5.0	4.6	5.3 ef
Means[3/]	4.1ns	5.6ns	6.3ns	7.5ns	6.6ns	6.0ns	5.8ns	

[1/]PRs and MCP with low (L) and high (H) rate; [2/]Nb-top and Nb-sub incubated at field soil water capacity without PRs and MCP; [3/]Mean of changed P_{BC} of each treatment and each time with the same letter not significantly different at $P < 0.01$ by DMRT and ns is non-significant diffirent.

Appendix Table A2 The variation of changed P_{BC} for Ak-soil incubated with PR and MCP treatments from 0 to 112 days by Duncan's multiple range test.

Treatment[1/]	Changed P_{BC} by incubation time (μg mL^{-1})							Mean[3/]
	0d	3d	7d	14d	28d	56d	112d	(P<0.01)
Ao Luk - topsoil (Ak-top)								
Control[2/]	3.5	4.0	4.7	3.4	3.9	5.1	4.5	4.2 g
LNCR	3.8	5.4	5.6	5.6	4.5	6.0	5.0	5.1 d
HNCR	4.0	8.9	9.0	8.8	8.0	10.0	8.2	8.1 b
LRat	4.0	5.3	5.6	5.1	4.7	6.1	5.5	5.2 d
HRat	5.1	7.5	8.6	8.8	8.0	11.2	11.3	8.7 a
LKan	3.4	4.5	4.8	4.5	4.1	5.2	4.8	4.5 ef
HKan	3.9	5.0	5.8	5.4	5.3	7.0	6.8	5.6 c
LRoi	3.7	4.5	4.5	4.0	4.0	4.8	4.5	4.3 fg
HRoi	3.9	4.9	5.1	4.1	4.3	5.6	4.3	4.6 e
LMCP	4.3	4.4	4.5	3.8	3.5	5.1	4.5	4.3 fg
HMCP	4.6	4.9	5.0	4.4	4.2	5.3	4.6	4.7 e
Mean[3/](P<0.01)	4.0d	5.4cb	5.7b	5.3cb	5.0c	6.5a	5.8b	
Ao Luk - subsoil (Ak-sub)								
Control[2/]	2.8	3.3	4.0	3.3	3.2	3.3	3.6	3.4 g
LNCR	3.4	4.2	4.6	4.5	3.7	4.3	3.9	4.1 de
HNCR	3.4	6.6	6.9	7.6	6.2	6.8	6.3	6.3 b
LRat	2.8	4.4	4.8	4.5	4.1	4.7	4.4	4.2 d
HRat	3.5	6.7	7.3	7.8	6.7	8.2	7.6	6.8 a
LKan	2.8	3.6	4.1	3.8	3.6	4.0	3.7	3.7 f
HKan	3.0	4.8	5.2	5.1	4.6	5.3	4.8	4.7 c
LRoi	3.6	3.6	4.1	3.5	3.3	3.6	3.4	3.6 fg
HRoi	3.7	3.8	4.5	3.9	3.6	4.1	3.9	3.9 e
LMCP	3.7	3.5	3.8	3.5	3.2	3.6	3.6	3.6 fg
HMCP	4.2	3.9	4.1	4.0	3.5	4.0	4.0	4.0e
Mean[3/](P<0.01)	3.4c	4.4ab	4.9a	4.7ab	4.2b	4.7ab	4.5ab	

[1/] PRs and MCP with low (L) and high (H) rate; [2/] Ak-top and Ak-sub incubated at field soil water capacity without PRs and MCP; [3/] Mean of changed P_{BC} of each treatment and each time with the same letter not significantly different at P < 0.01 by DMRT.

Appendix Table A3 The variation of changed P_{BC} for Kc-soil incubated with PR and MCP treatments from 0 to 112 days by Duncan's multiple range test.

Treatment[1/]	Changed P_{BC} by incubation time (µg mL^{-1})							Mean[3/]
	0d	3d	7d	14d	28d	56d	112d	(P<0.01)
Khlong Chak - topsoil (Kc-top)								
Control[2/]	4.8	5.0	5.4	5.1	4.9	4.8	4.8	5.0 f
LNCR	5.1	7.1	7.0	9.3	7.4	7.3	7.2	7.2 cd
HNCR	5.5	14.4	15.1	19.0	16.2	15.1	15.9	14.5 a
LRat	5.3	7.2	7.0	9.1	7.6	7.4	8.4	7.4 c
HRat	6.7	11.0	11.9	16.1	15.6	15.5	15.3	13.2 b
LKan	4.9	5.5	5.3	5.9	5.2	5.0	6.6	5.5 ef
HKan	5.1	6.6	7.1	8.6	6.6	6.9	8.0	7.0 cd
LRoi	4.8	5.1	5.3	6.0	5.1	4.7	5.2	5.2 ef
HRoi	5.0	5.9	7.4	6.3	5.2	5.2	5.5	5.8 e
LMCP	5.4	5.6	5.3	6.2	5.7	4.5	5.5	5.5 ef
HMCP	6.2	6.0	6.1	8.0	7.3	6.0	6.6	6.6 d
Mean[3/](P<0.05)	5.4b	7.2ab	7.5a	9.1a	7.9a	7.5a	8.1a	
Khlong Chak - subsoil (Kc-sub)								
Control[2/]	3.8	3.9	4.2	4.7	4.0	3.3	4.1	4.0 g
LNCR	4.2	6.3	6.6	7.9	6.5	5.5	5.6	6.1 d
HNCR	4.3	16.9	17.2	18.6	16.2	15.8	14.8	14.8 a
LRat	4.0	7.4	7.6	9.1	7.7	6.9	7.1	7.1 c
HRat	5.2	12.5	14.6	17.5	14.3	16.7	15.5	13.8 b
LKan	3.9	4.5	5.1	5.5	4.8	4.3	4.9	4.7 ef
HKan	3.9	6.8	7.8	9.2	8.5	8.1	8.4	7.5 c
LRoi	4.0	4.2	4.8	4.9	4.0	3.6	4.3	4.3 fg
HRoi	4.5	4.7	4.9	5.2	4.5	4.0	4.9	4.7 fg
LMCP	5.1	4.1	4.3	4.1	4.2	3.3	4.0	4.2 fg
HMCP	5.7	5.6	5.7	5.7	4.8	4.3	5.1	5.3 e
Mean[3/](P<0.01)	4.4b	7.0a	7.5a	8.4a	7.2a	6.9a	7.2a	

[1/]PRs and MCP with low (L) and high (H) rate; [2/]Kc-top and Kc-sub incubated at field soil water capacity without PRs and MCP; [3/]Mean of changed P_{BC} of each treatment and each time with the same letter not significantly different at $P < 0.05$ or < 0.01 by DMRT.

Appendix Table A4 The variation of changed P_{BC} for Klt-soil incubated with PR and MCP treatments from 0 to 112 days by Duncan's multiple range test.

Treatment[1/]	Changed P_{BC} by incubation time (µg mL^{-1})							Mean[3/]
	0d	3d	7d	14d	28d	56d	112d	(P<0.01)
Khlong Teng - topsoil (Klt-top)								
Control[2/]	5.0	4.7	5.5	6.2	5.1	4.6	5.3	5.2 f
LNCR	5.2	6.7	7.1	8.8	7.2	6.5	6.7	6.9 c
HNCR	5.5	10.4	11.4	15.1	12.9	11.8	10.9	11.2 a
LRat	5.2	6.0	6.8	7.9	7.1	6.6	7.2	6.7 c
HRat	5.8	6.7	7.9	10.5	9.4	9.4	9.4	8.4 b
LKan	5.4	5.5	5.6	7.1	5.6	5.1	6.1	5.8 de
HKan	5.6	5.6	6.3	8.4	7.1	6.5	6.8	6.6 c
LRoi	5.2	5.2	5.5	6.1	5.1	4.6	5.3	5.3 f
HRoi	5.3	5.6	6.1	6.3	5.3	4.8	5.3	5.5 ef
LMCP	4.8	5.4	5.4	6.6	5.0	5.1	5.5	5.4 ef
HMCP	6.9	5.8	6.1	6.8	5.2	5.0	6.4	6.0 d
Mean[3/]	5.4ns	6.1ns	6.7ns	8.2ns	6.8ns	6.4ns	6.8ns	
Khlong Teng - subsoil (Klt-sub)								
Control	3.4	3.6	3.8	4.0	3.7	2.7	3.4	3.5 g
LNCR	3.3	4.6	5.2	5.8	4.6	4.3	4.5	4.6 d
HNCR	3.7	8.6	9.5	10.8	9.6	9.2	8.4	8.5 a
LRat	3.6	5.1	5.5	6.1	5.1	4.9	5.1	5.1 c
HRat	4.1	5.8	6.8	7.2	6.5	8.5	8.5	6.7 b
LKan	3.6	4.0	4.4	4.8	4.3	3.7	4.1	4.1 ef
HKan	3.8	5.1	5.6	6.4	5.5	5.3	5.9	5.4 c
LRoi	3.6	3.8	4.2	4.4	3.6	3.0	3.6	3.7 fg
HRoi	4.0	4.0	4.3	4.5	4.1	3.3	4.2	4.1 ef
LMCP	4.6	3.4	3.7	4.5	3.6	3.1	3.7	3.8 fg
HMCP	6.3	4.0	4.4	4.8	4.1	3.5	4.1	4.4 de
Mean[3/]	4.0ns	4.7ns	5.2ns	5.8ns	5.0ns	4.7ns	5.0ns	

[1/] PRs and MCP with low (L) and high (H) rate; [2/] Klt-top and Klt-sub incubated at field soil water capacity without PRs and MCP; [3/] Mean of changed P_{BC} of each treatment and each time with the same letter not significantly different at P < 0.01 by DMRT and ns is non-significant different.

Appendix Table A5 The variation of changed P_{BC} for Nat-soil incubated with PR and MCP treatments from 0 to 112 days by Duncan's multiple range test.

Treatment$^{1/}$	Changed P_{BC} by incubation time (µg mL^{-1})							Means$^{3/}$
	0d	3d	7d	14d	28d	56d	112d	(P<0.01)
Nathawi - topsoil (Nat-top)								
Control$^{2/}$	4.3	4.4	5.0	5.7	5.0	4.4	5.5	4.9 e
LNCR	4.0	6.5	6.9	8.6	6.8	7.4	8.2	6.9 cd
HNCR	4.9	12.2	14.5	18.6	16.0	16.3	16.1	14.1 a
LRat	4.2	6.9	7.8	8.8	7.8	7.8	7.9	7.3 c
HRat	4.8	11.3	12.3	17.2	15.4	16.6	16.3	13.4 b
LKan	4.4	4.8	5.6	6.1	5.3	6.0	5.6	5.4 e
HKan	4.1	6.5	6.4	7.9	7.1	7.4	9.0	6.9 cd
LRoi	4.0	4.6	5.1	5.4	5.1	4.9	6.1	5.0 e
HRoi	4.3	5.0	5.2	6.0	5.8	5.6	5.6	5.4 e
LMCP	4.3	4.5	5.1	5.7	5.8	5.0	6.1	5.2 e
HMCP	4.6	5.4	6.4	7.4	7.2	6.5	7.9	6.5 d
Means$^{3/}$(P<0.01)	4.4c	6.6b	7.3ab	8.9a	7.9ab	8.0ab	8.6ab	
Nathawi - subsoil (Nat-sub)								
Control$^{2/}$	3.1	3.5	3.8	3.5	3.5	3.1	3.6	3.5 f
LNCR	3.2	4.9	5.2	5.9	4.9	4.2	4.6	4.7 e
HNCR	3.4	10.3	12.6	14.2	11.8	13.1	11.0	10.9 b
LRat	3.3	5.7	6.5	6.5	6.2	5.4	5.5	5.6 d
HRat	3.9	13.8	15.3	18.8	16.1	15.0	14.8	13.9 a
LKan	3.3	3.4	3.5	4.6	3.9	3.7	3.9	3.8 f
HKan	3.4	6.0	6.5	8.0	6.5	6.6	6.3	6.2 c
LRoi	3.2	3.7	4.1	4.1	3.6	3.2	3.5	3.6 f
HRoi	3.8	4.4	4.2	4.5	4.0	3.6	4.0	4.1 ef
LMCP	3.3	3.9	3.8	4.3	3.6	3.2	3.4	3.6 f
HMCP	4.2	4.4	4.2	5.6	4.3	4.2	4.1	4.5 e
Means$^{3/}$(P<0.01)	3.5b	5.8a	6.3a	7.3a	6.2a	5.9a	5.9a	

$^{1/}$PRs and MCP with low (L) and high (H) rate; $^{2/}$Nat-top and Nat-sub incubated at field soil water capacity without PRs and MCP; $^{3/}$Mean of changed P_{BC} of each treatment and each time with the same letter not significantly different at P < 0.01 by DMRT.

Appendix Table A6 The variation of changed P_{BC} for Tg-soil incubated with PR and MCP treatments from 0 to 112 days by Duncan's multiple range test.

Treatment[1/]	Changed P_{BC} by incubation time (μg mL^{-1})							Mean[3/]
	0d	3d	7d	14d	28d	56d	112d	(P<0.01)
Thung Wa - topsoil (Tg-top)								
Control[2/]	3.6	4.1	4.5	4.5	4.1	4.2	4.7	4.3 f
LNCR	4.0	5.5	5.6	7.7	7.9	9.9	9.3	7.1 b
HNCR	4.1	6.5	7.4	10.3	11.9	15.0	12.3	9.6 a
LRat	4.0	4.6	5.1	5.7	6.3	6.8	7.4	5.7 c
HRat	4.2	4.8	5.2	5.5	4.8	5.3	5.3	5.0 de
LKan	3.8	4.4	4.7	4.7	5.2	5.4	5.3	4.8 ef
HKan	4.4	4.6	5.1	5.4	4.9	6.1	6.1	5.2 cd
LRoi	4.0	4.5	4.7	5.0	4.3	4.2	4.5	4.5 ef
HRoi	4.3	4.9	5.0	5.2	4.6	4.8	5.4	4.9 de
LMCP	3.9	4.6	5.1	5.5	4.4	4.9	5.0	4.8 ef
HMCP	9.8	5.5	6.9	8.1	5.8	6.5	7.5	7.2 b
Mean[3/](P<0.05)	4.6c	4.9bc	5.4bc	6.2ab	5.8bc	6.6a	6.6a	
Thung Wa - subsoil (Tg-sub)								
Control[2/]	2.7	3.3	3.5	3.4	3.2	2.8	3.5	3.2 f
LNCR	3.2	6.1	6.6	7.6	6.0	6.9	7.3	6.2 bc
HNCR	3.5	13.2	13.9	16.3	12.2	16.5	16.4	13.2 a
LRat	3.2	5.4	6.5	6.9	5.4	7.0	7.6	6.0 bc
HRat	3.7	5.8	5.7	5.7	4.6	7.3	7.4	5.7 cd
LKan	3.3	3.7	4.3	4.0	3.9	3.7	4.5	3.9 e
HKan	3.4	4.7	5.1	5.1	4.6	5.6	7.6	5.2 d
LRoi	3.5	3.7	3.9	3.5	3.4	3.6	3.8	3.6 ef
HRoi	3.9	3.9	4.4	4.6	3.5	4.3	3.9	4.1 e
LMCP	3.5	2.9	3.5	3.9	3.6	4.5	3.7	3.7 ef
HMCP	7.0	6.5	6.8	6.6	6.6	5.5	6.0	6.4 b
Mean[3/](P<0.01)	3.7d	5.4bc	5.8bc	6.2ab	5.2c	6.2ab	6.5a	

[1/] PRs and MCP with low (L) and high (H) rate; [2/] Tg-top and Tg-sub incubated at field soil water capacity without PRs and MCP; [3/] Mean of changed P_{BC} of each treatment and each time with the same letter not significantly different at P < 0.05 or 0.01 by DMRT.

Appendix Table A7 The variation of changed P_{BC} for Hp-soil incubated with PR and MCP treatments from 0 to 112 days by Duncan's multiple range test.

