PREDICTING AMOUNTS OF ROCK PHOSPHATE NEEDED FOR CROP PRODUCTION IN WEST AFRICAN SOILS

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Dedications

To my mom,

Who was always there for me. I remember from my childhood how committed she was so that we I could get good education. She thought me the love of studying. Recently she devoted herself in taking excellent care of my son Cheick so that I could finish my Ph. D program. Without her, I could have never accomplished this achievement. This dissertation is the fruit of the tremendous work she has done.

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Abstract

The direct application of rock phosphate (RP) can be a good alternative to water-soluble P fertilizers. However, despite the extensive work done on RPs, there are no models to predict amounts of RP required. A study including both laboratory and field experiments was conducted to develop an algorithm for estimating amounts of rock phosphate (RP) needed for crop production in West African soils on a site-specific basis. Soil properties affecting RP dissolution and sorption processes were studied in laboratory incubation and incorporated into an algorithm. The accuracy of the method used for estimating RP dissolution (ΔNaOH-P) was assessed. Field experiments were conducted at Konobougou, Mali and Keur Madieng, Senegal to test the predictions made by the algorithm. Another incubation study was conducted to evaluate the limitation of RP dissolution in the Keur Madieng soil.

Results showed that amounts of RP for maximum yield could be predicted using plant critical P level, KCl-extractable acidity, Ca saturation, effective cation exchange capacity and clay content. The presence of water-soluble P in the RP might affect the accuracy of ΔNaOH-P method as a measure of the amount of P dissolved from RP. The ΔNaOH-P extraction can, however, be used as an estimate of the amount of P released from the RP material. The accuracy of the RP algorithm could not be conclusively tested because of the large variability in the field. However, there are indications that the RP algorithm could be overestimating RP amounts for maximum millet yield. A unique Bray 1-P critical level varying between 7 and 11 mg kg^{-1} was estimated for both soluble P fertilizers and RPs. The limitation of the RP dissolution in the Keur Madieng soil was due to the lack of soil acidity.

The results showed that the algorithm has a good potential to estimating quantitatively the amounts of RP needed for crop production. However more studies are needed for refining and generalizing the algorithm. The results indicate that RP dissolution needs to be improved in the sandy soils of West Africa.

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Chapter 1. Introduction

1.1. Problem

Soils of many regions of West Africa are generally weathered, commonly acid, low in organic matter and poorly buffered (Juo and Fox, 1977; Wilding and Hossner, 1989; Manu et al., 1991). Many research studies have provided evidence that soil fertility is the number one factor limiting crop production in the Sudano-Sahelian zone of West Africa (Onken and Wendt, 1989; Payne et al., 1991; Doumbia et al., 1993). Among soil fertility problems, phosphorus (P) is usually the most deficient and plant growth limiting nutrient in these soils (Jones and Wild, 1975; Pieri, 1986; Manu et al., 1991; Doumbia et al., 1993). Approximately 80% of these soils have been estimated to be affected by the P deficiency problem (Bationo, personal communication).

The addition of fertilizer P is one method used to raise soil available P to crop critical levels (Breman, 1990; McIntire and Powell, 1995). However, very little quantities of water-soluble P fertilizers are used due to high fertilizer cost. According to Bationo (personal communication) the use of P fertilizers in Sub-Saharan Africa is low (1.6 kg P ha^{-1} of cultivated land) compared to Latin America (7.9 kg P ha^{-1}) and Asia (14.9 kg P ha^{-1}). The use of rock phosphate (RP) in agriculture can be an attractive alternative for West African countries (Diouf et al., 1998) because of the following.

- Rock phosphate deposits are scattered throughout West Africa,

- The West African rock phosphate deposits are predominantly of sedimentary origin therefore being more soluble than igneous RP and
- The expected cost of RP is greatly less than the soluble P fertilizers.

Regardless of the excellent potential of RP in agriculture and the wide distribution of RP deposits throughout West Africa, however, RP use is very limited (Kamara et al., 1994; Diouf et al., 1998). Many factors have led to limited adoption of RP on a wide scale. These factors include the low solubility of RP, and in some cases, the lack of diagnostic tools for evaluating favorable conditions for their application.

1.2. Justification

It is desirable to find methods for predicting the amounts of RP needed to meet crop production needs. Not all of the RP resources are readily plant-available and agronomically effective when applied directly to soils. Rock phosphate dissolution varies and is influenced by many factors (Khasawneh and Doll, 1978). In addition, the P that is released from the RP dissolution can be fixed again. Therefore, RP effectiveness depends not only on RP dissolution, but also on the amount of P that remains available to plants after dissolution. The identification of mechanisms and factors that regulate the effectiveness of RP resources may allow us to predict the amount of RP required to meet plant needs. It is necessary to study the factors affecting both RP dissolution in a given soil and the P availability from RP dissolution in order to predict the amounts of

RP needed to satisfy the plant P requirements. Unfortunately, RP recommendation rates to meet crop needs in several countries in West Africa do not take these factors into account. This omission could explain, in part, the failure to use RP on a wide scale. The ability to predict RP fertilizer requirements and to develop accurate RP recommendations is, therefore, critical to sustainable agriculture in West African countries. The complexity of the factors affecting RP dissolution and their interaction justified the need for a modeling approach.

The ability to predict RP fertilizer requirements and to develop accurate RP recommendations on a site specific basis will represent an important contribution to improve P fertility status and to increase crop yields in West African soils.

1.3. Overall goal

The overall goal of this study is to increase agricultural productivity through the development of decision-aids for the management of soil fertility in West Africa.

1.4. General Objective

My dissertation topic proposes to develop a rock phosphate (RP) algorithm to predict the amounts needed to meet crop P requirements. In the future, this RP module will be linked to the 'Phosphorus Decision Support

System' (PDSS). PDSS is a decision support tool that operates on a site-specific basis. It enables users to diagnose P deficiencies, prescribe alternative correction actions and enable growers to achieve food security or remain competitive in the market place. While PDSS makes recommendations only for water-soluble P fertilizers, the inclusion of the RP algorithm will offer the option of using RP for correcting P deficiency.

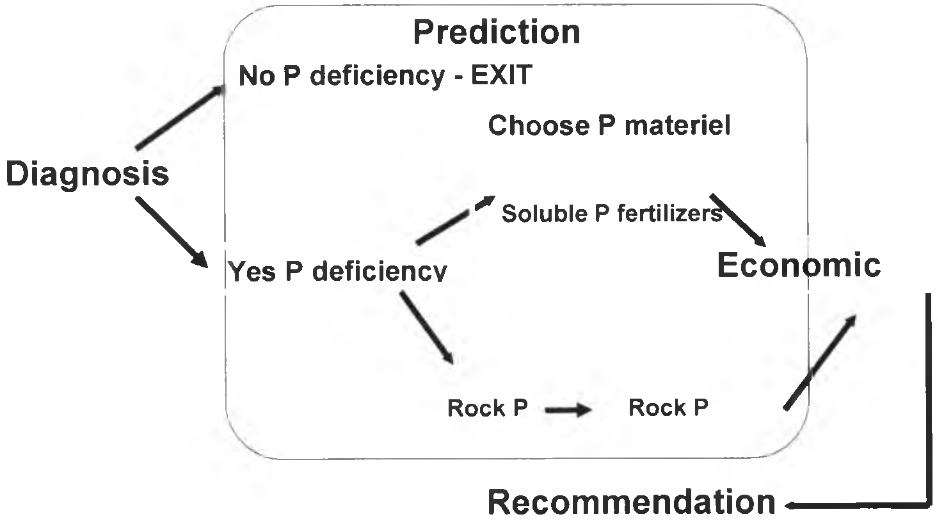

Figure 1.1. Phosphorus Decision Support System and linkage of RP module. Source: Diarra et al., 2004.

1.5. Specific objectives

The specific objectives of this study were to:

(i) Develop an algorithm that will predict the amounts of RP needed to meet crop P requirements on a site-specific basis by considering factors affecting RP dissolution and subsequent P sorption.

(ii) Assess the accuracy of the ΔNaOH-P method used to estimate the amounts of RP dissolved.

(iii) Field-test the RP algorithm in different climatic and management conditions to assess the accuracy of the algorithm

(iv) If needed, define refinement or modification of the algorithm and

(v) Evaluate limitation to RP dissolution in millet growing sandy soils of West Africa.

1.6. Dissertation organization

The present dissertation is organized in 7 chapters. The current chapter (Chapter 1) is the introduction to the study. This chapter introduces the problem and the justification of this study. In Chapter 2 we discuss soil P status in West Africa and review factors affecting RP suitability for direct application of RP in agriculture. Some of the other algorithms and decision-aids for RP are presented. Chapter 3 presents the study done in developing an algorithm for predicting the amounts of RP to meet crop P requirement in 5 Malian soils using Tilemsi RP. In Chapter 4, we assess the 0.5 *M* NaOH extractant in estimating the dissolved RP by a means of comparison with the changes in exchangeable Ca during the incubation period. Chapter 5 reports the multi-location field testing conducted in

Mali and Senegal. The information obtained from the multi-location field testing of the RP algorithm is used in order to identify needed refinements in the algorithm and to generalize the algorithm for prediction to a larger range of RPs. In Chapter 6 we examine the results of an incubation study comparing the dissolution of Tilemsi RP in closed and open systems. The last Chapter (Chapter 7) concludes and summarizes the major findings of the study. Some future axes of research are also presented in Chapter 7.

Chapter 2. Literature review

2.1. Phosphorus status and its significance in the Sudano- Sahelian zone of West Africa

The semi-arid region of West Africa located in the transition zone between the Sahara desert to the North and the sub-humid savannas and woodlands to the South is subdivided into 3 bioclimatic zones. These three bioclimatic zones are: i) the Sahelian zone where the rainy season lasts 75 to 90 days; ii) the Sudanian zone where the rainy season is 90 -165 days. The cropping systems are predominantly based on millet (*Pennisetum spp.*) and sorghum (*Sorghum bicolor,* L) cultivation; and iii) the Guinean zone where the rainy season lasts 165 to 210 days (Virmani et al., 1980).

The low soil P availability in many regions of the Sudano-Sahelian zone (transition zone between the Sahelian and Sudanian zones) of West Africa (Pieri, 1986) may be associated with the nature of the parent material (aeolian sand) and the soils' low organic matter. Many of the soils of West Africa are extremely sandy, low in organic carbon, and often acid as well as low in P. In a soil fertility study in West Africa, Manu et al. (1991), found that 77% of West African soils have Bray 1 extractable P levels less than 8 mg P kg^{-1}, the critical P level proposed by Bationo et al. (1989) to obtain 90% of the maximum millet yield in the sandy soils of Niger. Furthermore, the increased pressure on the land coupled with the unsustainable farming practices such as continuous removal of nutrients (nutrient mining) under traditional cropping systems (van der Pol, 1992), lack of return of crop residues, and the reduction of the length of fallow periods have resulted in high rates of loss of vegetation and severe land degradation. Smaling et al. (1997) and Doumbia et al. (1998) reported that annual nutrient depletion in Mali, excluding "Office du Niger" zone, ranges from 25 - 106 kg N ha^{-1}, 17 - 22 kg P ha^{-1} and 20 - 54 kg K ha^{-1} depending on the cropping system. "Office du Niger" the Niger delta in Mali where the cropping system is mostly based on paddy rice cultivation. Every year P is applied to rice, resulting in a buildup of P (Doumbia, personal communication).

The phosphorus deficiency problem is so severe that the use of other inputs is not effective unless P is also applied. Crop response to N fertilizers in most of these soils could be minimal or sometimes completely nonexistent until P requirements have been satisfied (Traoré, 1974; Doumbia et al., 1993). Bationo (in press) illustrated the ineffectiveness of nitrogen (N) and potassium (K) inputs without P deficiency correction in an experiment on pearl millet on Sadore soil conducted from 1980 through 1986. In this experiment Bationo reported that millet grain yield did not change with the application of N60P0K30 (270 kg ha^{-1}) compared to N0P0K0 (190 kg ha^{-1}); whereas the application of N60P45K30 statistically increased millet grain yield up to 1070 kg ha^{-1}. Jones and Wild (1975) also documented that P deficiency was so acute that plant growth stopped once the seed reserve of P had been depleted.

2.2. Some rock phosphates sources in Africa

Despite the acute P deficiency in West African soils, P inputs to most farmers' fields in Mali currently consist of organic sources such as manures, composts, and household wastes. None of these materials supplies adequate quantities of nutrients for optimum crop production (Palm et al., 1997). Applications of soluble P fertilizers are commonly recommended to satisfy crop P requirements (McIntire and Powell, 1995). None or very few farmers have access to or apply inorganic fertilizers (Doumbia, 2002), partly because soluble fertilizers are expensive and beyond the means of resource-poor farmers in West Africa. Thus, RP sources, from around the world have been evaluated for direct use in agriculture and soil fertility restoration as a low-cost alternative to soluble P fertilizers.

The principal phosphate minerals in RP are mainly apatites. The apatite found in RP can be of igneous, sedimentary or metamorphic origin. West Africa has vast RP deposits (van Kauwenbergh et al., 1991). Most of RP deposits of this region are predominantly of sedimentary origin and with medium to low solubility (van Kauwenbergh et al., 1991; Buresh et al., 1997). These major deposits have been identified in Senegal, Mali, Togo, Burkina Faso and Niger (Johnson, 1994). Igneous RP deposits found in East Africa are seldom suitable for direct application (Bationo and Mokwunye, 1991; Buresh et al., 1997). Figure 2.1 and Table 2.1 shows some major RP deposits in West Africa and their estimated reserves.

Benin

1.Mekrou

2. Pobe

Burkina Faso

3. Arly

4. Diapega-Kodjari

Guinea Bisau

5. Saliquinhe Ghana

6. Sekondi

Liberia

7. Bambuta-Bomi Hill

Mali

8. Assakerei

9. Tilemsi

Mauritania

10. Bofal-Loubboira

Niger

11. Aschia Tinamou

12. Tahoua

13. Tapoa

Nigeria

14. Abeokuta

Senegal

15. Gambia Namel

16. Matam

17. Taiba-Thies

18. Ziguinchor

Togo

19. Akoumape-Hahotoe

Figure 2.1. Rock phosphate deposits in West Africa

Source: adapted from Buresh et al., 1997.

Table 2.1. Estimated resources of some rock phosphates (RP) in West Africa.

Country	Name of deposit	Reactivity	Estimated reserves of RP (10^6 tonnes)
Burkina Faso	Kodjari	Low to medium	63
Mali	Tilemsi	Medium	20-25
Niger	Tahoua & Parc W	Low to medium	100
Senegal	Taiba	Low	155
Togo	Hahotoe	Low to medium	100

Source: Buresh et al., 1997; Truong et al., 1978.

Different types of RP have widely differing mineralogical, chemical and textural characteristics. Some characteristics of African RPs are shown in Table 2.2.

Table 2.2. Some characteristics of rock phosphates (RPs) from West Africa

RP properties	Tilemsi (Mali)	Tahoua (Niger)	Taiba (Senegal)	Kodjari (Burkina Faso)	Hahotoe (Togo)
Total P_2O_5 (g kg^{-1} rock)	286	278	361	254	1365
Solubility in*					
1st NAC**	54	40	39	21	41
2nd NAC***	58	42	43	26	41
2% citric acid	119	77	81	60	76
CO_3/PO_4	0.210	0.112	0.098	0.093	0.088

* P_2O_5, g kg^{-1} rock

** Neutral ammonium citrate, 1st extraction (ratio soil :solution = 1 :100)

*** Neutral ammonium citrate, 2nd extraction (ratio soil :solution = 1 :100)

Source: Chien et al., 2003; Truong et al., 1978.

Mokwunye (1995) pointed out that the most reactive RPs are those having a molar PO_4/CO_3 ratio less than 5. Chien (1977) found the citrate solubility of RP increases as the molar ratio of CO_3/PO_4 increases. Diamond (1978) subsequently proposed a classification of RP for direct application based on citrate solubility as follow: > 54 g kg^{-1} high; 32 - 45 g kg^{-1} medium and < 27 g kg^{-1} low. Among West African RPs, only Tilemsi RP from Mali (Truong et al., 1978; Henao and Baanante, 1997; Bationo et al., 1986) and Tahoua from Niger (Bationo and Mokwunye, 1991) have been found to be suitable for direct application.

2.3. Factors affecting RP effectiveness as P fertilizer

Rock phosphates are primarily added to soils as sources of P. Factors affecting RP effectiveness for direct application can be classified in five categories: soil properties, chemical and physical properties of the RP source, plant factors, and management factors.

2.3.1. Soil factors

Two important mechanisms for the use of RP as a P source for direct application to crop are dissolution of the RP and the sorption of the P resulting from the dissolved RP. These mechanisms are affected by soil properties. Several authors (Syers and Mackay, 1986; Wright et al., 1992) pointed out that soil properties that increase RP dissolution may not necessarily result in an increase in the amount of plant available P in soil. This was illustrated in simulation studies which showed that increases clay content increased not only dissolution but also P retention, resulting in a net decrease in P availability to crops (Yost, personal communication).

2.3.1.1. Soil properties affecting RP dissolution

The reaction of RP dissolution, Equation 2.1, and the reaction products listed are factors that affect RP dissolution: soil acidity, soil calcium (Ca) and P status define the direction of the dissolution reaction.

$$Ca_{10}(X)_2(PO_4)_6 + 12H^+ \rightarrow 10Ca^{2+} + 2X^- + 6H_2PO_4^{3-} \qquad [Eq. 2.1]$$

Where X can be F^-, OH^-, or Cl^-.

From this equation, it is generally believed that acid soils favor the potential use of RP for direct application. The more acid the soil is, the more rapid the dissolution rate of RP. The H^+ ions are the driving force for the dissolution of the carbonate apatite (Chien, 1977). Benefits from RP use as fertilizer can be obtained only generally if soil pH is lower than 5.5 (Diarra, 2004). Sanchez et al. (1997) reported that highly reactive RP can be used in acid soils with similar agronomic efficiencies as superphosphates, but seldom in soils with pH values above 6.2. Dissolution of North Carolina RP (Chien et al., 1980) and Araxa RP from Brazil (Yost et al., 1982) decreased with increasing soil pH.

However, several studies (Juo and Kang, 1978; Wright and al., 1991; Gilkes and Bolland, 1994; Diarra et al, 2004) found that soil pH was not such a successful measure of RP dissolution. For example, Mackay et al. (1986) and Gilkes and Bolland, (1994) pointed out that values of soil pH might be poorly predictive of RP dissolution. Juo and Kang (1978) also fount that under similar pH conditions (pH 6), the rock phosphates were a more effective P source in Alfisols than in a limed Ultisols. These results suggest that the dissolution of RP in soil may not depend solely on soil pH but also on other soil properties. Eq. 2.1, implies that the removal of the reaction product ions might enhance the solubility of the RP. Several studies have supported this implication. For example, Hammond et al. (1986a) reported that the effective dissolution of RP in soil requires not only low soil pH, but also low soil exchangeable Ca and low soil solution P concentrations. Wright et al. (1992) also reported a significant correlation between extent of RP dissolution and soil factors controlling the concentration of P and Ca in soil solution such as exchangeable Ca, soil Ca saturation, P in soil solution and P retention capacity. Diarra et al. (2004) suggested that soil Ca saturation higher than 30% reduced RP dissolution in Malian soils with contrasting pH and clay contents. The initial rate of dissolution of RP in soil is influenced by the concentration of Ca and P in the soil solution (Mackay et al., 1986). In this paper, using 30 contrasting soils, Mackay et al. (1986) found that Ca-saturation, P-sorption capacity, and cation exchange capacity of the soil were the three most important parameters influencing Sechura RP (from Peru) dissolution in soils. They found that the dissolution of

Sechura RP increased as exchangeable Ca decreased and as P-sorption capacity increased. Wilson and Ellis (1984) also found that an increase in the Ca^{2+} activity in solution at a constant pH resulted in a decrease in the rate of dissolution of RP. Many workers have reported that increased soil P-sorption capacity increased RP dissolution (Chu et al., 1962; Chien et al., 1980; Smyth and Sanchez, 1982; Bolland and Barrow, 1988). A high soil P sorption capacity might enhance RP dissolution by reducing the concentration of P in solution around the RP particle (Smyth and Sanchez, 1982; Kirk and Nye, 1986). Loss mechanisms for P and Ca, such as plant uptake and leaching, should encourage further dissolution of RP. Khasawneh and Doll (1978) also reported that soil organic matter content and soil texture may affect the extent of RP dissolution. Soil organic matter is related to bonding of Ca and provides an effective sink for Ca by increasing the CEC. Organic matter can also increase the soil water holding capacity and produce organic acids favorable for RP dissolution, both of which enhance dissolution of RP. Coarse-textured and sandy soils are not good sinks for P and Ca.

2.3.1.2. Soil factors affecting availability of dissolved P from RP

Phosphorus dynamics in soils, including P from RP, are complex, because, in addition to the dissolution reactions discussed above, they also involve effects of desorption (release) and sorption (fixation) processes.

The effectiveness of a RP source as a P fertilizer will depend not only on the dissolution of RP, but also on the availability of P to plant after the dissolution process. Thus, information concerning the soil properties controlling RP dissolution and plant availability of P in soil is required to predict situations where RP application would be successful.

Several authors (Syers and Mackay, 1986; Wright et al., 1992) pointed out that soil properties that increase RP dissolution in soil may not necessarily result in increasing the amount of plant available P in soil. For instance, in a study on acid sulfate soils of Thailand, Yampracha et al. (2005) indicated that increasing KCl extractable Al (Al_KCl) and oxalate extractable Fe (Fe_Ox) caused an increase in Kanchanaburi RP dissolution, but also increased the P sorption. Similarly, in a simulation study (Yost, personal communication), similar effects of increasing soil clay on the RP dissolution and P sorption were reported, causing a reduction in the availability of dissolved P. This is probably because sorption is considered the most important process controlling P availability in soils (Lajtha and Harrison, 1995). Phosphorus sorption is, in turn, controlled by mineral clay surfaces such as Al and Fe oxides and amorphous materials are particularly important in highly weathered soils (Sanchez and Uehara, 1980; Sanchez et al., 1982). Syers and Mackay (1986) found that the amounts of extractable P declined as the P sorption capacity of soils increased, in contrast to the increase in the extent of RP dissolution as the P sorption capacity increased (Smyth and Sanchez, 1982; Mackay et al., 1986). Although a high P sorption capacity can promote more rapid dissolution of RP, the short term agronomic effectiveness of RP decreases with increasing P sorption capacity due to the decrease in soil solution P (Mokwunye and Chien, 1980; Mokwunye and Hammond, 1992). Many other studies (Juo and Ellis, 1968; Lindsay and Moreno, 1960) also suggest that the availability of P from RP depends not only upon the rate of RP dissolution but upon the transformation into more unavailable forms of phosphates, i.e. aluminum and iron phosphates that control the P concentration in soil solution in acid soils. Consequently, it is important to distinguish between soil properties that control RP dissolution and those that control the subsequent plant availability of P.

2.3.2. Rock phosphate properties

Rock phosphate dissolution also depends on chemical and physical properties of the RP source which vary widely among apatites in RP materials. The chemical properties reported in characterization studies of some West African RP carried out by Truong et al. (1978) include the solubility in neutral ammonium citrate, the CO_3/PO_4 ratio: the extent of carbonate substitution in the apatite structure, and the surface area indicating potential reactivity.

The most important property related to RP materials is their reactivity. Rock phosphate (RP) reactivity is dependent on isomorphic substitution within the apatite mineral crystal lattice (Easterwood et al., 1989). Smith and Lehr (1966) and Chien and Black (1976) observed that a carbonate molecule could not only replace a tetrahedral phosphate molecule in an apatite crystal but it would also weaken the crystal structure of the mineral. Therefore, increasing isomorphic substitution results in greater mineral solubility under acid conditions (Chien, 1977; Khasawneh and Doll, 1978; Hughes and Gilkes, 1986). The citrate solubility of RP thus increases as the molar ratio of CO_3/PO_4 in the apatites increases. This agrees with the results reported by Lehr and McClellan (1972).

The extent of RP dissolution was positively related to the citrate soluble P. In general, the RP with the highest specific surface area also has the highest citrate solubility. Because the RP dissolution process is a reaction that occurs at the surface of the RP particle (Barrow, 1990) the size of the RP particle (Joos and Black, 1950) and its porosity (Caro and Hill, 1956; Yost, personal communication) affects its effectiveness. Many experiments have shown that the effectiveness of RP increases with decreasing particle size (Khasawneh and Doll, 1978; Joos and Black, 1950; Escobar and Reyes, 1994). Escobar and Reyes (1994) found that maize grain yield was almost doubled when the particle size of Baja California RP was reduced to a value lower than 100 mesh. Grinding increases the surface area, which increases RP solubility.

The presence of impurities such as calcite, dolomite and gypsum in the RP also inhibit RP dissolution. Howeler and Woodruff (1968) reported that the associated free carbonates in Arkansas rock reduced the effectiveness of the material as a P fertilizer. The presence of $CaCO_3$ is likely to cause an initial decrease the dissolution of the apatite by increasing the pH and Ca concentration in the solution film immediately surrounding the apatite particle (Mackay et al., 1984; Bolan and Hedley, 1990; Robinson and Syers, 1990; Robinson et al., 1994).

2.3.3. Plant

Plant factors include: (i) crop duration; (ii) the ability of the plant roots to take up the Ca or P in soil solution; (iii) the ability of plant root to acidify the rhizosphere (legumes); and (iii) high root density.

Potential positive effects of RP materials on yields occur with their use on longer term crops, acid tolerant perennial crops and trees intercropped with annual crops (Sales and Mokwunye, 1993). Pushparajah et al. (1990) reported that the agronomic effectiveness of RP can be equal or more than that of soluble P fertilizers when applied under acid tolerant perennial crops such as rubber and oil palm. Plant P requirements tend to decrease in the following order: vegetable (annual)>long term>perennial crops. Thus, while RP may be a cost-effective way to supply P and sustain the often deficient nutrient P, it is also clear that soluble P is needed in many cropping systems and soils of West Africa. Examples include intensive vegetable production.

For most crops, direct application of RP is recommended for acid soils but not for neutral and alkaline soils. However, Mnkeni et al. (2000) has successfully used rock phosphates in alkaline soils with canola (*Brassica napus*). Habid et al.

(1999) showed that the relative agronomic effectiveness values of Syrian RP for rape (*Brassica napus*) grown on an alkaline soil (pH 7.72) were 55%. This plant acidifies its rhizosphere by exuding malic and citric acids (Hoffland, 1992). Effectiveness of plant use of P from RP is then greater for plants that are able to acidify their rhizosphere (Mokwunye and Bationo et al., 1978). The acidification of rhizosphere will usually result in increased dissolution of RP particles (Kirk and Nye, 1986). For example, pigeon pea (*Cajanus cajan*) was shown to be more efficient at utilizing iron-bound phosphorus than several other crop species. The roots of this legume release piscidic acid that can complex iron to enhance the availability of iron-bound phosphorus (Ae et al., 1990). Thus, the subsequent or intercropping of crops and trees with annual crops (Sales and Mokwunye, 1993) may benefit from the enhanced dissolution of the RP. Deist et al. (1971) and Flach et al. (1987) suggested that high Ca uptake patterns of plants, like buckwheat (*Fagopyrum esculentum*), are responsible for improved responses of certain crops to applied RP. Growing plant roots can stimulate RP dissolution. Bohan and al. (1997) found that greater dissolution was obtained in the presence than in absence of plants. Removal of the dissolved Ca and P from the zone of RP dissolution is considered to be the main reason for the increased dissolution.

2.3.4. Management factors

2.3.4.1. Methods and rates of RP application

The degree of mixing of rock phosphate in soil and the amount of RP that is applied have a major effect on RP dissolution. Broadcasting, as opposed to band application, exposes the RP particles to larger volumes of soil. Rock phosphates are then more effective when mixed with soil (Khasawneh and Doll, 1978). Measurements of the dissolution of North Carolina RP in soil have shown a reduction in RP dissolution due to banding (Kanabo and Gilkes, 1988a).

Several workers have demonstrated that the proportion of RP that dissolves within the soil decreases with increasing level of RP application (Hughes and Gilkes, 1984; Kanabo and Gilkes, 1988a; Rajan et al., 1991). Yampracha et al. (2005) showed that the Kanchanaburi rock phosphate applied at 500 mg P kg^{-1} depressed RP dissolution. This decrease in RP dissolution was due to the high $CaCO_3$ content of the material, which increased soil pH and solution Ca.

2.3.4.2. Rock phosphate application period (timing)

Timing the application of RP is important for their effective use. The effectiveness of low solubility RP is enhanced when applied directly on acid soils well in advance of crop planting. The slow release of P from RP favors an enhancement of residual effects of RP over time when compared to soluble P fertilizers (Sale and Mokwunye, 1993). It was expected that early application of RP would allow some time for dissolution to begin. However, Chien (2001) reported no significant difference in the effectiveness of North Carolina RP when either applied at planting or 6 weeks before planting in soils with low P sorption capacity. Some studies done in Niger by Roesch and Pichot (1985) in soil with low P retention capacity have shown that the residual effects of Tahoua RP on millet yield were greater than their effects in the first year of RP application and the duration of the effects depended on the rate of RP application. In sandy soils of the Sahel, where P sorption and P availability are extremely low, medium reactive RP applied at 15 to 35 kg P ha^{-1}, increased in relative agronomic efficiencies to 68 and 104% within a 3-yr period (Bationo and Mokwunye, 1991). Similar results were obtained with Tilemsi RP (SAFGRAD, 1983). The crop in the second or third year of RP application could benefit from the residual effect of RP. These results suggest that the dissolution of the rock phosphate may have been the limiting factor rather than the sorption reactions. On the other hand, in soils with high P sorption capacity the effectiveness of RP was reduced when the RP was applied very early (Hammond et al., 1986a), suggesting that sorption reactions may have been the dominant reaction. In soils with high P sorption capacity, RP application at planting is recommended (Chien et al., 1990).

2.3.4.3. Liming

Liming increases pH and exchangeable Ca (Hanafi et al., 1992) and reduces exchangeable Al^{3+} concentration. High pH, low acidity and high exchangeable Ca negatively affect RP dissolution (Habib et al., 1999; Robinson and Syers, 1991). Therefore, liming decreases RP dissolution.

2.3.4.4. Other management factors

Several authors have also shown that RP can be successfully used in alkaline soils with concurrent inoculation of P solubilizing microorganisms (PSM). Such microorganisms release P from RP rapidly increasing plant growth and P uptake (Kucey, 1989; Whitelaw, 2000). Bar-Yosef et al. (1999) found that PSM produced acids, which react with the RP and released P into the solution.

Several studies have also demonstrated that arbuscular mycorrhizal fungi (AMF) improve plant growth and nutrient uptake by plants, particularly under low soil fertility conditions (Tinker, 1980). One of the most dramatic effects of mycorrhizal infection on the host plant is the increase in P (Koide, 1991; Ortaş et al., 1996; Lambert et al., 1979; Kothari et al., 1991; Ortas et al., 2001). AMF take up the same forms of P from the soil solution as roots do. There is no evidence of its ability to solubilize insoluble P (Pi) compounds (Bolan, 1991). The capacity of the mycorrhizal fungi to absorb phosphate from soil and transfer it to the host roots (Asimi et al., 1980) is mainly explained by the ability of mycorrhizal hyphae to extend several cm from the root surface; whereas, roots of the host plant only can absorb P a few mm away from their surface. Thus, AMF enable roots to access a greater volume of soil (Hattingh et al., 1973; Mosse, 1981) for immobile nutrients such as phosphorus. The improvement of P uptake by AMF results in the more effective removal P dissolved from RP, theoretically enhancing RP dissolution.

Besides all these management factors, the use of ammoniacal fertilizers could also acidify the rhizosphere and buildup the H^+ concentration in soil. Reaction involving H^+ is a driving force for RP dissolution to occur (Chien, 1977). Consequently, the use of ammoniacal fertilizers can enhance RP dissolution by acidifying the rhizosphere (Logan et al., 2000).

2.3.5. Moisture content

In addition to all the factors mentioned above, moisture is required for the dissolution reaction to occur. In addition, soil moisture permits both diffusive and convective removal of reaction products from the site of dissolution of the rock phosphate, usually the surface. In this way soil moisture helps to reduce the levels of Ca^{2+} and $H_2PO_4^-$ in soil solution near the site of dissolution, which would strongly influence the dissolution of RP (Wright et al., 1992). Rock phosphate dissolution is inhibited when soil moisture decreases below field capacity (Kanabo and Gilkes, 1988b). Data from field studies in Senegal (Hammond et al., 1986a) indicate that crop yield response to applied RP is linearly related to the mean annual rainfall between 500 and 1300 mm. High rates of leaching in sandy

West African soils created favorable environments for RP dissolution (Hanafi et al., 1992). Direct application of RP is normally not recommended for low rainfall areas, due to erratic agronomic effectiveness under conditions of low soil water content (Hammond et al., 1986a).

2.4. Some efforts to develop decision aids for P and particularly for RP

Numerous decision aids have been developed or proposed to assist P nutrient management. These decision aids include the Phosphorus Decision Support System (PDSS) (Yost et al., 1992), the algorithm for predicting amounts of RP in acid sulfate soils of Thailand (Yampracha et al., 2005 and 2006), and the Phosphate Rock Decision Support System (PRDSS) (Smallberger et al., 2006).

2.4.1. Phosphorus Decision Support System (PDSS)

Phosphorus Decision Support System (PDSS) is a decision aid developed by a project ‘Soil Management Collaborative Research Support Program’ (SM-CRSP) supported by the US Agency for International Development (USAID). PDSS is a decision support tool that operates on a site-specific basis. It enables users to diagnose nutrient deficiencies, prescribe alternative correction actions and enable growers to achieve food security or remain competitive in the market place. In the standard PDSS format, the user selects the crop, indicates the soil

P test and the soil P test value (the soil extractable-P level) of the field or land to be managed. PDSS then uses buffer coefficients, critical levels of the extractable P and the present soil extractable P to make P fertilizer recommendations (Yost et al., 1992). The buffer coefficient is estimated based on the soil clay content (Cox, 1994). If the soil test value is below the critical level then P is recommended. The amount of P is then determined. The difference between the critical level and the measured P in a given soil is the amount of P that must be added. PDSS then converts this value, called Delta P ($P_c - P_o$), into the amounts of soluble phosphate fertilizers. The formula used in PDSS is the following:

$$P = (P_c - P_o) / a2 * D/10 * BD \quad \text{[Eq. 2.2]}$$

Where P = P recommendation, kg ha^{-1}

P_c = critical levels of the extractable P, mg kg^{-1}

P_o = measured soil extractable P, mg kg^{-1}

a2 = P buffer coefficient

D = incorporation depth, cm

BD = bulk density

10 = coefficient for normalizing the incorporation depth (D) to 10 cm.

Unfortunately, PDSS does not offer the possibility to convert Delta P into the amounts of rock phosphate fertilizer.

2.4.2. An algorithm for predicting amounts of RP in acid sulfate soils of Thailand

An algorithm for predicting amounts of RP needed to meet crop P requirement has been proposed by Yampracha et al. (2005; 2006) for lowland rice in acid sulfate soils in Thailand. In this study, a range of acid sulfate soils and a wide range of RP were used. A model A-Be^{-cx} was used to describe RP dissolution. The parameters A, B and c were than regressed against soil and RP properties to identify which properties mostly affect RP dissolution. Soil pH, RP solubility in 2% citric acid, P content in the RP and RP particle size (fraction) were the parameters incorporated into the algorithm in predicting RP recommendation rates. The formula for estimating amounts of RP that should be added to supply crop P requirements is the following:

$$RPadded = \frac{(P_c - P_{Bray\ 2})}{PBC_{Bray\ 2}} \times \frac{\Delta P\_NaOH}{\Delta P\_Bray\ 2} \times \frac{500}{A - Be^{-cx}} \times \frac{depth}{10} \times BD \qquad [Eq.\ 2.3]$$

Where RP added = The amount of RP that should be added (kg ha^{-1}),

P_c = critical Bray2 P level for the soil (mg kg^{-1}),

P_{Bray2} = P in soil extracted by Bray 2 (mg kg^{-1}),

PBC_{Bray2} = P buffering coefficient as measured by Bray 2,

A-Be^{-cx} = amount of ΔP_NaOH in soil at time x for a specific soil (mg kg^{-1}),

Depth = soil depth (cm)

BD = bulk density (g cm^{-3})

A = 729 -169 * soil pH + 51 * citric acid soluble P in RP

B = 484 – 142 * soil pH + 67 * citric acid soluble P in RP

C = -0.3059 + 0.0819 * soil pH + 0.0046 * total P in RP + 0.0023 * RP particle size

2.4.3. Phosphate Rock Decision Support System (PRDSS)

A Decision Support System for Phosphate Rock (PRDSS) has been developed by the International Fertilizer Development Center (IFDC) in collaboration with FAO and the International Atomic Energy Agency (IAEA). PRDSS is an expert system for estimating the relative agronomic effectiveness (RAE) of freshly applied RP respect to water-soluble P fertilizers. It is conceptualized for use in tropical and subtropical countries for a range of food crops. PRDSS is conceptualized for predicting the agronomic effectiveness of RP with respect to water-soluble P fertilizers (Smallberger et al., 2006). The model uses the following parameters: RP solubility, soil pH, crop species, exchangeable Ca, organic matter, soil texture and rainfall. One of the major limitations of IFDC PRDSS is its inability to diagnose P deficiency and to predict amounts of RP for specific field conditions.