Treatment[1/]	Changed P_{BC} by incubation time (μg mL^{-1})							Mean[3/]
	0d	3d	7d	14d	28d	56d	112d	(P<0.01)
Huai Pong - topsoil (Hp-top)								
Control[2/]	7.4	7.4	7.7	9.0	7.2	8.6	8.5	8.0f
LNCR	7.9	11.0	12.4	16.0	13.2	16.3	14.7	13.1b
HNCR	8.2	17.3	19.2	28.3	23.7	27.8	25.2	21.4a
LRat	7.8	8.6	10.3	13.7	9.9	14.8	13.5	11.2cd
HRat	8.3	9.8	9.5	14.1	11.8	15.6	14.6	12.0c
LKan	8.1	8.0	8.5	10.2	10.1	11.8	10.2	9.6e
HKan	8.6	8.1	9.1	12.3	10.8	14.3	12.1	10.8d
LRoi	7.6	7.5	8.2	9.1	7.4	9.2	7.7	8.1f
HRoi	8.1	7.9	8.7	11.3	8.3	9.6	8.8	9.0e
LMCP	9.1	8.0	8.5	10.1	8.7	10.0	9.2	9.1e
HMCP	16.7	9.3	9.6	13.7	9.6	11.8	11.4	11.8c
Mean[3/](P<0.05)	8.9c	9.4c	10.2bc	13.4a	11.0bc	13.6a	12.4ab	
Huai Pong - subsoil (Hp-sub)								
Control[2/]	2.5	2.6	3.0	3.0	3.3	3.1	3.3	3.0f
LNCR	3.9	7.1	7.8	9.6	7.3	7.9	7.8	7.4c
HNCR	4.0	25.3	25.4	32.6	27.7	25.9	26.0	23.8a
LRat	3.6	7.1	7.1	9.1	7.0	9.5	10.5	7.7c
HRat	4.1	9.3	10.1	11.9	8.7	12.3	14.8	10.2b
LKan	3.1	4.1	5.0	5.1	4.2	4.7	5.7	4.6e
HKan	3.2	6.5	7.1	8.6	6.8	8.3	10.9	7.3c
LRoi	3.5	3.8	4.0	4.0	3.3	3.7	3.8	3.7ef
HRoi	3.7	4.2	4.6	4.4	4.1	4.4	4.7	4.3e
LMCP	3.6	2.9	3.4	3.7	3.3	3.4	3.5	3.4ef
HMCP	8.9	4.4	5.5	6.5	4.8	6.4	5.3	6.0d
Mean[3/](P<0.01)	4.0d	7.0c	7.6bc	9.0a	7.3bc	8.1bc	8.8ab	

[1/] PRs and MCP with low (L) and high (H) rate; [2/] Hp-top and Hp-sub incubated at field soil water capacity without PRs and MCP; [3/] Mean of changed P_{BC} of each treatment and each time with the same letter not significantly different at P < 0.05 or 0.01 by DMRT.

Appendix Table A8 The variation of changed P_{BC} for Koi-soil incubated with PR and MCP treatments from 0 to 112 days by Duncan's multiple range test.

Treatment[1/]	Changed P_{BC} by incubation time ($\mu g\ mL^{-1}$)							Mean[3/]
	0d	3d	7d	14d	28d	56d	112d	(P<0.01)
Khok Kloi - topsoil (Koi-top)								
Control[2/]	3.2	4.3	4.7	4.3	4.1	3.5	4.3	4.1e
LNCR	4.0	7.0	7.4	8.9	6.7	6.9	6.4	6.7c
HNCR	4.3	13.9	15.3	18.9	16.4	20.9	17.7	15.3a
LRat	4.1	6.6	7.5	9.3	7.4	9.0	8.3	7.5c
HRat	4.4	8.1	8.4	10.4	10.0	17.0	16.1	10.6b
LKan	3.8	4.7	5.0	5.6	4.5	5.6	4.9	4.9e
HKan	3.9	5.5	6.1	7.0	6.3	8.5	9.6	6.7c
LRoi	4.6	4.5	4.8	4.7	4.1	3.9	4.5	4.4e
HRoi	4.3	4.8	5.4	5.2	4.5	4.1	4.5	4.7e
LMCP	4.2	3.9	5.0	5.1	4.5	4.4	4.5	4.5e
HMCP	5.5	5.6	6.0	5.4	5.3	6.7	5.5	5.7d
Mean[3/](P<0.01)	4.2d	6.3c	6.9bc	7.7ab	6.7bc	8.2a	7.8ab	
Khok Kloi - subsoil (Koi-sub)								
Control[2/]	2.9	3.2	3.6	3.2	3.5	3.0	3.4	3.3h
LNCR	3.3	5.3	5.3	5.9	4.5	4.6	4.4	4.8e
HNCR	3.5	15.0	14.1	17.7	13.4	15.0	12.1	13.0b
LRat	3.6	6.2	6.5	7.4	6.2	5.3	5.6	5.8d
HRat	4.0	14.4	15.1	19.0	15.2	17.5	13.3	14.1a
LKan	3.1	3.8	3.8	4.3	3.9	3.1	3.8	3.7gh
HKan	3.4	6.4	7.5	8.1	7.7	7.8	7.2	6.9c
LRoi	3.1	3.6	4.0	3.7	3.5	3.1	3.6	3.5gh
HRoi	3.5	3.9	4.5	4.1	4.4	3.5	4.0	4.0fg
LMCP	3.6	2.7	3.3	3.8	2.6	2.5	3.6	3.2h
HMCP	4.6	3.5	4.4	5.4	4.3	3.4	4.1	4.2ef
Mean[3/](P<0.01)	3.5c	6.2b	6.6ab	7.5a	6.3ab	6.3ab	5.9b	

[1/] PRs and MCP with low (L) and high (H) rate; [2/] Koi-top and Koi-sub incubated at field soil water capacity without PRs and MCP; [3/] Means of changed P_{BC} of each treatment and each time with the same letter not significantly different at $P < 0.01$ by DMRT.

Appendix Table A9 The variation of changed P_{BC} for Knk-soil incubated with PR and MCP treatments from 0 to 112 days by Duncan's multiple range test.

Treatment	Changed P_{BC} by incubation time (µg mL^{-1})							Mean[3/]
	0d	3d	7d	14d	28d	56d	112d	(*P*<0.01)
Khlong Nokkra Thung - topsoil (Knk-top)								
Control	2.7	3.7	3.9	4.2	3.6	3.1	3.5	3.5e
LNCR	2.9	4.9	6.0	6.7	6.8	7.9	7.9	6.1b
HNCR	3.1	6.1	6.1	8.0	7.9	8.7	9.0	7.0a
LRat	3.1	3.7	4.4	4.3	4.4	5.4	6.4	4.5cd
HRat	3.6	4.1	4.4	4.6	4.2	3.4	3.9	4.0de
LKan	2.7	3.5	4.2	4.1	4.2	4.7	5.1	4.1de
HKan	3.1	3.7	4.3	4.9	4.0	3.6	4.0	3.9e
LRoi	3.4	3.9	4.2	4.1	3.8	3.2	3.9	3.8e
HRoi	3.8	4.2	4.7	4.7	4.2	6.1	4.7	4.6c
LMCP	3.5	4.6	4.9	5.9	4.6	5.2	5.1	4.8c
HMCP	7.2	5.5	8.4	7.8	6.1	7.3	5.9	6.9a
Mean[3/]	3.6ns	4.4ns	5.0ns	5.4ns	4.9ns	5.3ns	5.4ns	
Khlong Nokkra Thung - subsoil (Knk-sub)								
Control	2.9	3.4	3.6	4.0	3.1	2.8	3.3	3.3g
LNCR	3.0	5.1	5.6	6.8	5.5	6.7	7.3	5.7b
HNCR	3.2	5.6	6.2	7.1	6.3	7.7	7.4	6.2a
LRat	3.0	3.8	4.1	4.2	3.8	4.6	4.8	4.0de
HRat	3.3	5.6	4.7	4.3	3.8	3.6	3.9	4.2dc
LKan	3.1	3.8	4.2	4.3	3.8	3.8	4.4	3.9ef
HKan	3.3	3.9	4.1	4.1	3.6	3.1	3.8	3.7fg
LRoi	3.1	3.8	3.9	4.1	3.5	2.9	3.6	3.6fg
HRoi	4.2	4.2	4.4	4.8	4.0	3.8	4.6	4.3dc
LMCP	3.0	4.4	5.5	6.0	4.5	3.8	4.5	4.6c
HMCP	3.6	6.7	6.8	7.4	7.0	5.6	6.5	6.2a
Mean[3/]	3.2ns	4.6ns	4.8ns	5.2ns	4.5ns	4.4ns	4.9ns	

[1/]PRs and MCP with low (L) and high (H) rate; [2/]Knk-top and Knk-sub incubated at field soil water capacity without PRs and MCP; [3/]Means of changed P_{BC} of each treatment and each time with the same letter not significantly different at $P < 0.01$ by DMRT and ns is non-significant different.

Appendix Table A10 The variation of changed pH$_{H_2O}$ for Nb-soil incubated at 0 to 112 days by Duncan's multiple range test.

Treatment[1/]	Changed pH$_{H_2O}$ by incubation time							Mean[3/]
	0d	3d	7d	14d	28d	56d	112d	(P<0.01)
Nong Bon - topsoil (Nb-top)								
Control[2/]	4.50	4.67	4.67	4.50	3.87	3.90	3.87	4.28de
LNCR	4.50	4.67	4.53	4.40	3.87	3.90	3.87	4.25ef
HNCR	4.63	4.83	4.70	4.57	4.20	4.10	4.12	4.45b
LRat	4.63	4.70	4.70	4.47	3.97	4.03	4.03	4.36c
HRat	4.80	4.97	4.87	4.63	4.27	4.30	4.33	4.60a
LKan	4.53	4.83	4.67	4.47	3.93	3.97	3.97	4.34cd
HKan	4.57	4.73	4.60	4.43	3.97	4.00	4.03	4.33cd
LRoi	4.50	4.53	4.57	4.33	3.83	3.83	3.83	4.20f
HRoi	4.50	4.63	4.63	4.43	3.80	3.90	3.88	4.25ef
LMCP	4.47	4.67	4.60	4.40	3.90	3.83	3.97	4.26ef
HMCP	4.67	4.67	4.57	4.37	3.90	3.87	3.87	4.27e
Mean[3/](P<0.01)	4.57a	4.72a	4.65a	4.45a	3.95b	3.97b	3.98b	
Nong Bon - subsoil (Nb-sub)								
Control[2/]	4.97	5.13	5.20	5.20	5.03	4.90	4.53	5.00bc
LNCR	5.07	5.00	5.17	5.23	5.13	4.67	4.58	4.98bc
HNCR	5.07	5.10	5.27	5.27	5.07	4.70	4.68	5.02bc
LRat	5.07	5.17	5.23	5.17	5.17	4.60	4.57	5.00bc
HRat	5.30	5.30	5.33	5.30	5.13	4.87	4.82	5.15a
LKan	5.00	5.20	5.20	5.27	5.20	4.77	4.58	5.03b
HKan	5.07	5.17	5.23	5.27	5.23	4.63	4.67	5.04b
LRoi	4.97	5.03	5.13	5.13	5.10	4.93	4.50	4.97bc
HRoi	5.00	5.10	5.17	5.13	5.13	4.80	4.52	4.98bc
LMCP	5.03	5.07	5.20	5.20	5.07	4.87	4.50	4.99bc
HMCP	5.00	5.07	5.17	5.23	5.03	4.77	4.47	4.96c
Mean[3/](P<0.01)	5.05a	5.12a	5.21a	5.22a	5.12a	4.77b	4.58b	

[1/] PRs and MCP with low (L) and high (H) rate; [2/] Nb-top and Nb-sub incubated at field soil water capacity without PRs and MCP; [3/] Mean of changed pH$_{H_2O}$ of each treatment and each time with the same letter not significantly different at P < 0.01 by DMRT.

Appendix Table A11 The variation of changed pH_{H_2O} for Ak-soil incubated at 0 to 112 days by Duncan's multiple range test.

Treatment[1/]	Changed pH_{H_2O} by incubation time							Mean[3/]
	0d	3d	7d	14d	28d	56d	112d	(*P*<0.01)
Ao Luk - topsoil (Ak-top)								
Control[2/]	4.70	5.40	5.30	5.17	5.13	4.73	3.88	4.90ab
LNCR	4.67	5.40	5.37	5.13	5.03	4.30	3.58	4.79c
HNCR	4.77	5.40	5.47	5.30	5.10	3.90	3.67	4.80c
LRat	4.60	5.37	5.40	5.10	4.97	4.07	3.43	4.70d
HRat	4.83	5.67	5.60	5.43	5.23	3.87	3.83	4.92a
LKan	4.73	5.40	5.37	5.20	5.07	4.37	3.60	4.82c
HKan	4.77	5.40	5.40	5.20	5.10	4.07	3.53	4.78cd
LRoi	4.70	5.23	5.30	5.00	4.90	4.47	3.70	4.76cd
HRoi	4.60	5.37	5.43	5.13	5.03	4.47	3.62	4.81c
LMCP	4.63	5.33	5.43	5.17	5.07	4.50	3.73	4.84bc
HMCP	4.67	5.23	5.33	5.03	4.93	4.37	3.85	4.78cd
Mean[3/](*P*<0.01)	4.70b	5.38a	5.40a	5.17a	5.05a	4.28c	3.68d	
Ao Luk - subsoil (Ak-sub)								
Control[2/]	4.97	5.37	5.37	5.17	5.30	5.10	4.57	5.12ns
LNCR	5.00	5.27	5.23	5.23	5.20	5.10	4.43	5.07ns
HNCR	5.10	5.33	5.33	5.20	5.20	5.00	4.37	5.08ns
LRat	4.97	5.40	5.30	5.17	5.23	5.13	4.50	5.10ns
HRat	5.17	5.53	5.50	5.30	5.37	5.03	4.70	5.23ns
LKan	5.00	5.40	5.30	5.23	5.20	5.10	4.48	5.10ns
HKan	4.97	5.27	5.33	5.23	5.23	4.97	4.63	5.09ns
LRoi	4.97	5.40	5.33	5.13	5.33	5.07	4.42	5.10ns
HRoi	4.97	5.37	5.37	5.13	5.27	5.07	4.35	5.08ns
LMCP	4.90	5.23	5.27	5.27	5.27	5.20	4.75	5.13ns
HMCP	4.87	5.17	5.20	5.13	5.23	5.47	4.40	5.07ns
Mean[3/](*P*<0.05)	4.99a	5.34a	5.32a	5.20a	5.26a	5.11a	4.52b	

[1/] PRs and MCP with low (L) and high (H) rate; [2/] Ak-top and Ak-sub incubated at field soil water capacity without PRs and MCP; [3/] Mean of changed pH_{H_2O} of each treatment and each time with the same letter not significantly different at $P < 0.05$ or 0.01 by DMRT.

Appendix Table A12 The variation of changed pH_{H_2O} for Kc-soil incubated at 0 to 112 days by Duncan's multiple range test.

Treatment[1/]	Changed pH_{H_2O} by incubation time							Mean[3/]
	0d	3d	7d	14d	28d	56d	112d	(P<0.01)
Khlong Chak - topsoil (Kc-top)								
Control[2/]	4.67	4.67	4.67	4.53	4.10	3.90	3.83	4.34e
LNCR	4.77	4.77	4.67	4.57	4.17	4.03	4.15	4.45d
HNCR	4.83	4.90	4.87	4.70	4.37	4.30	4.38	4.62b
LRat	4.73	4.83	4.83	4.63	4.20	4.10	4.17	4.50c
HRat	5.10	5.07	5.00	4.80	4.57	4.53	4.55	4.80a
LKan	4.73	4.77	4.73	4.60	4.13	4.00	4.07	4.43d
HKan	4.90	4.80	4.73	4.67	4.23	4.17	4.17	4.52c
LRoi	4.67	4.67	4.67	4.50	4.10	3.90	3.88	4.34e
HRoi	4.63	4.73	4.70	4.50	3.93	3.90	3.92	4.33e
LMCP	4.73	4.70	4.63	4.53	4.10	3.90	3.93	4.36e
HMCP	4.77	4.70	4.63	4.53	4.10	3.90	3.77	4.34e
Mean[3/] (P<0.01)	4.78a	4.78a	4.74a	4.60a	4.18b	4.06b	4.07b	
Khlong Chak - subsoil (Kc-sub)								
Control[2/]	4.97	5.07	5.13	5.17	5.07	4.33	3.97	4.81gh
LNCR	5.17	5.00	5.20	5.23	5.10	4.33	4.40	4.92ef
HNCR	5.30	5.30	5.37	5.37	5.20	4.67	4.75	5.14b
LRat	5.27	5.13	5.27	5.23	5.07	4.43	4.57	5.00cd
HRat	5.40	5.50	5.53	5.50	5.30	4.93	5.07	5.32a
LKan	5.17	5.13	5.23	5.27	5.17	4.33	4.30	4.94de
HKan	5.20	5.27	5.30	5.30	4.90	4.53	4.63	5.02c
LRoi	5.00	5.07	5.10	5.10	4.93	4.17	4.00	4.77h
HRoi	5.10	5.17	5.07	5.17	5.07	4.13	4.05	4.82gh
LMCP	5.13	5.20	5.17	5.17	5.03	4.20	4.10	4.86fg
HMCP	5.10	5.03	5.10	5.17	5.03	4.17	4.13	4.82gh
Mean[3/](P<0.01)	5.16a	5.17a	5.22a	5.24a	5.08a	4.38b	4.36b	

[1/]PRs and MCP with low (L) and high (H) rate; [2/]Kc-top and Kc-sub incubated at field soil water capacity without PRs and MCP; [3/]Mean of changed pH_{H_2O} of each treatment and each time with the same letter not significantly different at $P < 0.01$ by DMRT.

Appendix Table A13 The variation of changed pH_{H_2O} for Klt-soil incubated at 0 to 112 days by Duncan's multiple range test.

Treatment[1/]	Changed pH_{H_2O} by incubation time							Mean[3/]
	0d	3d	7d	14d	28d	56d	112d	*(P<0.01)*
Khlong Teng - topsoil (Klt-top)								
Control[2/]	5.47	5.10	5.10	4.93	4.80	4.67	4.72	4.97g
LNCR	5.70	5.27	5.17	5.07	4.87	4.83	4.83	5.10d
HNCR	5.73	5.40	5.37	5.20	5.10	5.07	5.07	5.28b
LRat	5.67	5.30	5.18	5.07	4.93	4.90	5.00	5.15c
HRat	5.83	5.40	5.40	5.37	5.20	5.17	5.20	5.37a
LKan	5.67	5.23	5.17	4.97	4.87	4.80	4.80	5.07de
HKan	5.63	5.23	5.20	5.10	5.00	4.93	4.93	5.15c
LRoi	5.50	5.20	5.20	4.97	4.80	4.77	4.72	5.02f
HRoi	5.53	5.20	5.17	5.00	4.80	4.73	4.72	5.02f
LMCP	5.67	5.20	5.17	5.00	4.83	4.77	4.72	5.05ef
HMCP	5.70	5.23	5.17	4.97	4.83	4.73	4.63	5.04ef
Mean[3/] *(P<0.01)*	5.65a	5.25b	5.21bc	5.06bc	4.91bc	4.85c	4.85c	
Khlong Teng - subsoil (Klt-sub)								
Control	6.10	5.83	5.87	5.90	5.67	5.37	5.13	5.70ef
LNCR	6.10	5.80	5.90	5.93	5.67	5.27	5.37	5.72de
HNCR	6.17	5.93	6.10	6.00	5.70	5.60	5.63	5.88b
LRat	6.13	5.83	5.97	5.93	5.63	5.33	5.33	5.74d
HRat	6.30	6.00	6.37	6.10	5.80	5.83	5.70	6.01a
LKan	6.10	5.90	5.93	5.87	5.73	5.33	5.40	5.75cd
HKan	6.10	5.93	6.07	5.97	5.73	5.40	5.50	5.81bc
LRoi	5.93	5.80	5.87	5.90	5.70	5.20	5.13	5.65ef
HRoi	5.93	5.77	5.87	5.80	5.63	5.17	5.20	5.62f
LMCP	6.03	5.83	5.87	5.90	5.77	5.27	5.33	5.71de
HMCP	5.97	5.90	5.83	5.83	5.70	5.17	5.20	5.66ef
Mean[3/] *(P<0.01)*	6.08a	5.87ab	5.97ab	5.92ab	5.70b	5.36c	5.36c	

[1/] PRs and MCP with low (L) and high (H) rate; [2/] Klt-top and Klt-sub incubated at field soil water capacity without PRs and MCP; [3/] Mean of changed pH_{H_2O} of each treatment and each time with the same letter not significantly different at $P < 0.01$ by DMRT.

Appendix Table A14 The variation of changed pH$_{H_2O}$ for Nat-soil incubated at 0 to 112 days by Duncan's multiple range test.

Treatment[1/]	Changed pH$_{H_2O}$ by incubation time							Mean[3/]
	0d	3d	7d	14d	28d	56d	112d	*($P<0.01$)*
Nathawi - topsoil (Nat-top)								
Control[2/]	4.93	4.77	4.63	4.37	4.10	4.07	3.93	4.40gh
LNCR	4.93	4.87	4.67	4.43	4.13	4.10	4.05	4.45de
HNCR	5.00	4.93	4.80	4.57	4.30	4.33	4.27	4.60b
LRat	4.97	4.83	4.67	4.43	4.13	4.20	4.13	4.48d
HRat	5.33	5.03	4.93	4.70	4.50	4.47	4.40	4.77a
LKan	4.97	4.87	4.67	4.43	4.10	4.07	4.05	4.45ef
HKan	4.97	4.90	4.77	4.50	4.20	4.23	4.13	4.53c
LRoi	4.93	4.87	4.57	4.33	4.07	4.07	3.92	4.39gh
HRoi	4.90	4.77	4.63	4.33	4.00	4.07	3.98	4.38h
LMCP	4.97	4.87	4.63	4.40	4.07	4.07	4.03	4.43fg
HMCP	4.93	4.80	4.63	4.40	4.07	4.07	3.98	4.41gh
Mean[3/]*($P<0.01$)*	4.98a	4.86a	4.69ab	4.45bc	4.15c	4.16c	4.08c	
Nathawi - subsoil (Nat-sub)								
Control[2/]	5.17	5.10	5.17	5.10	5.03	4.83	4.20	4.94b
LNCR	5.07	4.97	5.23	5.20	4.77	4.37	4.33	4.85cd
HNCR	5.20	5.07	5.17	5.17	4.80	4.53	4.52	4.92bc
LRat	5.03	5.10	5.23	5.20	4.73	4.43	4.33	4.87cd
HRat	5.07	5.17	5.37	5.23	4.87	4.77	4.72	5.03a
LKan	5.00	5.17	5.30	5.17	4.87	4.33	4.35	4.88cd
HKan	5.00	5.10	5.23	5.20	4.77	4.50	4.50	4.90bc
LRoi	4.97	5.03	5.23	5.20	4.97	4.57	4.20	4.88cd
HRoi	4.97	5.13	5.27	5.20	4.83	4.20	4.12	4.82d
LMCP	5.03	5.03	5.20	5.23	4.83	4.53	4.17	4.86cd
HMCP	5.03	5.03	5.17	5.13	4.93	4.37	4.25	4.85cd
Mean[3/]*($P<0.01$)*	5.05ab	5.08ab	5.23a	5.18ab	4.85b	4.49c	4.33c	

[1/]PRs and MCP with low (L) and high (H) rate; [2/]Nat-top and Nat-sub incubated at field soil water capacity without PRs and MCP; [3/]Mean of changed pH$_{H_2O}$ of each treatment and each time with the same letter not significantly different at $P < 0.01$ by DMRT.

Appendix Table A15 The variation of changed pH_{H_2O} for Tg-soil incubated at 0 to 112 days by Duncan's multiple range test.

Treatment[1/]	Changed pH_{H_2O} by incubation time							Mean[3/]
	0d	3d	7d	14d	28d	56d	112d	*(P<0.01)*
Thung Wa - topsoil (Tg-top)								
Control[2/]	5.47	6.03	5.53	5.03	4.73	4.57	4.45	5.12d
LNCR	5.63	5.97	5.67	5.17	4.97	4.73	4.57	5.24cd
HNCR	5.77	6.07	5.63	5.33	5.13	5.03	5.03	5.43b
LRat	5.77	6.00	5.63	5.17	4.83	4.90	4.78	5.30c
HRat	6.00	6.10	5.97	5.70	5.07	5.73	5.53	5.73a
LKan	5.73	6.23	5.63	5.23	4.83	4.80	4.80	5.32bc
HKan	5.70	6.10	5.70	5.30	5.13	5.10	5.00	5.43b
LRoi	5.53	6.07	5.63	5.03	4.97	4.60	4.53	5.20cd
HRoi	5.53	6.13	5.67	5.10	4.80	4.57	4.38	5.17d
LMCP	5.57	6.07	5.67	5.13	5.30	4.77	4.73	5.32bc
HMCP	5.53	6.00	5.60	5.23	4.83	4.70	4.73	5.23cd
Mean[3/]*(P<0.01)*	5.66ab	6.07a	5.67ab	5.22bc	4.96c	4.86c	4.78c	
Thung Wa - subsoil (Tg-sub)								
Control[2/]	5.00	5.40	5.43	5.43	5.23	5.27	4.57	5.19de
LNCR	5.17	5.47	5.53	5.53	5.33	5.27	4.47	5.25cd
HNCR	5.17	5.60	5.70	5.77	5.57	4.93	4.90	5.38b
LRat	5.23	5.47	5.57	5.60	5.50	5.10	4.62	5.30c
HRat	5.73	6.23	6.10	6.03	5.73	5.40	5.37	5.80a
LKan	5.10	5.53	5.60	5.57	5.33	5.30	4.47	5.27c
HKan	5.17	5.70	5.73	5.73	5.67	5.00	4.70	5.39b
LRoi	5.00	5.33	5.43	5.43	5.07	5.23	4.38	5.13e
HRoi	5.03	5.37	5.43	5.40	5.20	5.17	4.33	5.13e
LMCP	5.03	5.40	5.50	5.43	5.17	5.27	4.40	5.17e
HMCP	5.03	5.30	5.47	5.40	5.13	5.23	4.38	5.14e
Mean[3/]*(P<0.01)*	5.15b	5.53a	5.59a	5.58a	5.36ab	5.20b	4.60c	

[1/]PRs and MCP with low (L) and high (H) rate; [2/]Tg-top and Tg-sub incubated at field soil water capacity without PRs and MCP; [3/]Mean of changed pH_{H_2O} of each treatment and each time with the same letter not significantly different at $P < 0.01$ by DMRT.

Appendix Table A16 The variation of changed pH$_{H_2O}$ for Hp-soil incubated at 0 to 112 days by Duncan's multiple range test.

Treatment[1/]	Changed pH$_{H_2O}$ by incubation time							Mean[3/]
	0d	3d	7d	14d	28d	56d	112d	*(P<0.01)*
Huai Pong - topsoil (Hp-top)								
Control[2/]	5.17	4.87	4.80	4.57	4.30	4.40	4.22	4.62e
LNCR	5.30	5.00	4.90	4.67	4.50	4.47	4.35	4.74d
HNCR	5.47	5.23	5.07	4.87	4.77	4.70	4.60	4.96b
LRat	5.50	5.13	5.03	4.73	4.63	4.53	4.43	4.86c
HRat	5.73	5.50	5.30	5.17	5.07	4.93	4.93	5.23a
LKan	5.20	5.07	4.93	4.70	4.50	4.40	4.42	4.75d
HKan	5.23	5.20	4.97	4.73	4.60	4.57	4.47	4.82c
LRoi	5.23	4.90	4.80	4.57	4.40	4.37	4.37	4.66e
HRoi	5.27	4.90	4.83	4.77	4.33	4.30	4.30	4.67e
LMCP	5.27	4.90	4.80	4.67	4.40	4.43	4.23	4.67e
HMCP	5.27	4.93	4.83	4.63	4.40	4.37	4.27	4.67e
Mean[3/]*(P<0.01)*	5.33a	5.06b	4.93bc	4.73cd	4.54de	4.50e	4.42e	
Huai Pong - subsoil (Hp-sub)								
Control	4.57	4.93	5.00	5.00	5.00	4.67	4.25	4.77cd
LNCR	4.47	4.80	4.87	4.87	4.63	4.63	4.20	4.64ef
HNCR	4.70	4.93	5.10	5.17	4.90	4.77	4.40	4.85bc
LRat	4.83	5.13	5.20	5.20	5.03	4.77	4.52	4.95b
HRat	5.50	5.50	5.70	5.63	5.57	5.10	5.13	5.45a
LKan	4.67	5.03	5.10	5.17	4.90	4.70	4.40	4.85bc
HKan	4.60	4.93	5.10	5.10	4.83	4.70	4.43	4.81c
LRoi	4.40	4.73	4.73	4.73	4.80	4.57	4.32	4.61ef
HRoi	4.53	4.93	4.93	4.93	4.83	4.70	4.30	4.74de
LMCP	4.30	4.70	4.77	4.80	4.63	4.63	4.33	4.60f
HMCP	4.47	4.77	4.90	4.90	4.80	4.63	4.20	4.67ef
Mean[3/]*(P<0.01)*	4.64cd	4.95ab	5.04a	5.06a	4.90ab	4.72bc	4.41d	

[1/] PRs and MCP with low (L) and high (H) rate; [2/] Hp-top and Hp-sub incubated at field soil water capacity without PRs and MCP; [3/] Mean of changed pH$_{H_2O}$ of each treatment and each time with the same letter not significantly different at $P < 0.01$ by DMRT.

Appendix Table A17 The variation of changed pH_{H_2O} for Koi-soil incubated at 0 to 112 days by Duncan's multiple range test.

Treatment[1/]	Changed pH_{H_2O} by incubation time							Mean[3/]
	0d	3d	7d	14d	28d	56d	112d	*(P<0.01)*
Khok Kloi - topsoil (Koi-top)								
Control[2/]	4.93	5.37	5.50	5.57	5.20	4.03	3.73	4.90e
LNCR	5.07	5.53	5.53	5.53	4.93	4.07	3.93	4.94de
HNCR	5.17	5.67	5.60	5.63	4.93	4.23	4.37	5.09b
LRat	5.07	5.60	5.57	5.53	4.87	4.00	3.98	4.95de
HRat	5.53	5.83	5.97	5.67	4.93	4.50	4.68	5.30a
LKan	5.07	5.60	5.67	5.60	5.00	4.20	3.95	5.01cd
HKan	5.13	5.67	5.63	5.60	4.87	4.13	4.17	5.03bc
LRoi	4.97	5.47	5.47	5.50	5.10	3.97	3.75	4.89e
HRoi	5.00	5.50	5.47	5.50	5.03	3.97	3.78	4.89e
LMCP	4.97	5.53	5.57	5.53	5.10	4.27	3.83	4.97de
HMCP	4.90	5.50	5.53	5.50	5.07	4.07	3.75	4.90e
Mean[3/]*(P<0.01)*	5.07b	5.57a	5.59a	5.56a	5.00b	4.13c	3.99c	
Khok Kloi - subsoil (Koi-sub)								
Control[2/]	4.97	5.37	5.23	5.30	5.13	5.13	4.40	5.08de
LNCR	5.07	5.23	5.27	5.30	5.33	5.23	4.53	5.14cd
HNCR	5.17	5.43	5.47	5.40	5.43	5.10	4.77	5.25b
LRat	5.13	5.27	5.27	5.30	5.40	5.23	4.55	5.16c
HRat	5.53	5.57	5.63	5.63	5.83	5.20	5.05	5.49a
LKan	5.13	5.27	5.27	5.33	5.20	5.17	4.58	5.14cd
HKan	4.93	5.33	5.30	5.37	5.37	5.17	4.72	5.17c
LRoi	4.83	5.20	5.23	5.27	5.07	5.30	4.38	5.04e
HRoi	5.00	5.27	5.23	5.23	5.00	5.13	4.30	5.02e
LMCP	5.10	5.30	5.33	5.33	5.37	5.23	4.42	5.15cd
HMCP	4.97	5.23	5.27	5.40	5.23	5.17	4.47	5.10de
Mean[3/]*(P<0.01)*	5.08a	5.32a	5.32a	5.35a	5.31a	5.19a	4.56b	

[1/] PRs and MCP with low (L) and high (H) rate; [2/] Koi-top and Koi-sub incubated at field soil water capacity without PRs and MCP; [3/] Mean of changed pH_{H_2O} of each treatment and each time with the same letter not significantly different at $P < 0.01$ by DMRT.

Appendix Table A18 The variation of changed pH_{H_2O} for Knk-soil incubated at 0 to 112 days by Duncan's multiple range test.