2.5. Missing information

Despite the extensive studies done on the factors affecting RP performance, scientists have not quantified the amounts of RP needed to meet plant P requirements on a site-specific basis. The few studies performed dealt only with the development of model that predicts the extent of RP dissolution (Mackay et al., 1986). PDSS and PRDSS were developed for making recommendation only for soluble P fertilizers (Yost et al., 1992) and for predicting RP agronomic effectiveness, respectively. Unfortunately, these studies either did not include work to evaluate the plant P availability after RP dissolution or did not address the option to quantify how much RP would be need as a possible source of P for crop. Moreover, research has not considered RP dissolution in West African. Nor has it addressed the development of an RP algorithm adapted to millet production systems on upland West African soils.

Chapter 3. An algorithm for estimating amounts of rock phosphate needed to meet crop phosphorus requirements in West African soils

3.1. Abstract

The direct application of rock phosphate (RP) can be a good alternative to water-soluble P fertilizers. However, despite the extensive work done on RPs, there are no models to predict amounts of RP required. An incubation study was conducted: (i) to investigate the influence of soil properties on the dissolution of Tilemsi rock phosphate (Tilemsi RP) and extractability of P after dissolution and (ii) to develop an algorithm for estimating amounts of rock P needed to meet crop P requirements in West African soils. Exchangeable acidity, Ca saturation, and effective cation exchange capacity appeared to be the factors controlling the Tilemsi RP dissolution. The amount of rock phosphate dissolved in contrasting Malian soils was predicted by a modified MacKay's equation of the form: $Y = A - B*e^{-c*time}$, where Y = amount of RP dissolved, measured by NaOH extraction;

$A = 78.1627 + 30.62149 * \text{acidity} – 0.63335 * \text{CaSat}$ (RMS=0.16132)

$B = - 16.58786 – 21.74709 * \text{acidity} + 4.07675 * \text{ECEC}$ (RMS = 0.01463)

c = curvature coefficient. The amount of RP to reach the optimal yield for a given crop can be estimated using the relationship ΔNaOH-P/ΔBray 1-P and the above modified MacKay's equation.

3.2. Introduction

For food production, P is one of the most deficient and plant growth limiting nutrients in West African soils (Enwezor and Moore, 1966; Jones and Wild, 1975; Poulain, 1976; Pieri, 1986; Manu et al., 1991). Rock phosphate (RP) materials around the world have been evaluated for their suitability as low-cost, direct application P fertilizers. However, many RP's have not proven to be sufficiently soluble for direct application in intensive agriculture production (Khasawneh and Doll, 1978). For RP to be a viable alternative fertilizer, it should first dissolve in soil. The second requirement is that the P released remains available to plants. As well documented in the literature, estimates of the amounts of RP dissolved is not usually sufficient to estimate plant availability.

Dissolution processes are affected by soil factors. Regarding soil properties that might be expected to affect the extent of RP dissolution in soils, Khasawneh and Doll (1978) listed the following:

(i) Concentration of H^+ in the soil and the H^+ buffer capacity in soil: the dissolution of RP in soils is driven by the supply of H^+, which is controlled by the initial soil pH and the pH buffer capacity of the soil. The presence of H^+ ions in the soil results in the rapid conversion of the PO_4^{3-} to $H_2PO_4^-$ and HPO_4^{2-}.

(ii) Concentration of P in soil solution and P buffering capacity of the soil: RP dissolution increases as the P retention capacity of soil increases; (Khasawneh and Doll, 1978)

(iii) Concentration of Ca^{2+} in soil solution: RP dissolution increases with lower exchangeable Ca in soil.

(iv) Organic matter content: organic matter is related to the bonding of Ca and provides additional exchange sites for Ca resulting in reduced Ca concentration in soil solution; thus allowing more RP dissolution to occur.

(v) Soil texture: coarse-textured soils and sands are, in general, do not sharply reduce soil solution levels of P and Ca.

Rock phosphate dissolution depends on chemical and physical properties of the RP and the soil properties (Khasawneh and Doll, 1978; Hammond et al., 1986a). Several scientists (Khasawneh and Doll, 1978; Hughes and Gilkes, 1986; Mokwunye, 1994) pointed out that RP dissolution is highly related to RP reactivity. The types of crop (Pushparajah et al., 1990; Mnkeni et al., 2000), management factors, and soil moisture (Wright et al., 1992) also affect RP dissolution.

Syers and Mackay (1986) pointed out that the soil properties that increase the extent of RP dissolution in soil may not necessarily result in an increase in the amount of plant available P. Factors such as clay content that increase RP dissolution sometimes also increase P sorption (Novais and Smyth, 1999), resulting in reduced P availability (Yost, personal communication). In developing the algorithm, it is therefore important to separate the two processes of dissolution and sorption in order to quantify processes affecting the reactions in a specific situation.

Numerous decision aids have been developed or proposed to assist nutrient P management. The Phosphorus Decision Support System (PDSS) is a decision support tool that enables users to diagnose nutrient deficiencies and prescribe alternative correction actions. PDSS uses buffer coefficients, critical levels of the extractable P and a specific field's extractable P to make P fertilizer recommendations (Yost et al., 1992). However, PDSS makes recommendation only for soluble P fertilizers. A rock phosphate algorithm for predicting RP amount is needed to meet P requirements of rice for acid sulfate soil was developed by Yampracha et al. (2006). That algorithm, however, is not suited for millet production systems on upland West African soils.

3.3. Hypothesis and Objectives

3.3.1. Hypothesis

The use of RP for direct application in agriculture depends on its ability to supply P to crops. The phosphorus availability of the P released from RP depends on the RP dissolution and the subsequent sorption processes that take place. We, thus hypothesize that predicting amounts of RP needed for any crop production should consider both dissolution and sorption processes. Identifying and incorporating soil properties affecting dissolution and sorption processes into an equation can be the basis for our modeling approach.

3.3.2. Objectives

The objectives of the study were to

(i) Determine which properties of West African soils most affect RP dissolution,

(ii) Establish a relationship between the dissolution of RP and the sorption processes, and

(iii) Develop an algorithm (method) that would produce quantitative estimates of the amount of rock phosphate necessary to provide nutrient P for crops in West Africa.

3.4. Materials and Methods

3.4.1. Soils

Incubation studies were carried out with five contrasting soils from Mali. Cinzana plateau, Cinzana slope and Cinzana valley soils were collected from a toposequence at the Cinzana research station. The sandy soil on the plateau and the slope of the toposequence are representative of millet (*Pennisetum spp*) growing soils. On the clayey soil of the valley, sorghum (*Sorghum bicolor,* L) is cultivated. Niessumana and Longorola soils were collected in Southern Mali. These 2 soils can be flooded in rainy season and are appropriate for paddy rice cultivation. The soils were collected at depth of 0 - 15 cm, air-dried and passed through a 2-mm sieve. Selected properties of the soils used in the investigation are shown in Table 3.1. The following chemical parameters were determined: pH in water at a soil:solution ratio 1:1, exchangeable cations by extraction with 1 *M* NH_4OAc (pH 7) (Thomas, 1982), extractable acidity (Thomas, 1982), ECEC (effective cation exchange capacity) was estimated by summing the exchangeable cations and exchangeable acidity, clay content was determined by the pipette method (Gee and Bauder, 1986), and index of plant available P was determined with Bray 1-solution (0.025 *M* HCl + 0.03 *M* NH_4F) (Bray and Kurtz, 1945). Iron (Fe) and aluminium (Al) were extracted using ammonium oxalate solution at pH 3 in the dark (Jackson et al., 1986).

3.4.2. Rock phosphate

The Tilemsi RP material used in this study was the same as used in the study done by Yampracha et al. (2006). Tilemsi RP (Tilemsi RP) was ground to pass a 250 μm sieve. Total P and Ca, and water-soluble P were measured by the 'Official methods of analysis of Association of Official Analytical Chemists' (AOAC, 1984). The second neutral ammonium citrate extraction has been recommended to assess RP solubility by the International Fertilizer Development Center (IFDC) (Chien, personal communication, 2005). The calcium carbonate equivalent (CCE) or the liming potential of the rock phosphate was determined by boiling 1 g of RP material in 50 ml of 0.5 *M* HCl for 5 min and then titrating it with 0.25 *M* NaOH to pH 5 as proposed by Sikora (2002). The characteristics of the RP material are given in Table 3.2.

Table 3.1.Soil properties of samples selected for rock phosphate dissolution study.

Soil	pH(H_2O) 1:1	Clay (%)	ECEC[*] (cmol$_c$ kg^{-1})	Exch. Ca[§]	Acidity[**]	CaSat[†] (%)	Fe_{ox}[€]	Al_{ox}[€]	5[¥]	10[¥]
				(cmol$_c$ kg^{-1})			(mg kg^{-1})		g PNT ha^{-1}	
Cinzana plateau	5.00	5.0	1.14	0.54	0.33	47	268.67	313.67	50	100
Cinzana valley	6.47	36.0	11.53	9.11	0.00	79	1369	1483	3568	7136
Cinzana slope	5.60	4.0	1.31	1.02	0.00	78	196.67	209.00	134	267
Niessumana	4.30	36.5	6.35	1.37	4.20	22	4892	1979	39	78
Longorola	4.90	36.5	7.34	2.08	3.83	28	7038	2943	72	143

[*] Effective cation exchange capacity

[§] Exchangeable ca

[**] KCl-extractable acidity

[†] Calcium saturation

[€] Ammonium oxalate extractable iron and aluminum.

[¥] Estimates of amounts of RP (Tilemsi) to increase Bray 1 by 5 and 10 mg P/kg, respectively.

Table 3.2. Selected chemical characteristics of Tilemsi RP.

Location	NAC2* (g P kg^{-1} of rock)	Total ($g\ kg^{-1}$)		Calcium carbonate equivalent (%)
		P	Ca	
Tilemsi, Mali	18.7	121	305	41.7

*Neutral ammonium citrate, second extraction (1 g soil: 100 ml solution)
Source: Yampracha et al., 2006.

3.4.3. Incubation

The Tilemsi RP was added to the soils at a rate of 500 mg P kg^{-1} soil, thoroughly mixed, moistened to field capacity (Uehara, personal communication) with deionized water and incubated at 22-24 °C. A control without RP was included for each soil and was similarly treated. Each treatment was replicated 3 times. Soils were aerated and the moisture content adjusted to field capacity every two days during the incubation. Treated and untreated (control) soils were sampled after 0, 3, 7, 15, 30 and 60 days of incubation to estimate the rate of dissolution of Tilemsi RP. The rock phosphate dissolution and Bray 1 extractable P were determined at each sampling time. Tilemsi RP dissolution in the various soil samples was estimated by the 0.5 *M* NaOH method (Mackay et al., 1986). Soil samples were extracted for 16 hours with 0.5 *M* NaOH at a soil to solution ratio of 1:100 following a prewash with 10 ml 1 *M* NaCl for 1 hour. Phosphorus in the extracts was determined colorimetrically by the method proposed by Murphy and Riley (1962) and absorbance was measured at 880 nm. The increase in NaOH-extractable P (ΔNaOH-P) between RP-treated and untreated samples was taken to represent the amount of P dissolved from the RP. The difference in Bray 1-extractable P (ΔBray 1-P) between treated and untreated samples was used as an index of P availability for plants after RP dissolution and subsequent reaction of the released P with soil.

3.4.4. Statistical analysis

3.4.4.1. Dissolution process

A model (Eq. 3.1) was fitted to the Tilemsi RP dissolution curves in the selected soils using nonlinear regression (proc NLIN) (SAS, 1985). The dissolution curves obtained for the 5 soils under study could be described by an equation of the form:

$$Y = A - (B^{*}e^{-c^{*}X}) \qquad \text{[Eq. 3.1]}$$

Where Y = amount of Tilemsi RP dissolved, measured by NaOH extraction at time X;

A = asymptote;

B = difference between the asymptote and the intercept and

c = curvature coefficient.

The parameters of the equation were then regressed on soil properties listed in Table 3.1 to determine which soil properties were the best predictors using stepwise regression analysis. The residual mean squared (RMS) was used to evaluate how well the equation predicted the dissolution parameters. Soil properties were then substituted into the equation to predict the dissolution. The predicted dissolution in each soil was then plotted over time and compared to the observed values.

3.4.4.2. Sorption process

We proposed measuring Bray 1 to establish the relationship between extractable P pools of these methods with the pools of NaOH. This relationship may not be as highly affected by management factors, as is the rock phosphate dissolution. It was also hypothesized that, after an initial period, the ratios would assume some nearly constant value. Perhaps this relationship will be sufficiently constant that it need be estimated only once for a particular soil or perhaps it can be predicted from other soil properties such as those used to predict buffer coefficient such as percent clay.

3.4.5. Developing an algorithm for predicting RP amounts needed to meet crop P requirements

The equation implemented in PDSS was used as the basis for predicting the amount of RP to be applied to meet crop requirements. The formula used in PDSS is the following:

$$P = (P_c - P_o) / a_2 * D/10 * BD \qquad \text{[Eq. 3.2]}$$

Where P = P recommendation, kg ha^{-1}

P_c = P critical level of the selected P testing method, mg kg^{-1}

P_o = measured soil P (by the P testing method specified for P_c), mg kg^{-1}

a_2 = P buffer coefficient

D/10 = incorporation depth D (cm) normalized to 10 cm

BD = bulk density

3.5. Results and Discussion

3.5.1. Rock phosphate dissolution – the dissolution process

The influence of soil properties on the rate and extent of dissolution of Tilemsi RP can be seen clearly in Figure 3.1. The Tilemsi RP dissolved to a differing extent in different soils. The rate of dissolution of Tilemsi RP ranged from 33 to 382 g kg^{-1} the total P added to the soils. The shapes of the dissolution curves were similar. The rate of dissolution rapidly slowed after about 7 – 15 days incubation. In each case, the reaction reached equilibrium or slowed down after 30 days. Other authors (Novais and Smyth, 1999; Kanabo and Gilkes, 1987; Robinson and Syers, 1990; Smyth and Sanchez, 1982) obtained similar shaped dissolution curves. The maximum RP dissolution increased with the decrease in soil Ca saturation as shown in other studies (Mackay et al., 1986; Robinson and Syers, 1990).

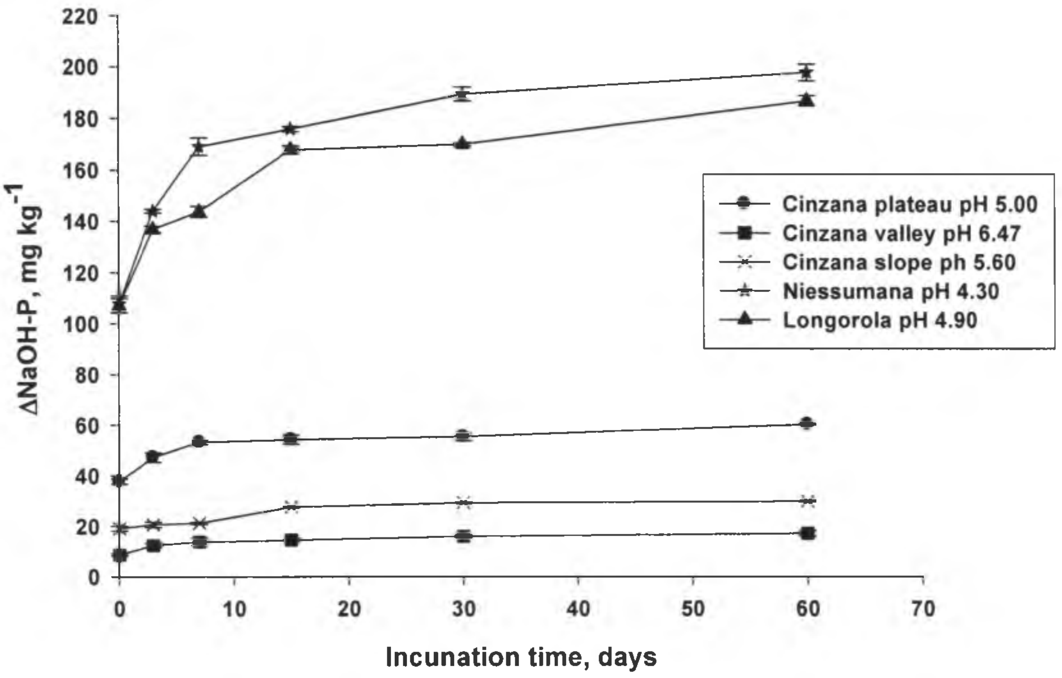

Figure 3.1. Dissolution of Tilemsi RP as measured by the difference in NaOH-P between RP-treated and untreated soils over time.

The parameters of the fitted curves describing the dissolution of Tilemsi RP in 5 Malian soils are listed in Table 3.3. The larger A is, the larger the amount of dissolved P from the RP, whereas the larger B is the greater the difference between the amounts of RP dissolved at days 0 and 60 (beginning and end of the incubation, respectively). c is a constant representing the curvature coefficient.

Table 3.3. Values for asymptote (A), difference between asymptote and intercept (B) and curvature coefficient (c) and an estimate (R^2) of the fit of the exponential curve.

Soil	A	B	c	R^2
Cinzana plateau	57.2004	19.3821	0.2099	0.97
Cinzana valley	16.406	7.3948	0.1468	0.96
Cinzana slope	30.5865	12.1643	0.0696	0.94
Niessumana	191.1	82.5316	0.1707	0.95
Longorola	180.7	70.3218	0.1058	0.95

The stepwise multiple linear regression gave the following equations to predict A and B.

A = 78.1627 + 30.62149 acidity – 0.63335 CaSat (RMS=0.16132) [Eq.3.3]

B = - 16.58786 – 21.74709 acidity + 4.07675 ECEC (RMS = 0.01463) [Eq.3.4]

c = constant

Where CaSat = Ca saturation, %. CaSat can be calculated from the data in Table 1. Acidity and ECEC are in $\mathrm{cmol_c\ kg^{-1}}$ as in Table 3.1.

These equations relate the RP dissolution to the percent Ca saturation, effective cation exchangeable capacity and soil acidity. Khasawneh (1978), MacKay et al. (1986), and Robinson and Syers (1990) showed that Ca saturation had a large influence on RP dissolution.

It was found that by setting the c value constant at the average for the 5 soils (0.14056), the shape and fit of the modified Mackay curves describing the dissolution of Tilemsi RP in soil, and calculated A and B values were only affected to a minor degree (Table 3.4 and Figure 3.2).

Table 3.4. Values for asymptote (A), difference between asymptote and intercept (B) of the fit of the exponential curve (c = 0.1406).

Soil	A	B
Cinzana plateau	58.2455	19.0365
Cinzana valley	16.4561	7.3902
Cinzana slope	28.7551	11.3242
Niessumana	193.4	82.0735
Longorola	180.7	69.9241

By using equations [3.1], [3.3] and [3.4] for acid soils (pH 5.6 or below), the extent of dissolution of Tilemsi RP can be determined.

3.5.2. Effects of Tilemsi RP on soil Bray 1-P levels.

Levels of Bray1-P varied with soils and time of incubation (Figure. 3.3). The Δ Bray-P in soil where Tilemsi RP was added increased with incubation time up to the 7 – 15 days and leveled off sometime between 14 and 30 days of incubation except for the Cinzana valley soil. The change in Bray 1-P (Δ Bray-P) ranged from 0.5 to 65.6 mg kg^{-1} at the end of the incubation period. The Δ Bray-P did not change for Cinzana valley soil because all dissolved P has been sorbed by that soil. Based on the Bray 1-P critical level of millet (*Pennisetum spp.*) of 11 mg P kg^{-1} (Yost et al., 1992), the ΔBray 1-P observed in all soils except Cinzana valley could be adequate for producing maximum yield.

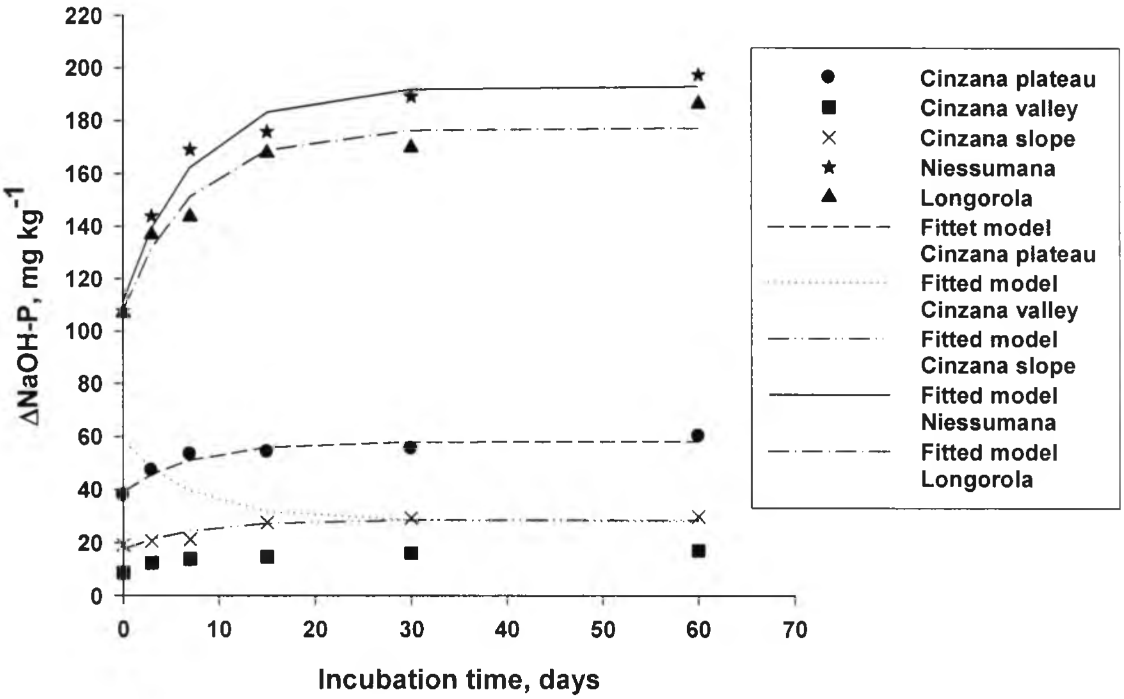

Figure 3.2. Comparing the predicted (lines) and measured (symbols) dissolution of Tilemsi RP in soils of varying acidity, Ca saturation, and effective cation exchange capacity.

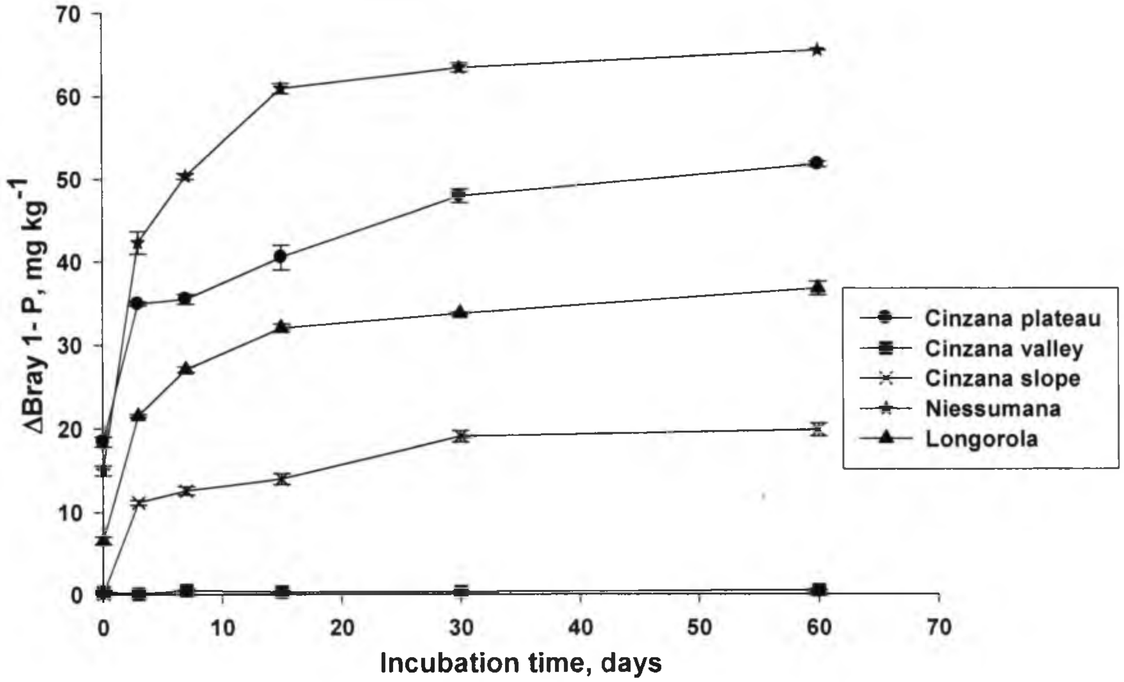

Figure 3.3. Changes in Bray 1-extractable P in soil during 60 days following Tilemsi RP addition at 500 mg P kg $^{-1}$.

3.5.3. Relationship between ΔNaOH-P and Bray 1-P – the sorption process

The evolution of the ΔNaOH-P/ΔBray-P ratio over time is presented in Figure 3.4. This relationship after an initial period became nearly constant in the incubation study after about 7 -15 days. We noted that for these soils, the ratios of ΔNaOH to ΔBray 1 were quite different among soils, suggesting that the buffering of these extractable P measures may differ substantially. The ΔNaOH-P/Bray 1-P ratios were consistently lower for sandy soils than clayey soils over time. This is probably due to the higher P sorption capacity of clay soils, reflected in their higher ammonium oxalate extractable-Fe and Al.

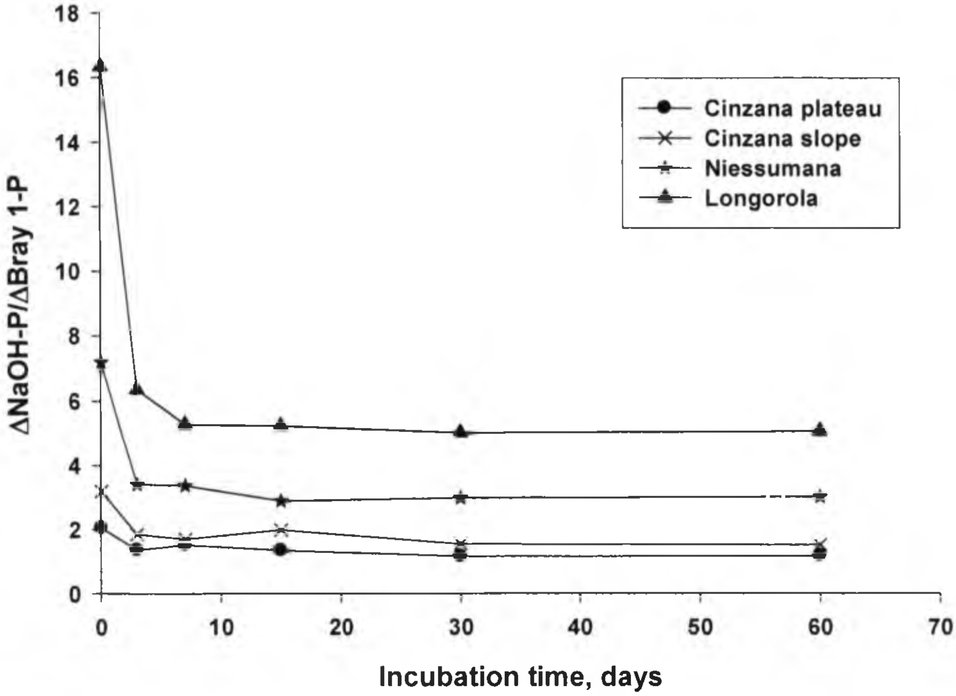

Figure 3.4. The ΔNaOH-P/ΔBray 1-P ratios of soil treated with Tilemsi RP during 60 days of incubation period.

Perhaps this relationship will be sufficiently constant that it need be estimated only once for a particular soil or perhaps it can be predicted from other soil properties such as those used to predict buffer coefficient such as percent clay. The relationship between ΔNaOH-P/ ΔBray 1-P ratio and clay content in soils could be described by the following equation: ΔNaOH-P /ΔBray 1-P =0.960 + 0.084*Clay (R^2 = 0.77). This relationship needs to be improved by including soils with the clay content ranging between 5 and 36.5%.

3.5.4. An algorithm to predict the amounts of rock phosphate necessary to meet plant requirements.

The method we propose begins with an analysis by the PDSS (Phosphorus Decision Support System), in which the user selects the crop and indicates the soil test and soil test values of the field or land to be managed (Figure 1.1). If the soil test value is below the critical level then P is recommended. The amounts of P must now be determined. As in the standard PDSS format the difference between the critical level and the measured P is the amount of P that must be added in the form of either soluble or rock phosphate fertilizers. This value will be called the DeltaP (P_c – P_o). We now need to determine the amounts of rock phosphate that will provide this amount of soluble P. Our approach now continues by converting the estimate of the extractable P needed to reach the P critical level into the amount of 0.5 *M* NaOH-P that needs to be increased. The ΔNaOH-P / ΔBray 1-P ratio can be used to convert the DeltaP into the amount of 0.5 *M* NaOH-P that needs to be increased. This value is now a multiple variable function that can be predicted from soil and site properties using equations (Eq. 3.1, 3.3, 3.4 and Table 3.1). As the factors in the equation indicated, this equation will require the input of Ca saturation, effective cation exchange capacity (ECEC), and soil acidity. Calcium saturation can be approximated by measures of exchangeable Ca and ECEC. Thus the proposed algorithm for predicting amounts of RP needed for crop requirements is as follows:

$$RPadded = \frac{(P_C - P_{Bray\ 1})}{a_2} \times \frac{\Delta NaOH\_P}{\Delta Bray\ 1\_P} \times \frac{500}{\Delta NaOH\_P} \times \frac{depth}{10} \times B.D. \qquad \text{Eq. 3.5}$$

Where RP added = Amount of RP to be added (kg ha^{-1})

P_c = Critical Bray 1-P level (mg P kg^{-1})

P_{Bray1} = P in soils extracted by Bray 1 (mg P kg^{-1})

a_2 = Buffer coefficient

ΔNaOH-P = $A\text{-}Be^{-cx}$, amount of RP dissolved in soil at time X (mg P kg^{-1}), with X in days

depth = Soil depth (cm)

B.D. = Bulk density (g cm^{-3})

500 = Coefficient for converting NaOH-P into RP. This coefficient is specific to the incubation conditions.

Thus we hypothesize that the amounts of rock phosphate can be predicted by relating soil test P levels to changes in NaOH extractable P. The first predictions of this are given in Table 3.1 on the far right columns of 5 and 10, indicating the predicted amounts of Tilemsi rock phosphate required to increase Bray 1 by 5 and 10 mg P kg^{-1}, respectively, after 30 days of incubation. Equation 3.5 can predict the amount of dissolved PR. This equation needs testing in field conditions.

The differences between Eq. 3.5 and 2.3 consist of:

1. The type of soil for which the equation was developed
2. The cropping system and
3. The parameters needed for estimating ΔNaOH-P (the amount of RP dissolved in soil at a given time).

3.6. Conclusions

In summary, results from this study demonstrated that RP dissolution varied from soil to soil but was fairly rapid over first the 7 -14 days of incubation and that a steady state was reached after approximately 30 days.

The extent of Tilemsi RP dissolution in 5 Malian soils at the end of the incubation period (after 60 days) ranged from 3.3 to 38% of the total P added.

Exchangeable acidity, calcium saturation and the effective cation exchange capacity were the most important factors influencing the Tilemsi RP dissolution. No single soil property was responsible for promoting RP dissolution for all soils investigated. Limited solubility of Tilemsi phosphate rock occurred in soil with combinations of low exchangeable acidity, high soil pH and high Ca saturation.

Soil acidity, ECEC and soil Ca saturation were the key factors in the RP dissolution algorithm. The sorption process was characterized by the ratio NaOH/Bray 1-P, which could be predicted from soil clay content.

An algorithm including soil properties affecting dissolution and sorption processes can be used to predict the amount of RP needed to supply nutrient P to crop. The proposed algorithm was not suitable for soils with pH greater than 6. More research is required, especially under field conditions to modify and validate the algorithm predicting RP dissolution in the presence of the plant and under leaching conditions.

Chapter 4. Assessing the accuracy of delta-NaOH-P as a measure of dissolved rock phosphate using the changes in exchangeable calcium

4.1. Abstract

Changes in NaOH-P have been often used as an estimate of RP dissolution. An incubation study was conducted to assess the accuracy of the 0.5 *M* NaOH method as a measure of the amount of P dissolved from RP using the changes in exchangeable Ca in comparison. Similar trends of the RP dissolution were observed for both methods. The calculated molar ratio of Ca/P for the hydroxyapatite was close to that of Tilemsi and Taiba RPs but was about 1.7 times lower than that of Gafsa RP probably due to the presence of $CaCO_3$ in the Gafsa RP. The percentage of RP that has been dissolved as measured by ΔNaOH-P was overestimated for Tilemsi RP (mean error (predicted – measured) = 2.8711 and mean square error = 3.1136) and underestimated for Gafsa RP (mean error = -2.1324 and mean square error = 2.7434) with respect to the ΔCa. The results of this incubation study indicated that both changes in ΔNaOH-P and ΔCa were due to the dissolution of rock phosphates. However, the presence of water-soluble P in the RP might affect the accuracy of 0.5 *M* NaOH method as a measure of the amount of P dissolved from RP. ΔNaOH-P appears to be useful as an estimate of the amount of P released from the RP material when RP is considered as a means to provide P to crop (P fertilizer).

4.2. Introduction

When RP is added to an acid soil, the apatite, the primary mineral of the RP decomposes and releases P, calcium (Ca) and other soluble compounds such as OH^-, F^-, Cl^-, CO_3^{2-}(Eq. 4.1) To simplify the dissolution reaction of RP in acid soil, let's represent RP by hydroxyapatite. When soil moisture is not limiting and soil conditions are favorable, the dissolution reaction is then

$$Ca_{10}(OH)_2\,(PO_4)_6 + 12H^+ \rightarrow 10Ca^{2+} + 6H_2PO_4^- + 2OH^- \qquad \text{[Eq. 4.1]}$$

The P released from RP dissolution, like the P from soluble P fertilizers, reacts with the soil constituents. In acid soils, the dissolved P reacts mainly with Al and Fe oxides and hydroxides.

The 0.5 *M* NaOH extractant has been used to estimate the amounts of rock phosphate (RP) dissolved in soils (MacKay et al., 1986; Syers et Mackay, 1986; Diarra et al., 2004; Yampracha et al., 2006; Yampracha et al., 2005). The 0.5 *M* NaOH solution is believed to extract P adsorbed to soil constituents after RP dissolution. The NaOH extractant is assumed to not dissolve the unreacted RP during the extraction period. Since NaOH extractant can extract soil organic P and the existing adsorbed P in soils not treated with RP, the differences in the NaOH-extractable P between the RP-treated and the RP-untreated soils were used as the estimate of dissolved P from the RP in the RP dissolution studies mentioned above.

According to equation [4.1], Ca is one of the products of RP dissolution which is released to the soil solution in amounts proportionate to the amount of P released (i.e. for each 5 moles of Ca^{2+} released 3 moles of P are released). While the dissolved P from RP reacts with soil Al and Fe compounds, the dissolved Ca remains in the soil as exchangeable Ca (Khasawneh and Doll, 1978). The differences in the exchangeable Ca between the RP-treated and the RP-untreated soils was proposed as an estimate of dissolved P from the RP

4.3. Hypothesis and Objectives

The hypothesis of this study is that because both Ca and P are released during RP dissolution, the changes in exchangeable Ca (the difference between soils treated with RP and the check) will be proportionate to the changes in NaOH-extractable P. The measure of the changes in exchangeable soil Ca may then serve as an estimate of RP dissolution as well as the changes in NaOH-P. The hypothesis then was therefore the percent of RP dissolved estimated by both methods must then be proportional.

The objective of this study was to assess the accuracy of the ΔNaOH-P method to estimate the amount of P dissolved from the RP using the changes in exchangeable Ca as described above.

4.4. Materials and Methods

4.4.1. Soil

The topsoil (0 - 15 cm depth) of an acid soil from Konobougou, Mali was selected as being representative of a large proportion of the soil in the food-producing region of Mali and West Africa. The soil was air-dried and passed through a 2-mm sieve. Selected properties of the soil are presented in Table 4.1. Soil pH was determined in water at the ratio 1:1. The P was extracted using the Bray 1 method (Bray and Kurtz, 1945) and subsequently determined by the Murphy and Riley method (1962). Acidity extractable by 1 *M* KCl was determined using the procedure proposed by Thomas (1982). Exchangeable cations (Ca^{2+}, Mg^{2+}, K^+, Na^+) were determined using a 1 *M* ammonium acetate (pH 7.0) extraction (Thomas, 1982; Knudsen et al., 1982; Lanyon et al., 1982). The effective CEC was calculated as the sum of exchangeable cations and extractable acidity.

Table 4.1. Soil properties of the selected soil.

pH H_2O (1:1)	Bray 1-P (mg kg^{-1})	KCl-extractable Acidity (cmol₊ kg^{-1})	Exchangeable (cmol₊ kg^{-1})				ECEC* (cmol₊ kg^{-1})
			Ca^{2+}	Mg^{2+}	K^+	Na^+	
4.87	2.68	0.50	0.46	0.21	0.14	0.02	1.33

*sum of Ca^{2+}, Mg^{2+}, K^+, Na^+ and KCl-extractable acidity

4.4.2. Rock phosphates

Taiba (Senegal), Tilemsi (Mali) and Gafsa (Tunisia) rock phosphates with low, medium and high solubility, respectively (Yost et al., 2003) were selected. The rock phosphates were passed through a 100-mesh sieve. The total P and water-soluble P analyses were performed using the procedures proposed by Houba et al. (1995). Total and water-soluble P were then determined by colorimetry (Murphy and Riley, 1962). The calcium carbonate equivalent (CCE) was determined by digesting 1 g of RP material in 50 ml of 0.5 *M* HCl for 5 min and then by titrating it with 0.25 *M* NaOH to pH 5 as proposed by Sikora, (2002). The iron (Fe) content was determined by x-ray fluorescence. The particle size distribution was done using 2-mm and 0.150-mm sieves. The RP characteristics are presented in Table 4.2.

Table 4.2. Rock phosphates and their characteristics

Properties	Rock phosphate (origin)		
	Gafsa (Tunisia)	Tilemsi (Mali)	Taïba (Senegal)
P (g kg^{-1})	135.2	112.6	170.3
Ca* (g kg^{-1})	334	305	350
Water-soluble P (mg kg^{-1})	1.50	4.11	2.10
CCE** (%)	51.67	35.50	45.08
Fe (g kg^{-1})	2	20	5

*Yampracha et al., 2006

**Calcium carbonate equivalent

4.4.3. Incubation

The three ground RP materials were added to the soil at the rates of 0 and 500 mg P kg^{-1} in 3 replications. The mixtures were moistened to field capacity and thoroughly mixed. The moisture content was maintained during the incubation. Soil samples were removed from the incubation containers at 0, 1, 3, 7, 15, 30 and 60 days of incubation. The RP dissolution was estimated by NaOH extraction as described by MacKay et al. (1986). This procedure consisted of extracting the P from the soil using 0.5 *M* NaOH at a soil:solution ratio of 1:100 during 16 hours. The extraction was preceded by prewashing with 10 ml of 1 *M* NaCl. The difference in NaOH-extractable P between the RP-treated and the untreated soil was considered as an estimate of the P dissolved from the RP. The exchangeable calcium (Ca) extracted with an unbuffered 1 *M* KCl was also determined at each sampling time. The change in exchangeable Ca (difference between the RP-treated and the untreated soil) was used as a second estimate of the RP dissolution.

4.4.4. Statistical analysis

Analysis of variance of ΔNaOH-P and Δexchangeable Ca was performed using SAS (SAS, 1985). A molar relationship was established between ΔNaOH-P and Δexchangeable Ca. The percent of RP dissolved was then calculated based on the total P and Ca contents of RPs and the amounts extracted from the soils after incubation. The Mean error (ME) and the Mean squared error (MSE) for each RP were used for a quantitative comparison (accuracy and precision, respectively) of ΔNaOH-P and ΔCa. The equations for calculating the ME and MSE were the following:

$$ME = \frac{\sum (X_{pred} - X_{obs})}{n} \qquad \text{[Eq. 4.2]}$$

$$MSE = \frac{\sum (X_{pred} - X_{obs})^2}{n} \qquad \text{[Eq. 4.3]}$$

Where X_{pred} = %RP dissolved estimated by NaOH-P

X_{obs} = %RP dissolved estimated by Ca

n = number of observations

4.5. Results and Discussion

The amount of dissolve rock P as estimated by the ΔNaOH-P and Δexchangeable Ca initially increased and slowed down or reached an equilibrium at about 15 to 30 days of incubation (Figure 4.1). The three selected RP materials dissolved differently in the Konobougou soil. For both methods, the sequence of the dissolution was the following: Gafsa>Taiba>Tilemsi. This sequence is contrary of the expectation (Gafsa>Tilemsi>Taiba) based on the solubility of the RPs in neutral ammonium citrate which are respectively high, medium and low (van Kauwenbergh, 1997). The solubility of the RP materials used in this study could have probably helped in explaining the low performance of Tilemsi RP compared to the others; however, due to technical reasons we were not able to determine those solubility data.

When the molar relationships between ΔNaOH-P and Δexchangeable Ca from the three RPs are plotted (Figures 4.2,4.3 and 4.4), it can be deduced that for each mole of P released by dissolution about 2.85, 1.74 and 1.49 moles of Ca were released for Gafsa, Tilemsi and Taiba RPs, respectively. Assuming that RP can be represented by Equation 4.1, for every 10 moles of Ca 6 moles of P are released; the expected molar ratio is about 1.7.

The molar ratio of Tilemsi and Taiba RPs are close to the estimated one. The difference, however, between the molar ratio of Gafsa RP and the one that was estimated might be due the presence of some carbonate calcium in the materials. The presence of the calcium carbonate in Gafsa RP was supported by effervescence observed when the RP material was treated with a solution of HCl.

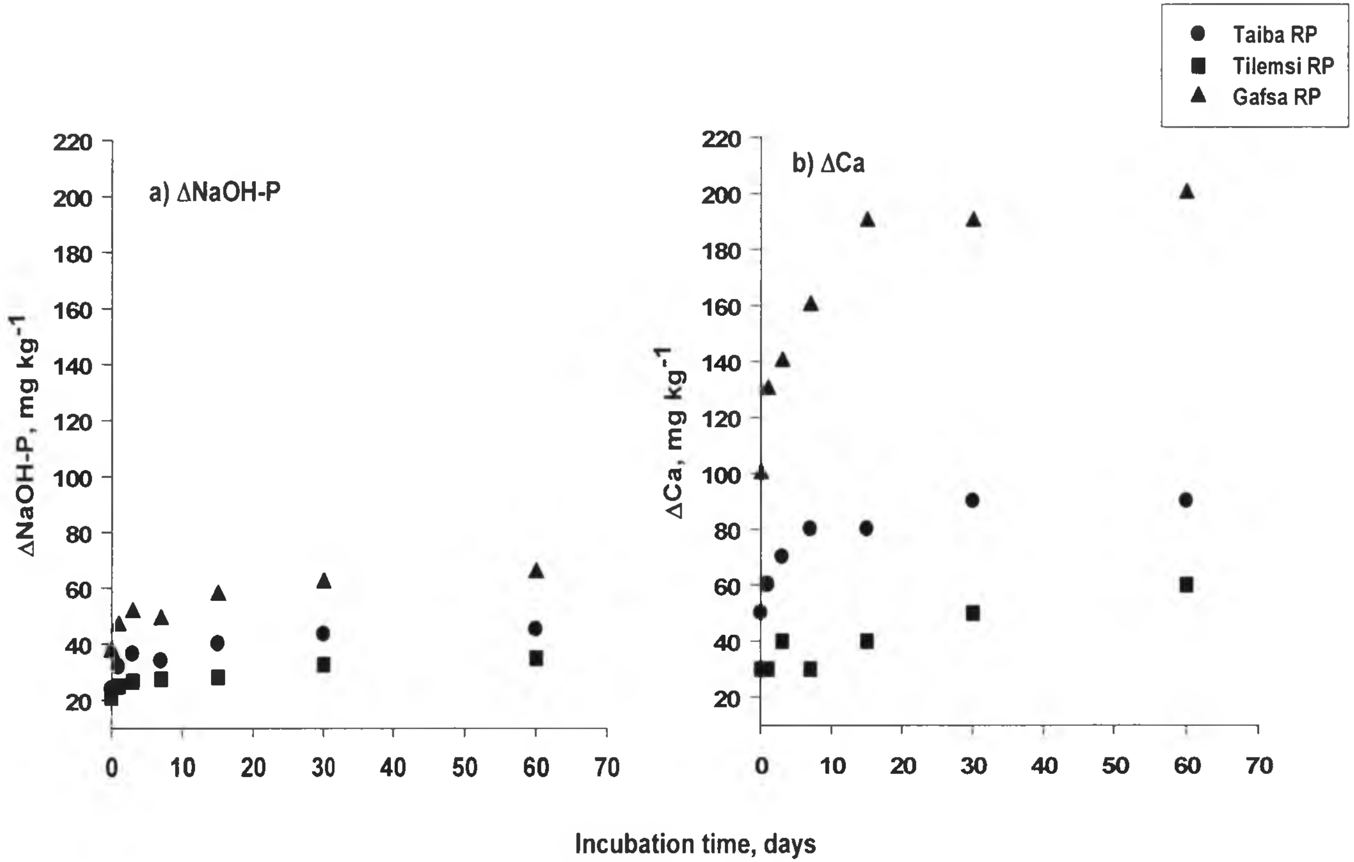

Figure 4.1. RP Dissolution as measured with a) 0.5 *M* NaOH and b) the KCl-extractable Ca.

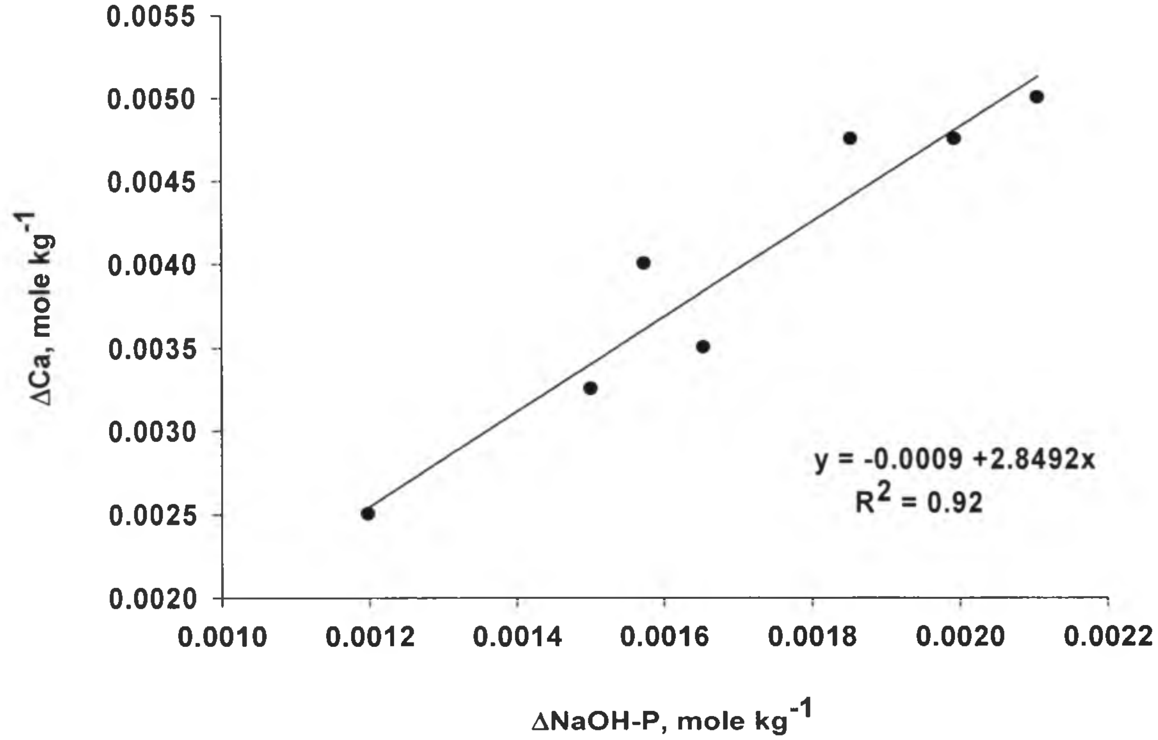

Figure 4.2. Gafsa RP molar relationship between ΔNaOH-P and ΔCa.

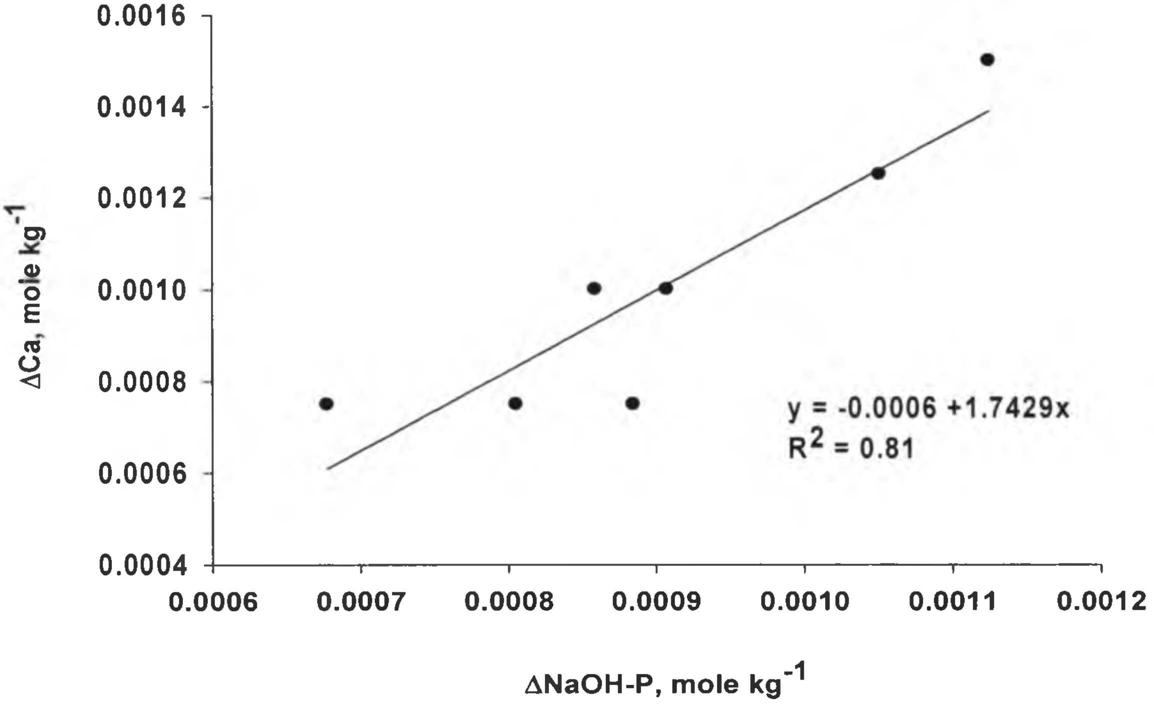

Figure 4.3. Tilemsi RP molar relationship between ΔNaOH-P and ΔCa.

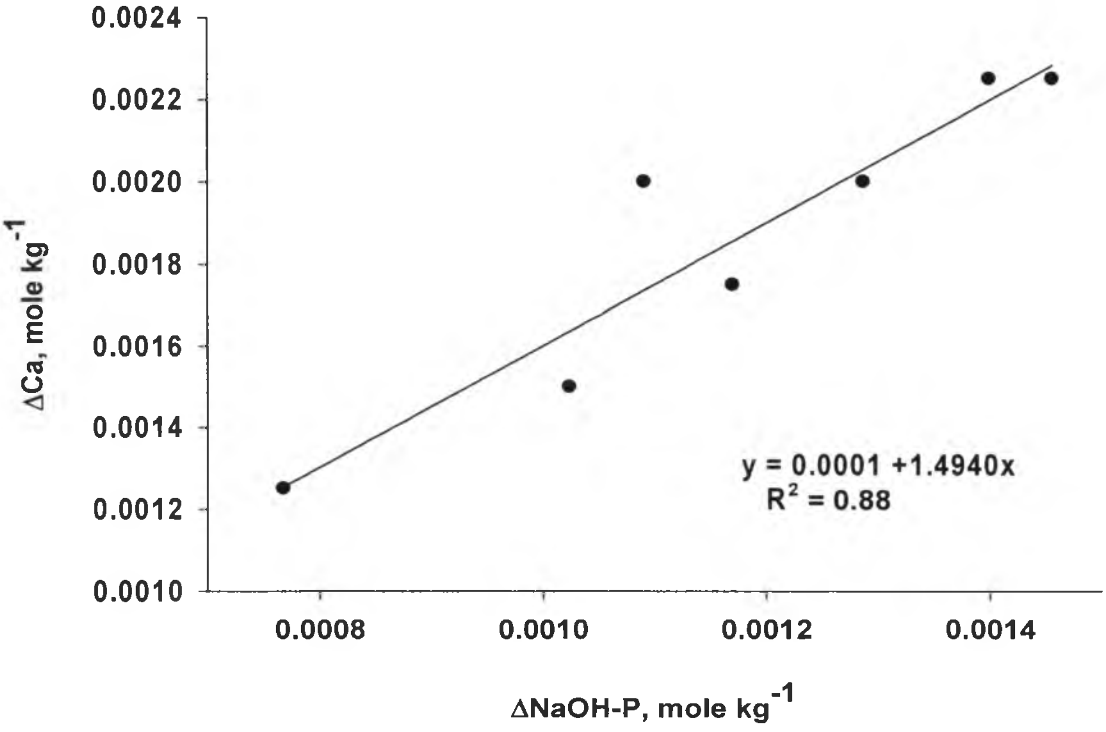

Figure 4.4. Taiba RP molar relationship between ΔNaOH-P and ΔCa.

Figure 4.5 shows the comparison of the percent RP dissolved as estimated by ΔNaOH-P and ΔCa. The percent of RP dissolved from Taiba RP as estimated by ΔNaOH-P are similar to those estimated by ΔCa (ME = 0.0126 and MSE = 0.4595). However, the percents of RP dissolved from Tilemsi and Gasfa RPs lie, respectively, above and below the 1:1 line. These results indicate that the percent of RP dissolved from Tilemsi RP are overestimated by the ΔNaOH-P method (ME = 2.8711 and MSE = 3.1136) and those from the Gafsa RP are underestimated by the ΔNaOH-P method (ME = -2.1324 and MSE = 2.7434). These overestimations are probably due to the presence of some water-soluble P in Tilemsi RP (Table 4.2) and the extraction of Ca from the $CaCO_3$ in the Gafsa RP.

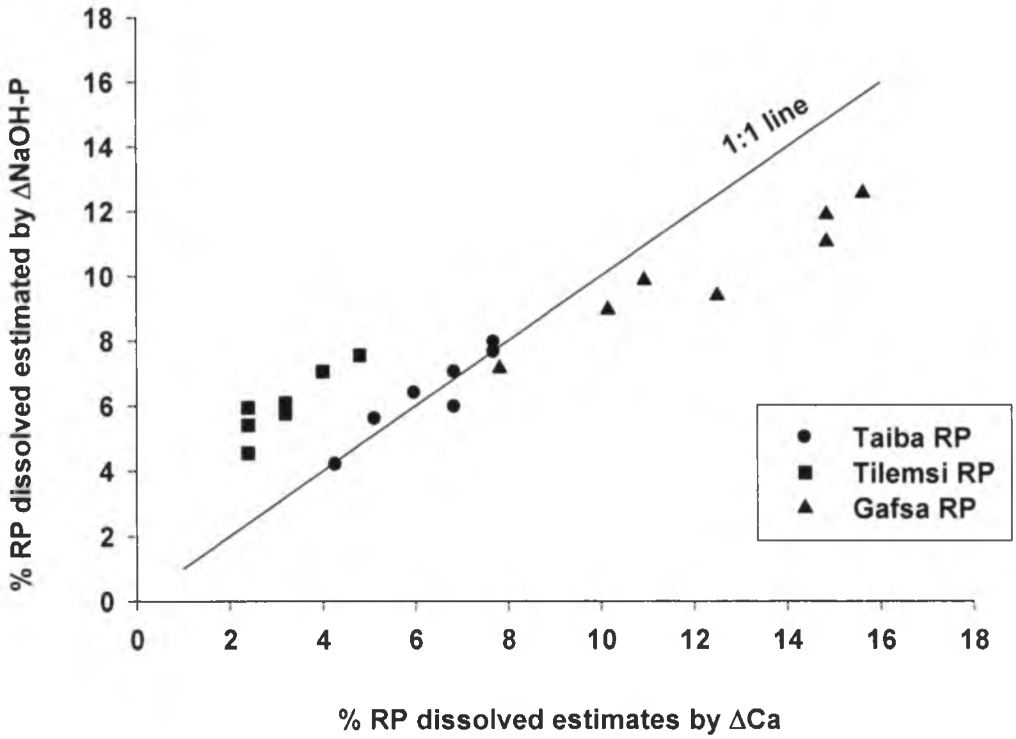

Figure 4.5. Comparison of the percentage of RP dissolved as estimated by ΔNaOH-P and ΔCa.

4.6. Conclusions

Because of the similar trends of ΔNaOH-P and ΔCa over time, the changes were caused mainly by the solubility of RP as amendments. The percent RP dissolved as estimated by both differences in NaOH-P and exchangeable Ca between RP-treated and untreated soil are affected by the presence of water-soluble P and $CaCO_3$; therefore affecting the accuracy of ΔNaOH-P and Δ exchangeable Ca as methods for estimating the RP dissolution. Changes in NaOH-extractable P appear to be useful as estimates of the amount of RP dissolution especially for RP materials containing $CaCO_3$ or under conditions where Ca losses cannot be accurately estimated. Where the RP contains water-soluble P, ΔNaOH-P did not measure dissolution from RP. However, if we consider the RP as a fertilizer, ΔNaOH-P may be used as an estimate of the total amount of P released from RP.

Chapter 5. Multi-location field-testing of the rock phosphate algorithm predictions

5.1. Abstract

The direct application of rock phosphate (RP) can be a good alternative to water-soluble P fertilizers. The complexity of the factors and their interactions led to the development of an algorithm to predict the amounts of RP needed to meet crop P requirements on a site specific basis. Two experiments were conducted at Konobougou (Konbougou 1 and 2), Mali and one experiment was conducted at Keur Madieng, Senegal to field test the predictions made by the algorithm. Treble super phosphate (TSP), Gafsa (GRP), Tilemsi (TRP) and/or Taiba (TaRP) RP were applied at 0, ¼X, ½X, 1X and/or 2X, where 1X, the predicted rates, were equivalent to

- 127 and 1403.8 kg ha^{-1} for TSP and TRP, respectively at Konobougou 1
- 113, 1794 and 733 kg ha^{-1} for TSP, TRP and GRP, respectively, at Konobougou 2
- 113, 2734, 5361.3 and 1301.3 kg ha^{-1} for TSP, TRP, TaRP and GRP, respectively at Keur Madieng.

These differences in the rate of application reflect both the different RP qualities and soil properties. Similar yields were produced by both TSP and the RPs. The accuracy of the RP algorithm could not be conclusively tested because of the large variability in the field. However, data from Tilemsi and Gafsa RP suggested

that the RP algorithm could be overestimating RP amounts for maximum millet yield. The maximum yields were achieved with the application of 826 rather than 1403.81 kg TRP ha^{-1} at Konobougou 1 and 652.08 rather than 1301 kg GRP ha^{-1} at Keur Madieng. A Bray 1-P critical level of 11 mg kg^{-1} could be used for identifying P deficient conditions and for predicting the amounts of both water-soluble P and RP needed for maximum yield. More experiments in controlled conditions are needed to test the proposed RP algorithm. It is also important to match soil and RP properties when opting for the use of RP to correct soil P deficiency. The generalization of the RP algorithm to a broader range of RPs is then needed for more accurate predictions.

5.2. Introduction

Food security is one of the major concerns in developing countries. With a rapid population growth rate (around 2.9% per year), food security becomes an urgent concern in Africa. This situation is aggravated in the Sudanian and Sahelian zones of West Africa because of the unusual nature of soils in that region. In fact, soils of this region of West Africa are generally weathered, sandy, commonly acid, low in organic matter, poorly buffered, and characterized by a dominance of kaolinite and sesquioxides (Juo and Fox, 1977; Wilding and Hossner, 1989; Takow et al., 1991; Manu et al., 1991). This inherent low soil fertility, particularly the phosphorus (P) deficiency, has long been known as one of the limiting factors for plant growth (Pieri, 1986). However, high variability in soil properties can be noticed throughout farmers' fields in the Sudano sahelian zone of West Africa due to the presence of shrubs. *Guiera senegalesis* is one of the major native shrubs in farmers' fields in this region. Under drought conditions, *G. senegalesis* was found to increase crop yield by improving soil quality and water conditions around the canopy and in the rhizosphere. Dossa (2007) found a high C content under the canopy of *G. senegalesis* compared to the open areas, creating soil fertility spots and heterogeneity in farmers' fields. The factors explaining this variability in soil properties and crop yields include the fact that shrubs contribute to retain or trap soil in areas affected by eolian erosion and the nutrient recycling under the canopy (Dossa, 2007).

Rock phosphate can be used to correct the P deficiency in soil. However, how well RP can perform in supplying P to crops depends on many factors such as soil and RP properties, plant, climate and management factors, as well as factors controlling available P from dissolved RP (Khasawneh and Doll, 1978). At present, however, there are only general (blanket) recommendations that attempt to relate how much rock P is needed. These methods have no diagnosis of crop, soil or management conditions. For example, the recommendation for Tilemsi RP to supply P for major crops in Malian soils ranges from 44 to 53 kg P ha^{-1} (Polain, 1976). According to Thibout (1980) 35 kg P ha^{-1} as Tilemsi RP was recommended to meet crop P requirements. Despite the extensive studies done on the factors affecting RP performance, scientists have not quantified the amounts of RP needed to meet plant P requirements on a site-specific basis. The large number of factors affecting RP suitability for direct use justifies the need for a modeling approach that could identify, quantify and combine the factors into a prediction algorithm. The International Fertilizer Development Center (IFDC) in collaboration with FAO and the International Atomic Energy Agency (IAEA) has developed a decision support system for RP (PRDSS) to predict the relative agronomic effectiveness of a particular RP in different environments as compared to soluble P fertilizer (Smallberger et al., 2006). However, there are no models to predict amounts of RP required. The algorithm proposed by Diarra et al. (2004) is, so far, the only approach to quantitatively predict the amount of RP needed that considers the soil and plant factors. The ability to predict RP fertilizer requirements and to develop accurate and site-specific RP recommendations will represent a substantial contribution to improve P fertility status and to increase crop yields in West African soils. The proposed algorithm needs to be tested in field conditions in representative locations of the region under study (West Africa). A multi-location field evaluation is essential in order to provide a realistic assessment of the performance of the RP algorithm, because RP suitability will be affected by soil and RP properties, as well as climate conditions, cropping systems and farming practices.

5.3. Hypothesis and Objectives

The hypothesis of this study was that RP dissolution in field conditions would be affected by soil properties, plant uptake, leaching conditions and the site characteristics such as climate and management practices and thus may require adjusting the rates predicted by the proposed algorithm for producing maximum millet yields.

The objectives of these field experiments were to:

(i) Test the predictions made by the proposed RP model under different climate and management conditions and to identify refinements needed in the model.

(ii) Develop a millet response curve and identify the P critical level

5.4. Materials and Methods

The field experiment (Konobougou 1) was initially conducted at Konobougou, Mali in 2004. Because Konobougou 1 included only Tilemsi RP from Mali, additional field trials were carried out at Konobougou, Mali (Konobougou 2) and Keur Madieng, Senegal during the 2005 and 2006 rainy season, and at Sadore, Niger in 2007 with the intention to include a range of RPs with low, medium and high reactivity. An additional rate of P material application was also included to better establish the RP rate for maximum yield. The rational for choosing Mali and Niger was that the rock phosphates from both these countries are the only ones recommended for direct application in agriculture in West Africa (Truong et al., 1978; Bationo et al., 1990). Senegal was chosen because the country has the Taiba RP deposit with low solubility. The rainfall gradient represented by the location of these selected sites also provides an opportunity to test the algorithm under a range of climate and management conditions. Because the Sadore, Niger experiment is on-going; data from that experiment are not yet available and will not be presented in this section. The experimental conditions at Sadore will be presented in Appendix.

5.4.1. Site selection

The Sites (Figure 5.1) were selected on the basis of the on-going activities of the research institutes of Mali (IER) and Senegal (ISRA). Selected characteristics of these sites are as follows (Sivakumar et al., 1984; Virmani et al., 1980; Spencer et al., 1995; PIRT, 1986):

5.4.1.1. Konobougou

Located about 80 km Southwest of Segou, this site is located in the Sudanian Zone of Mali (6° 51’ 15.23” W, 13° 7’ 44.72”N). It receives about 800 mm of rainfall annually. The rainy season lasts about 4 months (from June to October). The annual potential evapotranspiration (ETp) reaches about 1770 mm. In general, the maximum average temperature is 35° C (from May to June), while the average minimum temperature is 22° C (from December to January). Soil at Konobougou experimental site is sandy (Plinthic Paleustalfs (Soil Taxonomy)). The annual rainfall from 2004 to 2006 is shown in Figure 5.2.

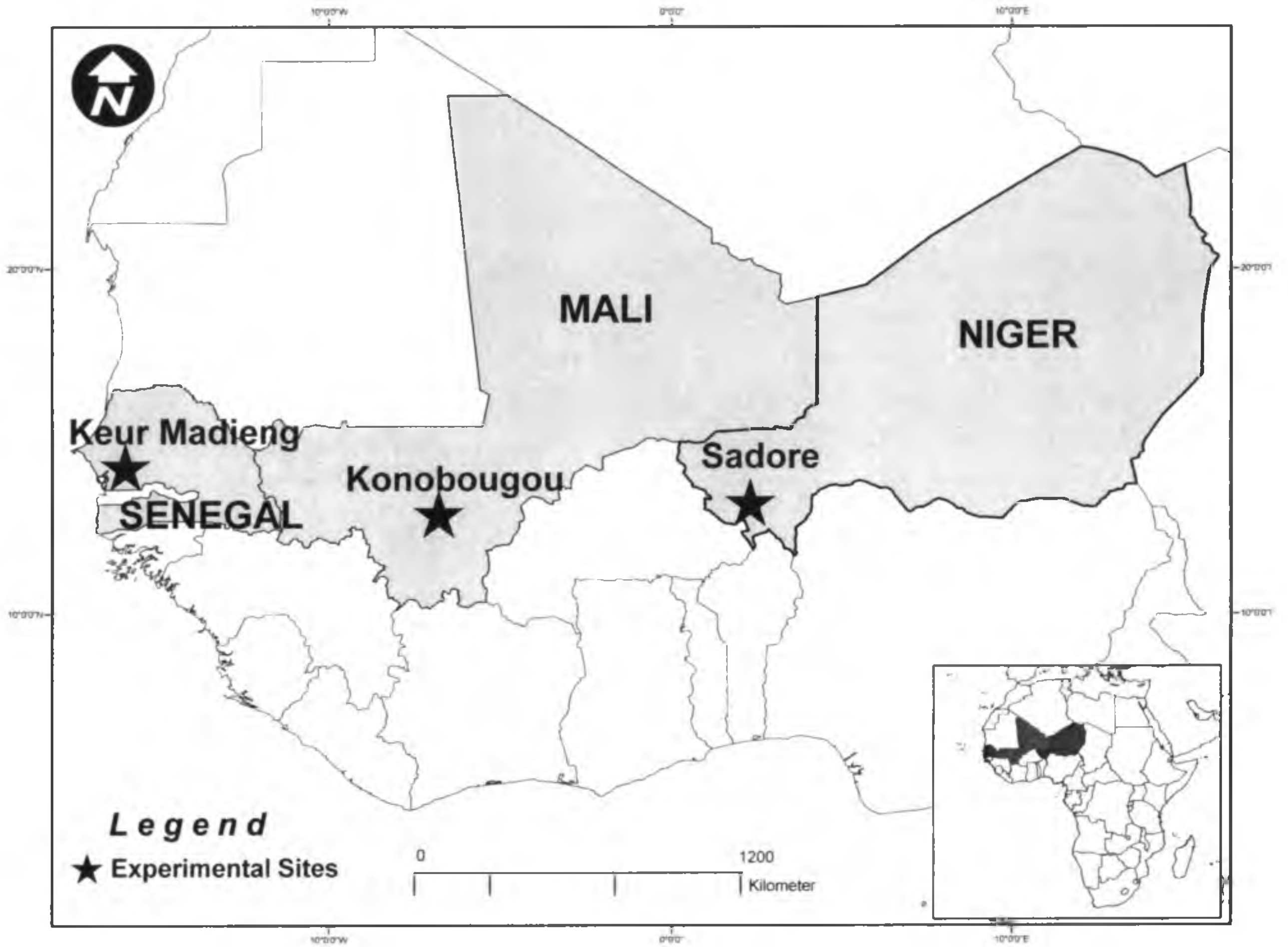

Figure 5.1. Map of the experimental sites.

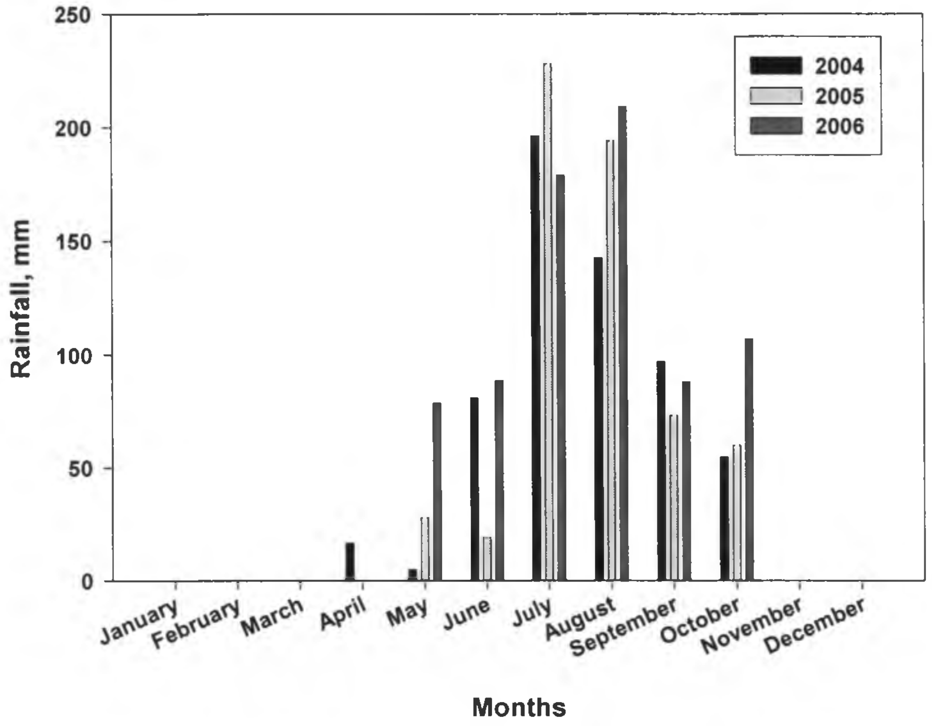

Figure 5.2. Annual rainfall at Konobougou, Mali (2004 to 2006).