Treatment[1/]	Changed pH_{H_2O} by incubation time							Mean[3/]
	0d	3d	7d	14d	28d	56d	112d	*($P<0.01$)*
Khlong Nokkra Thung -topsoil (Knk-top)								
Control[2/]	5.47	5.63	5.70	5.47	4.60	4.40	4.35	5.09f
LNCR	5.90	6.10	6.07	5.70	4.97	4.90	4.92	5.51d
HNCR	5.90	5.97	6.10	5.67	5.33	5.23	5.17	5.62c
LRat	5.93	6.17	6.03	5.57	5.20	5.07	5.00	5.57cd
HRat	6.20	6.53	6.47	6.47	6.37	6.27	6.17	6.35a
LKan	5.83	6.27	6.20	5.77	4.93	4.77	4.83	5.51d
HKan	5.87	6.23	6.17	5.63	5.57	5.40	5.25	5.73b
LRoi	5.37	6.00	5.77	5.47	4.63	4.40	4.35	5.14ef
HRoi	5.57	5.80	5.73	5.57	4.57	4.37	4.27	5.12ef
LMCP	5.63	6.00	5.87	5.57	4.60	4.43	4.43	5.22e
HMCP	5.57	5.73	5.87	5.57	4.60	4.40	4.43	5.17ef
Mean[3/]*($P<0.01$)*	5.75b	6.04a	6.00a	5.68b	5.03c	4.88c	4.83c	
Khlong Nokkra Thung - subsoil (Knk-sub)								
Control[2/]	5.60	5.80	5.93	5.90	5.67	5.00	4.53	5.49e
LNCR	5.77	6.03	6.23	6.17	6.00	5.10	5.37	5.81d
HNCR	6.03	6.00	6.23	6.20	5.77	5.40	5.60	5.89cd
LRat	6.03	6.23	6.33	6.27	5.57	5.30	5.35	5.83cd
HRat	6.80	7.03	7.17	6.97	7.13	6.97	6.70	6.97a
LKan	5.83	6.27	6.40	6.43	6.27	5.03	5.35	5.94c
HKan	6.00	6.40	6.60	6.40	6.00	5.67	5.97	6.15b
LRoi	5.63	5.80	5.83	5.90	5.77	4.63	4.53	5.44e
HRoi	5.63	5.97	5.93	5.93	5.77	4.70	4.57	5.50e
LMCP	5.57	5.90	6.00	6.00	5.70	4.83	4.65	5.52e
HMCP	5.53	5.67	5.87	5.93	5.73	4.77	4.68	5.45e
Mean[3/]*($P<0.01$)*	5.86b	6.10ab	6.23a	6.19a	5.94b	5.22c	5.21c	

[1/] PRs and MCP with low (L) and high (H) rate; [2/] Knk-top and Knk-sub incubated at field soil water capacity without PRs and MCP; [3/] Mean of changed pH_{H_2O} of each treatment and each time with the same letter not significantly different at $P < 0.01$ by DMRT.

Appendix Table A19 The variation of changed pH_{CaCl_2} for Nb-soil incubated at 0 to 112 days by Duncan's multiple range test.

Treatment[1/]	Changed pH_{CaCl_2} by incubation time							Mean[3/]
	0d	3d	7d	14d	28d	56d	112d	*(P<0.01)*
Nong Bon - topsoil (Nb-top)								
Control[2/]	4.00	3.83	4.30	4.03	3.63	3.67	3.53	3.86cd
LNCR	3.90	3.83	4.30	3.83	3.60	3.67	3.50	3.80cd
HNCR	3.97	4.10	4.20	4.10	3.70	3.73	3.63	3.92b
LRat	3.97	3.97	4.10	3.97	3.63	3.73	3.57	3.85cd
HRat	4.17	4.17	4.53	4.03	3.70	3.93	3.73	4.04a
LKan	3.90	3.90	4.13	4.10	3.60	3.67	3.57	3.84cd
HKan	3.90	3.93	4.13	4.10	3.67	3.77	3.60	3.87bc
LRoi	3.83	3.87	4.00	3.93	3.53	3.67	3.50	3.76d
HRoi	3.90	3.90	4.33	3.93	3.50	3.70	3.53	3.83cd
LMCP	3.87	3.87	4.23	4.40	3.53	3.70	3.50	3.87bc
HMCP	3.83	3.90	4.33	4.00	3.53	3.70	3.53	3.83cd
Mean[3/]*(P<0.01)*	3.93bc	3.93bc	4.24a	4.04ab	3.60cd	3.72cd	3.56d	
Nong Bon - subsoil (Nb-sub)								
Control[2/]	4.07	4.20	4.53	4.33	3.90	4.10	3.80	4.13de
LNCR	4.07	4.17	4.43	4.03	3.97	4.07	3.90	4.09e
HNCR	4.20	4.43	4.67	4.47	4.13	4.13	4.07	4.30b
LRat	4.13	4.30	4.50	4.07	3.93	4.10	3.87	4.13de
HRat	4.37	4.63	4.83	4.53	4.30	4.43	4.33	4.49a
LKan	4.10	4.17	4.37	4.33	3.93	4.07	3.87	4.12de
HKan	4.27	4.40	4.60	4.13	4.10	4.17	4.07	4.25bc
LRoi	4.07	4.17	4.47	4.40	4.07	4.07	3.87	4.16de
HRoi	4.13	4.17	4.43	4.40	3.90	4.07	3.83	4.13de
LMCP	4.17	4.60	4.33	4.60	4.00	4.07	3.83	4.23cd
HMCP	4.07	4.50	4.57	4.10	4.00	4.07	3.87	4.17de
Mean[3/]*(P<0.05)*	4.15bc	4.34ab	4.52a	4.31ab	4.02bc	4.12bc	3.94c	

[1/] PRs and MCP with low (L) and high (H) rate; [2/] Nb-top and Nb-sub incubated at field soil water capacity without PRs and MCP; [3/] Mean of changed pH_{CaCl_2} of each treatment and each time with the same letter not significantly different at $P < 0.05$ or 0.01 by DMRT.

Appendix Table A20 The variation of changed $\text{pH}_{\text{CaCl}_2}$ for Ak-soil incubated at 0 to 112 days by Duncan's multiple range test.

Treatment[1/]	Changed $\text{pH}_{\text{CaCl}_2}$ by incubation time							Mean[3/]
	0d	3d	7d	14d	28d	56d	112d	*(P<0.01)*
Ao Luk - topsoil (Ak-top)								
Control[2/]	3.97	4.07	4.23	3.97	4.00	3.77	3.47	3.92e
LNCR	4.00	4.13	4.20	4.07	4.00	3.70	3.30	3.91e
HNCR	4.17	4.37	4.70	4.27	4.27	3.60	3.40	4.11b
LRat	4.53	4.33	4.30	4.07	3.97	3.63	3.33	4.02cd
HRat	4.47	4.70	4.83	4.43	4.33	3.63	3.50	4.27a
LKan	3.97	4.33	4.27	4.07	4.00	3.70	3.40	3.96de
HKan	4.13	4.33	4.60	4.13	4.20	3.60	3.37	4.05bc
LRoi	3.93	4.03	4.20	3.93	3.87	3.73	3.43	3.88e
HRoi	3.97	4.03	4.20	4.00	4.00	3.73	3.47	3.91e
LMCP	3.97	4.03	4.43	3.97	4.00	3.77	3.50	3.95de
HMCP	3.93	4.03	4.07	3.90	3.97	3.70	3.50	3.87e
Mean[3/] *(P<0.01)*	4.09b	4.22a	4.37a	4.07b	4.05b	3.69c	3.42d	
Ao Luk - subsoil (Ak-sub)								
Control[2/]	4.20	4.27	4.27	4.17	4.20	4.10	3.80	4.14d
LNCR	4.23	4.50	4.57	4.33	4.27	4.17	3.87	4.28c
HNCR	4.33	4.97	5.07	4.63	4.60	4.43	4.00	4.58b
LRat	4.33	4.50	4.63	4.37	4.40	4.23	3.87	4.33c
HRat	4.70	5.13	5.20	4.80	4.90	4.73	4.50	4.85a
LKan	4.27	4.57	4.47	4.30	4.27	4.20	3.90	4.28c
HKan	4.27	4.80	4.90	4.83	4.57	4.37	4.00	4.53b
LRoi	4.23	4.47	4.40	4.17	4.20	4.07	3.80	4.19d
HRoi	4.17	4.50	4.50	4.17	4.23	4.07	3.77	4.20d
LMCP	4.30	4.40	4.30	4.23	4.20	4.10	3.80	4.19d
HMCP	4.23	4.30	4.33	4.20	4.17	4.10	3.80	4.16d
Mean[3/] *(P<0.01)*	4.30ab	4.58a	4.60a	4.38ab	4.36ab	4.23ab	3.92c	

[1/] PRs and MCP with low (L) and high (H) rate; [2/] Ak-top and Ak-sub incubated at field soil water capacity without PRs and MCP; [3/] Mean of changed $\text{pH}_{\text{CaCl}_2}$ of each treatment and each time with the same letter not significantly different at $P < 0.01$ by DMRT.

Appendix Table A21 The variation of changed pH$_{CaCl_2}$ for Kc-soil incubated at 0 to 112 days by Duncan's multiple range test.

Treatment[1/]	Changed pH$_{CaCl_2}$ by incubation time							Mean[3/]
	0d	3d	7d	14d	28d	56d	112d	*(P<0.01)*
Khlong Chak - topsoil (Kc-top)								
Control[2/]	3.97	4.00	4.33	4.50	3.70	3.80	3.63	3.99bc
LNCR	4.07	4.13	4.20	3.93	3.70	3.87	3.70	3.94cd
HNCR	4.13	4.33	4.33	4.00	3.90	4.00	3.83	4.08b
LRat	4.13	4.10	4.40	4.07	3.70	3.83	3.70	3.99bc
HRat	4.33	4.37	4.70	4.33	4.00	4.10	3.87	4.24a
LKan	4.03	4.03	4.10	4.00	3.73	3.83	3.70	3.92cd
HKan	4.03	4.17	4.43	4.13	3.70	3.87	3.73	4.01bc
LRoi	4.03	4.00	4.17	3.93	3.70	3.77	3.60	3.89d
HRoi	4.00	4.00	4.20	4.30	3.70	3.77	3.63	3.94cd
LMCP	4.00	4.00	4.30	4.00	3.63	3.77	3.73	3.92cd
HMCP	4.07	4.00	4.23	3.83	3.63	3.80	3.63	3.89d
Mean[3/]*(P<0.01)*	4.07ab	4.10ab	4.31a	4.09ab	3.74c	385bc	3.71c	
Khlong Chak - subsoil (Kc-sub)								
Control[2/]	4.03	4.10	4.23	3.93	3.73	3.87	3.70	3.94f
LNCR	4.10	4.13	4.37	4.23	3.87	3.93	3.77	4.06d
HNCR	4.10	4.50	4.53	4.50	4.10	4.20	3.97	4.27b
LRat	4.13	4.23	4.50	3.83	3.80	3.97	3.80	4.04de
HRat	4.50	4.90	4.97	4.37	4.40	4.50	4.20	4.55a
LKan	4.03	4.07	4.33	4.17	3.80	3.93	3.77	4.01ef
HKan	4.07	4.30	4.50	4.23	3.93	4.07	3.87	4.14c
LRoi	4.00	4.00	4.30	3.97	3.73	3.90	3.70	3.94f
HRoi	4.30	4.03	4.23	4.10	3.73	3.87	3.67	3.99ef
LMCP	4.00	4.07	4.27	4.07	3.73	3.87	3.70	3.96ef
HMCP	3.97	4.03	4.23	4.07	3.80	3.90	3.70	3.96ef
Mean[3/]*(P<0.05)*	4.11cd	4.22ab	4.41a	4.13bc	3.88cd	4.00cd	3.80d	

[1/]PRs and MCP with low (L) and high (H) rate; [2/]Kc-top and Kc-sub incubated at field soil water capacity without PRs and MCP; [3/]Mean of changed pH$_{CaCl_2}$ of each treatment and each time with the same letter not significantly different at $P < 0.05$ or 0.01 by DMRT.

Appendix Table A22 The variation of changed pH_{CaCl_2} for Klt-soil incubated at 0 to 112 days by Duncan's multiple range test.

Treatment[1/]	Changed pH_{CaCl_2} by incubation time							Mean[3/]
	0d	3d	7d	14d	28d	56d	112d	*(P<0.01)*
Khlong Teng - topsoil (Klt-top)								
Control[2/]	4.53	4.60	4.60	4.43	4.10	4.23	4.07	4.37f
LNCR	4.73	4.67	4.73	4.53	4.17	4.33	4.23	4.49cd
HNCR	4.80	4.80	4.87	4.63	4.50	4.57	4.40	4.65b
LRat	4.83	4.70	4.70	4.57	4.20	4.37	4.23	4.51c
HRat	5.07	4.93	4.90	4.83	4.50	4.63	4.50	4.77a
LKan	4.73	4.63	4.67	4.53	4.10	4.30	4.20	4.45de
HKan	4.83	4.70	4.70	4.57	4.23	4.40	4.30	4.53c
LRoi	4.73	4.63	4.67	4.47	4.00	4.27	4.13	4.41ef
HRoi	4.77	4.63	4.63	4.47	4.07	4.23	4.10	4.41ef
LMCP	4.67	4.63	4.60	4.53	4.10	4.30	4.03	4.41ef
HMCP	4.70	4.60	4.60	4.57	4.10	4.27	4.13	4.42e
Mean[3/]*(P<0.01)*	4.76a	4.68a	4.70a	4.56ab	4.19c	4.35bc	4.21c	
Khlong Tengs - subsoil (Klt-sub)								
Control[2/]	4.33	4.70	4.77	4.73	4.37	4.40	4.20	4.50g
LNCR	4.70	4.77	4.93	4.97	4.40	4.50	4.37	4.66e
HNCR	4.93	5.20	5.23	5.13	4.77	4.87	4.70	4.98b
LRat	4.87	4.97	5.00	4.97	4.50	4.63	4.43	4.77d
HRat	5.50	5.43	5.67	5.23	5.20	5.00	4.90	5.28a
LKan	4.60	4.70	4.97	4.90	4.33	4.47	4.37	4.62ef
HKan	4.67	5.03	5.13	5.07	4.73	4.70	4.60	4.85c
LRoi	4.50	4.70	4.77	4.77	4.27	4.40	4.20	4.51g
HRoi	4.53	4.70	4.80	4.77	4.60	4.43	4.20	4.58fg
LMCP	4.57	4.67	4.83	4.63	4.40	4.40	4.27	4.54g
HMCP	4.60	4.67	4.97	4.77	4.37	4.40	4.27	4.58fg
Mean[3/]*(P<0.05)*	4.71bc	4.87ab	5.01a	4.90ab	4.54bc	4.56bc	4.41c	

[1/]PRs and MCP with low (L) and high (H) rate; [2/]Klt-top and Klt-sub incubated at field soil water capacity without PRs and MCP; [3/]Mean of changed pH_{CaCl_2} of each treatment and each time with the same letter not significantly different at $P < 0.05$ to 0.01 by DMRT.

Appendix Table A23 The variation of changed pH$_{CaCl_2}$ for Nat-soil incubated at 0 to 112 days by Duncan's multiple range test.