5.4.1.2. Keur Madieng

Located in the Sudanian zone of Senegal at about 78 km out of Bambey, Keur Madieng (15° 58' 24.13" W, 14° 21' 18.69" N) is characterized by a mean annual rainfall of 650 mm year^{-1} distributed between beginning of July and middle of October. The annual ETp is about 1770 mm (Virmani et al., 1980). The soil of the experimental site is a Typic Haplustalf. The annual rainfall received in 2005 and 2006 is shown in Figure 5.3.

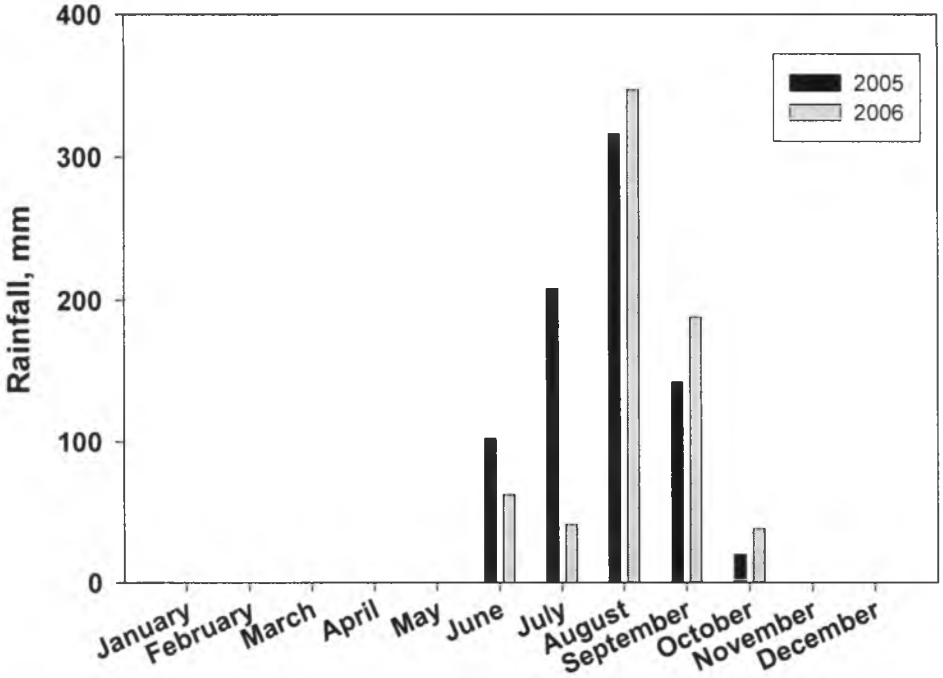

Figure 5.3. Annual rainfall at Keur Madieng, Senegal (2005 and 2006).

5.4.2. Features common to all experiments

All experiments were conducted under on-farm conditions. The predictions made by the RP algorithm were tested for millet -- the staple food in the Sahel of West Africa. The experiments were conducted on P-deficient (i.e. Bray1 less than 7 mg kg^{-1}) and acid (pH< 5.5) soils. However, high variability in soil properties was noticed throughout the plots, especially at Keur Madieng and probably due to the presence of *Guiera senegalesis.*

Factorial experiments (sources of P x application rates) were implemented at all sites in randomized complete blocks replicated 4 times in Mali and 5 times in Keur Madieng. Phosphorus sources initially included one soluble P fertilizer (treble super phosphate – TSP) and three RPs with high, medium and/or low solubility. However, the experiment at Konobougou (Konobougou 2) did not include Taïba RP from Senegal (low solubility) because of the difficulties encountered during the shipment of the material from Senegal to Mali. Gafsa RP with high solubility has been provided by the World Phosphate Institute (IMPHOS-Morocco). The RP with medium solubility was Tilemsi RP from Mali (Table 5.3). Tilemsi RP had been imported to Senegal for the purpose of the experiment. The rates of RP application were 0, ¼, ½, 1 and 2 times the amount of RP predicted by the algorithm.

The rationale for developing a crop response curve to the application of RP material was to evaluate the agronomic value of the RPs. This type of response provides an integration of factors associated with the soil, the rock phosphate, and the crop responsiveness. For example:

- Some soils have so little acidity that they can only dissolve relatively small amounts of applied rock phosphate, thus a response to the application of 100kg may be entirely different from that to 200 kg and thus it is important to determine the response to a range of applications.

- At differing rates of application constituents other than the apatite of the rock phosphate may significantly affect the use of the material. For example, rock phosphates with substantial free carbonates and liming potential, when applied in small quantities are unlikely to change soil pH, however, at high levels of application soil pH may change substantially and retard or arrest the dissolution of the material (Yampracha et al., 2005). Conversely, some soils have such high acidity that the neutralization of the acidity is a direct benefit as are the additions of Ca.

- Other crops acidify the rhizosphere in response to nitrogen supply or do so due to physiological reasons related to their genetic makeup. It may be that the response to differing amounts of applied rock phosphate will vary due to this factor.

Because of all the reasons mentioned above, a response curve would enable detecting whether the algorithm under predicts, accurately predicts, or over predicts RP needs and by how much.

Soil analysis Soil samples (depths of 0 - 15 and 15 – 30 cm) were collected in each experimental unit prior to the application of fertilizer at the beginning of the experiments and after harvest. The soil samples were air-dried, sieved through a 2-mm sieve, and analyzed for

- pH in a 1:1 soil/water mixture,
- Bray 1 extractable P (Bray and Kurtz, 1945),
- 0.5 *M* NaOH-extractable P (MacKay et al., 1986)
- KCl-extractable acidity (Thomas, 1982)

- 1 *M* NH4OAc, pH 7 exchangeable cations (Thomas, 1982)

The Phosphorus Decision Support System (PDSS) was used to predict TSP application rates. Properties of topsoil samples from each experimental unit and the developed algorithm were used to predict application rates for Tilemsi RP. The predictions for Gafsa and Taiba RPs were calculated by multiplying the Tilemsi RP rates by ½ and 2, respectively, based on the solubility of the RP materials. The solubility of the RP materials in the neutral ammonium citrate and 2% citric acid are presented in Table 5.1.

Table 5.1. Solubility of selected RP materials.

RP	Solubility (g P_2O_5 kg^{-1} rock)	
	2nd NAC†	2% citric acid
Gafsa	65	107
Tilemsi	58	119
Taiba	43	81

† Neutral ammonium citrate: second extraction (1 g of RP: 100 ml of solution)
Source: Chien et al., 2003.

Chien et al. (2003) have reported a classification of the agronomic potential of rock phosphate for direct application, based on a second neutral ammonium citrate solubility as follows: high -- 55-67 g P_2O_5 kg^{-1}; medium --18-35 g P_2O_5 kg^{-1}; low -- 5-18 g P_2O_5 kg^{-1}; and very low -- 2-7 g P_2O_5 kg^{-1}.

Rock phosphate analysis *The* Tilemsi RP applied at Konobougou 1 was the same as the Tilemsi RP material used in the study done by Yampracha et al., (2006). The total P and Ca were determined using AOAC (1984) procedures. The citrate- and 2% acid citric-soluble P second extraction was performed by IFDC (Institutional Fertilizer Development Center). The method described by Sikora (2002) was used the determined the calcium carbonate equivalent.

For the RPs used at Konobougou 2 and Keur Madieng, the RP analyses were determined as follows. The total P and water-soluble P analyses were performed at ICRISAT-Niamey using the procedures described by Houba et al. (1995). The RP materials were characterized for total P by digestion in a mixture of concentrated H_2SO_4, salicylic acid and H_2O_2 in the presence of selenium as a catalyst. Total and water-soluble P were then determined by colorimetry (Murphy and Riley, 1962). The calcium carbonate equivalent (CCE) of the rock phosphate was determined by boiling 1 g of RP material in 0.5 *M* HCl during 5 min and then by titrating it with 0.25 *M* NaOH to pH 5 as proposed by Sikora (2002) (Tables 5.2 and 5.3).

Table 5.2. Selected characteristics of Tilemsi RP used in the Konobougou 1 experiment.

Solubility	Total P (g kg^{-1})	Total Ca (g kg^{-1})	NAC2** (g P kg^{-1} rock)	2%Citric acid (g P kg^{-1})	CCE* (%)	Particle size (<100 mesh) (%)
Medium	121	305	18.7	48.9	41.7	96.7

* Calcium carbonate equivalent

**Neutral ammonium citrate, second extraction

Source: Yampracha et al., 2005.

Table 5.3. Selected characteristics of the RP materials used in the Keur Madieng and Konobougou 2 experiments.

RP material and Origin	Solubility	Total (g kg^{-1})		Fe (g kg^{-1})	CCE** (%)	Solubility Water (mg kg^{-1})	Particle size distribution (%)		
		P	Ca*				>9 mesh	9-100 mesh	<100 mesh
Tilemsi, Mali	Medium	112.6	305	20	35.50	4.11	0.54	14.56	84.91
Taiba, Senegal	Low	170.3	350	5	45.08	2.10	0.00	41.64	58.36
Gafsa, Tunisia	High	135.2	334	2	51.67	1.50	5.36	66.39	28.25

* Yampracha et al., 2005.

** Calcium carbonate equivalent

5.4.3. Experimental conditions specific for each site

5.4.3.1. Konobougou 1.

A 2 x 4 factorial experiment was conducted at Konoboudou during 3 years (2004 – 2005). The experimental design was a randomized complete block with each experimental treatment replicated 3 times. Individual plots were 67.5 m^2 (6.75 m x 10 m). The P material type and application rates are given in Table 5.4.

Table 5.4. Application rates of the selected P materials for the Konobougou 1, Mali field experiment.

P material	P material application rates (kg ha^{-1})			
	0 X*	½ X*	1 X*	2 X*
TSP	0	63.5	127	254
Tilemsi RP	0	736.3	1403.8	2811.6

*Where 1 X was equivalent to the predicted rate

Soil properties Soil properties analyzed from the topsoil samples are presented in Table 5.5.

Crop Millet (*Pennisetum spp*) variety Sanioba 03 was planted on July 13 in 2004. Seeds were pretreated with an insecticide Apron® and planted at 0.5 m apart in the row and the distance between rows was 0.75 m. The seedlings were thinned to three plants per planting hill 27 days after planting on August 9, 2004, giving a population of 79,800 plants ha^{-1}.

Table 5.5. Selected soil properties at Konobougou 1, Mali (depth 0 – 15 cm).

pH$_{water}$ (1:1)	Acidity* (cmol$_c$ kg^{-1})	Bray 1-P (mg kg^{-1})	Exchageable cations (cmol$_c$ kg^{-1})				ECEC** (cmol$_c$ kg^{-1})	Ca saturation (%)	Clay (%)
			Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}			
4.81	0.45	3.20	0.50	0.26	0.14	0.01	1.35	36.87	7
(0.031)	(0.022)	(0.084)	(0.016)	(0.009)	(0.006)	(0.0008)	(0.03)	(0.998)	

Numbers in parentheses are standard error

*KCl-extractable acidity

**Effective cation exchange capacity

Crop management Techniques for tillage were those usually applied in this area: broadcast application of P and/or K and incorporation by plowing prior to planting. The application rates of the P materials are shown in Table 3. Nitrogen was applied once, 45 days after planting on August 27, 2004 (31 kg N ha^{-1} as urea) followed by weeding. The second weeding was carried out 66 days after planting (on September 17, 2004). Harvest was performed from a 5.95 m^2 area 131 days after planting (on November 21, 2004). Four plants were sampled from the harvested area and were air-dried for further laboratory analyses. The plants were dried and the grain and biomass yields were recorded. Soil samples were collected from each experimental plot after harvesting.

Evaluating the residual effects of the P materials The experiment was repeated in 2005 and 2006 without re-application of P to evaluate the residual effects of the P applied in 2004. The experiment has been conducted as explained above. The field was tilled using animal traction on July 16, 2005 and July 15, 2006. The Sanioba 03 variety was pretreated with the insecticide Apron®, planted on the ridges (July 16, 2005 and July 15, 2006), thinned to 3 plants per planting hill 20 and 18 days after planting in 2005 and 2006, respectively (August 8, 2005 and August 2, 2006). Three weedings were performed 16, 30 and 47 days after planting (on July 31, August 14 and September 01, 2005), while in 2006 only 2 weedings were carried out 18 and 50 days after planting (August 02 and September 03, 2006). Harvest was performed

129 and 140 days after planting in 2005 and 2006, respectively (November 22, 2005 and December 2, 2006). The size of harvest area was 5.95 m^2.

Fertilizer application Nitrogen was applied once 30 days after planting in 2005 (on August 14, 2005) (31 kg N ha^{-1} as urea). In 2006, N was split applied 18 and 50 days after planting on August 02 and September 03, 2006 (86.5 kg N ha^{-1} each time) and K was applied at 87 kg K ha^{-1} as K_2SO_4 before planting (July 15, 2006).

5.4.3.2. Konobougou 2

A 3 x 5 factorial experiment was conducted at Konobougou in 2005 and 2006. The experimental design was a randomized complete block with each experimental treatment replicated four times. Individual plots were square with 3 m on each side. The P material type and application rates are given in Table 5.6.

Table 5.6. Application rates of the selected P materials for the Konobougou 2, Mali field experiment.

P material	P material application rates (kg ha^{-1})				
	0 X*	¼ X*	½ X*	1 X*	2 X*
TSP	0	34	68	113	272
Gafsa RP	0	178.9	339.8	733	1589
Tilemsi RP	0	326.5	789.5	1794	2656

*Where 1 X was equivalent to the predicted rate

Soil properties Soil properties analyzed from the topsoil samples are presented in Table 5.7.

Crop Millet (*Pennisetum spp*) variety Sanioba 03 was planted on July 21, 2005. Seeds were pretreated with an insecticide Apron® and planted at 0.5 m apart in the row and the distance between rows was 0.75 m. The seedlings were thinned to three plants per planting hill on August 8, 2005, giving a population of 79,800 plants ha^{-1}. The first replication was eliminated from the analysis because of the damage caused by runoff from the intense rainfall.

Crop management Techniques for tillage were those usually applied in this area: broadcast application of P and or K and incorporation by plowing prior to planting. The application rates of the P materials are shown in Table 3. Nitrogen was applied once on August 20, 2005 (31 kg N ha^{-1} as urea). Hand weeding was carried out 27 and 47 days after planting (on August 17 and September 6, 2005), respectively. Harvest was performed from 5.25 m^2 area 125 days after planting (on November 23, 2005). Four plants were sampled from the harvested area and were air-dried for further laboratory analyses. The plants were air-dried and the grain and biomass yields were recorded. Soil samples were collected from each experimental plot after harvesting.

Table 5.7. Selected soil properties at Konobougou 2, Mali (depth 0 – 15 cm).

pH_{water} (1:1)	Acidity* ($cmol_c\ kg^{-1}$)	Bray 1-P ($mg\ kg^{-1}$)	Exchangeable cations ($cmol_c\ kg^{-1}$)				ECEC** ($cmol_c\ kg^{-1}$)	Ca saturation (%)	Clay (%)
			Ca^{2+}	Mg^{2+}	K^+	Na^+			
4.68 (0.019)	0.61 (0.026)	2.03 (0.055)	0.33 (0.011)	0.25 (0.007)	0.14 (0.005)	0.01 (0.003)	1.34 (0.028)	24.92 (0.864)	8

Numbers in parentheses are standard error

*KCl-extractable acidity

**Effective cation exchange capacity

Evaluating the residual effects of the P materials The experiment was repeated in 2006 without re-application of P on the same plots as 2005 to evaluate the residual effects of the P applied the previous year. The experiment was conducted as explained above for 2005. The Sanioba 03 variety was pretreated with the insecticide Apron®, planted (July 16, 2006), thinned 17 days after planting (August 2, 2006) and harvested 140 days after planting (December 3, 2006). The total amounts of N and K supplied (173 kg N ha^{-1} as urea and 87 kg K ha^{-1} as K_2SO_4), were determined so as to be not limiting. Nitrogen was split applied 17 and 49 days after planting on August 2, 2006 and September 3, 2006 (86.5 kg N ha^{-1} each time). Nitrogen and K were mistakenly not applied to the controls (plots which did not receive P).

5.4.3.3. Keur Madieng, Senegal

An experiment similar to that at Konobougou was implemented at Keur Madieng during two years (2005 and 2006) in a rotation of millet-peanut as practiced in the area. The field was selected based on preliminary pH and Bray 1 soil test results (< 5.5 and < 7 mg kg^{-1}, respectively). However, upon our arrival at Keur Madieng, the soil variability in the field was visually obvious. This variability was probably due to the presence of *G. senegalensis* shrub. The choice of changing the field was limited because all fields in the proximity were already cultivated and planted. The factorial 4 x 5 (P materials x application rates) experiment was designed as a randomized complete block with 5 replications.

The P material type and application rates are presented in Table 5.8. The size of the experimental plots was 9 m^2.

Table 5.8. Application rates of the selected P materials for Keur Madieng, Senegal field experiment.

P material	P material application rates ($kg\ ha^{-1}$)				
	0 X*	¼ X*	½ X*	1 X*	2 X*
TSP	0	28.25	56.6	113	226.5
Gafsa RP	0	303.2	652.4	1301.33	2437.8
Tilemsi RP	0	627.6	1217.3	2734.3	4514
Taiba RP	0	1159.7	2397	5361.3	8916

*Where 1 X was equivalent to the predicted rate

Soil properties Soil properties analyzed from the topsoil samples are presented in Table 5.9.

Crop The variety of millet (*Pennisetum spp.)* selected was Souna 3. Planting was performed in hills spaced 0.5 m x 0.5 m on July 14, 2005 after treating the seeds with Granox®. Plants were thinned to 2 plants per hill at the 10th day after planting, giving a final population of 80,000 plants ha^{-1}.

Table 5.9. Selected soil properties at Keur Madieng, Senegal (depth 0 – 15 cm).

pH_{water} (1:1)	Acidity* ($cmol_c\ kg^{-1}$)	Bray 1-P ($mg\ kg^{-1}$)	Exchangeable cations ($cmol_c\ kg^{-1}$)				ECEC** ($cmol_c\ kg^{-1}$)	Ca saturation (%)	Clay (%)
			Ca^{2+}	Mg^{2+}	K^+	Na^+			
5.27 (+/-0.032)	0.18 (+/-0.026)	2.79 (+/-0.112)	0.55 (+/-0.014)	0.33 (+/-0.008)	0.06 (+/-0.003)	0.003 (+/-0.001)	1.12 (+/-0.030)	49.86 (+/-1.020)	3

Numbers in parentheses are standard error

*KCl-extractable acidity

**Effective cation exchange capacity

Crop management Stumps of *Guiera senegalensis* were removed prior to fertilization and planting. Nitrogen was applied as urea and potassium as K_2SO_4 at the recommended rates. Nitrogen was split applied to millet (15, 23 and 23 kg N ha^{-1} at planting, at thinning 10 days after planting and at 45 days after planting, respectively). Phosphorus materials (Table 5.8) and potassium (40 kg K_2O ha^{-1} as K_2SO_4) were applied just prior to planting. The fertilizers were applied by broadcast and then incorporated using a hoe. Weeding was carried out at thinning 10 days after planting and at 27 days after planting. Plants were harvested at the 90th day after planting. The harvested area was 4.5 m^2. Plants were dried and grain and biomass yields were recorded. Plant tissue from 4 plants, selected randomly in the harvested area and grain, leaves and stalks were collected, dried, and ground.

Evaluating the residual effects of the P materials. In 2006 the experiment was repeated without re-application of P on the same plots as in 2005 to evaluate the residual effects of the P materials on peanut grain yield. Because of the rotation millet-peanut practiced in Keur Madieng and because of the locust attack in 2005, it was decided to plant peanut (*Arachis hypogea,*) variety 55-435 in 2006 to avoid locust attacks. The field was cleaned from the remaining stumps of *Guiera senegalensis* and weeds. Nitrogen was applied at the rate of 77 kg N ha^{-1} as urea (by mistake rather than the intended 30 kg) on July 6 (6 days before planting). Potassium was split applied (75 kg K ha^{-1} as K_2SO_4) on July 6 and 28 (16 days after planting). After the broadcast application, N and K were incorporated to a depth of 7 - 10 cm (shallow) using animal traction. Before planting, peanut seeds were pretreated with an insecticide/ fungicide mixture: Saxal® containing 25% Thirame® + 20% Lindane®. Planting was performed using a peanut planter at 0.5 m apart on July 12, 2006. Two weeks after planting, it was noticed that two rows in 10 experimental units of replication 4 had not germinated. Those rows were then replanted to give a population of 80,000 plants ha^{-1}. The first weeding was done before end of July using animal traction between rows and with the hoe "*daba*" between plants within the row. The second weeding was performed on August 11, 2006, 30 days after planting. Nodules were collected from plants in the borders of the experimental plots on August 10 and 25. The efficiency of the nodules was evaluated by the color inside the nodules. During the first observation, no efficient nodules were observed. However redness was observed in some nodules during the second observation of the nodules on August 25. The beginning of flowering and 50% flowering were observed on August 4 and 11, respectively or 23 days and 30 days after planting. Plant mortality was noticed and recorded on August 26. On August 30, peanut aphids were detected. The presence of aphids was a frequently occurring phenomenon on peanut and cowpea at Keur Madieng. The attack coincided with flowering. However, aphids disappeared after an intense rain. Several plants were missing in plots 101, 102, 110, 116, 117 and 120 of the first replicate at the date of September 13. Plants were harvested from October 06 to 08 (from 86 to 88 days after planting). Plants were air-dried and dry grain and haulm yields were recorded. Grain and haulm samples were collected and ground for total P determination. After harvest, soil samples were also collected from each experimental plot from 0 - 15 and 15 - 60 cm depths for lab analyses.

5.4.4. Statistical analysis

The analyses of variance and the mean breakdown were performed. The linear regression plateau (LRP) analysis was done to estimate the RP rates that produced maximum yields for each RP (Shuai et al., 2003). A similar analysis was also used to determine the Bray 1-P critical level.

5.5. Results and Discussion

5.5.1. Konobougou 1

5.5.1.1. Effects of P material rate and type on millet grain yield

Millet grain yield linearly increased with TSP application rates. The yield increased by 675.47 kg ha^{-1} with the increase of TSP application rate by 1X ($p < 0.0001$) (Figure 5.4a). This response of millet to P application confirmed that the soil was deficient in P. At the maximum rate of TSP application (2X), millet yield increased by 1381 kg ha^{-1} over the control (0X). The maximum yield was supposed to be reached at 1X of TSP application. PDSS underestimated the amount of TSP needed for maximum yield. However, millet yield linearly increased with Tilemsi RP application rate up to 0.5X (slope = 1111.5 kg ha^{-1}, p =

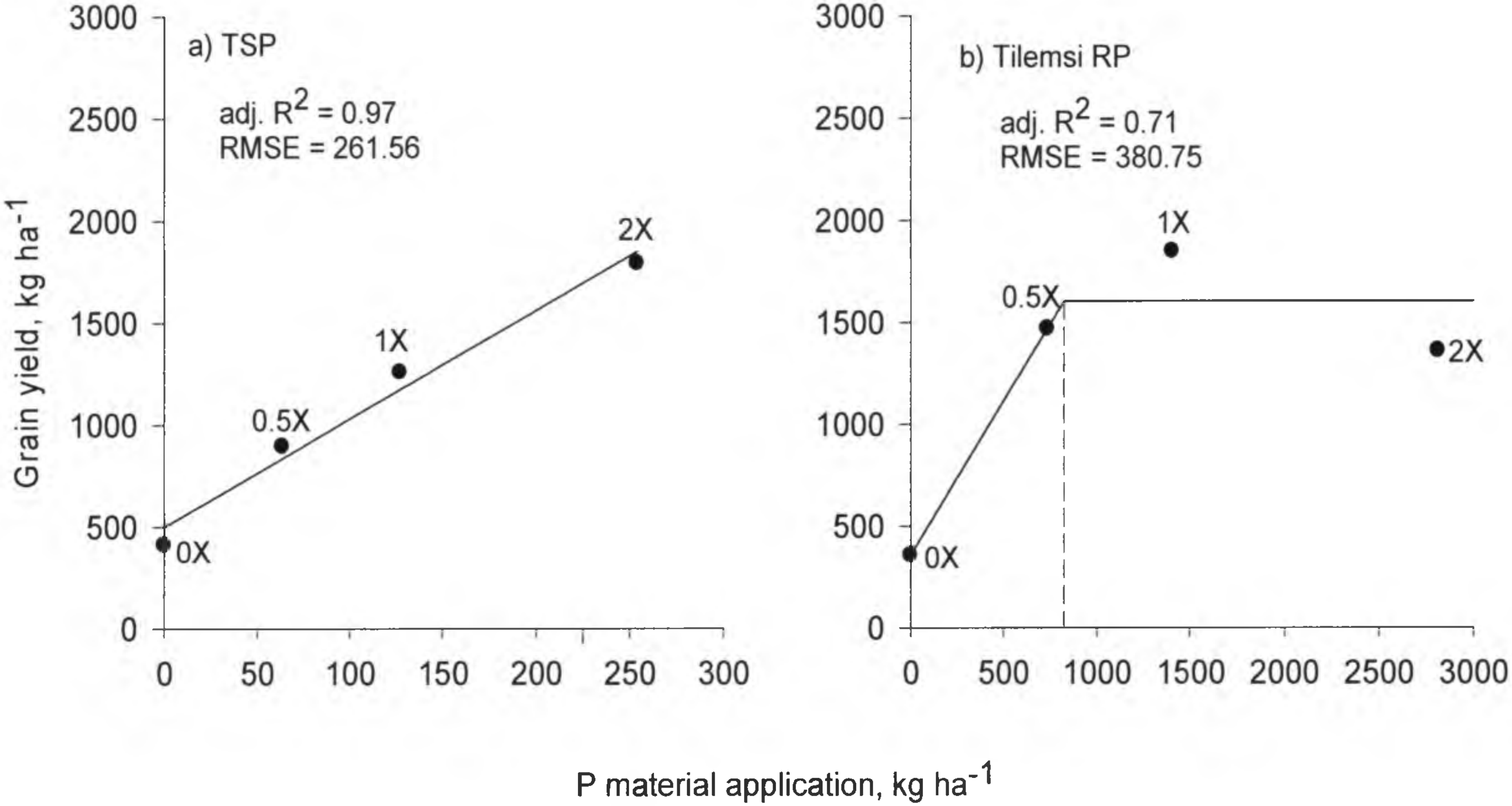

Figure 5.4. Millet response to the P materials application, 2004 (Konobougou 1, Mali).

0.0100) and then remained constant with further additions of Tilemsi RP (slope = -131.0 kg ha^{-1}, p = 0.6143) (Figure 5.4b). A linear regression model was applied to the crop response to TSP because of the linearity in the response. The linear response plateau estimated that 826 rather than 1404 kg Tilemsi ha^{-1} is needed to produce the maximum yield. This suggests that the RP algorithm overestimated the amount of Tilemsi RP needed to meet crop P requirement. High variability reflected in the root mean square of error (coefficient of variation CV = 24% for TSP and 30% for Tilemsi RP) characterized millet grain yield the Konobougou 1 experiment.

5.5.1.2. Effects of soil Bray 1-extractable P on millet grain yield

Millet grain yield increased with the increase in Bray1-P level up to the critical level of 10.94, 8.11 and 7.19 mg kg^{-1} in 2004, 2005 and 2006, respectively (Figures 5.5, 5.6 and 5.7). Millet grain yield response to the increase in soil Bray 1-P levels followed the same path for both TSP and Tilemsi RP treated soils, suggesting that the same critical P level can be used for both P materials. This critical P level is close to the 11 mg P kg^{-1} used in the Phosphorus decision Support System (PDSS) (Yost, 1992). However, a critical Bray 1-P level of 7.9 mg kg^{-1} was established by Bationo and his coworkers (personal communication).

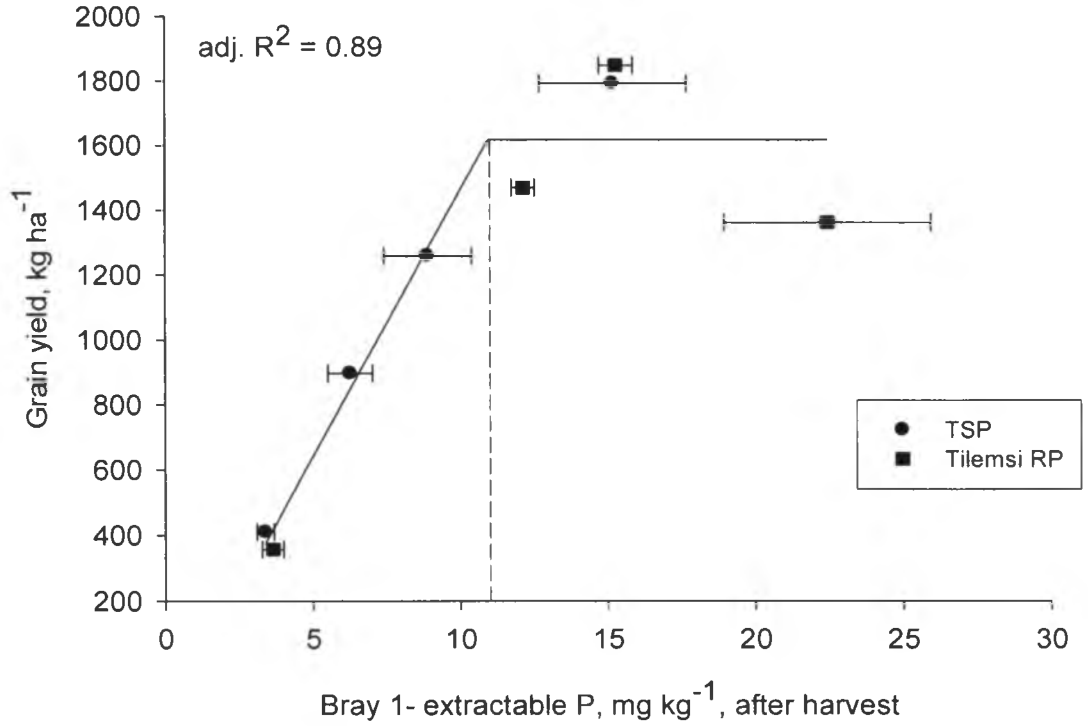

Figure 5.5. Millet response to soil Bray 1-extractable P levels (Konobougou 1, Mali), 2004.

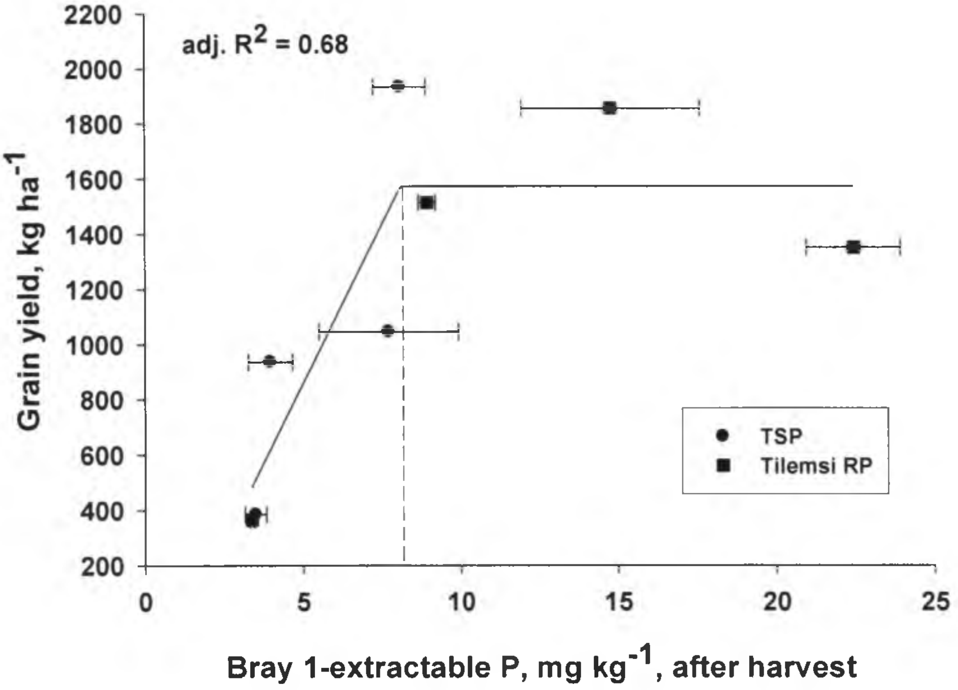

Figure 5.6. Millet response to soil Bray 1-extractable P levels (Konobougou 1, Mali), 2005.

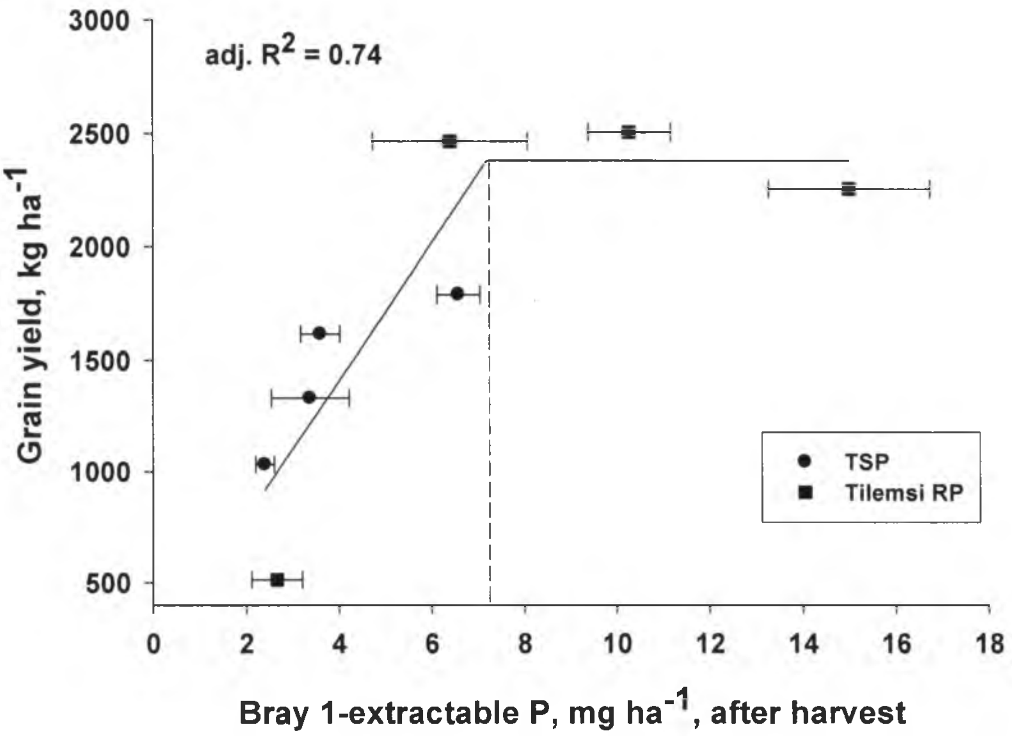

Figure 5.7. Millet response to soil Bray 1-extractable P levels (Konobougou 1, Mali), 2006.

5.5.1.3. Effects of P materials and rates on RP dissolution

ΔNaOH-P increased with the increase in the P material rate of application after harvest in 2004 and in 2006 (Figures 5.8 and 5.9). The slope of the regression line between ΔNaOH-P and TSP rates of application decreased from 13.07 mg kg^{-1} ($p = 0.0005$) in 2004 to 4.71 mg kg^{-1} in 2006 ($p = 0.009$) (Figure 5.8), while the slope for Tilemsi RP was 10.88 mg kg^{-1} in 2004 ($p = 0.008$), 14.29 mg kg^{-1} in 2005 ($p = 0.0028$) and 13.40 mg kg^{-1} in 2006 ($p = 0.0027$) (Figure 5.9). The decrease in the slope for TSP is probably because part of the soluble P from

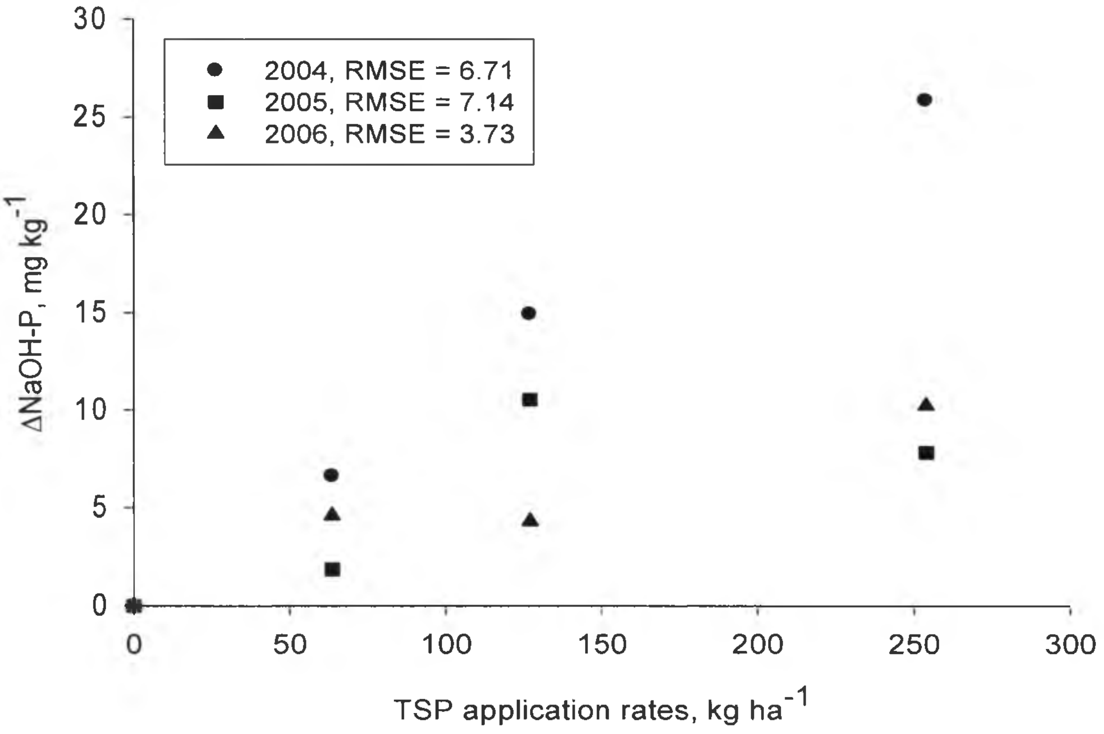

Figure 5.8. Changes in NaOH-P in P-treated soils at Konobougou 1 (TSP).

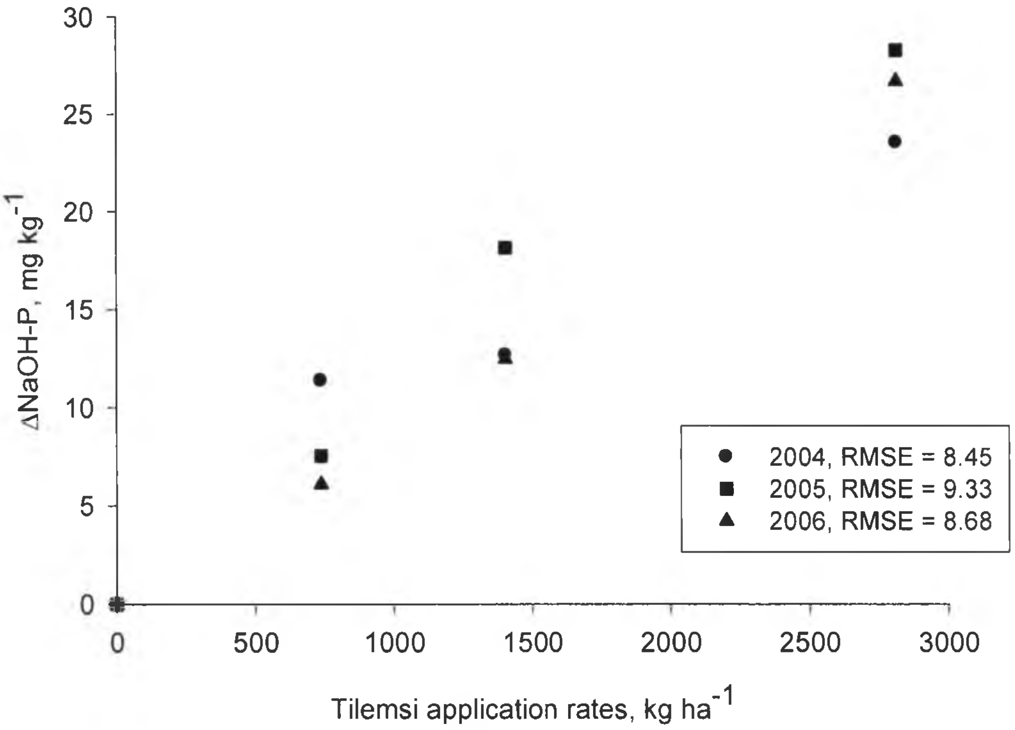

Figure 5.9. Changes in NaOH-P in RP-treated soils at Konobougou 1 (Tilemsi RP).

the TSP had strongly reacted with soil constituents. The increase in the slope for Tilemsi RP indicates that dissolution was incomplete the first season.

5.5.1.4. Relationship between ΔNaOH-P and ΔCa

When rock phosphate dissolves both P and Ca are released. Consequently, the changes in Ca may also be useful to quantify dissolution between RP-treated and untreated soil. A linear positive relationship ($r = 0.73$, 0.91 and 0.85 in 2004, 2005 and 2006, respectively) was detected between ΔNaOH-P and ΔCa at Konobougou 1 (Figures 5.10, 5.11 and 5.12). These high correlation coefficients suggest that the losses of Ca were not substantial and that ΔCa could be used as an estimate of RP dissolved this experiment.

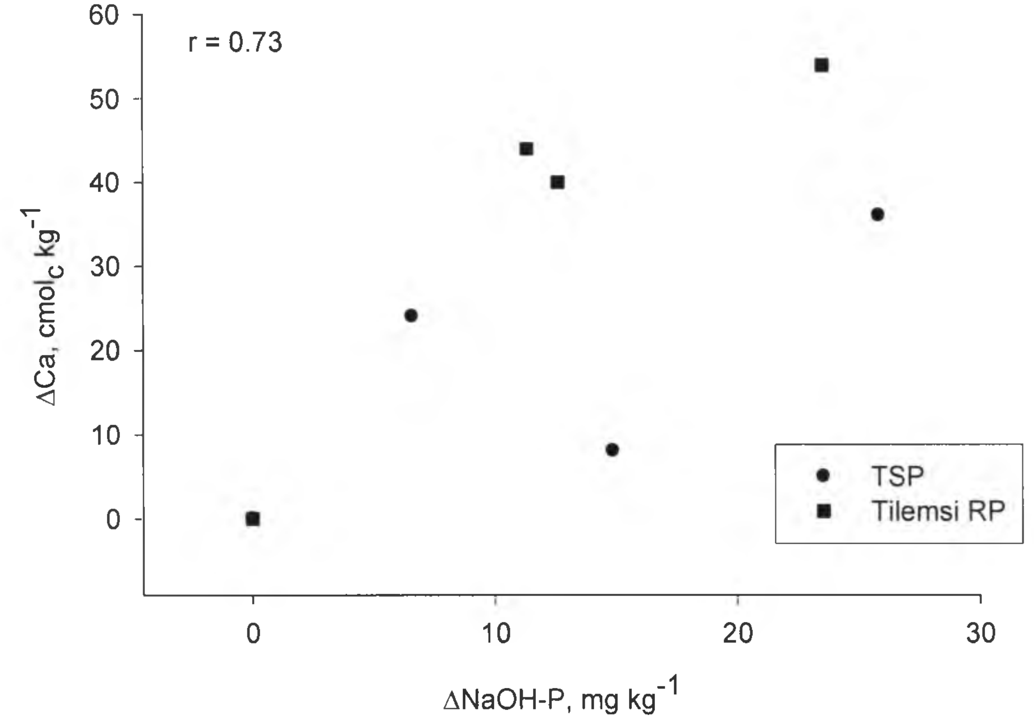

Figure 5.10. Relationship between ΔNaOH-P and ΔCa after harvest at Konobougou 1 (2004).

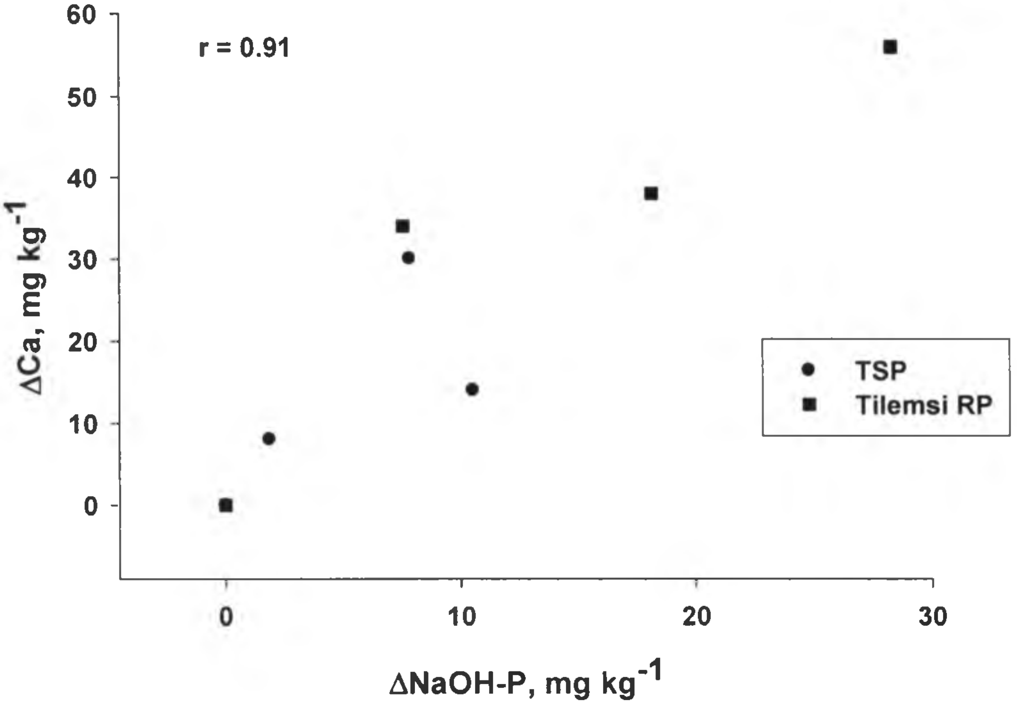

Figure 5.11. Relationship between ΔNaOH-P and ΔCa after harvest at Konobougou (2005).

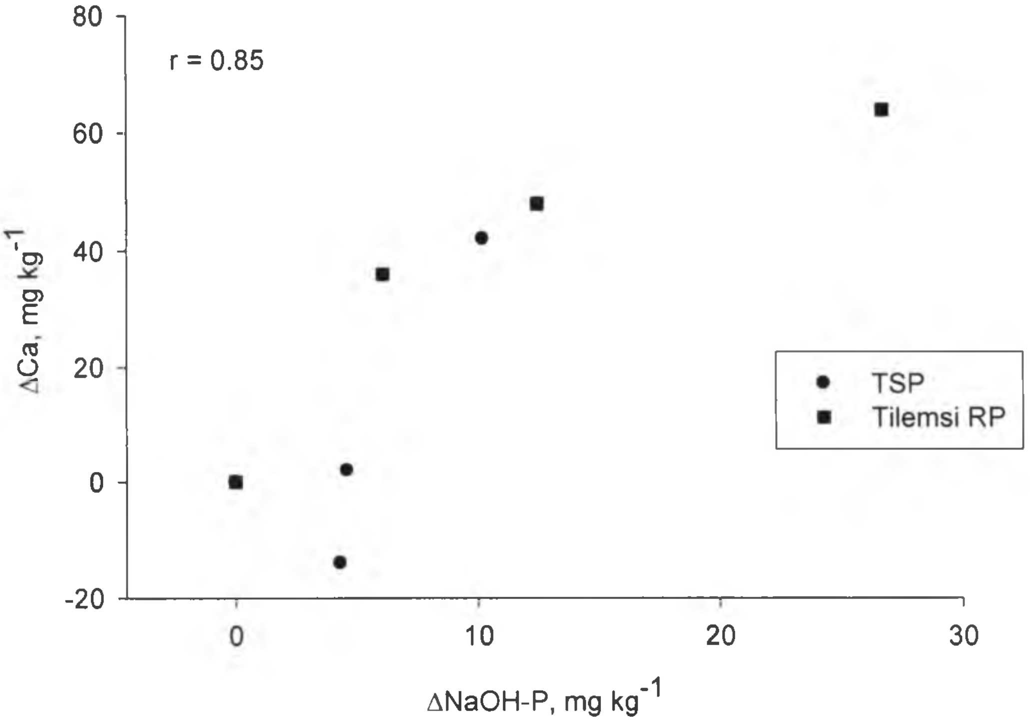

Figure 5.12. Relationship between ΔNaOH-P and ΔCa after harvest at Konobougou 1 (2006).

5.5.1.5. Effects of P material rate and type on soil properties

Both TSP and Tilemsi RP affected soil Bray 1-P over time (Tables 5.10 and 5.12). An increment in the TSP rate of application by 127 kg ha^{-1} (1X) resulted in an increase in Bray-1 P by 5.89 mg kg^{-1} ($p < 0.0001$), 2.52 mg kg^{-1} ($p = 0.0148$) and 2.05 mg kg^{-1} ($p = 0.0002$) in 2004, 2005 and 2006, respectively (Tables 10 and 11). The highly significant slopes for Tilemsi were 8.89, 9.50 and 6.14 mg kg^{-1} in 2004, 2005 and 2006, respectively ($p < 0.0001$) (Tables 5.12 and

5.13). The slope decreased in the third year of cropping probably because of some sorption of the earlier dissolved P.

The rates of application of TSP did not affect soil pH ($p = 0.1481$), soil KCl-extractable acidity, effective cation exchange capacity (ECEC) and Ca saturation (Tables 5.10 and 5.11). The absence of the effect of TSP application rates on the Ca saturation is surprising because of the increase in soil Ca levels. Soil exchangeable Ca level increased by 0.07 ($p = 0.0151$) and by 0.076 cmol_c kg^{-1} ($p = 0.047$) in 2004 and 2005 with each unit (1X) increase of TSP. (Table 5.10). This increase in Ca is probably due to the Ca contained in TSP. Soil Ca level was not affected in 2006, probably because of the losses of Ca during the previous three years of cropping.

The effects of Tilemsi RP application rates on soil properties are presented in Tables 5.12 and 5.13. The changes in soil pH and in KCl-extractable acidity due to the different Tilemsi RP application rates was described by a quatratic equation in 2004 with the coefficients and their p-values shown in Table 5.12. When analyzed segment by segment, with the increased of Tilemsi RP application rates up to 0.5X, the soil pH increased by 0.4 units ($p = 0.0009$) while soil KCl-extractable acidity dropped by -0.32 cmol_c kg^{-1} ($p = 0.0076$). However, with further increase of the rate of application, soil pH and KCl-extractable acidity did not changed statistically ($p = 0.1781$ and 0.3605, respectively). Soil exchangeable Ca levels linearly increased by 0.11cmol_c kg^{-1} with each increase of Tilemsi RP application rate by 1X in 2004 ($p = 0.0305$), while the relationship between Ca saturation and Tilemsi RP application rates was described by a quadratic regression. The Ca saturation increased by 21.41% ($p = 0.0045$) with the application of 0.5X Tilemsi RP. However the Ca saturation did not change significantly with further increases in Tilemsi RP rate (slope = -1.12 with $p = 0.5909$).

In 2005 soil pH increased (slope = 0.15, $p = 0.0269$) and acidity decreased (slope = -0.20 $\text{cmol}_c\ \text{kg}^{-1}$, $p = 0.0136$) linearly with the increase of Tilemsi RP application rates (Table 5.12). Soil Ca saturation also increased (slope = 12.59, $p = 0.0045$) probably due to the increase in the Ca levels (slope 0.13 $\text{cmol}_c\ \text{kg}^{-1}$, $p = 0.016$) with a unit (1X) increase of Tilemsi RP rate.

Besides on Bray 1-P, the effect of Tilemsi RP was observed only the exchangeable Ca levels in 2006. The exchangeable Ca increased (slope = 0.15 $\text{cmol}_c\ \text{kg}^{-1}$, $p = 0.0085$) with each 1X increase of Tilemsi RP application rate (Table 5.13).

Table 5.10. Effects of TSP rates on soil properties after harvest at Konobougou, 2004 and 2005.

TSP rates	Soil properties after harvest											
	pH_{water} (1:1)		Acidity (cmol$_c$ kg^{-1})		Bray 1-P (mg kg^{-1})		Exchangeable Ca (cmol$_c$ kg^{-1})		ECEC (cmol$_c$ kg^{-1})		Ca saturation (%)	
	2004	2005	2004	2005	2004	2005	2004	2005	2004	2005	2004	2005
0X	4.59	4.69	0.62	0.70	3.38	3.50	0.32	0.31	1.17	1.25	28.42	25.00
0.5X	4.66	4.68	0.54	0.78	6.26	3.97	0.44	0.35	1.28	1.39	32.87	25.13
1X	4.64	4.75	0.68	0.65	8.89	7.72	0.37	0.38	1.31	1.29	28.64	29.56
2X	4.71	4.69	0.50	0.75	15.18	8.08	0.50	0.46	1.28	1.53	39.55	29.70
Lin.*	0.05	0.008	-0.05	0.009	5.89	2.52	0.07	0.08	0.04	0.12	4.63	2.66
p-value	0.1481	0.8889	0.4967	0.8957	0.0001	0.0148	0.0151	0.047	0.5767	0.1372	0.0752	0.2129
RMSE	0.0856	0.1362	0.1757	0.1633	2.3446	2.1939	0.0641	0.086	0.1971	0.1908	5.9725	5.1147

*parameter estimates of the linear regression

Table 5.11. Effects of TSP rates on soil properties after harvest at Konobougou 1, 2006.

TSP rates	Soil properties after harvest					
	pH_{water} (1:1)	Acidity ($cmol_c$ kg^{-1})	Bray 1-P (mg kg^{-1})	Exchangeable Ca ($cmol_c$ kg^{-1})	ECEC ($cmol_c$ kg^{-1})	Ca saturation (%)
0X	4.84	1.15	2.40	0.25	1.58	15.94
0.5X	4.52	1.02	3.38	0.26	1.47	19.35
1X	4.51	1.18	3.60	0.18	1.50	12.05
2X	4.57	1.12	6.58	0.46	1.82	23.74
Lin.*	-0.10	0.008	2.05	0.10	0.14	3.20
P-value	0.0968	0.9326	0.0002	0.1326	0.2227	0.3126
RMSE	0.1409	0.2250	0.9188	0.1592	0.2725	7.7214

*parameter estimates of the linear regression

Table 5.12. Effects of Tilemsi RP rates on soil properties after harvest at Konoubougou 1, 2004 and 2005.

Tilemsi RP rates	Soil properties after harvest											
	pH_{water} (1:1)		Acidity ($cmol_c$ kg^{-1})		Bray 1-P (mg kg^{-1})		Exchangeable Ca ($cmol_c$ kg^{-1})		ECEC ($cmol_c$ kg^{-1})		Ca saturation (%)	
	2004	2005	2004	2005	2004	2005	2004	2005	2004	2005	2004	2005
0X	4.57	4.72	0.61	0.77	3.63	3.38	0.43	0.41	1.32	1.47	32.28	27.49
0.5X	4.97	4.84	0.29	0.52	12.12	8.94	0.65	0.58	1.22	1.39	53.19	41.28
1X	4.86	4.89	0.32	0.52	15.29	14.77	0.63	0.60	1.22	1.39	51.84	43.26
2X	4.85	5.03	0.38	0.32	22.45	22.44	0.68	0.69	1.33	1.27	51.36	54.82
Lin.*	0.57	0.15	-0.53	-0.20	8.89	9.50	0.11	0.13	0.02	-0.093	34.60	12.59
P-value	0.0052	0.0269	0.0106	0.0136	<0.0001	<0.0001	0.0305	0.016	0.7913	0.0241	0.0015	0.0045
Quad**	-0.23		0.22								-13.16	
P-value	0.0106		0.0196								0.0051	
RMSE	0.1098	0.1497	0.1185	0.1739	3.2574	2.6135	0.1076	0.1129	0.1652	0.0898	5.4947	8.8379

*parameter estimates of the linear regression

**parameter estimates of the quadratic regression

Table 5.13. Effects of Tilemsi RPs rate on soil properties after harvest at Konobougou 1, 2006.

Tilemsi RP Rates	Soil properties after harvest					
	pH_{water} (1:1)	Acidity ($cmol_c\ kg^{-1}$)	Bray 1-P ($mg\ kg^{-1}$)	Exchangeable Ca ($cmol_c\ kg^{-1}$)	ECEC ($cmol_c\ kg^{-1}$)	Ca saturation (%)
0X	4.88	1.08	2.66	0.30	1.59	18.65
0.5X	4.83	0.85	6.40	0.48	1.50	31.84
1X	4.87	0.98	10.27	0.54	1.71	32.20
2X	4.87	0.98	15.00	0.61	1.83	33.96
Lin.*	0.003	-0.02	6.14	0.15	0.15	6.39
P-value	0.945	0.8697	<0.0001	0.0085	0.0891	0.0646
RMSE	0.1242	0.2609	2.1346	0.1143	0.1982	7.8778

*parameter estimates of the linear regression

5.5.2. Konobougou 2

5.5.2.1. Effects of P material rate and type on millet grain yield

Figures 5.13, 5.14 and 5.15 present millet response curves to TSP, Tilemsi and Gafsa RPs, respectively. High variability was observed in millet yield (CV = 36% for TSP; 48% for Tilemsi RP and 31 for Gafsa RP). The grain yields obtained for millet varied from 574.6 to 2110.5 kg ha^{-1}. The linear increase in grain yield caused by TSP (slope = 507 kg ha-1) was not significant (p = 0.0582) (Figure 5.13). The quadratic model 699.56 + 1158.87x – 316.07x^2 with (p = 0.2451 for 1158.87) and (p = 0.4897 for -316.07) was also not significant. However, the effect of increasing TSP rate had significantly increased the dry biomass yield (slope 1898 kg ha^{-1} for each increase of TSP by 1X, p = 0.0098) (Table 5.14). This crop response to TSP indicated that the soil was deficient in P as in the Konogougou 1 experiment. The yield linearly increased with the rate of the 2 RP materials (Figures 5.14 and 5.15). The increase per unit (1X) RP material was 614.8 kg ha^{-1} (p = 0.041) and 572.4 kg ha^{-1} (p = 0.0079) for Tilemsi and Gafsa RPs. The linear response plateau was not applied to the response curves because the sufficiency level was not attained for any of the P materials. The rock phosphate algorithm underestimated the amount of P needed for maximum yield in the Konobougou 2 experiment.

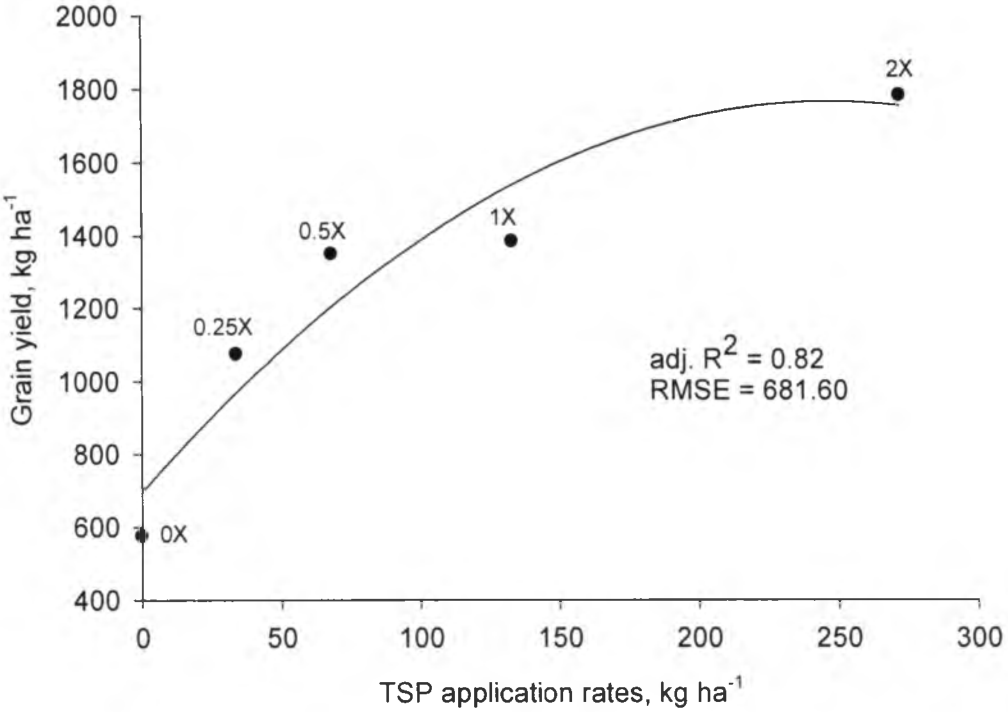

Figure 5.13. Millet grain response to the application of TSP, 2005 (Konobougou 2, Mali).

Table 5.14. Millet biomass response to the application of TSP, 2005 (Konobougou 2, Mali).

TSP rate	Millet biomass yield (kg ha^{-1})
0x	1778
0.25X	2984
0.5X	3429
1X	5460
2X	5651
Linear	1898
P-value	0.0098
RMSE	1719.9137

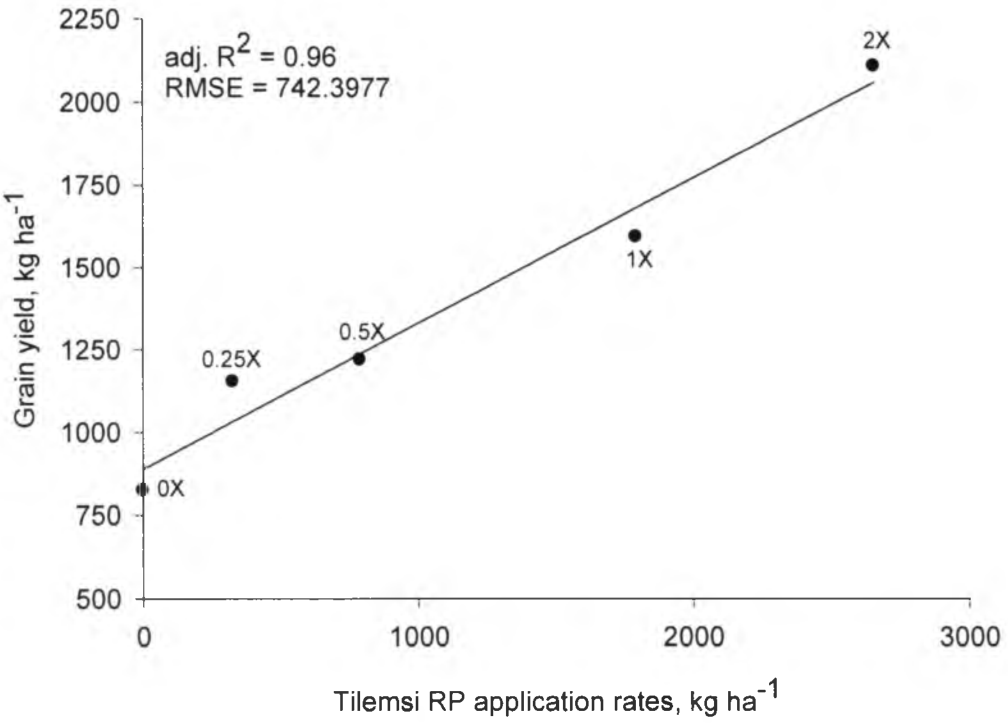

Figure 5.14. Millet response to the application of Tilemsi RP, 2005 (Konobougou 2, Mali).

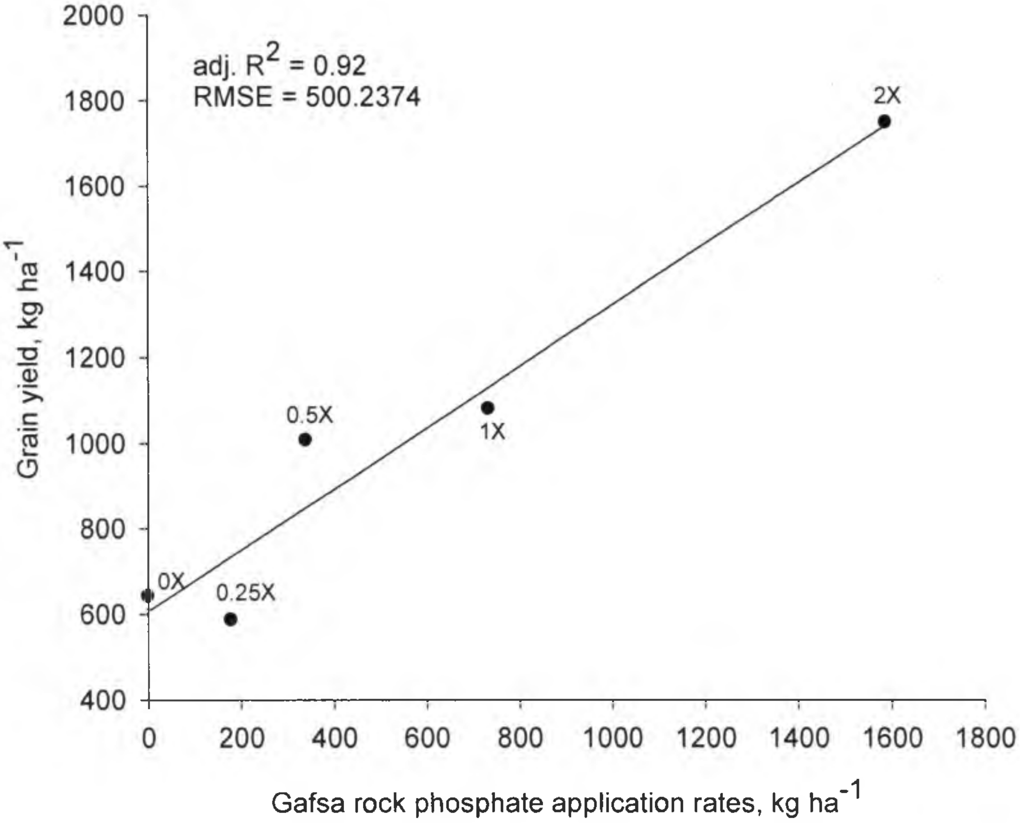

Figure 5.15. Millet response to the application of Gafsa RP, 2005 (Konobougou 2, Mali).

5.5.2.2. Effects of soil Bray 1-extractable P on millet grain yield

Millet grain yield increased with the increased soil Bray 1-P level both in 2005 and 2006 (Figures 5.16 and 5.17). The plateau (sufficiency level) was not reached in either year. The linear aspect of the response did not allow using LRP for estimating the critical P level. At about the highest levels of Bray 1-P obtained in 2005 and 2006 (13 and 8 mg P kg^{-1}, respectively) millet yield was still increasing. These Bray 1-P levels are close to the P critical levels obtained in Konobougou 1 experiment during the first and second years of cropping, suggesting that not enough RP dissolution took place to sufficiently increase Bray 1-P level above the critical level probably explaining why yields failed to attain plateau at 2X rate of P material application. Contrary to the finding of Chien (1978), millet response to Bray 1-P in soils treated with TSP and various RP suggests that this method of measuring extractable P appears to be useful regardless the source of P.

The higher grain yields observed in 2006 compared to 2005 even with lower Bray 1-P levels were probably due to the higher amounts of urea and K_2SO_4 applied (173 kg N ha^{-1} and 87 kg K ha^{-1} in 2006 and 31 kg N ha^{-1} and 0 kg K ha^{-1} in 2005).

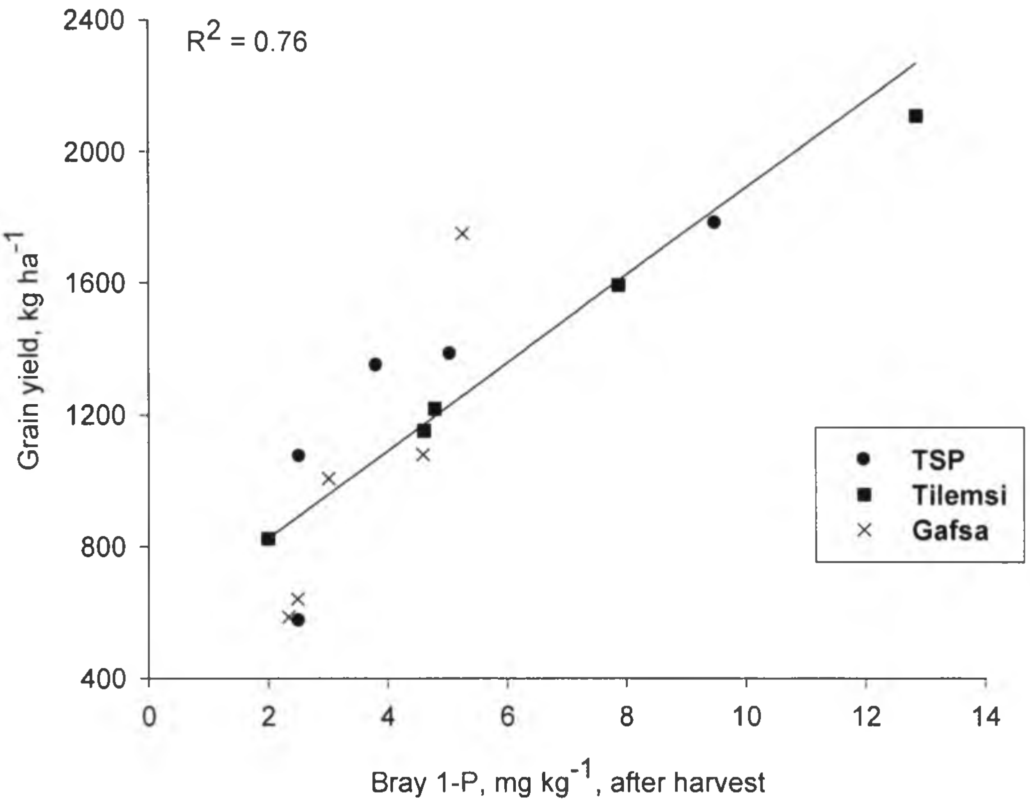

Figure 5.16. Millet response to soil Bray 1-extractable P levels (Konobougou 2, Mali), 2005.

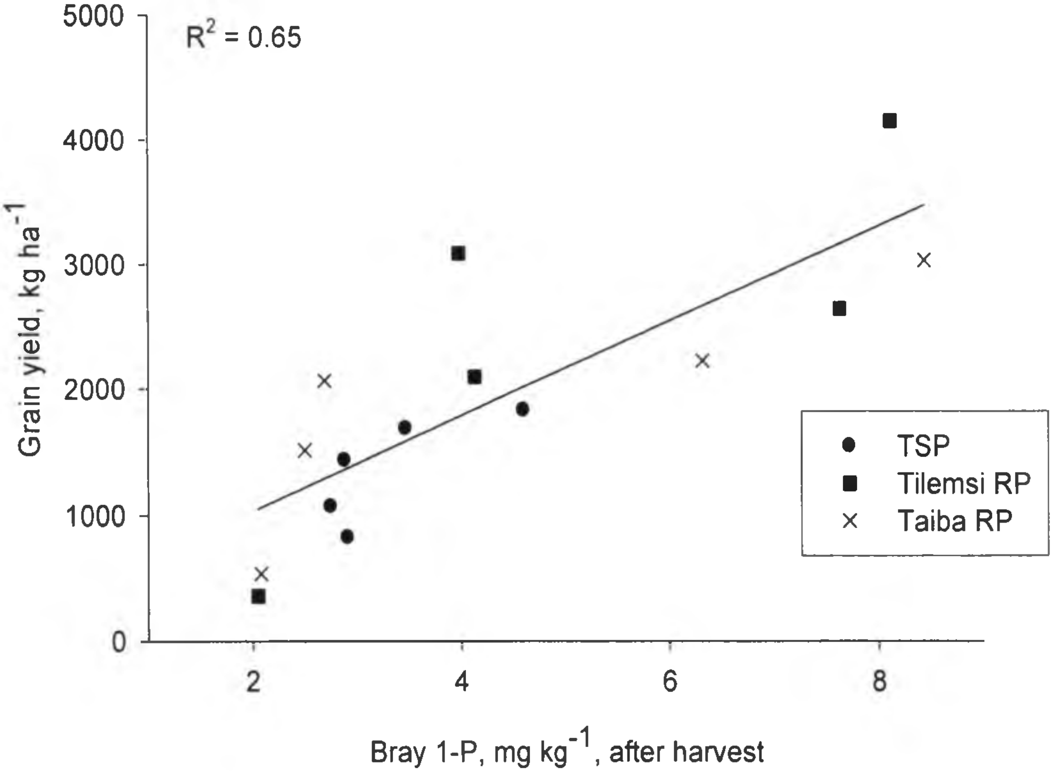

Figure 5.17. Millet response to soil Bray 1-extractable P levels (Konobougou 2, Mali), 2006.