Treatment[1/]	Changed pH$_{CaCl_2}$ by incubation time							Mean[3/]
	0d	3d	7d	14d	28d	56d	112d	*($P<0.01$)*
Nathawi - topsoil (Nat-top)								
Control[2/]	4.03	3.97	4.07	3.93	3.77	3.73	3.63	3.88de
LNCR	4.10	4.03	4.33	3.93	3.63	3.77	3.67	3.92cd
HNCR	4.17	4.20	4.43	4.13	3.77	3.87	3.73	4.04b
LRat	4.13	4.13	4.13	3.93	3.67	3.80	3.63	3.92cd
HRat	4.43	4.37	4.37	4.13	3.93	4.07	3.80	4.16a
LKan	4.03	4.00	4.27	3.90	3.60	3.77	3.60	3.88de
HKan	4.13	4.13	4.23	3.93	3.70	3.80	3.67	3.94c
LRoi	4.13	4.00	4.07	3.83	3.67	3.73	3.57	3.86de
HRoi	4.00	3.97	4.00	3.87	3.67	3.77	3.53	3.83e
LMCP	4.00	4.03	4.20	3.83	3.70	3.77	3.60	3.88de
HMCP	4.03	4.03	4.23	3.93	3.67	3.73	3.63	3.90de
Mean[3/]*($P<0.01$)*	4.11a	4.08ab	4.21a	3.94bc	3.71cd	3.80bc	3.64d	
Nathawi – subsoil (Nat-sub)								
Control[2/]	4.07	3.97	4.23	4.03	3.77	3.87	3.63	3.94cd
LNCR	3.97	4.07	4.20	4.00	3.80	3.83	3.67	3.93cd
HNCR	4.10	4.20	4.23	4.20	3.90	4.00	3.80	4.06b
LRat	4.27	4.07	4.23	4.10	3.80	3.87	3.70	4.00bc
HRat	4.63	4.43	4.73	4.30	4.07	4.17	4.00	4.33a
LKan	4.03	4.07	4.27	4.07	3.80	3.87	3.70	3.97cd
HKan	4.03	4.17	4.17	4.03	3.87	3.93	3.73	3.99bc
LRoi	4.00	3.93	4.23	3.90	3.77	3.83	3.67	3.90d
HRoi	4.20	4.00	4.43	4.00	3.77	3.77	3.63	3.97cd
LMCP	4.03	3.93	4.37	4.07	3.77	3.80	3.63	3.94cd
HMCP	4.00	3.97	4.17	3.97	3.70	3.80	3.67	3.90d
Mean[3/]*($P<0.01$)*	4.12ab	4.07bc	4.30a	4.06bc	3.82cd	3.88cd	3.71d	

[1/] PRs and MCP with low (L) and high (H) rate; [2/] Nat-top and Nat-sub incubated at field soil water capacity without PRs and MCP; [3/] Mean of changed pH$_{CaCl_2}$ of each treatment and each time with the same letter not significantly different at $P < 0.01$ by DMRT.

Appendix Table A24 The variation of changed pH_{CaCl_2} for Tg-soil incubated at 0 to 112 days by Duncan's multiple range test.

Treatment[1]	Changed pH_{CaCl_2} by incubation time							Mean[3]
	0d	3d	7d	14d	28d	56d	112d	*($P<0.01$)*
Thung Wa - topsoil (Tg-top)								
Control[2]	4.53	5.10	4.57	4.23	4.03	4.03	3.90	4.34f
LNCR	4.83	5.23	4.77	4.30	4.20	4.20	4.07	4.51de
HNCR	4.87	5.20	4.77	4.43	4.43	4.43	4.33	4.64b
LRat	4.90	5.23	4.97	4.40	4.20	4.33	4.13	4.60bc
HRat	5.53	5.57	5.47	4.87	5.40	5.10	4.97	5.27a
LKan	4.70	5.17	4.87	4.43	4.17	4.23	4.10	4.52cd
HKan	4.80	5.27	4.93	4.53	4.47	4.47	4.37	4.69b
LRoi	4.67	5.07	4.53	4.23	4.10	4.07	4.07	4.39f
HRoi	4.67	5.10	4.80	4.27	4.03	4.10	3.90	4.41ef
LMCP	4.67	5.03	4.73	4.27	4.17	4.17	4.03	4.44ef
HMCP	4.67	5.10	4.67	4.37	4.07	4.17	4.07	4.44ef
Mean[3]*($P<0.01$)*	4.80b	5.19a	4.82b	4.39c	4.30c	4.30c	4.18c	
Thung Wa - subsoil (Tg-sub)								
Control[2]	4.07	4.20	4.53	4.07	3.97	4.00	3.63	4.07e
LNCR	4.20	4.60	4.50	4.33	4.20	4.23	3.70	4.25cd
HNCR	4.33	4.90	4.73	4.67	4.67	4.43	4.20	4.56b
LRat	4.27	4.63	4.60	4.47	4.30	4.20	3.83	4.33c
HRat	4.87	5.50	5.50	5.07	5.10	4.77	4.60	5.06a
LKan	4.07	4.40	4.60	4.27	4.20	4.13	3.70	4.20d
HKan	4.17	4.83	4.93	4.67	4.57	4.27	3.93	4.48b
LRoi	4.03	4.30	4.33	4.10	4.00	4.03	3.70	4.07e
HRoi	4.03	4.17	4.47	4.10	4.00	4.00	3.53	4.04e
LMCP	4.07	4.33	4.20	4.07	4.00	4.10	3.63	4.06e
HMCP	4.03	4.30	4.40	4.03	4.00	3.97	3.63	4.05e
Mean[3]*($P<0.01$)*	4.19c	4.56ab	4.62a	4.35bc	4.27bc	4.19c	3.83d	

[1] PRs and MCP with low (L) and high (H) rate; [2] Tg-top and Tg-sub incubated at field soil water capacity without PRs and MCP; [3] Means of changed pH_{CaCl_2} of each treatment and each time with the same letter not significantly different at $P < 0.01$ by DMRT.

Appendix Table A25 The variation of changed pH_{CaCl_2} for Hp-soil incubated at 0 to 112 days by Duncan's multiple range test.

Treatment[1]	Changed pH_{CaCl_2} by incubation time							Mean[3]
	0d	3d	7d	14d	28d	56d	112d	*(P<0.01)*
Huai Pong - topsoil (Hp-top)								
Control[2]	4.53	4.33	4.27	3.93	3.83	3.97	3.73	4.09e
LNCR	4.70	4.50	4.37	3.93	3.93	4.07	3.83	4.19cd
HNCR	4.93	4.63	4.60	4.17	4.23	4.20	4.00	4.40b
LRat	4.73	4.60	4.63	4.00	4.03	4.03	3.83	4.27c
HRat	5.37	4.83	4.93	4.47	4.37	4.40	4.23	4.66a
LKan	4.20	4.40	4.27	4.13	3.97	4.03	3.73	4.10de
HKan	4.63	4.67	4.33	4.07	4.03	4.10	3.93	4.25c
LRoi	4.53	4.37	4.47	3.93	3.87	3.97	3.73	4.12de
HRoi	4.53	4.30	4.43	4.10	3.83	3.90	3.70	4.11de
LMCP	4.63	4.37	4.37	3.97	3.83	3.97	3.77	4.13de
HMCP	4.57	4.40	4.13	3.93	3.80	3.97	3.70	4.07e
Mean[3] *(P<0.01)*	4.67a	4.49a	4.44a	4.06b	3.98b	4.05b	3.89b	
Huai Pong - subsoil (Hp-sub)								
Control[2]	4.17	4.43	4.40	4.23	4.10	3.97	3.63	4.13de
LNCR	4.23	4.30	4.37	4.17	4.13	4.00	3.63	4.12ef
HNCR	4.17	4.57	4.67	4.40	4.40	4.27	3.80	4.32bc
LRat	4.23	5.03	4.90	4.53	4.27	4.13	3.77	4.41b
HRat	4.83	5.37	5.57	4.90	4.80	4.47	4.37	4.90a
LKan	4.20	4.60	4.47	4.33	4.20	4.03	3.70	4.22cd
HKan	4.27	4.63	4.67	4.37	4.47	4.17	3.77	4.33bc
LRoi	3.80	4.37	4.50	4.73	4.17	3.93	3.63	4.06ef
HRoi	4.03	4.47	4.43	4.17	4.17	3.97	3.67	4.13de
LMCP	3.87	4.17	4.27	3.97	4.10	3.90	3.67	3.99f
HMCP	4.07	4.43	4.30	4.33	4.03	3.97	3.60	4.10ef
Mean[3] *(P<0.01)*	4.17c	4.58ab	4.59a	4.31bc	4.26bc	4.07c	3.75d	

[1] PRs and MCP with low (L) and high (H) rate; [2] Hp-top and Hp-sub incubated at field soil water capacity without PRs and MCP; [3] Mean of changed pH_{CaCl_2} of each treatment and each time with the same letter not significantly different at $P < 0.01$ by DMRT.

Appendix Table A26 The variation of changed $\text{pH}_{\text{CaCl}_2}$ for Koi-soil incubated at 0 to 112 days by Duncan's multiple range test.

Treatment[1/]	Changed $\text{pH}_{\text{CaCl}_2}$ by incubation time							Mean[3/]
	0d	3d	7d	14d	28d	56d	112d	*(P<0.01)*
Khok Kloi - topsoil (Koi-top)								
Control[2/]	4.00	4.33	4.37	4.07	4.03	3.73	3.47	4.00de
LNCR	4.13	4.43	4.37	4.03	4.10	3.77	3.60	4.06d
HNCR	4.23	4.70	4.80	4.30	4.33	4.00	3.77	4.30b
LRat	4.23	4.60	4.77	4.07	4.20	3.77	3.63	4.18c
HRat	4.67	5.10	4.80	4.67	4.20	4.20	3.90	4.50a
LKan	4.20	4.37	4.33	4.17	4.03	3.80	3.60	4.07d
HKan	4.27	4.57	4.60	4.30	4.20	3.90	3.70	4.22c
LRoi	4.03	4.27	4.40	4.07	3.93	3.70	3.47	3.98e
HRoi	4.07	4.27	4.40	4.00	3.93	3.73	3.50	3.99e
LMCP	4.13	4.30	4.33	4.03	4.00	3.73	3.50	4.00de
HMCP	4.10	4.27	4.33	4.03	3.93	3.67	3.50	3.98e
Mean[3] *(P<0.01)*	4.19b	4.47a	4.50a	4.16b	4.08b	3.82c	3.60c	
Khok Kloi - subsoil (Koi-sub)								
Control	4.00	4.10	4.10	3.90	3.87	3.90	3.70	3.94d
LNCR	4.23	4.07	4.20	4.00	3.80	4.00	3.73	4.00d
HNCR	4.27	4.43	4.73	4.17	4.07	4.27	4.00	4.28b
LRat	4.17	4.20	4.23	4.33	4.00	4.07	3.77	4.11c
HRat	4.47	4.87	4.97	4.53	4.67	4.60	4.50	4.66a
LKan	4.03	4.07	4.17	3.93	3.93	4.00	3.97	4.01d
HKan	4.07	4.23	4.43	4.20	4.13	4.13	3.87	4.15c
LRoi	4.00	4.10	4.30	3.80	3.87	3.87	3.63	3.94d
HRoi	4.03	4.07	4.23	3.90	3.87	3.90	3.73	3.96d
LMCP	4.10	4.07	4.27	3.93	3.83	3.90	3.70	3.97d
HMCP	4.13	3.97	4.17	3.97	3.87	3.93	3.70	3.96d
Mean[3] *(P<0.01)*	4.14b	4.20ab	4.35a	4.06b	3.99bc	4.05b	3.85c	

[1/] PRs and MCP with low (L) and high (H) rate; [2/] Koi-top and Koi-sub incubated at field soil water capacity without PRs and MCP; [3/] Mean of changed $\text{pH}_{\text{CaCl}_2}$ of each treatment and each time with the same letter not significantly different at $P < 0.01$ by DMRT.

Appendix Table A27 The variation of changed pH$_{CaCl_2}$ for Knk-soil incubated at 0 to 112 days by Duncan's multiple range test.

Treatment[1]	Changed pH$_{CaCl_2}$ by incubation time							Mean[3]
	0d	3d	7d	14d	28d	56d	112d	*(P<0.01)*
Khlong Nokkra Thung - topsoil (Knk-top)								
Control[2]	4.57	4.43	4.63	4.40	4.10	3.97	3.90	4.29e
LNCR	4.77	5.30	4.93	4.67	4.30	4.37	4.27	4.66cd
HNCR	4.97	5.07	5.10	4.50	4.47	4.57	4.57	4.75c
LRat	5.27	5.33	5.17	4.57	4.33	4.47	4.47	4.80bc
HRat	6.10	5.87	6.03	5.47	5.77	5.57	5.40	5.74a
LKan	4.63	5.37	4.80	4.37	4.13	4.53	4.13	4.57d
HKan	4.80	5.47	5.43	4.67	4.73	4.73	4.63	4.92b
LRoi	4.60	4.50	4.53	4.33	4.60	4.03	3.93	4.32e
HRoi	4.33	4.57	4.73	4.20	4.00	4.00	3.97	4.26e
LMCP	4.50	4.73	4.67	4.23	4.00	4.00	3.97	4.30e
HMCP	4.50	4.67	4.73	4.50	3.93	4.03	3.97	4.33e
Mean[3]*(P<0.01)*	4.82a	5.03a	4.98a	4.54b	4.40b	4.39b	4.29b	
Khlong Nokkra Thung - subsoil (Knk-sub)								
Control[2]	4.43	4.47	4.67	4.27	4.07	4.20	3.97	4.30e
LNCR	4.83	5.17	5.17	4.67	4.40	4.57	4.50	4.76d
HNCR	5.00	5.23	5.57	5.13	4.77	4.80	4.67	5.02c
LRat	5.07	5.67	5.73	4.90	4.70	4.67	4.77	5.07c
HRat	6.17	6.23	6.40	5.57	6.20	6.07	5.77	6.06a
LKan	4.60	5.10	5.23	4.60	4.60	4.30	4.33	4.68d
HKan	4.97	5.97	5.70	5.33	4.93	5.10	5.17	5.31b
LRoi	4.43	4.63	5.10	4.27	4.23	4.20	3.90	4.40e
HRoi	4.40	4.57	4.67	4.30	4.27	4.17	3.97	4.33e
LMCP	4.37	4.63	4.73	4.43	4.07	4.13	3.97	4.33e
HMCP	4.33	4.63	4.80	4.57	3.97	4.53	3.97	4.40e
Mean[3]*(P<0.01)*	4.78bc	5.12ab	5.25a	4.73bc	4.56c	4.61c	4.45c	

[1] PRs and MCP with low (L) and high (H) rate; [2] Knk-top and Knk-sub incubated at field soil water capacity without PRs and MCP; [3] Mean of changed pH$_{CaCl_2}$ of each treatment and each time with the same letter not significantly different at $P < 0.01$ by DMRT.

Appendix Table A28 The variation of changed EC for Nb-soil incubated at 0 to 112 days by Duncan's multiple range test.

Treatment[1/]	Changed EC by incubation time (mS cm^{-1})							Mean[3/]
	0d	3d	7d	14d	28d	56d	112d	
Nong Bon - topsoil (Nb-top)								
Control[2/]	0.06	0.06	0.06	0.03	0.08	0.07	0.12	0.07ns
LNCR	0.08	0.03	0.06	0.05	0.08	0.09	0.13	0.08ns
HNCR	0.07	0.05	0.04	0.05	0.11	0.09	0.14	0.08ns
LRat	0.05	0.03	0.07	0.04	0.07	0.09	0.13	0.07ns
HRat	0.07	0.04	0.04	0.05	0.08	0.09	0.14	0.07ns
LKan	0.07	0.05	0.05	0.04	0.08	0.10	0.14	0.08ns
HKan	0.05	0.03	0.03	0.05	0.09	0.09	0.14	0.07ns
LRoi	0.04	0.07	0.06	0.05	0.08	0.08	0.13	0.07ns
HRoi	0.06	0.07	0.06	0.05	0.11	0.08	0.13	0.08ns
LMCP	0.05	0.03	0.08	0.08	0.08	0.09	0.13	0.08ns
HMCP	0.06	0.04	0.04	0.05	0.07	0.09	0.13	0.07ns
Mean[3/]*($P<0.01$)*	0.06bc	0.04c	0.05bc	0.05bc	0.08b	0.09b	0.13a	
Nong Bon – subsoil (Nb-sub)								
Control	0.04	0.08	0.03	0.06	0.08	0.03	0.04	0.05ns
LNCR	0.03	0.04	0.03	0.06	0.02	0.03	0.04	0.04ns
HNCR	0.04	0.03	0.03	0.04	0.03	0.05	0.04	0.04ns
LRat	0.02	0.04	0.02	0.09	0.02	0.03	0.04	0.04ns
HRat	0.03	0.03	0.03	0.08	0.05	0.03	0.04	0.04ns
LKan	0.03	0.04	0.02	0.03	0.03	0.03	0.03	0.03ns
HKan	0.03	0.03	0.02	0.05	0.03	0.03	0.04	0.03ns
LRoi	0.06	0.04	0.03	0.04	0.05	0.02	0.04	0.04ns
HRoi	0.03	0.04	0.02	0.04	0.02	0.03	0.03	0.03ns
LMCP	0.03	0.03	0.03	0.04	0.03	0.03	0.04	0.03ns
HMCP	0.02	0.10	0.03	0.07	0.02	0.04	0.04	0.05ns
Mean[3/]	0.03ns	0.05ns	0.03ns	0.05ns	0.03ns	0.03ns	0.04ns	

[1/]PRs and MCP with low (L) and high (H) rate; [2/]Nb-top and Nb-sub incubated at field soil water capacity without PRs and MCP; [3/]Mean of changed EC of each treatment and each time with the same letter not significantly different at $P < 0.01$ by DMRT, and ns is non-significant different.