5.5.2.3. Effects of P materials and rates on RP dissolution as measured by ΔNaOH-P

The ΔNaOH-P in Konobougou 2 experiment was generally less than in Konobougou 1. For rates 2X of Tilemsi RP, the respective levels were 25.34 mg kg^{-1} in Konobougou 1 and 15.84 mg kg^{-1} in Konobougou 2, even with approximately same rainfall in 2004 (592 mm) and in 2005 (602 mm). However, Tilemsi RP materials used in Konobougou 1 and 2 experiments were purchased at separate times, and with the natural variability of the RP deposit (Truong et al., 1978), the materials may have differed in solubility.

The increase in the application rates of all P materials resulted in linear increases in ΔNaOH-P in 2005. ΔNaOH-P increased by 6.76 mg kg^{-1} with each unit increment (by 1X) of TSP ($p < 0.0001$) (Figure 5.18). Figures 5.19 and 5.20 indicate that the slopes of ΔNaOH-P were 7.50 and 6.39 mg kg^{-1} with each unit increment (by 1X) of Tilemsi and Gafsa RP. ($p = 0.0005$ and $p < 0.0001$ for Tilemsi and Gafsa, respectively).

In 2006, no significant increase in ΔNaOH-P was detected from the residual TSP (Figure 5.18). This is probably because P from the fertilizer had strongly reacted with soil constituents possibly through the absorption of P into the soil aggregates by the second year of cropping. However, where Tilemsi and Gafsa RP were applied, increased ΔNaOH-P resulted ΔNaOH-P increases with slopes of 4.40 mg kg^{-1} ($p = 0.0137$) and 6.94 mg kg^{-1} ($p = 0.0001$), respectively (Figures 5.19 and 5.20). These results suggest that RPs did not completely

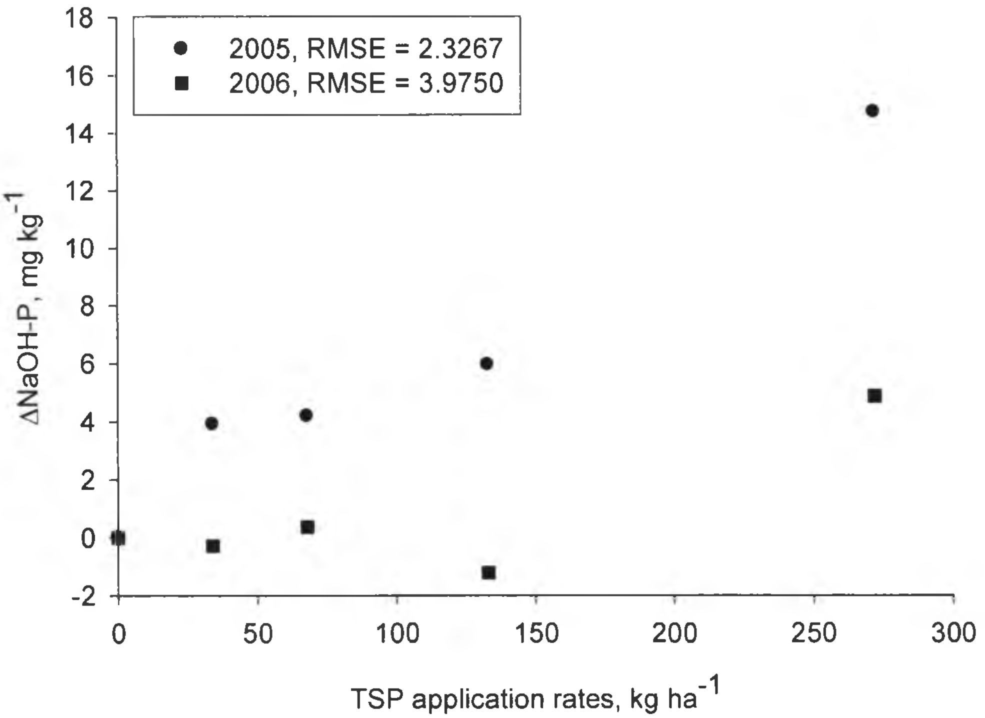

Figure 5.18. Changes in NaOH-P in P-treated soils at Konobougou 2 (TSP).

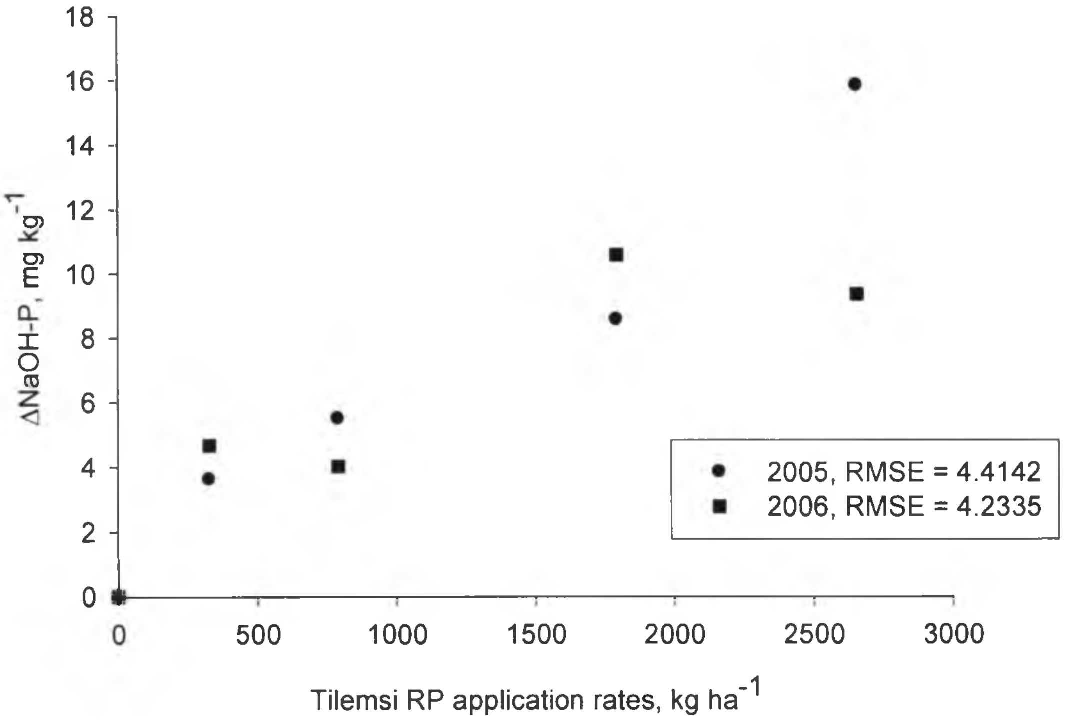

Figure 5.19. Changes in NaOH-P in RP-treated soils at Konobougou 2 (Tilemsi RP).

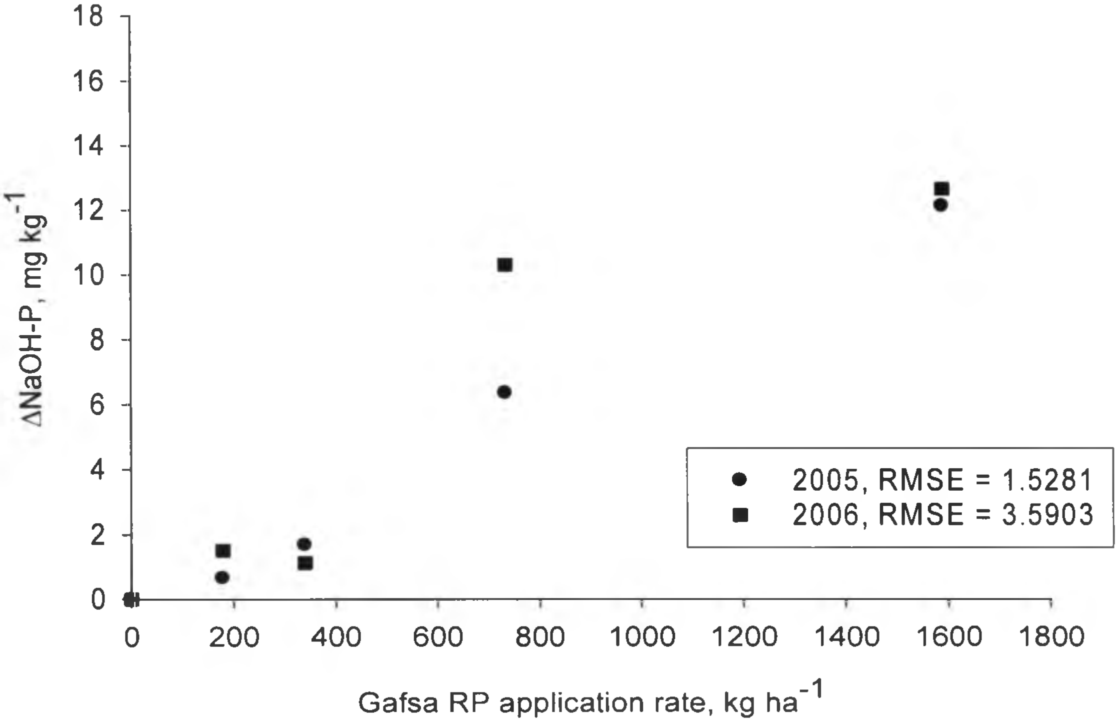

Figure 5.20. Changes in NaOH-P in RP-treated soils at Konobougou 2 (Gafsa RP).

dissolve in 2005; consequently the RPs had higher residual effects that TSP. The low ΔNaOH-P levels might explain why millet responded to the increased application rates of Tilemsi and Gafsa RPs. The dissolution was so low that the high rate actually led to benefit.

5.5.2.4. Relationship between ΔNaOH-P and ΔCa

The relationship between ΔCa and ΔNaOH-P was not very strong ($r = 0.54$) in 2005 (Figure 5.21). The TSP rate of application affected ΔNaOH-P (linear = 6.76 mg P kg^{-1}, $p < 0.0001$) (Figure 5.18) whereas it did not affect the ΔCa (slope = -2 mg Ca kg^{-1}, $p = 0.7343$) (Table 15). This is probably due to some Ca losses that took place due to the intense rain that also destroyed the first replication of Konobougou 2 experiment about 2 weeks after planting. These Ca losses are more accentuated for TSP than for the RPs, probably because of the greater water solubility.

In 2006 a strong relationship was detected between ΔCa and ΔNaOH-P ($r = 0.90$) (Figure 5.22). This strong correlation is probably due to the fact that TSP rate of application did not significantly affect either ΔNaOH ($p = 0.132$) or ΔCa ($p = 0.5556$). The high susceptibility of Ca to leaching appears to cause the ΔCa measurement to be inaccurate in assessing the extent of RP dissolution.

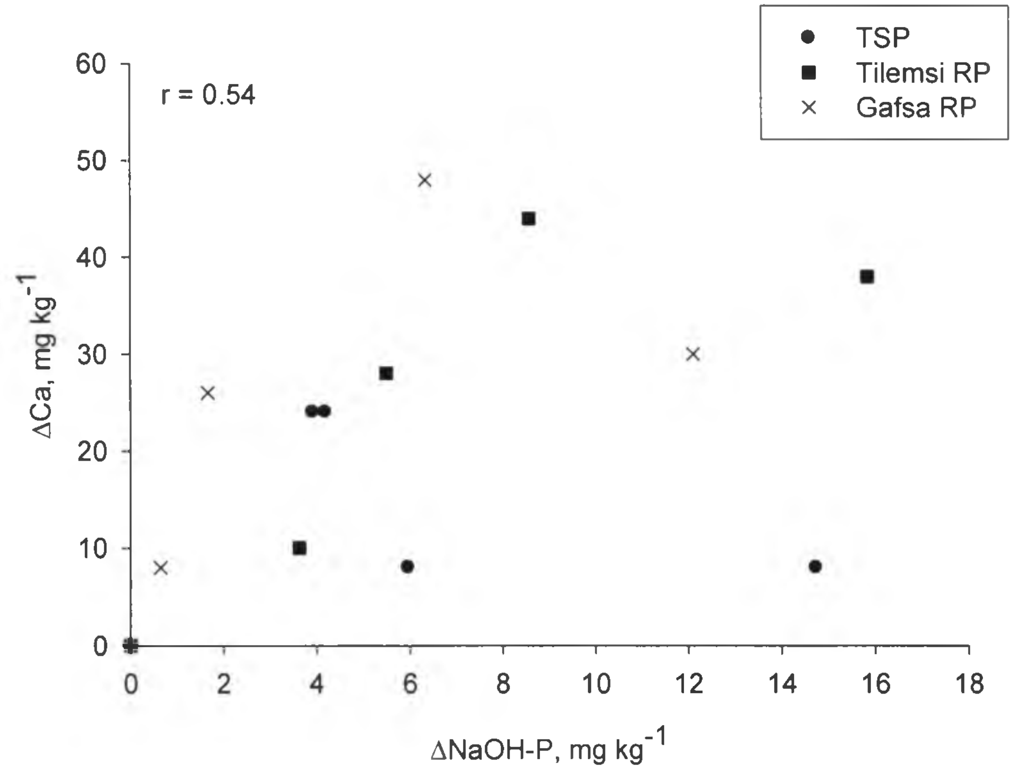

Figure 5.21. Relationship between ΔNaOH-P and ΔCa after harvest at Konobougou 2 (2005).

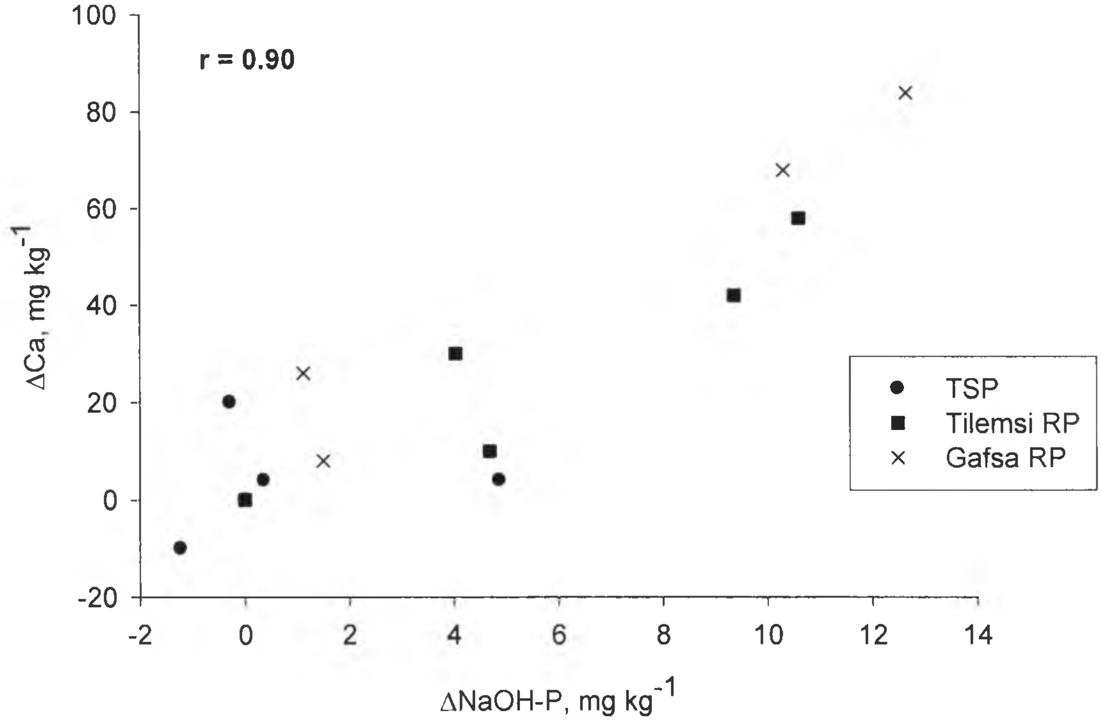

Figure 5.22. Relationship between ΔNaOH-P and ΔCa after harvest at Konobougou 2 (2006).

5.5.2.5. Effects of P material rate and type on soil properties

The variability in soil properties prior to the application of P materials makes the interpretation difficult. TSP application rates affected only soil Bray 1-P levels in 2005 (Table 5.15). The increase in Bray 1-P was highly significant ($p < 0.0001$) with a slope of 3.61 mg kg^{-1}. The ECEC surprisingly decreased in 2006 (slope = -0.15, p = 0.0467).

The increase in Tilemsi RP increased soil Bray 1-P (slope = 5.21 mg kg^{-1}, $p < 0.0001$) in 2005 (Table 5.16). There was a quadratic relationship between soil pH, exchangeable Ca and Tilemsi RP application rates (Table 5.16). Soil pH and exchangeable Ca increased by 0.18 and 0.22 $cmol_c$ kg^{-1} with the first increment (1X) of Tilemsi RP and did not change with further increase in Tilemsi RP rate (slope = -0.04, p = 0.6230 for pH and slope = -0.03 cmolc kg^{-1}, p = 0.5824 for exchangeable Ca). Tilemsi RP, however, linearly increased soil Ca saturation (slope = 4.30%, p = 0.0147).

The effect of Tilemsi RP rate of application on soil pH, KCl-extractable acidity and ECEC was not significant in 2006 (Table 5.16). Exchangeable Ca increased quadratically with the increase of Tilemsi RP rate, while Ca saturation surprisingly did not change (slope = 4.72%, p = 0.0781). Soil exchangeable Ca increased by 0.29 $cmol_c$ kg^{-1} (p = 0.0006) with the first increment (1X) of Tilemsi RP and did not change with further increase in Tilemsi RP rate (slope = -0.08, p = 0.3575).

Gafsa RP also increased soil Bray 1-P levels in both 2005 (slope = 1.57 mg kg^{-1}, $p = 0.0002$) and 2006 (slope = 3.46 mg kg^{-1}, $p < 0.0001$) (Table 5.17). Gafsa RP rate quadratically increased soil exchangeable Ca in 2005. Exchangeable Ca increased by 0.25 cmol$_c$ kg^{-1} ($p < 0.0001$) with the first increase of Gafsa RP by 1X and then remained constant (slope = -0.09 cmol$_c$ kg^{-1}, $p = 0.2355$) in 2005. However, Exchangeable Ca linearly increased in 2006 (slope = 0.22 cmol$_c$ kg^{-1}, $p < 0.0001$). Soil Ca saturation also increased linearly with the increase in Gafsa RP rate (slope = 4.80%, $p = 0.0069$) in 2005 and in 2006 (slope = 12.56%, $p < 0.0001$). This increase of exchangeable Ca, and Ca saturation are consistent with the increased Gafsa RP dissolution as measured by ΔNaOH-P in 2006 (slope = 6.94 mg kg^{-1}, $p = 0.0001$). Soil pH also increased in 2005 (slope = 0.12, $p = 0.0026$) while it did not change in 2006 (slope = 0.07, $p = 0.2272$). Soil acidity did not change in 2005 (slope = -0.07 cmol$_c$ kg^{-1}, $p = 0.194$) while pH was increasing. However, soil acidity dropped in 2006 (slope = -0.20, $p = 0.007$) and when soil pH did not change. These inconsistencies are difficult to explain. The changes in pH and KCl-extractable acidity over time for 0X plots and the plots receiving TSP are inconsistent.

Table 5.15. Effects of TSP rates on soil properties after harvest at Konobougou 2, 2005 and 2006.

TSP rates	Soil properties after harvest											
	pH$_{water}$ (1:1)		Acidity (cmol$_c$ kg^{-1})		Bray 1-P (mg kg^{-1})		Exchangeable Ca (cmol$_c$ kg^{-1})		ECEC (cmol$_c$ kg^{-1})		Ca saturation (%)	
	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006
0X	4.62	5.07	0.77	0.90	2.51	2.91	0.42	0.40	1.47	1.57	28.43	25.96
0.25X	4.73	4.52	0.83	0.92	2.52	2.75	0.54	0.50	1.74	1.71	31.28	29.13
0.5X	4.82	4.79	0.67	0.80	3.81	3.47	0.54	0.42	1.53	1.53	35.16	27.59
1X	4.79	4.67	0.70	0.93	5.05	2.88	0.46	0.36	1.45	1.55	31.28	22.97
2X	4.78	4.77	0.70	0.62	9.50	4.60	0.47	0.42	1.45	1.32	32.11	33.22
Lin.*	0.055	-0.051	-0.04	-0.13	3.61	0.82	-0.01	-0.02	-0.07	-0.15	0.66	-0.02
P-value	0.1498	0.6415	0.324	0.0727	<0.0001	0.1569	0.7164	0.5556	0.2383	0.0467	0.4834	0.2256
RMSE	0.0984	0.2930	0.1158	0.1847	0.8298	1.4864	0.0738	0.080	0.1294	0.1906	3.5023	2.2975

*parameter estimates of the linear regression

Table 5.16. Effects of Tilemsi RP rates on soil properties after harvest at Konobougou2, 2005 and 2006.

Tilemsi RP rates	Soil properties after harvest											
	pH$_{water}$ (1:1)		Acidity (cmol$_c$ kg^{-1})		Bray 1-P (mg kg^{-1})		Exchangeable Ca (cmol$_c$ kg^{-1})		ECEC (cmol$_c$ kg^{-1})		Ca saturation (%)	
	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006
0X	4.56	5.05	0.63	0.87	2.00	2.05	0.21	0.37	1.00	0.64	21.26	58.14
0.25X	4.77	4.74	0.70	1.25	4.61	3.98	0.24	0.42	1.10	0.68	21.55	62.58
0.5X	4.78	4.79	0.60	0.93	4.79	4.13	0.28	0.52	1.04	0.77	27.27	67.74
1X	4.88	5.02	0.60	0.77	7.88	7.63	0.32	0.66	1.12	1.02	28.47	65.79
2X	4.84	4.91	0.63	0.87	12.85	8.12	0.31	0.58	1.09	0.88	28.25	66.04
Lin.*	0.0.47	0.002	-0.013	-0.009	5.21	3.00	0.35	0.45	0.09	0.05	4.30	4.72
P-value	0.0014	0.8182	0.7593	0.5027	<0.0001	0.001	0.0037	0.021	0.1972	0.6764	0.0147	0.0781
Quad.**	-0.18						-0.12	-0.17				
P-value	0.006						0.0181	0.0092				
RMSE	0.0826	0.1946	0.1167	0.3708	2.5195	1.9352	0.0699	0.08456	0.1733	0.3466	4.1818	6.7596

*parameter estimates of the linear regression

**parameter estimates of the quadratic regression

Table 5.17. Effects of Gafsa RP rates on soil properties after harvest at Konobougou 2, 2005 and 2006.

Gafsa RP rates	Soil properties after harvest											
	pH_{water} (1:1)		Acidity ($cmol_c\ kg^{-1}$)		Bray 1-P ($mg\ kg^{-1}$)		Exchangeable Ca ($cmol_c\ kg^{-1}$)		ECEC ($cmol_c\ kg^{-1}$)		Ca saturation (%)	
	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006
0X	4.64	4.99	0.63	0.83	2.49	2.08	0.39	0.37	1.31	1.47	29.52	24.95
0.25X	4.70	4.75	0.80	0.97	2.35	2.50	0.43	0.41	1.56	1.69	27.53	24.89
0.5X	4.73	4.90	0.80	0.98	3.01	2.69	0.51	0.49	1.65	1.82	30.88	27.30
1X	4.85	4.96	0.63	0.70	4.59	6.32	0.63	0.71	1.62	1.71	39.31	41.42
2X	4.87	5.03	0.60	0.55	5.26	8.44	0.54	0.78	1.47	1.66	36.63	47.23
Lin.*	0.12	0.07	-0.07	-0.20	1.57	3.46	0.40	0.22	0.03	0.48	4.80	12.56
P-value	0.0026	0.2272	0.194	0.007	0.0002	<0.0001	0.001	<0.0001	0.7582	0.0772	0.0069	<0.0001
Quad.**							-0.16			-0.21		
P-value							0.0038			0.0906		
RMSE	0.0862	0.1548	0.1333	0.1685	0.8215	1.1395	0.0667	0.0737	0.2323	0.1786	4.0932	4.8266

*parameter estimates of the linear regression

**parameter estimates of the quadratic regression

5.5.3. Keur Madieng

5.5.3.1. Effects of P material type and rate on millet yield

Millet grain yields were extremely low or even nonexistent in certain plots. They were, thus, not considered an accurate representation of plant response to the rock phosphate. Millet dry biomass yields were used as the response variable for the LRP and other analyses involving millet yield. Millet biomass yield linearly increased with TSP application rates from 1072.7 kg ha^{-1} at 0X to 2643.3 kg ha^{-1} at 2X (Figure 5.23) with a slope of 705.58 kg ha^{-1} (for each 1X) ($p = 0.0017$) indicating that the site was, indeed, deficient in phosphate. The parameter estimates of quadratic regression analysis were not significant (Lin. = 1442.72, $p = 0.0702$; Quad. = -357.40, $p = 0.3245$). The application of Tilemsi and Taiba rock phosphates (RP), however, did not significantly increase the dry biomass yield according to both linear and quadratic coefficients ($p = 0.1887$ and 0.1047, respectively) and quadratic ($p_{lin.} = 0.104$ and $p_{quad.} = 0.1808$ for Tilemsi RP; and $p_{lin} = 0.1642$ and $p_{quad} = 0.3136$ for Taiba RP) regression analyses (Figures 5.24 and 5.25). This absence of millet response to Tilemsi and Taiba RP was probably due the large variability in the field (CV = 45 and 42%, respectively). Millet response to different rates of Gafsa RP was described by a quadratic equation (Figure 5.26). Millet dry biomass yield increased with the application of Gafsa RP up to rate 0.5X (slope = 1982.9 kg ha^{-1}, $p = 0.0143$). A further increase in Gafsa RP rate over 0.5X did not significantly decrease millet dry biomass yield (slope = -427.4 kg ha^{-1}, $p = 0.1196$) (Figures 5.26). The failure of millet dry biomass to

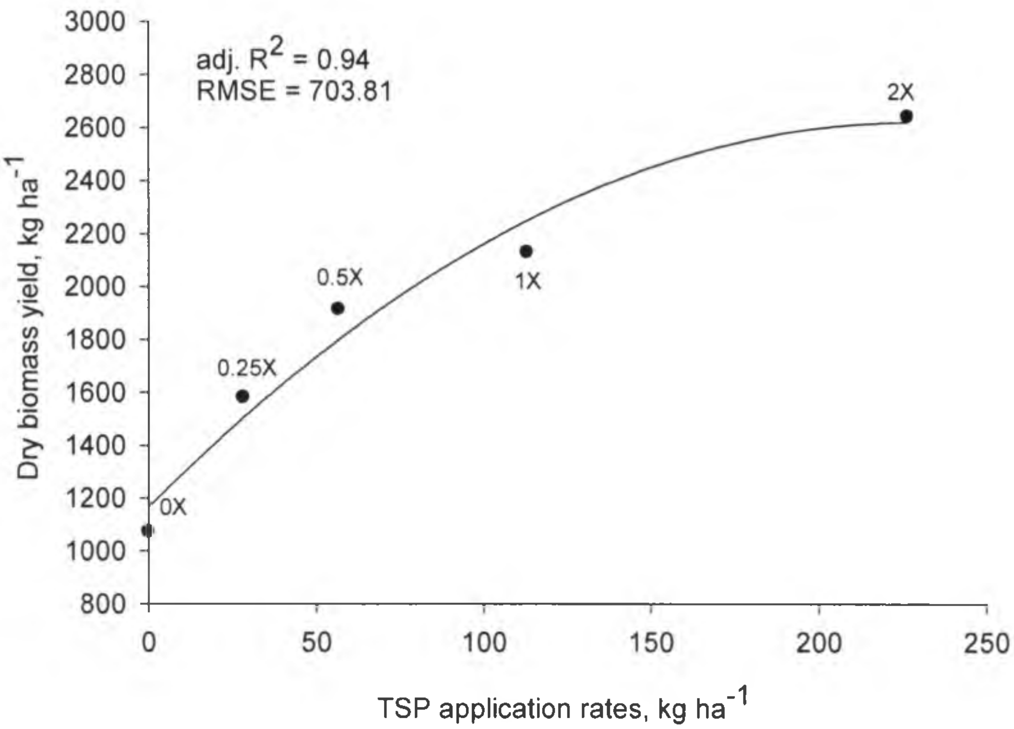

Figure 5.23. Millet response to the application of TSP, 2005 (Keur Madieng, Senegal).

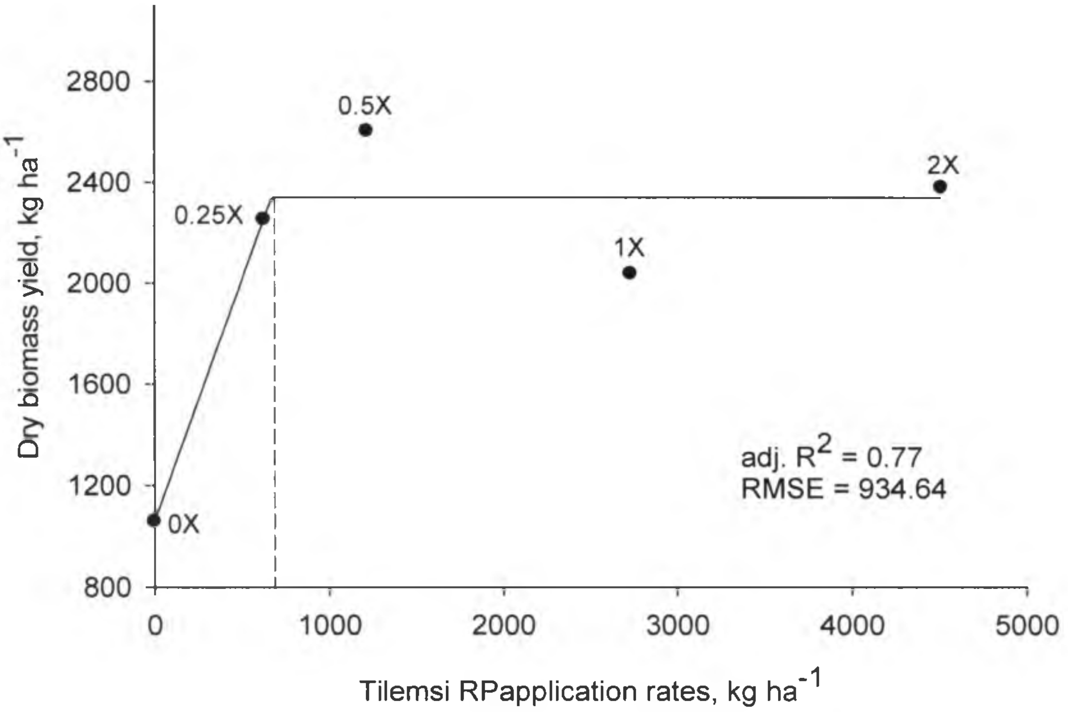

Figure 5.24. Millet response to the application of Tilemsi RP, 2005 (Keur Madieng, Senegal).

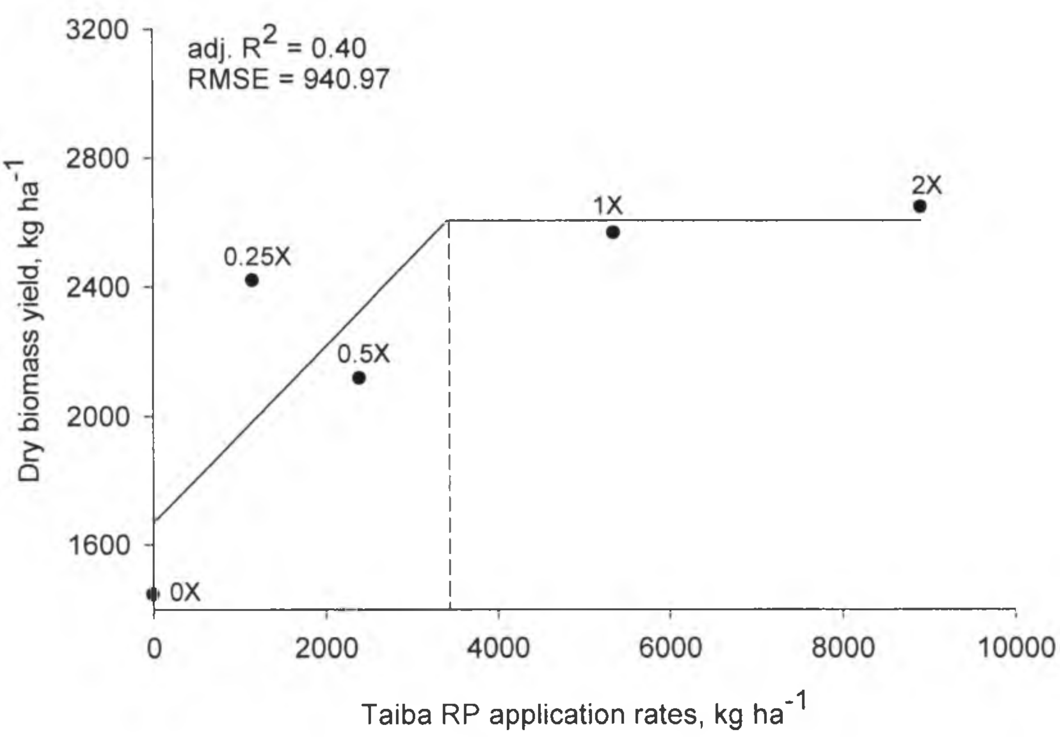

Figure 5.25. Millet response to the application of Taiba RP, 2005 (Keur Madieng, Senegal).

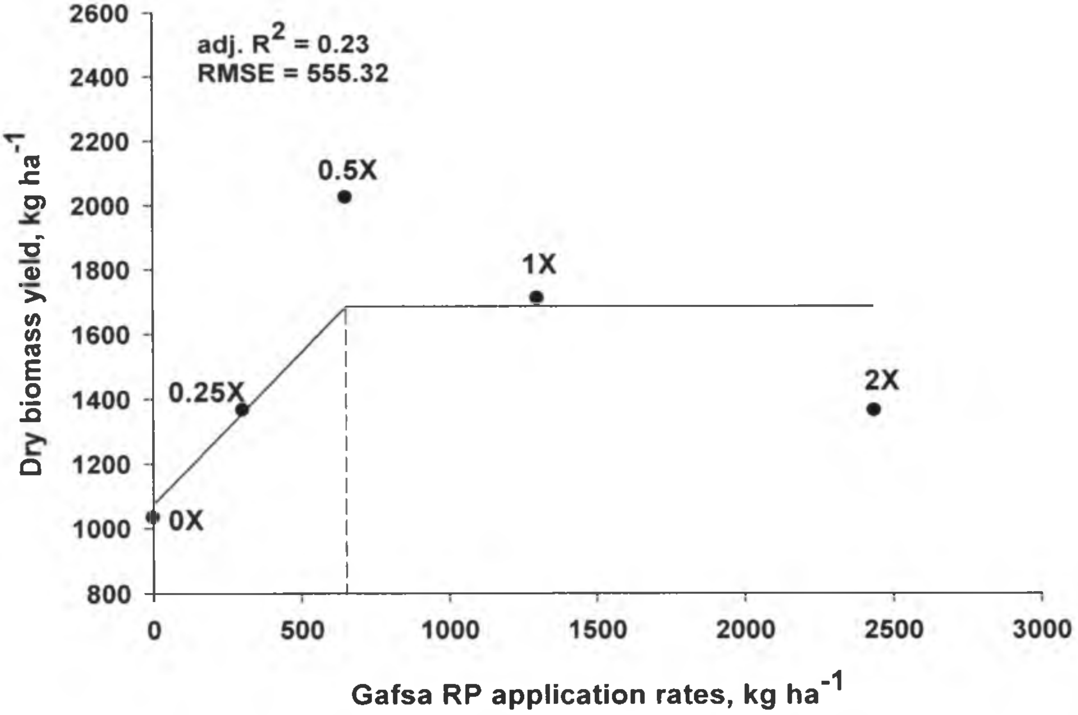

Figure 5.26. Millet response to the application of Gafsa RP, 2005 (Keur Madieng, Senegal).

increase to applications greater than 0.5X of Gafsa RP may be due to the presence of free carbonates and, consequently, the liming potential of the material (Table 5.3) coupled with the low acidity level and ECEC of Keur Madieng soil (Table 5.9).

The linear response plateau (LRP) was not used for TSP because the plateau was not well defined (yield was still increasing at 2X TSP application rate). The amount of Gafsa RP needed for producing maximum yield as estimated by LRP was 652 kg Gafsa RP ha^{-1}, rather than 1301 kg ha^{-1} predicted by the algorithm (Figure 5.26 and Table 5.18). The rock P algorithm thus appears to overestimate the amounts of RP needed for producing maximum yield for Gafsa RP. Due to the large variability which resulted in the nonsignificance in the yields produced by Tilemsi and Taiba application rates, no strong inference could be made regarding the LRP analysis and consequently the accuracy of the RP algorithm predictions for Taiba RP could not be decisively tested.

Table 5.18. Rock P algorithm predicted rates and observed rates using a linear response plateau model (LRP) for maximum yield (Keur Madieng).

RP	Predicted Amount (1X) (kg ha^{-1})	Observed Maximum (LRP node) (kg ha^{-1})
Gafsa	1301	652
Tilemsi	2734	674
Taiba	5361	3416

5.5.3.2. Effects of soil Bray 1-extractable P on crop yields

Millet biomass yields reached a maximum at generally similar levels of extractable P as measured by the Bray 1 method for all RP, even TSP (Figures 5.27 and 5.28). The biomass yield increased with the increases in Bray 1-extractable P level and then reached a plateau above 5.37 mg kg^{-1} in 2005 (Figure 5.27). This linear response plateau (LRP) estimated critical P level was less than the critical P level (11 mg kg^{-1}) used in the Phosphorus Decision Support System (PDSS) (Yost, 1992) and the critical P level (7.9 mg kg^{-1}) established by Bationo (personal communication) to obtain 90% of the maximum millet yield in the sandy soils of Niger. This low critical P level might be due to the presence of some other factors that are limiting. Factors most affecting yields were planting date, cultivation depth, insect control and crop nutrition (Jones and Wild, 1975). In fact, the conditions under which the experiment was implemented were not optimum, for instance the delayed planting date at the experiment at Keur Madieng and the locust attack.

Generally, peanut grain yields were extremely low. This might be due to the peanut aphid attack that coincided with flowering and the low plant population. In Mali, the average peanut yield in farmers' fields was about 800 kg ha^{-1} in 1995 (IER, 1995). The Bray 1-P critical level for peanut for producing maximum yield was about 8 mg kg^{-1} (Figure 5.28). Figure 5.27 indicates that a small increment in Bray1-P below 8 mg kg^{-1} can produce large increases in

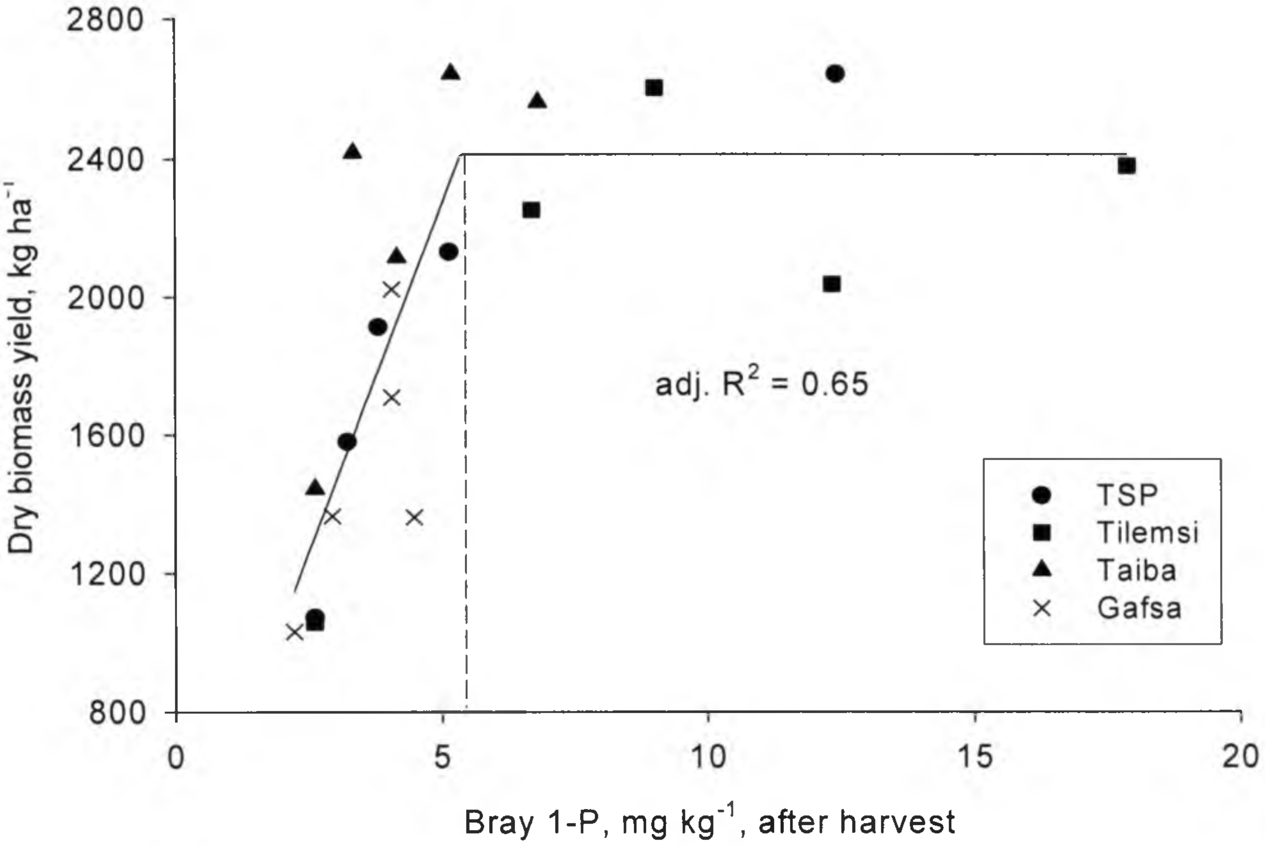

Figure 5.27. Millet response to soil Bray 1-extractable P levels (Keur Madieng, Senegal), 2005.

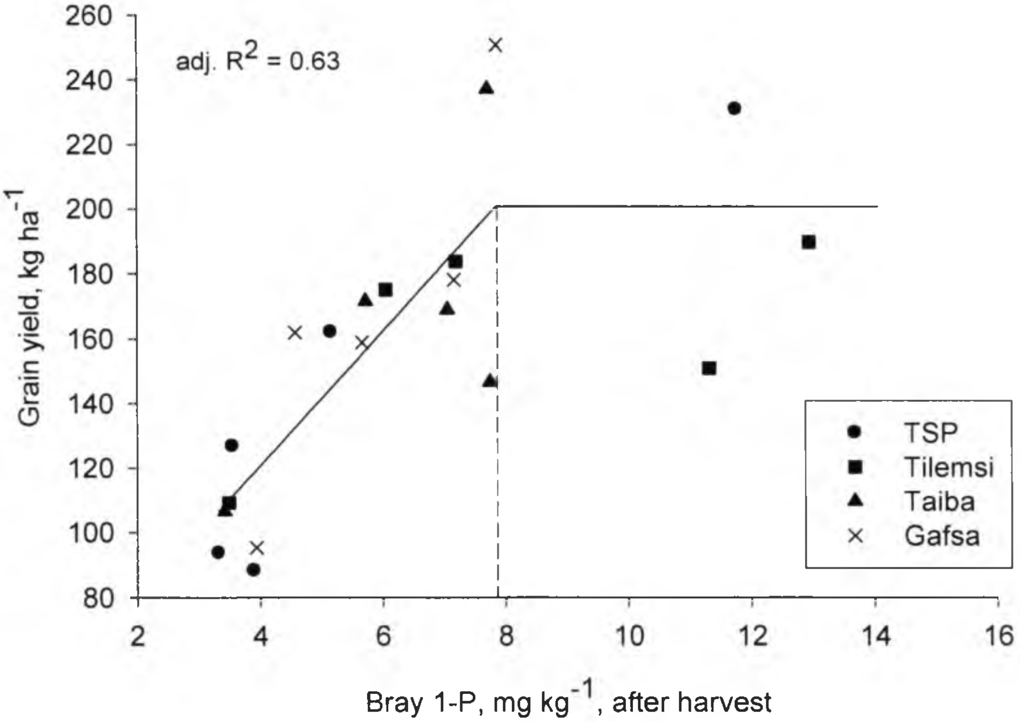

Figure 5.28. Peanut response to soil extractable P levels (Keur Madieng), 2006.

peanut yield. This response curve is a useful diagnostic tool for identifying P deficiency conditions.

As for Konobougou 1 and 2, millet response to Bray 1-P levels (Figures 5.27 and 5.28) seemed to follow the same path for TSP and all RPs. Conversely to the findings of Barnes and Kamprath (1975), Chien (1978) and Hammond et al. (1986b), these results suggest that Bray 1 method of measuring extractable P appears to be useful where both RPs and soluble P have been applied.

5.5.3.3. Effects of P materials and rates on RP dissolution as measured by ΔNaOH-P

ΔNaOH-P was generally low at Keur Madieng in 2005 (Figure 5.29). There was a highly significant linear increase in ΔNaOH-P level with the TSP application rates (slope = 6.39 mg kg^{-1}, $p < 0.0001$) (Figure 5.29.a)). Gafsa RP dissolution as measured by ΔNaOH-P was not significantly affected by the rate of application (linear = 4.80 mg kg^{-1}, p = 0.0594; quadratic = -1.79 mg kg^{-1}, p = 0.1278) (Figure 5.29.b). The quasi absent dissolution obtained from Gafsa RP might be due to the calcium carbonate equivalent (CCE) (Table 5.3) and the presence of $CaCO_3$ in the material coupled with the properties of Keur Madieng soil (low acidity and relatively high Ca saturation). For Tilemsi RP, the increase in rate of application resulted into a linear increase in ΔNaOH-P (slope = 3.20 mg kg^{-1}, p = 0.0283) (Figure 5.29c). Taiba RP dissolution, as affected by the rates of application, was described by a quadratic equation (linear =13.65 mg kg^{-1}, p =

0.007; quadratic = -5.29 mg kg^{-1}, p = 0.0222). Taiba RP dissolution increased up to rate 1X with a slope = 8.62 mg kg^{-1} (p = 0.0017) and then remained constant over rate 1X (slope = -3.43 mg kg^{-1}, p = 0.3997) (Figure 5.29d). The lack of increase in ΔNaOH-P at Taiba RP application rate 2X is probably due to the fact that a very large amount of Taiba RP (8900 kg ha^{-1}) was applied. At such a high rate, RP probably affected soil properties, resulting in a negative feedback on the RP dissolution (Table 7). If rock phosphates are compared among themselves,

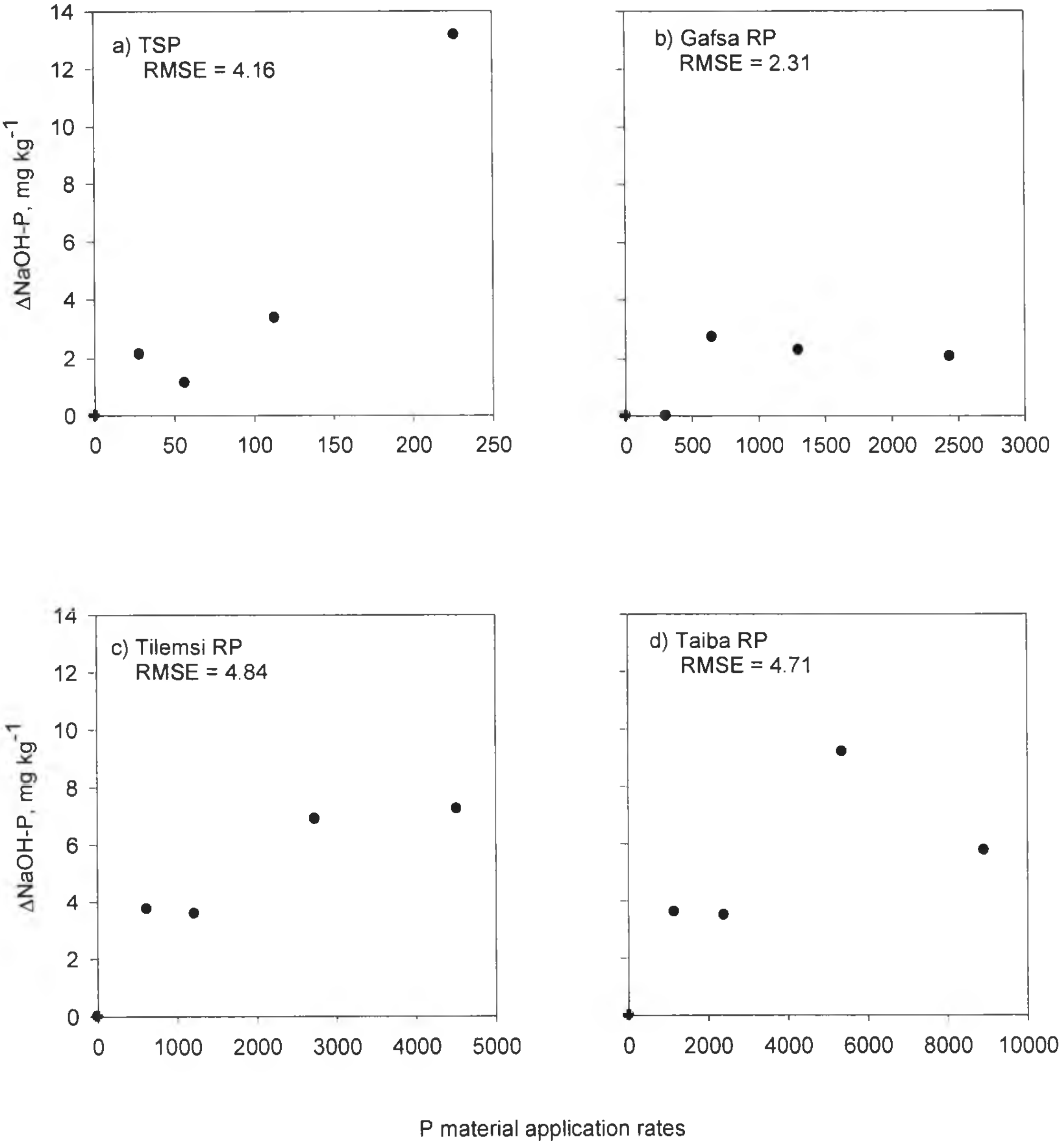

Figure 5.29. Changes in NaOH-P in P-treated soils at Keur Madieng (2005).

the initial slopes of dissolution were in the following order Gafsa < Tilemsi < Taiba. The order of dissolution expected was Gafsa> Tilemsi >Taiba according to their solubility in neutral ammonium citrate (van Kauwenbergh, 1997). Solubility data may have explained these differences in dissolution; however that analysis could not be done because of technical constraints.

The ΔNaOH-P levels after harvest of the experiment at Keur Madieng in 2006 are presented in Figure 5.30. ΔNaOH-P linearly increased with application rates of TSP (slope = 7.07 mg kg^{-1}, $p < 0.0001$) (Figure 5.30a) and Gafsa RP (slope = 3.63 mg kg^{-1}, $p = 0.0031$) (Figure 5.30b). The quadratic regression was not significant for Gafsa RP (linear = 10.89 mg kg^{-1}, $p = 0.0119$; quadratic = -3.52mg kg^{-1}, $p = 0.0714$). The trends of Tilemsi and Taiba RPs dissolution were quadratic (linear = 24.41 mg kg^{-1} with $p = 0.0025$; quadratic = -7.98 mg kg^{-1} with $p = 0.0260$ for Tilemsi RP and linear = 18.89 mg kg^{-1} with $p = 0.0133$, quadratic = -6.45 mg kg^{-1} with $p = 0.05$ for Taiba RP). Tilemsi and Taiba RPs dissolution increased by 16.78 mg kg^{-1} ($p < 0.0001$) for Tilemsi RP and by 18.89 mg kg^{-1} ($p = 0.0133$) for Taiba RP with each increase by 1X of RP. Over 1X, the dissolution essentially stopped and remained constant both for Tilemsi RP (slope = -1.23 mg kg^{-1}, $p = 0.8554$) and Taiba RP (slope = -6.45 mg kg^{-1}, $p = 0.9924$) (Figures 5.30c and 5.30d). The decrease in Ca (from 0.55 $cmol_c$ kg^{-1} to about 0.39 $cmol_c$ kg^{-1}, on the average for the plots receiving 0X RP) and Ca saturation (from about 50% to about 30% in average for plots receiving 0X RP) between the beginning and the end of the experiment in 2005 could explain why all the RPs performed

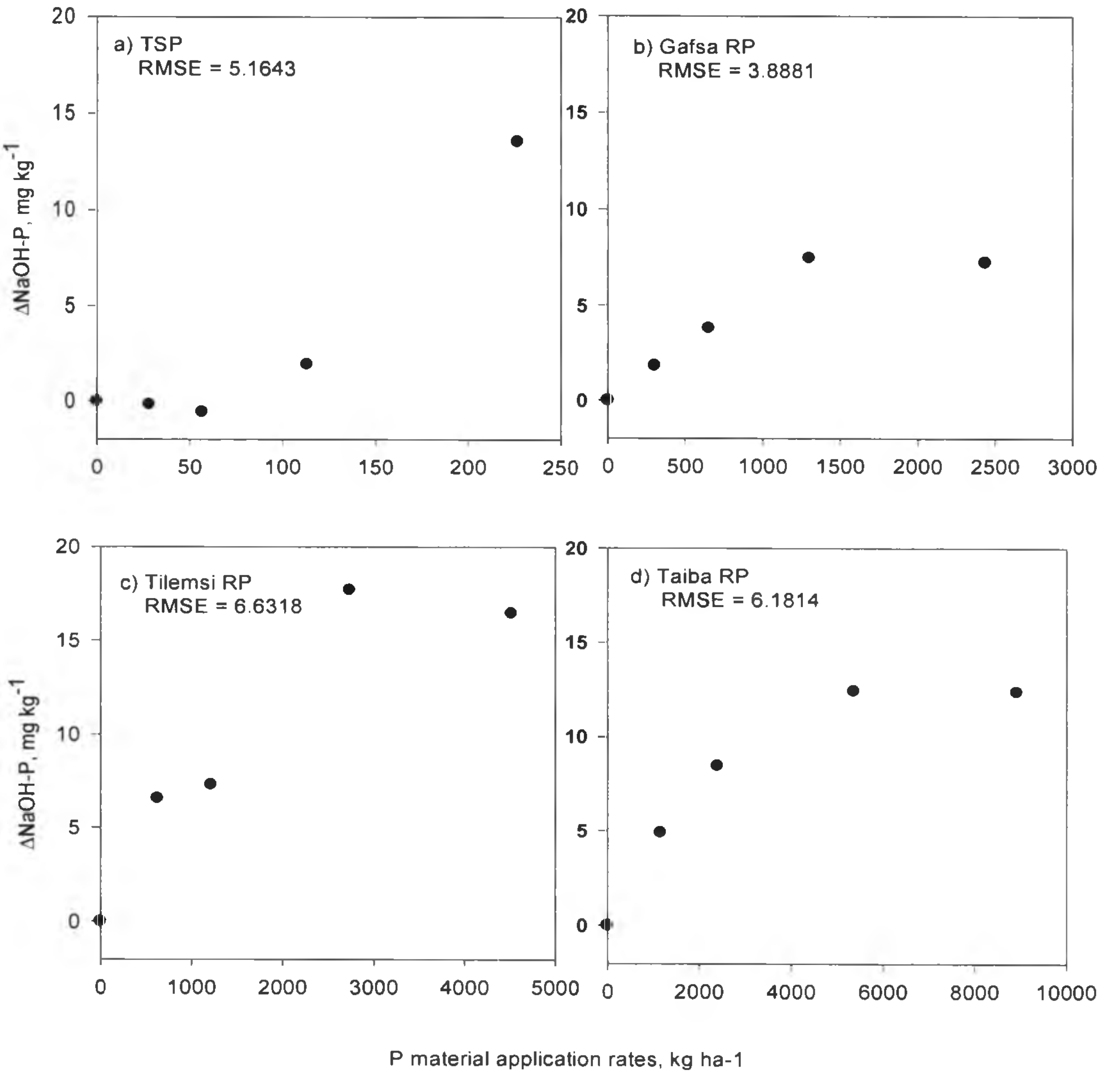

Figure 5.30. Changes in NaOH-P in P-treated soils after harvest at Keur Madieng (2006).

better in 2006 compared to 2005. We suggest that the lack of increase in ΔNaOH-P at higher application rates of Tilemsi and Taiba RPs is due to the effect of the RPs on soil properties: the increase in exchangeable Ca and Ca saturation with Tilemsi and Taiba RPs rates negatively affected their dissolution. The soil at Keur Madieng has so little capacity to absorb the Ca resulting from rock phosphate dissolution that high levels of application may lead to high Ca and could cause a reduction in dissolution. The better performance of Tilemsi RP compared to that of Taiba RP in 2006 than in 2005 might be due to the increase in Ca and Ca saturation, and the decrease in the KCl-extractable acidity at the end of 2005 caused by Taiba RP application, which may have slowed the dissolution in 2006. Tilemsi RP did not affect soil Ca level, Ca saturation nor KCl-extractable acidity in 2005, which favored the dissolution in 2006.

5.5.3.4. Relationship between ΔNaOH-P and ΔCa

When rock phosphate dissolves both P and Ca are released. Consequently, the changes in Ca may also be useful to quantify dissolution between RP-treated and untreated soil. However, a very weak linear positive relationship (r = 0.32) was detected between ΔNaOH-P and ΔCa at Keur Madieng in 2005 (Figure 5.31). This lack of a high correlation may be due to the loss of Ca that could occur in field conditions by leaching and plant uptake. Jones and Wild (1975) reported that leaching losses of Ca plus Mg at Bambey ranged from 20 to 79 kg/ha/year from natural soil levels, which are already very low.

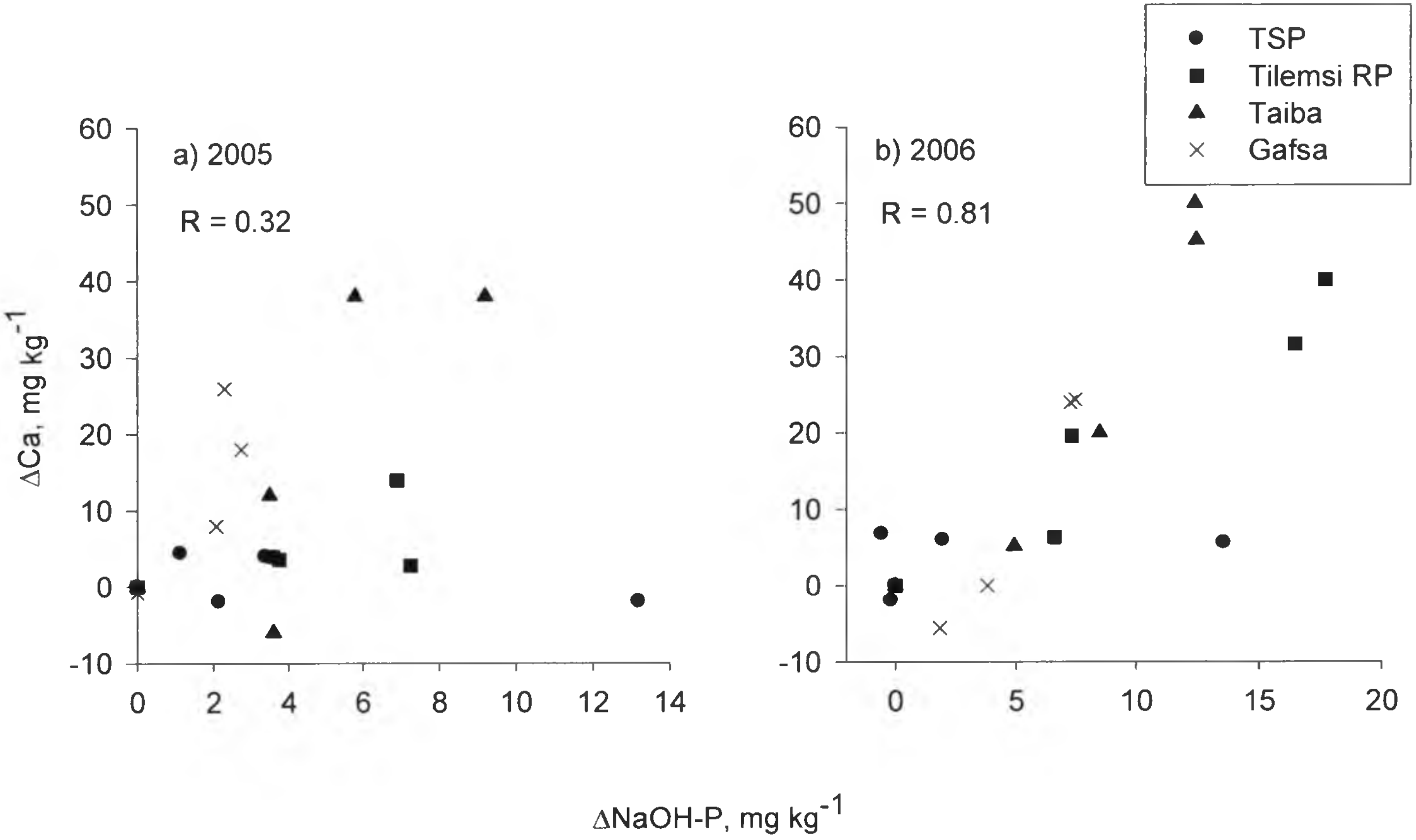

Figure 5.31. Relationship between ΔNaOH-P and ΔCa after harvest at Keur Madieng (2005 and 2006).

This number would be much higher with freshly applied materials (Yost, personal communication). In 2006 the correlation between ΔCa and ΔNaOH-P was stronger than in 2005 probably because of the decrease (120 mm) in the amount of rainfall in 2006 compared to that of 2005, which could have resulted in a less leaching of the Ca released during the dissolution of the RPs. These results suggest that ΔCa is not a good estimate of dissolved RP in field conditions on sandy soils with moderately high rainfall.

5.5.3.5. Effects of P material rate and type on soil properties

The effects of P material type and rate on soil properties in 2005 and 2006 are presented in Tables 5.19 through 5.22. The large variability in the soil properties makes the interpretation of the effects of P material rate and type on soil properties difficult.

Both in 2005 and 2006, there was no apparent effect of high rates of application on soil pH, even Gafsa RP which has a $CaCO_3$ equivalent (CCE) of 51.7% and contained some $CaCO_3$ (the presence of $CaCO_3$ was concluded based on the effervescence when treated with a solution of HCl). The effects of the P material rate and type were statistically evident, however, on the soil Bray 1-P level. Bray 1-P linearly increased with the increase of rate of application of TSP (slope = 4.92 mg kg^{-1}, $p < 0.0001$), Tilemsi RP (slope = 7.09 mg kg^{-1}, $p < 0.0001$) and Gafsa RP (slope = 0.92 mg kg^{-1}, $p = 0.0136$). However, the increase in Taiba RP up to initially increased soil Bray 1-P level by 3.84 mg kg^{-1} (p =

0.0015) and a further increase of Taiba RP up to 2X did not significantly change soil Bray 1-P (slope = -1.80 mg kg^{-1}, p = 0.2759), thus following the same pattern as ΔNaOH-P.

In 2006, the residual effect of increasing TSP application rate on Bray 1-P level was described by a quadratic equation (Table 5.19). The residual effect of TSP rates up to 1X did not cause the Bray 1-P level to increase (slope = 1.87 mg kg^{-1}, $p < 0.0574$). This lack of increase in Bray 1-P level might be due to the fact that TSP is soluble and that all the P from the fertilizer would have strongly reacted with the soil constituents. Further increases in TSP rate significantly increased the Bray 1-P level (slope = 8.91 mg kg^{-1}, p = 0.0146). For all RP materials also, the application rate quadratically affected soil Bray 1-P (Tables 5.20, 5.21 and 5.22). The increment in Bray 1-P per unit (1X) increment of RP rates was as follows: 9.26, 3.84 and 4.00 mg kg^{-1} for Tilemsi RP (p = 0002), Taiba RP (p = 0.0013) and Gafsa RP (p = 0.0005), respectively. However, further increase in the application rate did not significantly affect Bray 1-P level. The trends of the Bray 1-P levels are consistent with that of ΔNaOH-P, which initially increased for Tilemsi and Taiba RPs and then remained constant. However, the changes in Bray 1-P due to the increase in Gafsa RP rates did not follow the linear increase in ΔNaOH-P.

Soil exchangeable Ca levels did not change with the application rates of TSP and Tilemsi RP, but they did linearly increase with Taiba RP application rates (slope = 0.12 $cmol_c$ kg^{-1}, p = 0.0107) in 2005. However, even before the application of the P material, the exchangeable Ca levels were higher for Taiba RP at rates 1X and 2X compared to the control (Table 5.23). The effects of the P material type and rate on the soil exchangeable Ca levels were probably masked by the leaching of this element. The relationship between exchangeable Ca and Gafsa application rates was described by a quadratic equation in 2005 (Table 5.22) The increase in Gafsa RP application rate up to 1X increased soil exchangeable Ca level (slope = 0.14 cmolc kg^{-1}, p = 0.0268) and flattened out with further increases in the application (slope = -0.09 $cmol_c$ kg^{-1}, p = 0.1754). This pattern did not agree with the linear increase in ΔNaOH-P caused by the increase in Gafsa RP application rate probably because of the leaching that could take place in Keur Madieng soil.

The increased application of all RPs probably caused the soil exchangeable Ca levels to rise in 2006. The application of Taiba and Gafsa RPs linearly increased the exchangeable Ca (slope = 0.13 cmolc kg^{-1}, p = 0.0052 for Taiba RP and 0.08 $cmol_c$ kg^{-1}, p = 0.0083 for Gafsa RP). For Tilemsi RP, the relationship was quadratic (Table 5.20). Soil exchangeable Ca increased by 0.21 $cmol_c$ kg^{-1} with the first 1X increment of Tilemsi RP and then flattened out with further applications of Tilemsi RP (slope = -0.04 $cmol_c$ kg^{-1}, p = 0.4342). This pattern of the effect of Tilemsi RP rates on soil exchangeable Ca agreed with ΔNaOH-P pattern for Tilemsi in 2006. Only TSP did not affect the soil Ca levels. This is not surprising because probably all the Ca from TSP – a soluble material, leached out from the soil during the first year of cropping. The increase in the soil

Ca levels receiving RP was due to the fact that RPs slowly dissolved and releases Ca more gradually and also because of the smaller amount of rainfall received in 2006 (676 mm) compared to 2005 (788 mm) which probably reduced the amount of Ca leaching that took place. This increase in Ca content was also depicted in increased Ca saturation for Tilemsi and Taiba RPs.

Calcium saturation after harvest statistically increased only for Taiba RP in 2005 (Table 5.21). This could be explained by the higher initial Ca saturation (prior to the application of the material) of the plots receiving 1X and 2X Taiba RP. However, Taiba RP dissolution as measured by ΔNaOH-P also increased which could also increase Ca saturation. Both Tilemsi and Taiba RPs increased the Ca saturation in 2006, probably because of the increase in slopes of ΔNaOH-P with the increased rates of application (from 3.20 mg kg^{-1} in 2005 to 16.78 mg kg^{-1} in 2006 for Tilemsi RP and from 8.62 mg kg^{-1} in 2005 to 18.89 mg kg^{-1} in 2006 for Taiba RP). Gafsa RP did not increase soil Ca saturation even though there was an increase in soil exchangeable Ca, which is contradictory with our expectation.

Soil KCl-extractable acidity was affected only by the rates of application of Taiba TP in 2005 (slope = -0.144 $cmol_c$ kg^{-1}, p = 0.0229). This is probably due to the higher rate of Taiba dissolution (13.65 mg kg^{-1}) compared to Tilemsi and Gafsa RPs (3.20 and 5.08 mg kg^{-1}). However, we expected Gafsa RP to affect soil pH because of its higher CCE. Soil KCl-extractable acidity was not affected by any of the RP materials in 2006.

Table 5.19. Effects of TSP rates on soil properties after harvest, 2005 and 2006 (Keur Madieng).

TSP rates	Soil properties after harvest											
	pH_{water} (1:1)		Acidity ($\text{cmol}_c\ \text{kg}^{-1}$)		Bray 1-P (mg kg^{-1})		Exchangeable Ca ($\text{cmol}_c\ \text{kg}^{-1}$)		ECEC ($\text{cmol}_c\ \text{kg}^{-1}$)		Ca saturation (%)	
	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006
0X	4.94	5.32	0.74	0.67	2.62	3.32	0.41	0.32	1.45	1.20	27.76	26.79
0.25X	4.95	5.25	0.70	0.93	3.22	3.55	0.40	0.31	1.42	1.49	28.83	23.19
0.5X	5.05	5.44	0.50	0.60	3.81	3.90	0.43	0.35	1.23	1.22	35.32	30.23
1X	4.95	5.41	0.64	0.67	5.14	5.15	0.43	0.35	1.37	1.27	32.03	29.19
2X	4.91	5.51	0.64	0.58	12.43	11.76	0.39	0.35	1.30	1.16	30.37	30.52
Lin.*	-0.003	0.11	-0.03	-0.09	4.92	-1.46	-0.005	0.02	-0.06	-0.07	10.57	2.48
P-value	0.4088	0.1862	0.6508	0.4259	<0.0001	<0.6347	0.8463	0.4668	0.4607	0.4803	0.1852	0.3363
Quad.**						3.35					-4.76	
P-value						0.0275					0.2019	
RMSE	0.1109	0.2771	0.2159	0.3925	2.5934	2.8120	0.0938	0.0745	0.2629	0.3637	7.1721	8.9384

*parameter estimates of the linear regression

**parameter estimates of the quadratic regression

Table 5.20. Effects of Tilemsi RP rates on soil properties after harvest, 2005 and 2006 (Keur Madieng).

Tilemsi RP rate	Soil properties after harvest											
	pH_{water} (1:1)		Acidity ($cmol_c\ kg^{-1}$)		Bray 1-P ($mg\ kg^{-1}$)		Exchangeable Ca ($cmol_c\ kg^{-1}$)		ECEC ($cmol_c\ kg^{-1}$)		Ca saturation (%)	
	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006
0X	4.99	5.46	0.60	0.49	2.62	3.49	0.42	0.34	1.29	1.05	33.20	32.72
0.25X	5.04	5.34	0.64	0.47	7.38	6.05	0.44	0.37	1.36	1.05	35.77	36.12
0.5X	4.99	5.51	0.58	0.48	8.40	7.19	0.44	0.43	1.31	1.16	35.35	41.11
1X	5.07	5.65	0.54	0.25	12.35	12.94	0.49	0.54	1.32	1.04	38.33	52.97
2X	5.02	5.49	0.54	0.36	17.89	11.32	0.44	0.49	1.22	1.08	37.21	47.62
Lin.*	0.01	0.054	-0.042	-0.084	7.09	13.58	0.01	0.31	-0.05	0.004	1.79	30.85
P-value	0.8067	0.4708	0.6120	0.2639	<0.0001	0.0034	0.7367	0.0002	0.5030	0.9564	0.5884	0.008
Quad.**						-4.66		-0.11				-11.10
P-value						0.0249		0.0022				0.0352
RMSE	0.1771	0.2603	0.2888	0.2593	4.8027	3.8378	0.0894	0.0633	0.2473	0.2561	11.5277	9.8086

*parameter estimates of the linear regression

**parameter estimates of the quadratic regression

Table 5.21. Effects of Taiba RP rates on soil properties after harvest at Keur Madieng, 2005 and 2006.