Appendix Table A29 The variation of changed EC for Ak-soil incubated at 0 to 112 days by Duncan's multiple range test.

Treatment[1/]	Changed EC by incubation time (mS cm^{-1})							Mean[3/]
	0d	3d	7d	14d	28d	56d	112d	($P<0.01$)
Ao Luk - topsoil (Ak-top)								
Control[2/]	0.07	0.05	0.04	0.07	0.08	0.08	0.21	0.09f
LNCR	0.08	0.05	0.04	0.07	0.08	0.09	0.32	0.10cd
HNCR	0.07	0.06	0.04	0.07	0.10	0.17	0.35	0.12ab
LRat	0.07	0.05	0.04	0.07	0.08	0.12	0.36	0.11cd
HRat	0.07	0.06	0.05	0.08	0.10	0.21	0.35	0.13a
LKan	0.10	0.04	0.04	0.06	0.08	0.10	0.30	0.10de
HKan	0.10	0.05	0.04	0.06	0.08	0.13	0.36	0.12bc
LRoi	0.08	0.05	0.04	0.06	0.08	0.08	0.21	0.09f
HRoi	0.06	0.05	0.04	0.06	0.08	0.08	0.24	0.09f
LMCP	0.09	0.05	0.04	0.06	0.09	0.08	0.23	0.09ef
HMCP	0.10	0.05	0.03	0.06	0.08	0.09	0.24	0.09ef
Mean[3/]($P<0.01$)	0.08bc	0.05c	0.04c	0.06bc	0.08bc	0.11b	0.29a	
Ao Luk - subsoil (Ak-sub)								
Control[2/]	0.06	0.03	0.03	0.06	0.05	0.03	0.02	0.04ns
LNCR	0.08	0.04	0.03	0.03	0.06	0.03	0.03	0.04ns
HNCR	0.07	0.05	0.02	0.03	0.05	0.03	0.05	0.04ns
LRat	0.12	0.03	0.03	0.02	0.06	0.06	0.04	0.05ns
HRat	0.09	0.07	0.03	0.03	0.04	0.04	0.05	0.05ns
LKan	0.07	0.03	0.02	0.03	0.03	0.04	0.03	0.03ns
HKan	0.08	0.05	0.03	0.03	0.04	0.03	0.04	0.04ns
LRoi	0.07	0.03	0.02	0.03	0.04	0.04	0.03	0.04ns
HRoi	0.12	0.03	0.03	0.02	0.04	0.03	0.04	0.04ns
LMCP	0.07	0.03	0.02	0.02	0.04	0.03	0.02	0.03ns
HMCP	0.05	0.03	0.03	0.06	0.04	0.03	0.03	0.04ns
Mean[3/]($P<0.01$)	0.08a	0.04b	0.03b	0.03b	0.04b	0.03b	0.03b	

[1/]PRs and MCP with low (L) and high (H) rate; [2/]Ak-top and Ak-sub incubated at field soil water capacity without PRs and MCP; [3/]Mean of changed EC of each treatment and each time with the same letter not significantly different at $P < 0.01$ by DMRT, and ns is non-significant different.

Appendix Table A30 The variation of changed EC for Kc-soil incubated at 0 to 112 days by Duncan's multiple range test.

Treatment[1/]	Changed EC by incubation time (mS cm^{-1})							Mean[3/]
	0d	3d	7d	14d	28d	56d	112d	
Khlong Chak - topsoil (Kc-top)								
Control[2/]	0.03	0.04	0.05	0.09	0.07	0.07	0.12	0.07ns
LNCR	0.04	0.04	0.04	0.10	0.05	0.08	0.12	0.07ns
HNCR	0.09	0.04	0.04	0.06	0.06	0.09	0.13	0.07ns
LRat	0.05	0.05	0.05	0.06	0.06	0.08	0.12	0.07ns
HRat	0.04	0.09	0.04	0.07	0.06	0.08	0.13	0.07ns
LKan	0.04	0.04	0.03	0.05	0.10	0.08	0.12	0.07ns
HKan	0.06	0.05	0.04	0.05	0.07	0.08	0.13	0.07ns
LRoi	0.06	0.04	0.04	0.07	0.06	0.07	0.12	0.07ns
HRoi	0.04	0.04	0.03	0.05	0.06	0.08	0.13	0.06ns
LMCP	0.08	0.04	0.04	0.05	0.06	0.10	0.13	0.07ns
HMCP	0.03	0.04	0.03	0.11	0.05	0.09	0.13	0.07ns
Mean[3/]*($P<0.01$)*	0.05bc	0.05bc	0.04c	0.07bc	0.06bc	0.08b	0.13a	
Khlong Chak - subsoil (Kc-sub)								
Control[2/]	0.02	0.03	0.02	0.03	0.03	0.03	0.04	0.03ns
LNCR	0.04	0.07	0.03	0.03	0.03	0.03	0.04	0.04ns
HNCR	0.02	0.03	0.02	0.04	0.03	0.03	0.04	0.03ns
LRat	0.02	0.02	0.03	0.03	0.03	0.03	0.04	0.03ns
HRat	0.02	0.02	0.02	0.04	0.03	0.03	0.04	0.03ns
LKan	0.04	0.02	0.02	0.03	0.03	0.03	0.03	0.03ns
HKan	0.03	0.03	0.02	0.05	0.08	0.03	0.04	0.04ns
LRoi	0.02	0.03	0.03	0.04	0.02	0.03	0.04	0.03ns
HRoi	0.04	0.03	0.02	0.04	0.05	0.03	0.04	0.03ns
LMCP	0.02	0.03	0.03	0.02	0.02	0.03	0.04	0.03ns
HMCP	0.02	0.03	0.03	0.05	0.02	0.03	0.04	0.03ns
Mean[3/]	0.03ns	0.03ns	0.02ns	0.04ns	0.03ns	0.03ns	0.04ns	

[1/] PRs and MCP with low (L) and high (H) rate; [2/] Kc-top and Kc-sub incubated at field soil water capacity without PRs and MCP; [3/] Mean of changed EC of each treatment and each time with the same letter not significantly different at $P < 0.01$ by DMRT, and ns is non-significant different.

Appendix Table A31 The variation of changed EC for Klt-soil incubated at 0 to 112 days by Duncan's multiple range test.

Treatment[1/]	Changed EC by incubation time (mS cm^{-1})							Mean[3/]
	0d	3d	7d	14d	28d	56d	112d	*(P<0.05)*
Khlong Teng - topsoil (Klt-top)								
Control[2/]	0.06	0.06	0.06	0.08	0.09	0.12	0.17	0.09b
LNCR	0.05	0.06	0.06	0.09	0.08	0.11	0.18	0.09b
HNCR	0.04	0.07	0.07	0.09	0.07	0.11	0.17	0.09b
LRat	0.07	0.07	0.06	0.08	0.08	0.10	0.17	0.09b
HRat	0.07	0.06	0.05	0.10	0.09	0.10	0.18	0.09ab
LKan	0.07	0.05	0.06	0.09	0.07	0.11	0.18	0.09b
HKan	0.06	0.06	0.07	0.11	0.07	0.12	0.17	0.09ab
LRoi	0.05	0.05	0.05	0.07	0.08	0.11	0.17	0.08b
HRoi	0.05	0.05	0.06	0.07	0.07	0.10	0.18	0.08b
LMCP	0.06	0.18	0.06	0.08	0.08	0.10	0.17	0.10a
HMCP	0.07	0.06	0.05	0.09	0.08	0.10	0.18	0.09b
Mean[3/]*(P<0.01)*	0.06b	0.07b	0.06b	0.09b	0.08b	0.11b	0.17a	
Khlong Teng - subsoil (Klt-sub)								
Control[2/]	0.02	0.02	0.02	0.03	0.02	0.03	0.03	0.02ns
LNCR	0.03	0.03	0.02	0.02	0.03	0.04	0.04	0.03ns
HNCR	0.02	0.02	0.02	0.02	0.02	0.02	0.04	0.03ns
LRat	0.04	0.03	0.02	0.03	0.02	0.03	0.04	0.03ns
HRat	0.03	0.02	0.02	0.07	0.03	0.03	0.04	0.03ns
LKan	0.04	0.02	0.02	0.03	0.03	0.03	0.04	0.03ns
HKan	0.02	0.06	0.03	0.02	0.03	0.03	0.04	0.03ns
LRoi	0.02	0.03	0.02	0.03	0.03	0.04	0.04	0.03ns
HRoi	0.02	0.03	0.02	0.03	0.03	0.03	0.04	0.03ns
LMCP	0.02	0.02	0.03	0.02	0.01	0.03	0.05	0.03ns
HMCP	0.02	0.02	0.03	0.05	0.02	0.02	0.04	0.03ns
Mean[3/]	0.03ns	0.03ns	0.02ns	0.03ns	0.02ns	0.03ns	0.04ns	

[1/] PRs and MCP with low (L) and high (H) rate; [2/] Klt-top and Klt-sub incubated at field soil water capacity without PRs and MCP; [3/] Mean of changed EC of each treatment and each time with the same letter not significantly different at $P < 0.05$ or 0.01 by DMRT, and ns is non-significant different.

Appendix Table A32 The variation of changed EC for Nat-soil incubated at 0 to 112 days by Duncan's multiple range test.

Treatment[1/]	Changed EC by incubation time (mS cm^{-1})							Mean[3/]
	0d	3d	7d	14d	28d	56d	112d	
Nathawi - topsoil (Nat-top)								
Control[2/]	0.04	0.03	0.03	0.07	0.05	0.08	0.10	0.06ns
LNCR	0.05	0.03	0.04	0.08	0.10	0.09	0.13	0.07ns
HNCR	0.04	0.03	0.04	0.06	0.07	0.09	0.13	0.07ns
LRat	0.04	0.03	0.04	0.04	0.06	0.09	0.12	0.06ns
HRat	0.03	0.03	0.04	0.05	0.06	0.09	0.14	0.06ns
LKan	0.02	0.07	0.03	0.05	0.06	0.08	0.13	0.07ns
HKan	0.06	0.03	0.07	0.05	0.04	0.08	0.13	0.07ns
LRoi	0.08	0.04	0.04	0.04	0.06	0.08	0.12	0.07ns
HRoi	0.04	0.03	0.08	0.08	0.06	0.08	0.12	0.07ns
LMCP	0.05	0.03	0.04	0.05	0.08	0.14	0.13	0.07ns
HMCP	0.03	0.03	0.06	0.05	0.07	0.09	0.13	0.07ns
Mean[3/]*($P<0.01$)*	0.05cd	0.03d	0.05cd	0.06cd	0.06bc	0.09b	0.13a	
Nathawi - subsoil (Nat-sub)								
Control[2/]	0.04	0.04	0.04	0.04	0.02	0.05	0.04	0.04ns
LNCR	0.03	0.04	0.04	0.05	0.02	0.04	0.05	0.04ns
HNCR	0.03	0.06	0.05	0.05	0.03	0.07	0.05	0.05ns
LRat	0.03	0.02	0.06	0.03	0.03	0.05	0.04	0.04ns
HRat	0.07	0.02	0.07	0.03	0.03	0.08	0.05	0.05ns
LKan	0.03	0.03	0.06	0.03	0.02	0.04	0.04	0.04ns
HKan	0.03	0.03	0.02	0.03	0.03	0.04	0.05	0.03ns
LRoi	0.02	0.03	0.03	0.04	0.02	0.03	0.04	0.03ns
HRoi	0.04	0.04	0.03	0.02	0.02	0.04	0.06	0.04ns
LMCP	0.05	0.04	0.02	0.05	0.06	0.03	0.05	0.04ns
HMCP	0.05	0.03	0.02	0.02	0.04	0.03	0.05	0.03ns
Mean[3/]	0.04ns	0.03ns	0.04ns	0.04ns	0.03ns	0.05ns	0.05ns	

[1/]PRs and MCP with low (L) and high (H) rate; [2/]Nat-top and Nat-sub incubated at field soil water capacity without PRs and MCP; [3/]Means of changed EC of each treatment and each time with the same letter not significantly different at $P < 0.01$ by DMRT, and ns is non-significant different.

Appendix Table A33 The variation of changed EC for Tg-soil incubated at 0 to 112 days by Duncan's multiple range test.

Treatment[1/]	Changed EC by incubation time (mS cm^{-1})							Mean[3/]
	0d	3d	7d	14d	28d	56d	112d	
Thung Wa - topsoil (Tg-top)								
Control[2/]	0.03	0.04	0.04	0.04	0.06	0.06	0.11	0.06ns
LNCR	0.04	0.04	0.04	0.05	0.07	0.08	0.12	0.06ns
HNCR	0.05	0.03	0.05	0.04	0.09	0.07	0.11	0.06ns
LRat	0.03	0.04	0.04	0.05	0.07	0.06	0.10	0.05ns
HRat	0.07	0.05	0.04	0.04	0.06	0.08	0.07	0.06ns
LKan	0.03	0.04	0.03	0.03	0.06	0.07	0.09	0.05ns
HKan	0.03	0.04	0.03	0.05	0.06	0.07	0.09	0.05ns
LRoi	0.03	0.03	0.04	0.04	0.06	0.05	0.11	0.05ns
HRoi	0.03	0.04	0.03	0.04	0.06	0.08	0.10	0.05ns
LMCP	0.03	0.03	0.03	0.04	0.07	0.06	0.09	0.05ns
HMCP	0.03	0.03	0.03	0.04	0.11	0.08	0.09	0.06ns
Mean[3/]*($P<0.01$)*	0.04c	0.04c	0.04c	0.04c	0.07b	0.07b	0.10a	
Thung Wa - subsoil (Tg-sub)								
Control[2/]	0.03	0.05	0.02	0.03	0.05	0.03	0.03	0.04ns
LNCR	0.05	0.02	0.03	0.03	0.04	0.04	0.04	0.03ns
HNCR	0.05	0.02	0.03	0.02	0.04	0.03	0.05	0.04ns
LRat	0.05	0.06	0.02	0.04	0.04	0.03	0.04	0.04ns
HRat	0.05	0.03	0.02	0.03	0.03	0.04	0.04	0.03ns
LKan	0.04	0.03	0.02	0.02	0.09	0.03	0.04	0.04ns
HKan	0.06	0.03	0.02	0.03	0.04	0.03	0.04	0.04ns
LRoi	0.07	0.03	0.03	0.02	0.04	0.03	0.03	0.04ns
HRoi	0.06	0.03	0.03	0.02	0.05	0.03	0.03	0.04ns
LMCP	0.07	0.03	0.02	0.02	0.03	0.03	0.04	0.03ns
HMCP	0.05	0.02	0.02	0.04	0.02	0.02	0.04	0.03ns
Mean[3/]	0.05ns	0.03ns	0.02ns	0.03ns	0.04ns	0.03ns	0.04ns	

[1/] PRs and MCP with low (L) and high (H) rate; [2/] Tg-top and Tg-sub incubated at field soil water capacity without PRs and MCP; [3/] Mean of changed EC of each treatment and each time with the same letter not significantly different at $P < 0.01$ by DMRT, and ns is non-significant different.

Appendix Table A34 The variation of changed EC for Hp-soil incubated at 0 to 112 days by Duncan's multiple range test.

Treatment[1/]	Changed EC by incubation time (mS cm^{-1})							Mean[3/]
	0d	3d	7d	14d	28d	56d	112d	*($P<0.01$)*
Huai Pong - topsoil (Hp-top)								
Control[2/]	0.06	0.04	0.05	0.07	0.11	0.07	0.13	0.08d
LNCR	0.10	0.05	0.05	0.08	0.12	0.11	0.16	0.10bc
HNCR	0.11	0.06	0.05	0.10	0.12	0.10	0.18	0.10a
LRat	0.09	0.06	0.06	0.09	0.12	0.08	0.16	0.09bc
HRat	0.10	0.06	0.06	0.09	0.12	0.11	0.15	0.10ab
LKan	0.07	0.04	0.05	0.11	0.12	0.08	0.15	0.09bc
HKan	0.08	0.05	0.06	0.09	0.12	0.11	0.16	0.10bc
LRoi	0.07	0.05	0.06	0.07	0.12	0.09	0.15	0.09c
HRoi	0.09	0.04	0.06	0.07	0.12	0.09	0.15	0.09bc
LMCP	0.07	0.05	0.06	0.08	0.13	0.10	0.15	0.09bc
HMCP	0.09	0.05	0.06	0.09	0.12	0.10	0.16	0.10ab
Mean[3/]*($P<0.01$)*	0.08c	0.05d	0.06d	0.09c	0.12b	0.09c	0.16a	
Huai Pong - subsoil (Hp-sub)								
Control[2/]	0.08	0.05	0.03	0.07	0.08	0.03	0.05	0.06ns
LNCR	0.05	0.07	0.04	0.04	0.04	0.05	0.07	0.05ns
HNCR	0.08	0.05	0.04	0.04	0.06	0.05	0.11	0.06ns
LRat	0.08	0.03	0.03	0.03	0.05	0.03	0.08	0.05ns
HRat	0.09	0.04	0.03	0.04	0.04	0.05	0.08	0.05ns
LKan	0.04	0.04	0.05	0.03	0.07	0.03	0.07	0.04ns
HKan	0.08	0.10	0.03	0.04	0.05	0.03	0.08	0.06ns
LRoi	0.07	0.04	0.04	4.73	0.08	0.03	0.05	0.72ns
HRoi	0.05	0.03	0.04	0.03	0.07	0.03	0.06	0.05ns
LMCP	0.04	0.03	0.05	0.04	0.05	0.06	0.06	0.05ns
HMCP	0.08	0.04	0.03	0.03	0.07	0.03	0.06	0.05ns
Mean[3/]*($P<0.05$)*	0.07a	0.05ab	0.04b	0.47b	0.06ab	0.04b	0.07a	

[1/]PRs and MCP with low (L) and high (H) rate; [2/]Hp-top and Hp-sub incubated at field soil water capacity without PRs and MCP; [3/]Mean of changed EC of each treatment and each time with the same letter not significantly different at $P < 0.05$ or 0.01 by DMRT, and ns is non-significant different.

Appendix Table A35 The variation of changed EC for Koi-soil incubated at 0 to 112 days by Duncan's multiple range test.

Treatment[1/]	Changed EC by incubation time (mS cm^{-1})							Mean[3/]
	0d	3d	7d	14d	28d	56d	112d	
Khok Kloi - topsoil (Koi-top)								
Control[2/]	0.06	0.02	0.02	0.02	0.04	0.06	0.12	0.05ns
LNCR	0.03	0.03	0.02	0.04	0.04	0.07	0.13	0.05ns
HNCR	0.04	0.03	0.02	0.03	0.05	0.07	0.14	0.06ns
LRat	0.03	0.03	0.02	0.05	0.04	0.07	0.13	0.05ns
HRat	0.03	0.06	0.03	0.04	0.06	0.07	0.12	0.06ns
LKan	0.05	0.03	0.03	0.03	0.04	0.07	0.13	0.05ns
HKan	0.03	0.07	0.02	0.03	0.05	0.07	0.12	0.06ns
LRoi	0.05	0.03	0.02	0.02	0.04	0.06	0.14	0.05ns
HRoi	0.04	0.03	0.02	0.02	0.03	0.06	0.14	0.05ns
LMCP	0.04	0.04	0.02	0.02	0.03	0.10	0.14	0.05ns
HMCP	0.03	0.04	0.02	0.03	0.03	0.07	0.14	0.05ns
Mean[3/]*($P<0.01$)*	0.04c	0.04cd	0.02d	0.03cd	0.04c	0.07b	0.13a	
Khok Kloi - subsoil (Koi-sub)								
Control[2/]	0.05	0.03	0.03	0.04	0.03	0.03	0.01	0.03ns
LNCR	0.04	0.03	0.03	0.05	0.05	0.03	0.03	0.04ns
HNCR	0.06	0.03	0.02	0.03	0.03	0.03	0.02	0.03ns
LRat	0.06	0.03	0.02	0.03	0.03	0.03	0.02	0.03ns
HRat	0.04	0.02	0.03	0.02	0.02	0.03	0.02	0.03ns
LKan	0.05	0.02	0.03	0.02	0.08	0.02	0.03	0.04ns
HKan	0.04	0.04	0.02	0.02	0.04	0.05	0.02	0.03ns
LRoi	0.04	0.02	0.02	0.03	0.07	0.03	0.03	0.03ns
HRoi	0.04	0.03	0.02	0.03	0.06	0.03	0.02	0.03ns
LMCP	0.05	0.07	0.02	0.02	0.03	0.02	0.02	0.03ns
HMCP	0.08	0.03	0.02	0.04	0.03	0.03	0.02	0.04ns
Mean[3/]	0.05ns	0.03ns	0.02ns	0.03ns	0.04ns	0.03ns	0.02ns	

[1/]PRs and MCP with low (L) and high (H) rate; [2/]Koi-top and Koi-sub incubated at field soil water capacity without PRs and MCP; [3/]Mean of changed EC of each treatment and each time with the same letter not significantly different at $P < 0.01$ by DMRT, and ns is non-significant different.

Appendix Table A36 The variation of changed EC for Knk-soil incubated at 0 to 112 days by Duncan's multiple range test.

Treatment[1/]	Changed EC by incubation time (mS cm^{-1})							Mean[3/]
	0d	3d	7d	14d	28d	56d	112d	
Khlong Nokkra Thung - topsoil (Knk-top)								
Control[2/]	0.04	0.04	0.02	0.04	0.03	0.06	0.04	0.04ns
LNCR	0.10	0.02	0.02	0.03	0.03	0.04	0.05	0.04ns
HNCR	0.08	0.03	0.03	0.02	0.03	0.03	0.05	0.04ns
LRat	0.05	0.02	0.03	0.04	0.03	0.04	0.04	0.04ns
HRat	0.04	0.02	0.02	0.03	0.03	0.03	0.05	0.03ns
LKan	0.03	0.02	0.03	0.03	0.03	0.03	0.05	0.03ns
HKan	0.02	0.02	0.03	0.04	0.03	0.03	0.04	0.03ns
LRoi	0.03	0.02	0.02	0.02	0.04	0.04	0.05	0.03ns
HRoi	0.03	0.02	0.02	0.03	0.04	0.03	0.06	0.03ns
LMCP	0.01	0.03	0.02	0.03	0.03	0.03	0.05	0.03ns
HMCP	0.05	0.05	0.02	0.02	0.03	0.03	0.05	0.03ns
Mean[3/](P<0.05)	0.04ab	0.03c	0.02c	0.03bc	0.03bc	0.04bc	0.05a	
Khlong Nokkra Thung - subsoil (Knk-sub)								
Control	0.02	0.03	0.03	0.02	0.03	0.02	0.02	0.02ns
LNCR	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02ns
HNCR	0.02	0.02	0.04	0.02	0.02	0.02	0.03	0.02ns
LRat	0.03	0.02	0.02	0.03	0.03	0.03	0.02	0.02ns
HRat	0.02	0.02	0.03	0.02	0.04	0.03	0.02	0.03ns
LKan	0.02	0.02	0.02	0.03	0.02	0.02	0.01	0.02ns
HKan	0.01	0.02	0.02	0.02	0.03	0.02	0.02	0.02ns
LRoi	0.01	0.02	0.02	0.02	0.03	0.04	0.02	0.02ns
HRoi	0.02	0.03	0.03	0.03	0.02	0.03	0.02	0.03ns
LMCP	0.02	0.03	0.05	0.02	0.03	0.02	0.02	0.03ns
HMCP	0.02	0.03	0.02	0.03	0.03	0.03	0.03	0.03ns
Mean[3/]	0.02ns	0.02ns	0.03ns	0.02ns	0.03ns	0.03ns	0.02ns	

[1/] PRs and MCP with low (L) and high (H) rate; [2/] Knk-top and Knk-sub incubated at field soil water capacity without PRs and MCP; [3/] Mean of changed EC of each treatment and each time with the same letter not significantly different at $P < 0.05$ by DMRT, and ns is non-significant different.

Appendix Table A37 The stepwise equations relating soil properties to ΔP_{BC} for soil incubation for 14 days.

(The log-transformed data are more suitable for this statistical treatment)

PRs	Equation (y = Log ΔP_{BC})	$P < 0.05$	r^2
LNCR	$y = -0.36 + 0.65 \log \%sand$	0.0035	0.42
	$y = -0.43 + 0.61 \log \%sand + 0.58 \log P_{BII}$	0.00003	0.76
	$y = -0.16 + 0.33 \log \%sand + 0.94 \log P_{BII} - 0.50 \log \%OC$	0.00002	0.82
	$y = -0.84 + 0.67 \log \%sand + 0.87 \log P_{BII} - 0.53 \log \%OC + 0.41 \log \%clay$	0.00002	0.86
	$y = -0.72 + 0.59 \log \%sand + 0.78 \log P_{BII} - 0.39 \log \%OC + 0.61 \log \%clay - 0.40 \log Fe_d$	0.00001	0.92
	$y = -1.18 + 0.70 \log \%sand + 0.69 \log P_{BII} - 0.34 \log \%OC + 0.67 \log \%clay - 0.55 \log Fe_d + 0.22 \log \%silt$	0.00002	0.92
	$y = -1.54 + 0.83 \log \%sand + 0.58 \log P_{BII} - 0.19 \log \%OC + 0.93 \log \%clay - 0.57 \log Fe_d + 0.44 \log \%silt - 0.41 \log CEC$	0.00003	0.94
HNCR	$y = 2.66 - 0.58 \log pH_{H_2O}$	0.0115	0.34
	$y = 2.44 - 0.89 \log pH_{H_2O} + 0.59 \log \%sand$	0.0014	0.58
	$y = -1.81 - 0.26 \log pH_{H_2O} + 1.36 \log \%sand + 1.32 \log \%clay$	0.00003	0.81
	$y = -4.19 - 0.20 \log pH_{H_2O} + 1.75 \log \%sand + 1.92 \log \%clay - 0.36 \log Ex.Na$	0.000004	0.89
	$y = -2.06 - 0.14 \log pH_{H_2O} + 1.60 \log \%sand + 1.56 \log \%clay - 0.25 \log Ex.Na - 0.23 \log I(pH_{H_2O})$	0.000003	0.92
	$y = -2.76 + 0.16 \log pH_{H_2O} + 1.60 \log \%sand + 2.17 \log \%clay - 0.17 \log Ex.Na - 0.34 \log I(pH_{H_2O}) - 0.53 \log Al_o$	0.000004	0.94
	$y = -3.22 + 0.14 \log pH_{H_2O} + 1.67 \log \%sand + 2.16 \log \%clay - 0.20 \log Ex.Na - 0.32 \log I(pH_{H_2O}) - 0.56 \log Al_o + 0.14 \log \%silt$	0.00001	0.95
	$y = -4.28 + 0.35 \log pH_{H_2O} + 1.76 \log \%sand + 2.71 \log \%clay - 0.18 \log Ex.Na - 0.34 \log I(pH_{H_2O}) - 0.64 \log Al_o + 0.31 \log \%silt - 0.42 \log CEC$	0.00001	0.97

Appendix Table A37 (Continued).

PRs	Equation ($y = \text{Log } \Delta P_{BC}$)	$P < 0.05$	r^2
LRat	$y = -0.62 + 0.61 \text{ Log } P_{BC}$	0.0074	0.37
	$y = 0.86 + 0.59 \text{ Log } P_{BC} - 0.50 \text{ Log } pH_{KCl}$	0.0007	0.62
	$y = 0.48 + 0.73 \text{ Log } P_{BC} - 0.76 \text{ Log } pH_{KCl} + 0.52 \text{ Log } \%\text{Sand}$	0.00004	0.80
	$y = -2.11 + 0.46 \text{ Log } P_{BC} - 0.25 \text{ Log } pH_{KCl} + 1.05 \text{ Log } \%\text{sand} + 1.03 \text{ Log } \%\text{clay}$	0.000005	0.89
	$y = -2.69 + 0.51 \log P_{BC} - 0.20 \log pH_{KCl} + 1.10 \log \%\text{sand} + 1.09 \log \%\text{clay} - 0.13 \log I(EC)$	0.00002	0.90
	$y = -3.62 + 0.55 \log P_{BC} - 0.20 \log pH_{KCl} + 1.24 \log \%\text{sand} + 1.01 \log \%\text{clay} - 0.23 \log I(EC) + 0.27 \log \%\text{silt}$	0.00001	0.93
	$y = -2.60 + 0.71 \log P_{BC} - 0.46 \log pH_{KCl} + 0.92 \log \%\text{sand} + 1.0 \log \%\text{clay} - 0.31 \log I(EC) + 0.42 \log \%\text{silt} - 0.69 \log PBCc$	0.000001	0.97
	$y = -1.70 + 0.53 \log P_{BC} - 0.40 \log pH_{KCl} + 0.96 \log \%\text{sand} + 1.09 \log \%\text{clay} - 0.34 \log I(EC) + 0.48 \log \%\text{silt} - 0.80 \log PBCc - 0.23 \log pH_{CaCl_2}$	0.000003	0.97
HRat	$y = 6.39 - 0.85 \log I(pH_{CaCl_2})$	0.00001	0.72
	$y = 7.14 - 0.68 \log I(pH_{CaCl_2}) - 0.36 \log pH_{KCl}$	0.000002	0.83
	$y = 7.24 - 0.76 \log I(pH_{CaCl_2}) - 0.33 \log pH_{KCl} - 0.16 \log Ex.K$	0.000006	0.85
	$y = 6.56 - 0.70 \log I(pH_{CaCl_2}) - 0.27 \log pH_{KCl} - 0.26 \log Ex.K + 0.22 \log Mn_d$	0.00001	0.87
	$y = 8.88 - 0.84 \log I(pH_{CaCl_2}) - 0.40 \log pH_{KCl} - 0.26 \log Ex.K + 0.42 \log Mn_d - 0.40 \log EA$	0.00002	0.89
	$y = 9.45 - 0.90 \log I(pH_{CaCl_2}) - 0.41 \log pH_{KCl} - 0.29 \log Ex.K + 0.44 \log Mn_d - 0.77 \log EA + 0.34 \log CEC$	0.00004	0.91
	$y = 9.21 - 0.87 \log I(pH_{CaCl_2}) - 0.19 \log pH_{KCl} - 0.32 \log Ex.K + 0.42 \log Mn_d - 0.86 \log EA + 0.48 \log CEC - 0.25 \log pH_{H_2O}$	0.00009	0.92

Appendix Table A37 (Continued).

PRs	Equation ($y = \log \Delta P_{BC}$)	P <0.05	r^2
LKan	$y = 0.26 + 0.56 \log Mn_d$	0.0151	0.32
	$y = 0.34 + 0.95 \log Mn_d - 0.51 \log Fe_o$	0.0154	0.43
	$y = -0.20 + 0.98 \log Mn_d - 0.74 \log Fe_o + 0.50 \log P_{BC}$	0.0024	0.63
	$y = -0.85 + 1.07 \log Mn_d - 1.20 \log Fe_o + 0.53 \log P_{BC} + 0.55 \log \%silt$	0.0007	0.75
	$y = -0.77 + 1.31 \log Mn_d - 1.0 \log Fe_o + 0.45 \log P_{BC} + 0.86 \log \%silt - 0.71 \log CEC$	0.0003	0.82
	$y = -0.95 + 1.46 \log Mn_d - 0.91 \log Fe_o + 0.63 \log P_{BC} + 0.86 \log \%silt - 0.68 \log CEC - 0.43 \log \%OC$	0.0003	0.87
	$y = -0.87 + 1.63 \log Mn_d - 0.81 \log Fe_o + 0.50 \log P_{BC} + 0.98 \log \%silt - 1.1 \log CEC - 0.44 \log \%OC + 0.26 \log Ex.Al$	0.00037	0.89
	$y = -2.56 + 1.59 \log Mn_d - 0.81 \log Fe_o + 0.64 \log P_{BC} + 0.84 \log \%silt - 1.1 \log CEC - 0.21 \log \%OC + 0.53 \log Ex.Al + 0.47 \log \Delta pH_{CaCl_2}$	0.00017	0.94
HKan	$y = -0.08 + 0.74 \log \%clay$	0.0005	0.55
	$y = -1.55 + 1.23 \log \%clay + 0.59 \log \%sand$	0.0004	0.65
	$y = -1.66 + 1.53 \log \%clay + 0.53 \log \%sand - 0.44 \log Fe_o$	0.0004	0.72
	$y = -1.49 + 1.25 \log \%clay + 0.59 \log \%sand - 1.20 \log Fe_o + 1.15 \log Al_o$	0.00006	0.83
	$y = -0.995 + 1.09 \log \%clay + 0.43 \log \%sand - 1.60 \log Fe_o + 1.46 \log Al_o + 0.27 \log Ex.Ca$	0.00004	0.88
	$y = -0.61 + 1.18 \log \%clay + 0.36 \log \%sand - 1.60 \log Fe_o + 1.61 \log Al_o + 0.36 \log Ex.Ca - 0.35 \log CEC$	0.00009	0.89
	$y = -0.40 + 1.25 \log \%clay + 1.35 \log \%sand - 1.70 \log Fe_o + 1.56 \log Al_o + 0.33 \log Ex.Ca - 0.36 \log CEC + 0.15 \log \Delta EC$	0.00015	0.91
	$y = -0.47 + 1.30 \log \%clay + 0.36 \log \%sand - 1.50 \log Fe_o + 1.27 \log Al_o + 0.37 \log Ex.Ca - 0.20 \log CEC + 0.40 \log \Delta EC - 0.33 \log Ex.K$	0.00021	0.93

Appendix Table A37 (Continued).