Taiba RP rates	Soil properties after harvest											
	pH_{water} (1:1)		Acidity ($cmol_c$ kg^{-1})		Bray 1-P (mg kg^{-1})		Exchangeable Ca ($cmol_c$ kg^{-1})		ECEC ($cmol_c$ kg^{-1})		Ca saturation (%)	
	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006
0X	5.00	5.37	0.68	0.62	2.63	3.42	0.38	0.33	1.30	1.17	29.36	28.25
0.25X	4.85	5.42	0.82	0.56	3.34	5.72	0.35	0.35	1.41	1.12	24.38	31.48
0.5X	4.97	5.50	0.60	0.49	4.33	7.05	0.44	0.43	1.32	1.16	33.25	38.79
1X	5.00	5.45	0.54	0.56	6.82	7.74	0.57	0.55	1.45	1.41	40.97	41.52
2X	5.01	5.41	0.46	0.40	5.17	7.70	0.57	0.58	1.33	1.25	42.55	45.49
Lin.*	0.04	0.002	-0.144	-0.09	6.67	6.59	0.12	0.13	0.002	0.07	8.36	7.95
P-value	0.3679	0.8114	0.0228	0.2386	0.003	0.0017	0.0107	0.0052	0.9799	0.5298	0.0036	0.0056
Quad.**					-2.60	-2.37						
P-value					0.011	0.0106						
RMSE	0.1455	0.2204	0.2086	0.2582	1.8591	1.6229	0.1466	0.1426	0.2771	0.3723	9.1059	8.9453

*parameter estimates of the linear regression

**parameter estimates of the quadratic regression

Table 5.22. Effects of Gafsa RP rates on soil properties after harvest at Keur Madieng, 2005 and 2006.

Gafsa RP rates	Soil properties after harvest											
	pH$_{water}$ (1:1)		Acidity (cmol$_c$ kg^{-1})		Bray 1-P (mg kg^{-1})		Exchangeable Ca (cmol$_c$ kg^{-1})		ECEC (cmol$_c$ kg^{-1})		Ca saturation (%)	
	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006
0X	4.99	5.56	0.68	0.52	2.23	3.94	0.37	0.39	1.32	1.16	29.85	36.06
0.25X	5.12	5.57	0.60	0.50	2.94	4.57	0.36	0.36	1.27	1.09	28.68	34.17
0.5X	5.06	5.58	0.48	0.49	4.07	5.66	0.45	0.39	1.21	1.08	37.33	37.81
1X	5.07	5.57	0.56	0.34	4.06	7.85	0.50	0.51	1.36	1.08	37.16	47.64
2X	5.01	5.59	0.62	0.43	4.48	7.16	0.41	0.51	1.27	1.16	33.08	44.41
Lin.*	-0.02	0.01	-0.06	-0.055	0.98	5.88	0.25	0.08	-0.0004	0.01	11.83	5.54
P-value	0.6598	0.7745	0.9293	0.3835	0.0136	0.002	0.0278	0.0083	0.9940	0.8353	0.4905	0.0624
Quad.**						-2.03	-0.11					
P-value						0.017	0.0397					
RMSE	0.1363	0.1586	0.2365	0.2189	1.2997	1.5561	0.1066	0.0953	0.1870	0.2186	9.2388	9.9968

*parameter estimates of the linear regression

**parameter estimates of the quadratic regression

Table 5.23. Exchangeable Ca of the soil at the Keur Madieng experiment prior to Taiba RP application

Taiba RP rate	Exchangeable Ca ($cmol_c\ kg^{-1}$)
0X	0.53
0.25X	0.44
0.5X	0.52
1X	0.70
2X	0.71
$LSD_{0.05}$	0.14

5.6. Conclusions

The millet growing soils are extremely infertile and sandy. Since soils were P deficient in all the sites, the application of P as TSP or RP generally increased crop yield except Tilemsi and Taiba RPs at Keur Madieng where variability was too high to statistically detect yield increases.

Because of the large variability in the field, the capability of the RP algorithm to accurately predict RP to meet crop P requirement was not well tested. However, from the results of Tilemsi RP at Konobougou 1 and those of Gafsa RP at Keur Madieng, the algorithm seems to overestimate amounts of RP needed. More experiments in more controlled conditions are needed to draw strong inferences about the accuracy of the RP algorithm. However, we can conclude that the extremely high RP application rates (greater than 1X) are not needed.

Nonetheless, the experiments showed that it is important to match soil and RP properties when opting for the use of RP to correct P soil P deficiency. The choice of RP to be applied should include consideration of the plant, soil properties, rock phosphate properties, as well as the site characteristics and management options. For example, highly reactive RPs with a CCE of about 50% are not the most suitable for sandy soils with pH close to 5.5 and with low buffering capacity because the low acidity could be neutralized by the RP material and soil Ca could be increased, thus depressing RP dissolution.

The rock phosphate algorithm tested in these field experiments considers only soil properties. The different results obtained from Konobougou 1 and 2 experiments using Tilemsi RP (same origin but most probably different sampling time) support the need for generalizing the algorithm to the broader range of RP by the inclusion of the RP properties which would affect the most RP dissolution into the algorithm.

For a given crop, one single Bray 1-P critical level could be used to identify P deficiency conditions and predict amounts of P both from water-soluble P and RP needed to meet crop P requirements. Considering that millet grain yield was disastrously low at Keur Madieng, the Bray 1-P critical level for producing maximum millet yield for millet producing soils of West Africa varied between 7 and 11 mg kg^{-1}. Additional study can be conducted to validate the critical P value for millet.

Because of the high susceptibility of Ca to be lost either by leaching or by plant uptake, ΔCa cannot be recommended as a measure of RP dissolution in field conditions.

Chapter 6. The effect of leaching on Tilemsi RP dissolution

6.1. Abstract

In order to supply the nutrient phosphorus (P) to plants rock phosphate (RP) must first dissolve. Closed incubation systems were often used to study RP dissolution. Such laboratory incubation studies are a convenient way to study dissolution; however, they have some disadvantages. One problem is that the exchange sites for the dissolution products namely Ca^{2+} and $H_2PO_4^-$ can be rapidly saturated in such conditions, resulting in the cessation of the dissolution process. We hypothesize that more RP dissolution could take place in an open-incubation system where the dissolution products such as Ca are removed from the soil solution by leaching. A study was conducted to evaluate the limitation of Tilemsi RP dissolution in a soil from Keur Madieng, Senegal. Closed- and open-incubation systems were compared. Rock phosphate dissolution was estimated using both the changes (Δ) in NaOH-P and exchangeable Ca in the RP-treated soil compared to the untreated soil. The losses of Ca were also monitored in the percolating water. Generally, not much dissolution (about 4 to 5%) occurred in either system. However, both ΔNaOH-P and ΔCa methods showed that more dissolution occurred in the open system. A maximum of 24 mg P kg^{-1} and 33.5 mg Ca kg^{-1} was released in the open system compared with 20 mg P kg^{-1} and 27 mg Ca kg^{-1} in the closed system. The greater dissolution appeared to be due to the leaching of the Ca with the percolating water (19 to 25% of the dissolved Ca).

The dissolution decreased and eventually stopped by the end of the incubation period probably because of the lack of soil acidity and insufficient P exchange sites. Although the open-incubation systems better approximated field conditions than the closed system, the additional dissolution of Tilemsi RP in the open system could not fully explain the overestimation of the RP requirement that occurred in the Keur Madieng, Senegal experiment.

6.2. Introduction

The rock phosphate dissolution studies in soil that were considered in the development the proposed algorithm (Diarra et al., 2004) were developed in a closed incubation, that is there was no leaching of reaction products from the soil. Most incubation studies have been conducted in such closed-incubation systems where dissolution products accumulated (Smyth and Sanchez, 1982; Mackay et al., 1986; Syers and Mackay, 1986; Yampracha et al., 2005 et 2006). In these conditions, RP dissolution increases and then reaches an equilibrium within less than 60 days of incubation. Assuming moisture and acidity are not limiting for RP dissolution to continue, the dissolution products (especially Ca^{2+}, $H_2PO_4^-$) must be removed from the system and low Ca and $H_2PO_4^-$ levels must be maintained in the vicinity of the RP particles in order to simulate field conditions. The $H_2PO_4^-$ ions usually react with soil Fe and Al compounds maintaining a low soil solution P level. On the other hand, the Ca^{2+} is expected to be held by soil's exchange complex. Soils with high cation exchange capacity

(Mackay et al., 1986) and high organic matter, which provide exchange sites to hold Ca, enhance RP dissolution (Khasawneh and Doll, 1978). Mackay et al. (1986) and Yampracha et al. (2005) have also shown that soil with high P-soption capacity promotes RP dissolution. In soils where RP dissolution has reached an equilibrium, Robinson et al. (1992) and Robinson and Syers (1991) were able to create conditions for dissolution to continue by using Ca-exchange resin or Fe_2O_3, respectively, as artificial "sinks" for Ca and P. The fact that RP dissolution reaches an equilibrium in a closed-incubation system was attributed to the size of the "sink" for additional Ca (Hanafi et al., 1992; Robinson and Syers, 1990). The removal of Ca^{2+} and $H_2PO_4^-$ by plant uptake or leaching under field conditions could provide a supplementary "sink" for the dissolution products. Those field conditions are probably better mimicked by an open-incubation system in which leaching is allowed to occur than a closed-incubation system.

6.3. Hypothesis and Objective

Rock P dissolution would be greater in an open-incubation system than in a closed-system due to the removal of Ca from the system. The additional exchange sites for Ca would promote further dissolution.

The objective was to compare the dissolution of Tilemsi RP in a closed-incubation and an open-incubation system.

6.4. Materials and Methods

Because of the overestimation of the predictions made by the RP algorithm for maximum yield in the field experiments conducted at Konobougou, Mali, 2004 (Mali) and at Keur Madieng (2005), an incubation study was set up to compare Tilemsi RP dissolution using Keur Madieng soil in open and closed systems. In the closed-incubation system, the soil was incubated in pots where the dissolution products accumulated in the system. In the open system, leaching occurred daily to remove the dissolution products.

6.4.1. Soil

Surface (0 – 15 cm) soil samples from the Keur Madieng, Senegal field site were selected for the laboratory experiment. The soil was air-dried and ground to pass through a 2-mm sieve. Particle size distribution was determined by the pipette method. Soil pH was measured in water (1:1). Bray 1-P was determined by shaking 2 g soil with 14 ml 0.03 *M* NH_4F and 0.025 *M* HCl for 1 minute (Bray and Kurtz, 1945). The P concentration was determined by the colorimetric method of Murphy and Riley (1962). The acidity extractable by 1 *M* KCl was determined by the method described by Thomas (1982). Exchangeable cations were determined using the 1 *M* NH_4OAc, pH 7 extraction (Thomas, 1982) and measured by inductively coupled plasma spectroscopy (ICP). Selected soil properties of the soil are presented in Table 6.1.

Table 6.1. Selected properties of the soil used in the open and closed system study.

pH H_2O (1:1)	Bray 1-P (mg kg^{-1})	Clay (%)	KCl-extractable Acidity (cmol+ kg^{-1})	Exchangeable (cmol+ kg^{-1})				ECEC* (cmol+ kg^{-1})
				Ca^{2+}	Mg^{2+}	K^+	Na^+	
4.98	3.73	3	0.15	0.45	0.23	0.08	0.05	0.96

*sum of Ca^{2+}, Mg^{2+}, K^+, Na^+ and KCl-extractable acidity

6.4.2. Rock phosphate

Tilemsi rock phosphate from Mali with a medium solubility based on the solubility in neutral ammonium citrate (Chien et al., 2003) was used in this incubation study (Table 6.2). The rock phosphate was sieved to pass through a 100-mesh sieve. The total P and water-soluble P were measured using the Houba et al. (1995) procedure. Total P and water-soluble P were both determined by colorimetric method (Murphy and Riley, 1962). The calcium carbonate equivalent (CCE) was determined by boiling 1 g of RP with 50 ml 0.5 *M* HCl for 5 minutes and measured by titration with 0.25 *M* NaOH to pH 5 (Sikora, 2002).

Table 6.2. Some characteristics of Tilemsi rock phosphate.

Origin	P ($g\ kg^{-1}$)	Ca* ($g\ kg^{-1}$)	Water-soluble P ($mg\ kg^{-1}$)	CCE** (%)
Mali	112.6	305	4.11	35.5

*Yampracha et al., 2006.

**CCE = calcium carbonate equivalent

6.4.3. Incubation

A factorial RP x incubation system x time of incubation (2x2x8) study was conducted with 3 replicates. The ground Tilemsi RP levels were 0 and 500 mg P kg^{-1}. The incubation method study included an open- and a closed-incubation system. The incubation times were 0, 1, 3, 7, 14, 28, 42 and 56 days. The RP material was added to 50 g of soil to achieve the rates given above (0 and 500 mg P kg^{-1}).The mixtures were placed in a pot without a drain for the closed system and in ceramic funnels with a vacuum for the open system. For both systems, the moisture was maintained at field capacity and the mixtures were incubated during a 56-day period. The soils in the open system were percolated daily with an amount of water corresponding to the one received in the field experiment site with a rainfall of 650 mm per year distributed over 3-month period (56 ml per day). The percolates were collected daily and the amount of calcium leached was measured at 1, 3, 7, 14, 28, 42 and 56 days. Soil samples were also collected at times 0, 1, 3, 7, 14, 28, 42 and 56 days to determine the 0.5 *M* NaOH-P and exchangeable Ca. The differences in 0.5 *M* NaOH-P and exchangeable Ca between RP-treated and untreated soils were used as the estimates of dissolved RP.

6.4.4. Statistical analysis

The data were statistically analyzed using SAS procedures (1985). Analyses of variance were performed. The time effect on RP dissolution (ΔNaOH-P and ΔCa) was evaluated using the regression analysis. The correlation between ΔNaOH-P and ΔCa was also analyzed by SAS.

6.5. Results and Discussion

Tilemsi RP dissolution, as measured by ΔNaOH-P and ΔCa in the closed incubation system in Keur Madieng soil (Figure 6.1), was about 20 mg P kg^{-1} and 28 mg Ca kg^{-1} were released at day zero (1 hour) of the incubation. Further dissolution did not occur during the incubation period based on the results obtained from both ΔNaOH-P method (slope = 0.02 mg kg^{-1}, p = 0.2008) and ΔCa method (slope = -0.05 mg kg^{-1}, p = 0.3141). In other studies done in closed incubation system, RP dissolution also reaches equilibrium during a certain period of the incubation (generally before the 60th day of incubation) (Mackay et al., 1986; Diarra et al., 2004; Yampracha et al., 2005, 2006).

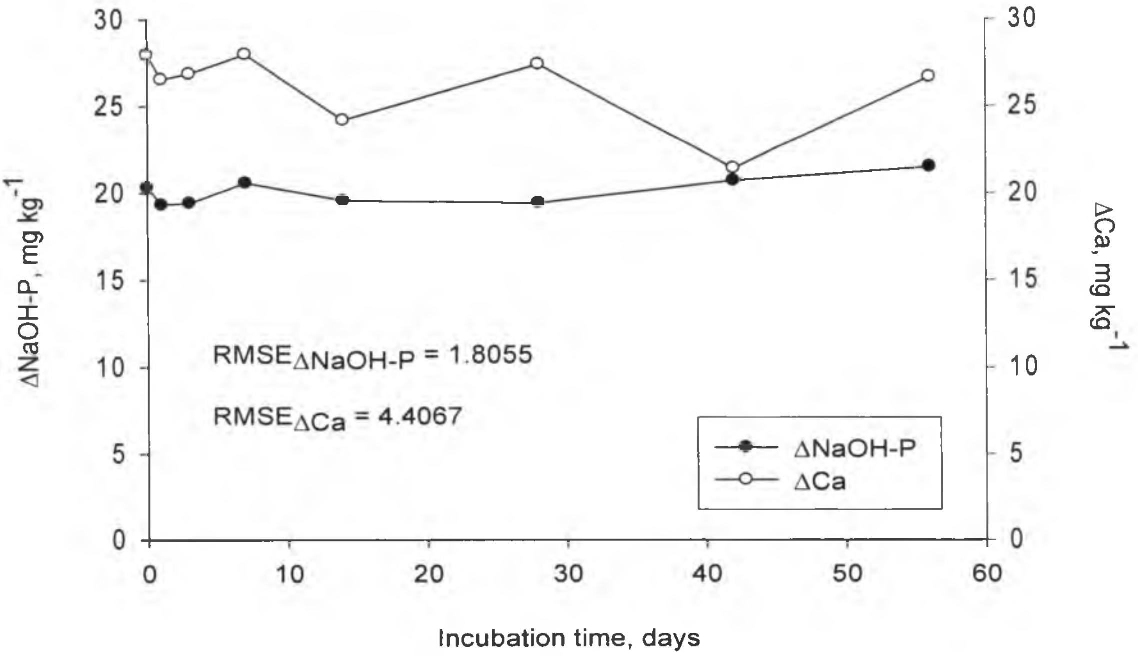

Figure 6.1. Changes in NaOH-P (ΔNaOH-P) and in exchangeable Ca (ΔCa) in Keur Madieng soil incubated with Tilemsi RP at 500 mg P kg^{-1} soil in a closed system.

Assuming, however, that Tilemsi RP can be represented by a hydroxapatite, the dissolution reaction will be as follows:

$Ca_{10}(OH)_2(PO_4)_6 + 14H^+ = 10Ca^{2+} + 2F^- + 6H_2PO_4^-$. [Eq.6.1]

Then for each mole of P released 2.33 moles of H^+ are consumed. For the extent of dissolution that occurred in the closed system (about 20.33 mg P kg^{-1}, which is equivalent to 0.66 mmol P kg^{-1} was released) 1.53 mmol H^+ has been consumed. Thus it seems that all the initial acidity of the soil was consumed. This is probably why the equilibrium seems to have been reached within 1 hour in the closed-incubation system. This could explain why RP dissolution has stopped soon after the initialization of the incubation. Conversely, Hanafi et al. (1992) suggested that the size of the Ca “sink” was responsible for the RP dissolution to stop in a closed incubation study using Gafsa RP and Christmas Island RP in several soils with contrasting P-retention capacity. Tilemsi RP dissolution as measured by ΔNaOH-P and ΔCa in closed and open-incubation system is presented in Figure 6.2.

Tilemsi RP dissolution over time as measured both by ΔNaOH-P and ΔCa in the open system was described by a quadratic relationship (linear = 0.38 mg P kg^{-1} with p = 0.0003, quadratic = -0.006 mg P kg^{-1} with p = 0.0015 for ΔNaOH-P method; and linear = 0.51 mg Ca kg^{-1} with p = 0.0077, quadratic = -0.09 mg Ca kg^{-1} with p = 0.0103 for ΔCa method). ΔNaOH-P method indicated that RP dissolution increased in the open system by 0.29 mg P kg^{-1} per day (p = 0.0144) up to day 14 and then reached a plateau (slope = -0.03 mg P kg^{-1} with p = 0.5518) whereas ΔCa increased by 0.61 mg Ca kg^{-1} per day (p = 0.0110) up to 14 days and flattened out (slope = -0.14 mg Ca kg^{-1} with p = 0.1163). The initial increase in ΔNaOH-P and ΔCa in the open system might be due to the substantial amount of exchangeable Ca (19 to 24% of the total dissolved Ca from the RP) that was removed by the percolating water (Figure 6.3). The loss of Ca

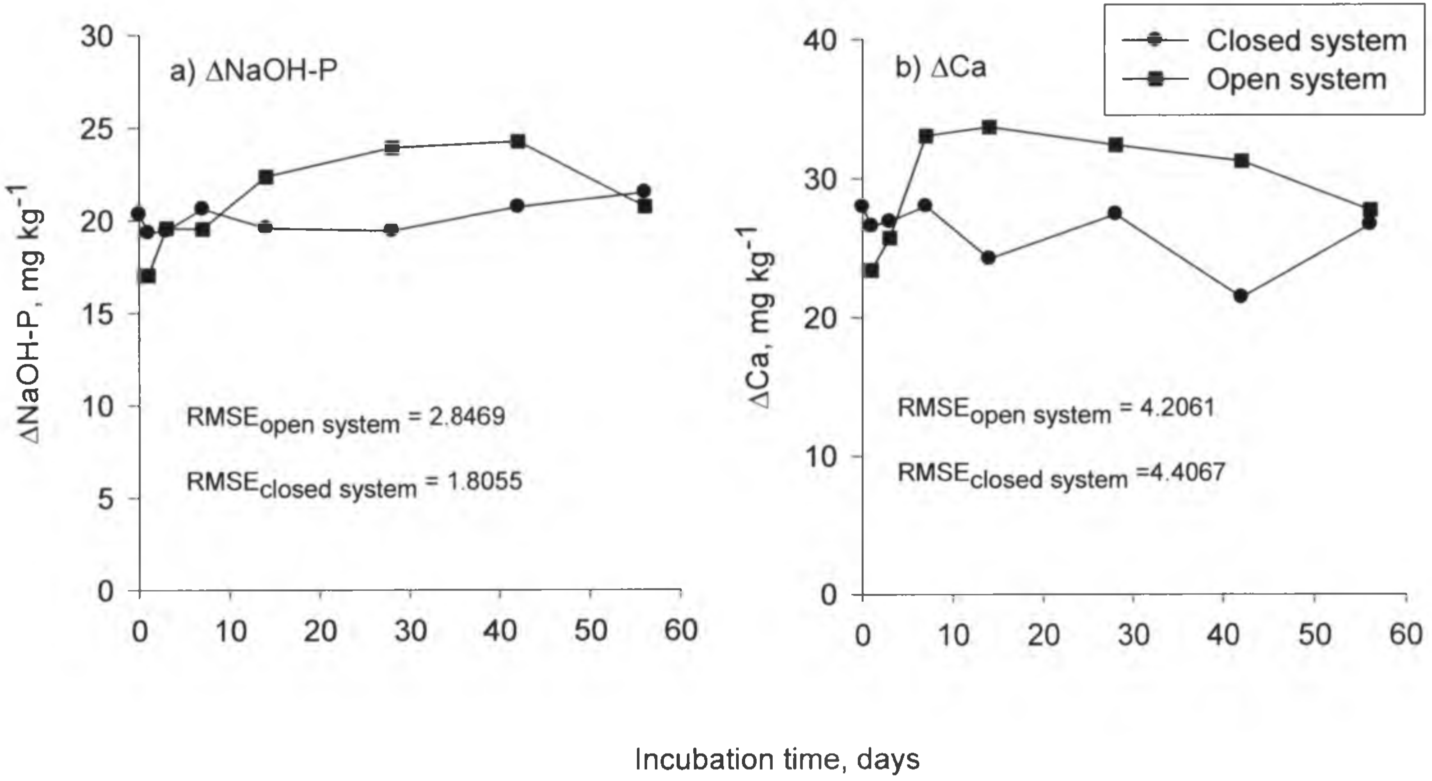

Figure 6.2. Tilemsi rock phosphate dissolution in Keur Madieng soil as measured by a) ΔNaOH-P and b) ΔCa methods in closed- and open-leaching incubation systems.

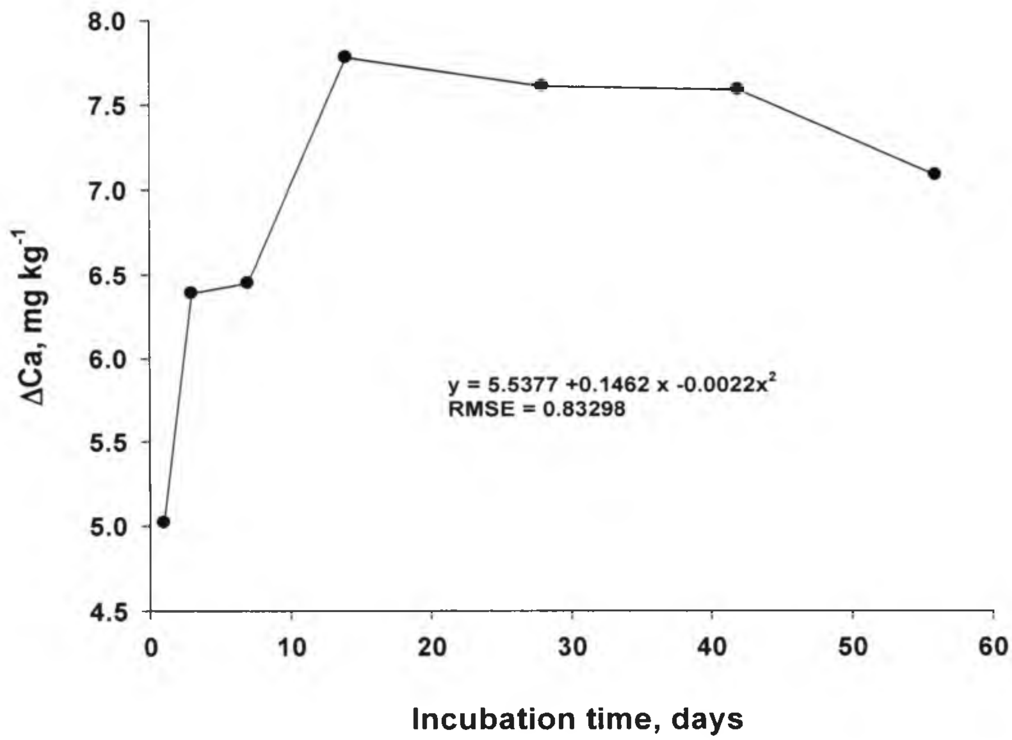

Figure 6.3. Changes in Ca losses from Keur Madieng soil amended with Tilemsi RP at the rate of 500 mg P kg^{-1}.

remained constant by the end of the incubation period suggesting that no further dissolution took place even with the continuous leaching. This again might be due to the negative feedback of the soil properties on the RP dissolution. Contrary to the cessation of the dissolution process observed in the current study, Hanafi et al. (1992) observed a continued RP dissolution in an open-leaching system, probably due to the renewal of the Ca exchange sites during leaching. In the same experiment, the workers obtained up to 94% of RP dissolution in the open system compared to 22-71% dissolution for Gafsa RP and 26-42% for Christmas Island RP in the closed system. In Hanafi et al. (1992) study, more dissolution took place compared to the current study because the limitation to the dissolution in the later study was the exchange sites for Ca not soil acidity.

The additional dissolution that occurred in the open system compared to that of the closed system could be explained by the leaching of the Ca enabling more dissolution to happen. This supports the hypothesis that RP dissolution could be reduced due to the accumulation of Ca in the soil solution in a closed-incubation system. Considering the field experiment at Keur Madieng, Senegal with a predicted and estimated (linear response plateau) Tilemsi RP rates of 2734 and 673.55 kg ha^{-1} , respectively, for producing millet maximum yield, the additional dissolution obtained in the open-incubation system cannot fully explain the overestimation of the prediction. In conditions where losses through leaching are not measured, the ΔCa method would not be a good estimate of the dissolved RP in field conditions where Ca can be leached.

6.6. Conclusions

In summary, the results from this incubation study suggested that dissolution not sorption affected the suitability of the RP as source of P. The dissolution in Keur Madieng soil was indeed limited by the soil acidity rather than the Ca exchange sites. However, we can conclude that open-incubation systems better simulate field conditions than closed systems.

Because there was not a sufficient amount of acidity to dissolve the RP, the suitability of the direct use of RP in the Keur Madieng soil seems questionable. Perhaps alternatives such as acidifying the rhizosphere such as plants, ammonium fertilizers, elemental sulfur, etc are needed to enhance RP dissolution in this type of soil. Perhaps RP needs to be preprocessed locally to improve their solubility before application rather than use it for direct application.

Chapter 7. General conclusions and summary

7.1. General conclusions and summary

According to the World Bank (1989), food production must increase by 4% in the Sub-Saharan Africa in order to achieve self-sufficiency and alleviate poverty. This challenge can be attained only through agricultural intensification by replenishing and improving soil fertility, which requires use of external inputs. The direct use of RP in agriculture can be a good alternative to correct soil P deficiency in this region; however, further economic evaluation is needed. The ability to predict RP fertilizer requirements and to develop accurate and specific RP recommendations will represent an enormous contribution to improve P fertility status and to increase crop yields in that region. The need for accurate and site-specific RP recommendation and the large number of factors affecting RP suitability for direct use justifies the need for a modeling approach that could identify, quantify and combine the factors into a prediction algorithm.

A simple algorithm considering dissolution and sorption processes is proposed to predict amounts of RP needed to meet crop P requirements. Soil KCl-extractable acidity, Ca saturation and the effective cation exchangeable capacity and the ratio between ΔNaOH-P and ΔBray 1-P are the required parameters for predicting amounts of RP needed for crop production in West African soils. It is also worthwhile to mention that this proposed algorithm is so far the only approach that attempts to quantitatively predict the amount of RP needed considering plant and soil P status.

In this study, the amounts of RP dissolved were estimated using the changes in 0.5 *M* NaOH-P between RP-treated and untreated soils (ΔNaOH-P). Based on the comparison with the changes in exchangeable Ca (ΔCa) between RP treated and untreated soils, ΔNaOH-P can be used as an estimate of the RP dissolution especially for RP containing $CaCO_3$ and in conditions where Ca losses occur and are not estimated. Because of the high susceptibility of Ca to be lost either by leaching or by plant uptake, ΔCa cannot be recommended as a measure of RP dissolution in field conditions.

The millet growing soils in West Africa are sandy, deficient in P, and characterized by a natural variability resulting in extremely difficult situations for field experiments. Because of this large variability in the field, the capability of the RP algorithm to accurately predict RP to meet crop P requirement was not well tested. However, there are indications that the algorithm seems to overestimate the amounts of RP needed. Additional experiments in more controlled conditions are needed to assess the accuracy of the RP algorithm and to define modifications needed to the algorithm. However, it can be already pointed out that the extremely high RP application rates (greater than 1X) are not needed.

When opting for the use of RP to correct soil P deficiency, the choice of RP to apply should include consideration of the RP properties itself and the soil properties to which the RP will be applied. For example, highly reactive RPs with

CCE greater than 50% are not the most suitable for sandy soils with pH close to 5.5 and with low buffering capacity because the low acidity could be neutralized by the RP material and soil Ca could be increased, also depressing RP dissolution.

It is important to integrate RP properties into the RP algorithm. The rock phosphate algorithm tested in these field experiments considers only soil properties. The different results obtained from Konobougou 1 and 2 experiments using Tilemsi RP (same origin but most probably different sampling time) support the need to also consider RP properties such as the solubility in neutral ammonium citrate, 2% citric and formic acids, particle size, CCE etc. in the algorithm. Similarly, an economic evaluation of rock phosphate and soluble P materials based on the quantified amounts provide by this algorithm is needed.

For identifying P deficiency conditions and predicting amounts of P needed to meet crop P requirements, one single Bray 1-P critical level of a given crop could be used for both water-soluble P and RP materials. Because the Bray-1 P critical level varied, an additional study can be carry out to validate the P critical level for producing maximum millet yield for millet producing soils of West Africa.

Rock phosphate dissolution in Keur Madieng soil seems limited because of the low soil acidity. Because there was not sufficient acidity to dissolve the RP, the suitability of the direct use of RP in soil with pH close to 5.5 and low buffering capacity like Keur Madieng soil seems questionable. Alternatives such as acidifying the rhizosphere such as plants, ammonium fertilizers, elemental sulfur, etc. help to enhance RP dissolution in this type of appear necessary. Perhaps RP needs to be preprocessed locally to improve their solubility before application rather than use it for direct application.

While RP may be a cost-effective way to supply P and sustain the often deficient nutrient P, it is also clear that soluble P is needed in many cropping systems and soils of West Africa.

7.2. Further research studies needed

1. Diagnosis of conditions suitable for direct application of rock phosphates: after diagnosing the existence of P deficiency, the diagnosis section must assist the user in evaluating the options and deciding whether or not to use RP on a case-by case basis. We propose outlining a procedure that takes in account the major factors affecting RP dissolution and P availability from dissolved P to evaluate suitability of RP for direct application. The categories of factors we propose to consider in the diagnosis phase are:
    a. crop type, duration, and special conditions, such as legumes, plants acidifying their rhizosphere, acid tolerant perennial crops etc.
    b. soil factors such as soil pH, Ca and P status, and soil water content
    c. rock phosphate properties, such as their solubility and
    d. soil management factors.

This step will conclude with a recommendation as to whether the use of RP is appropriate for the given soil, crop and management practices.

2. Considering the complexity around the use of RP for direct application, the RP algorithm must be tested in more controlled conditions before field testing it in farmers' fields which are characterized by high natural soil variability. Such study would allow generalizing the RP algorithm to a large range of RP materials and define refinement or modification needed to the algorithm.
3. Because major crops in West Africa grow on soils where substantial Ca leaching can take place, additional incubation study should be conducted with a range of West African soils having contrasting acidity and P sorption capacity.
4. Determine the uncertainties of RP algorithm by identifying the error propagation of each variable included in the algorithm on the prediction.
5. Conduct an economic analysis of the RP prediction over several years as compared to the soluble P fertilizer. This step should be associated with the diagnosis, and prediction steps that will be used to make recommendation on the option of using or not RP to supply P to crops. After a P deficiency diagnosis, the RP module could evaluate the suitability of RP to supply P needs for crop in a case by case basis similar to site-specific nutrient management and provide a recommendation for the amount and type of RP needed and give an economic analysis based on soil, crop, RP and management factors. It will allow users to determine the consequences of their decisions and allow them to make a better choice between soluble P fertilizer and RP.

8. Appendix. Site description and materials and methods used in Sadore, Niger field experiment

8.1. Site description

Sadore (2° 20' 29.55" E, 13° 16' 56.47" N) is located at about 45 km from Niamey in the Sahelian zone of Niger with an annual rainfall of 450 mm. The rainy season last about 108 days (June – September). The ETp reaches the highest levels of the three sites under study (2000 mm year^{1}).

8.2. Materials and Methods

A 4 x 5 factorial experiment was conducted at ICRISAT center at Sadore, Niger in 2007. The experimental design was a randomized complete block with each experimental treatment replicated 4 times. Individual plots were 56 m^{2} (7 m x 8 m). The crop considered in this experiment is considered as staple food in the semi-arid region of West Africa– millet (*Pennisetum spp*). Acid soils (pH < 5.5) with a low extractable P level (Bray 1-P < 7 mg kg^{-1}) was selected. Phosphorus sources included one soluble P fertilizer (treble super phosphate – TSP) and three RPs: Gafsa, Tahoua (Niger) and Taiba RPs. The rate of RP application included 0X, ¼X, ½X, 1X and 1.5X; where 1X was the predicted rate from the algorithm. Such a response curve permitted detecting whether the algorithm under predicts, accurately predicts, or over predicts RP needs. Soil samples (depths of 0 - 15 and 15 - 30 cm) were collected in each experimental unit prior to the application of RP rates. These samples were initially analyzed at ICRISAT-Niger for texture, pH (water), Bray 1-extractable, 1 *M* KCl acidity and exchangeable cations (1 *M* ammonium acetate pH 7.0). The different methods used are described in Chapter 5. Properties of the topsoil samples from each experimental unit were used to predict application rates of different RP. Rock phosphate samples will be analyzed for their solubility in different solution (Neutral ammonium citrate, 2% formic acid and 2% citric acid) with the courtesy of IFDC-Alabama. Statistical analysis will be performed (regression analysis) using SAS (SAS, 1985). The 4th replication of the experiment will be eliminated from the analysis because the quantities of RP were insufficient to totally cover this replication. Linear response plateau analysis (Shuai et al., 2003) will be used to estimate the RP rates that produced maximum yields for each RP. A similar analysis was also used to determine the Bray 1-P critical level.

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