PRs	Equation ($y = \mathrm{Log}\Delta IP_{BC}$)	$P < 0.05$	r^2
LRoi	$y = 2.61 - 0.47\ \mathrm{Log}\ I(pH_{H_2O})$	0.0579	0.22
	$y = 1.70 - 0.63\ \mathrm{Log}\ I(pH_{H_2O}) + 0.47\ \mathrm{Log}\ pH_{H_2O}$	0.0182	0.41
	$y = -\ 0.27 - 0.56\ \mathrm{Log}\ I(pH_{H_2O}) + 0.76\ \mathrm{Log}\ pH_{H_2O} + 0.48\ \mathrm{Log\ Smax}$	0.0108	0.54
	$y = -\ 2.39 - 0.40\ \mathrm{Log}\ I(pH_{H_2O}) + 1.09\ \mathrm{Log}\ pH_{H_2O} + 0.74\ \mathrm{LogSmax}$	0.0089	0.62
	$+\ 0.42\ \mathrm{Log}\ I(EC)$		
	$y = -\ 1.17 - 0.64\ \mathrm{Log}\ I(pH_{H_2O}) + 1.08\ \mathrm{Log}\ pH_{H_2O} + 0.82\ \mathrm{Log\ Smax}$	0.0126	0.66
	$+\ 0.33\ \mathrm{Log}\ I(EC) - 0.33\ \mathrm{Log}\ \%OC$		
	$y = -\ 3.41 - 0.34\ \mathrm{Log}\ I(pH_{H_2O}) + 1.13\ \mathrm{Log}\ pH_{H_2O} + 1.02\ \mathrm{Log\ Smax}$	0.0133	0.72
	$+\ 0.39\ \mathrm{Log}\ I(EC) - 0.51\ \mathrm{Log}\ \%OC + 0.45\ \mathrm{Log}P_{B2}$		
	$y = -\ 1.96 - 0.50\ \log I(pH_{H_2O}) + 1.01\ \log pH_{H_2O} + 0.86\ \log \mathrm{Smax}$	0.0162	0.76
	$+\ 0.16\ \log I(EC) - 0.87\ \log \%OC + 0.48\ \log P_{B2} + 0.40\ \log Mn_d$		
	$y = -0.98 - 0.20\ \log I(pH_{H_2O}) + 1.29\ \log pH_{H_2O} + 0.96\ \log \mathrm{Smax}$	0.0098	0.83
	$+\ 0.57\ \log I(EC) - 1.1\ \log \%OC + 0.52\ \log P_{B2} + 0.58\ \log Mn_d$		
	$-\ 0.51\ \log I(pH_{CaCl_2})$		
HRoi	$y = -\ 0.26 + 0.85\ \mathrm{Log}\ P_{BII}$	0.00004	0.72
	$y = -\ 0.30 + 0.87\ \mathrm{Log}\ P_{BII} - 0.17\ \mathrm{Log\ Ex.Mg}$	0.0001	0.75
	$y = -\ 0.30 + 0.81\ \mathrm{Log}\ P_{BII} - 0.41\ \mathrm{Log\ Ex.Mg} + 0.35\ \mathrm{LogEx.Ca}$	0.0002	0.80
	$y = 0.23 + 0.61\ \mathrm{Log}P_{BII} - 0.51\ \mathrm{Log\ Ex.Mg} + 0.44\ \mathrm{Log\ Ex.Ca}$	0.0002	0.84
	$+\ 0.28\ \mathrm{Log}\ I(EC)$		
	$y = 1.76 + 0.46\ \mathrm{Log}\ P_{BII} - 0.44\ \mathrm{Log\ Ex.Mg} + 0.50\ \mathrm{Log\ Ex.Ca}$	0.00045	0.86
	$+\ 0.37\ \mathrm{Log}\ I(EC) - 0.22\ \mathrm{Log}\ \Delta pH_{CaCl_2}$		
	$y = 3.01 + 0.67\ \mathrm{Log}\ P_{BII} - 0.38\ \mathrm{Log\ Ex.Mg} + 0.58\ \mathrm{LogEx.Ca}$	0.0001	0.93
	$+\ 0.53\ \mathrm{Log}\ I(EC) - 0.40\ \mathrm{Log}\ \Delta pH_{CaCl_2} - 0.51\ \mathrm{Log}\ \%OC$		
	$y = 2.80 + 0.75\ \mathrm{Log}\ P_{BII} - 0.39\ \mathrm{Log\ Ex.Mg} + 0.64\ \mathrm{LogEx.Ca}$	0.00017	0.95
	$+\ 0.69\ \mathrm{Log}\ I(EC) - 0.53\ \mathrm{Log}\ \Delta pH_{CaCl_2} - 0.51\ \mathrm{Log}\ \%OC$		
	$+\ 0.29\ \mathrm{Log}\ I(pH_{H_2O})$	0.00021	0.97
	$y = 1.79 + 1.01\ \mathrm{Log}\ P_{BII} - 0.50\ \mathrm{Log\ Ex.Mg} + 0.62\ \mathrm{Log\ Ex.Ca}$		
	$+\ 0.70\ \mathrm{Log}\ I(EC) - 0.54\ \mathrm{Log}\ \Delta pH_{CaCl_2} - 0.74\ \mathrm{Log}\ \%OC$		
	$+\ 0.47\ \mathrm{Log}\ I(pH_{H_2O}) + 0.29\ \mathrm{Log\ CEC}$		

Appendix Table A37 (Continued).

PRs	Equation ($y = \mathrm{Log}\Delta IP_{BC}$)	$P < 0.05$	r^2
LMCP	$y = -3.59 + 0.75 \log pH_{H_2O}$	0.0004	0.56
	$y = -5.66 + 1.07 \log pH_{H_2O} + 0.48 \log Smax$	0.0002	0.69
	$y = -4.45 + 0.86 \log pH_{H_2O} + 0.90 \mathrm{Log}\ Smax - 0.61 \log \%clay$	0.0003	0.73
	$y = -4.91 + 0.82 \log pH_{H_2O} + 0.92 \log Smax - 0.77 \log \%clay + 0.25 \log P_{BC}$	0.0003	0.78
	$y = -7.50 + 0.61 \log pH_{H_2O} + 0.74 \log Smax - 0.72 \log \%clay + 0.39 \log P_{BC} + 0.34 \log I(pH_{CaCl_2})$	0.0002	0.84
	$y = -7.96 + 0.60 \log pH_{H_2O} + 0.65 \log Smax - 0.58 \log \%clay + 0.39 \log P_{BC} + 0.40 \log I(pH_{CaCl_2}) - 0.14 \log b$	0.0004	0.86
	$y = -6.59 + 0.60 \log pH_{H_2O} + 0.68 \log Smax - 0.64 \log \%clay + 0.30 \log P_{BC} + 0.42 \log I(pH_{CaCl_2}) - 0.15 \log b - 0.17 \log I(pH_{H_2O})$	0.00091	0.87
	$y = -6.40 + 0.63 \log pH_{H_2O} + 0.92 \log Smax - 0.43 \log \%clay + 0.28 \log P_{BC} + 0.51 \log I(pH_{CaCl_2}) - 0.10 \log b - 0.25 \log I(pH_{H_2O}) - 0.48 \log \%FC$	0.0016	0.89
HMCP	$y = 0.37 - 0.40 \log b$	0.0995	0.16
	$y = 1.95 - 0.45 \log b - 0.33 \log I(pH_{H_2O})$	0.0942	0.27
	$y = 4.65 - 0.49 \log b - 0.93 \log I(pH_{H_2O}) - 0.81 \log \%OC$	0.0059	0.58
	$y = 4.92 - 0.47 \log b - 1.10 \log I(pH_{H_2O}) - 0.61 \log \%OC - 0.49 \log Ex.K$	0.0016	0.72
	$y = 4.22 - 0.37 \log b - 1.20 \log I(pH_{H_2O}) - 0.54 \log \%OC - 0.57 \log Ex.K + 0.35 \log pH_{H_2O}$	0.0005	0.81
	$y = 3.47 - 0.43 \log b - 1.2 \log I(pH_{H_2O}) - 0.70 \log \%OC - 0.59 \log Ex.K + 0.39 \log pH_{H_2O} + 0.34 \log \%silt$	0.0001	0.89
	$y = 4.33 - 0.55 \log b - 1.30 \log I(pH_{H_2O}) - 0.73 \log \%OC - 0.60 \log Ex.K + 0.38 \log pH_{H_2O} + 0.31 \log \%silt + 0.21 \log Ex.Na$	0.0001	0.91
	$y = 4.51 - 0.55 \log b - 1.30 \log I(pH_{H_2O}) - 0.64 \log \%OC - 0.61 \log Ex.K + 0.32 \log pH_{H_2O} + 0.49 \log \%silt + 0.27 \log Ex.Na - 0.32 \log CEC$	0.00017	0.94

Remark: $I(pH_{H_2O})$, $I(pH_{CaCl_2})$ and I(EC) = pH_{H_2O}, pH_{CaCl_2} and EC of soil incubated for 14 days

Appendix Table A38 Soil pH (soil : water = 1:1) classes.

Rating	Range
Ultra acid	< 3.5
Extremely acid	3.5-4.5
Very strongly acid	4.5-5.0
Strongly acid	5.1-5.5
Moderately acid	5.6-6.0
Slightly acid	6.1-6.5
Neutral	6.6-7.3
Slightly alkaline	7.4-7.8
Moderately alkaline	7.9-8.4
Strongly alkaline	8.5-9.0
Very strongly alkaline	> 9.0

Appendix Table A39 Available phosphorus (Bray II) classes.

Rating	Range (mg kg^{-1})
Very low	< 3
Low	3-6
Moderately low	6-10
Medium	10-15
Moderately high	15-25
High	25-45
Very high	> 45

Appendix Table A40 Cation exchange capacity (CEC) classes.

Rating	Range (cmol kg^{-1})
Very low	< 3
Low	3-5
Moderately low	5-10
Medium	10-15
Moderately high	15-20
High	20-30
Very high	> 30

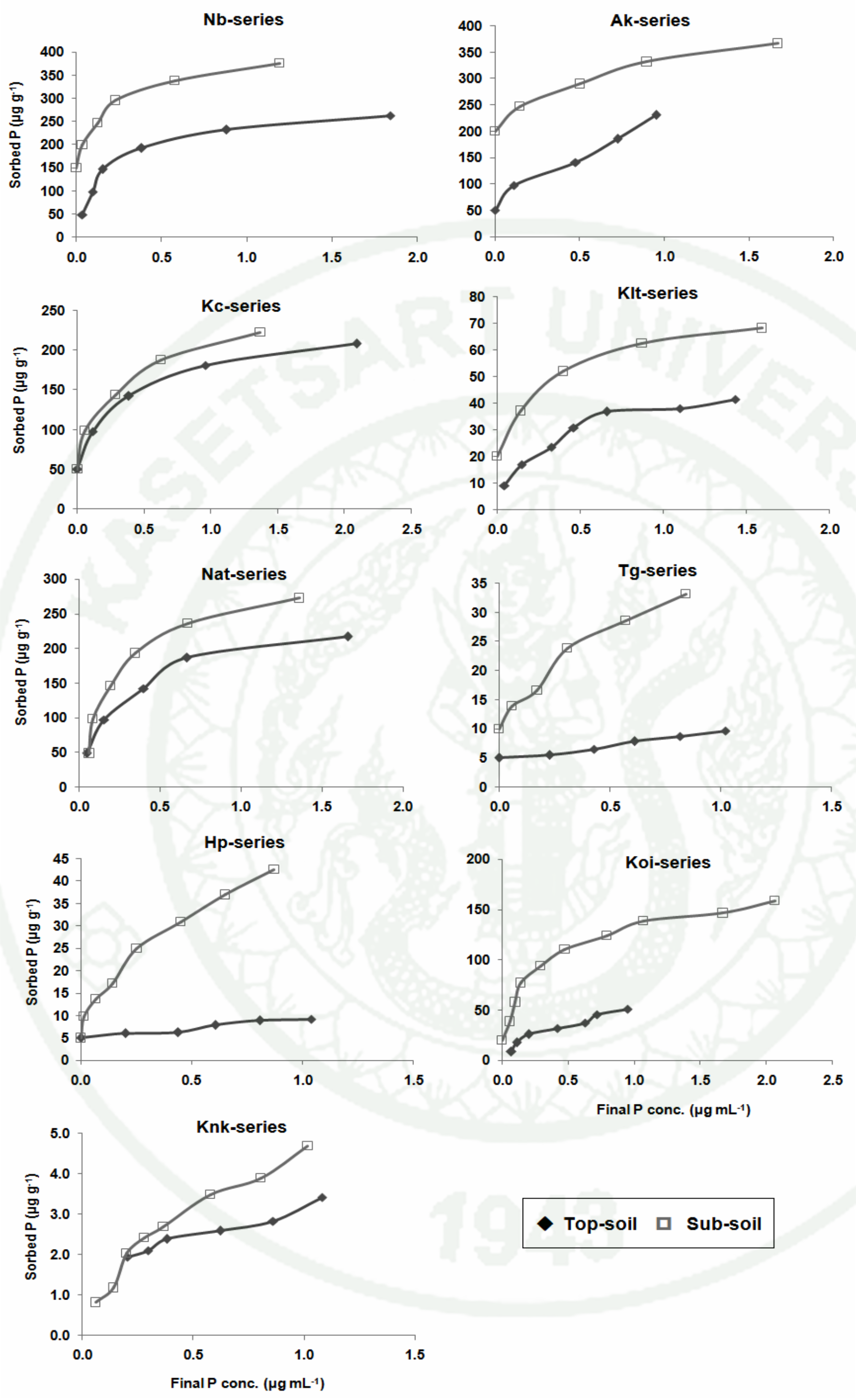
Appendix Table A41 Extractable acidity (EA) classes.

Rating	EA (cmol kg^{-1})
Very low	< 1.0
Low	1.0-2.0
Medium	2.0-5.0
Moderately high	5.0 10.0
High	10.0-20.0
Very high	> 20.0

Source: Kanchanaprasert (1986)

Appendix B

Figure



Appendix Figure B1 Isotherm for P sorption of all soils studied.

CURRICULUM VITAE

NAME : Ms. Chanida Charanworapan

BIRTH DATE : December 23, 1971

BIRTH PLACE : Nonthaburi, Thailand

EDUCATION :

YEAR	INSTITUTE	DEGREE/DIPLOMA
1996	Ramkhamhaeng Univ.	B.Sc. (Chemistry)
2003	Kasetsart Univ.	M.S. (Agriculture)

POSITION/TITLE : Scientist

WORK PLACE : Office of Science for Land Development, Land Development Department

PUBLICATIONS :

Charanworapan, C., J. Chancharoensook, C. Suwannarat and I. Sooksathan. 2003. Effects of trace elements and dairy waste water addition on the contents of available trace elements and yield of rice plant in a paddy calcareous soil. The Proceedings of 41st Kasetsart University Annual Conference (Subject: Plants).

Sukreeyapongse, O. and C. Charanworapan. 2004. Phosphorus index for a rice field. Publication Research of Office of Science for Land Development, Land Development Department (in Thai).