DISSERTATION

IMPROVEMENT OF SOIL TEST P CALIBRATION AND FERTILIZER P MANAGEMENT IN CROP ROTATIONS IN MOROCCAN DRYLAND AGRICULTURE

Submitted by

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WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY MOHAMED AMRANI ENTITLED IMPROVEMENT OF SOIL TEST P CALIBRATION AND FERTILIZER P MANAGEMENT IN CROP ROTATIONS IN MOROCCAN DRYLAND AGRICULTURE BE ACCEPTED AS FULFILLING IN PART REQUIREMENT FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

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ABSTRACT OF DISSERTATION

IMPROVEMENT OF SOIL TEST P CALIBRATION AND FERTILIZER P MANAGEMENT IN CROP ROTATIONS IN MOROCCAN DRYLAND AGRICULTURE

Although the main limitation of crop production in the arid and semiarid regions of Morocco is lack of sufficient rainfall, phosphorus (P) nutrient deficiencies also are major obstacle to maximum crop production. Fertilizer management is an important step in sustainability of crop production where both economic and environmental concerns are important. The objectives of this study were (i) to improve fertilizer P recommendations by the inclusion of P sorption capacities of individual soils in the P requirement model and (ii) to determine the effect of direct, cumulative, and residual P on wheat (*Triticum aestivum*) and chickpea (Cicer *arietinum L.*) yields under field conditions in two cropping systems: continuous wheat and chickpea-wheat.

Phosphorus buffering indices were determined from sorption isotherms developed using 19 soils from the Abda, Chaouia, and Ben Sliman zones of Morocco. The greenhouse study consisted of growing wheat *(cv.* Merchouch) on 13 soils with four P rates (0, 3.4, 6.7, and 13.4 mg P kg^{-1}). Maximum buffering capacity (MBC) of soils was incorporated into the Mitscherlich model to determine P fertilizer requirement. Soils showed a contrasting ability to adsorb P. Maximum P adsorption (Xm) varied from 146 to 808 mg P kg^{-1} soil. The tentative calculations of P requirement, assuming the soil test P levels in all 13 soils was 3 mg P kg^{-1}, showed that the amount of fertilizer needed for 90% of maximum yields varied from 1 to 15 mg P kg^{-1} soil. However, the fertilizer P

recommendation by the usual method was 12 mg P kg^{-1} for all soils with a soil test P of 3 mg kg^{-1}. These results suggest that the inclusion of buffer indices in determining P requirement can increase the accuracy of P recommendations.

In a greenhouse study, two other crops were grown after wheat. Corn (*Zea mays L.*, cv Kamla) was harvested after 60 days and wheat was grown to maturity. The treatments were four P rates applications (0, 3.4, 6.7, and 13.4 mg P kg^{-1}) using 13 soils on the first and third crop (wheat). This greenhouse study showed that a significant response of corn to residual P occurred in soils with initial $NaHCO_3$-P test levels less than 6 mg P kg^{-1}. The response was inconsistent between 6 and 10 mg P kg^{-1}, and no response occurred above a soil test P level of 10 mg P kg^{-1}. In general, soils with more than 14 mg kg^{-1} $NaHCO_3$-P level provided adequate P for maximum yield for three succeeding crops under greenhouse conditions.

Field experiments were conducted in 1994-96 at three locations: Khmis Zemamra, Sidi El Aydi, and Khmis Sidi Rhhal. Phosphorus was applied at 0, 8.9, 17.8, and 26.7 kg P/ha on both wheat and chickpea the first year. The second year, plots were split into with and without P fertilizer treatments. Phosphorus rates of 8.9, 17.8, and 53.4 kg P ha^{-1} were required to increase and maintain soil test P level to a sufficiency level for three succeeding crops at Khmis Zemamra, Sidi El Aydi, and Khmis Sidi Rhhal, respectively. The effect of cropping system was not consistent. The residual P effect did not produce maximum wheat yield. Based on the range of P rates used in this study, a single application of P will not supply adequate nutrition for the following crop. If we assume

that a chickpea grain yield of 2 Mg ha^{-1} is a satisfactory yield in a CP-W rotation where wheat is the principal crop, P requirement for chickpea can be met by residual P. Using current wheat and fertilizer prices, the combinations of 17.8-17.8, 26.7-0, and 8.9-17.8 kg P ha^{-1} would be the recommended P application rates for continuous wheat, W-CP, and CP-W rotations, respectively.

Based upon my results I recommend that farmers consider both soil adsorption capacity and rotation (previous P applications and cropping system) to better manage P and optimize profit from fertilizer use.

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DEDICATION

I dedicate this dissertation to:

- My wonderful and beautiful wife Assia for her love, support, and endurance.
- Our expected baby.
- My parents: ma toch, icha, and ba, my brothers and sisters.
- My parents in law and brothers in law.
- My uncle dada, his wife Amina and their children for their support.
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- My friends El Hafid R., AitLhaj A., and their wives.

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List of Abbreviations

Abbreviation	Definition
AC	affinity constant
BC	buffering constant at C =1 mg L^{-1}
Ca	Exchangeable calcium
CL	clay content
Coef	coefficient
CV	coefficient of variation
DM	dry matter
GY	grain yield
Int	intercept
K	binding energy
KSR	Khmis Sidi Rhhal
KZ	Khmis Zemamra
L	lime content
MBC	maximum buffering capacity
Mg	exchangeable magnesium
Na	exchangeable sodium
NLIN	non linear regression
P	soil test P
Padd	phosphorus added
PR	phosphorus requirement
RGY	relative grain yield
S	sand content
SA	Sidi El Aydi
SBC	standardized buffering capacity
SL	silt content
ST	standardized test
TRD	theoretical P desorption
Xm	adsorption maxima (mg kg^{-1} soil)

INTRODUCTION

Although the main limitation of crop production in the arid and semiarid regions of Morocco is lack of sufficient rainfall, nutrient deficiencies also are major obstacles to maximum crop production. Fall cereal (wheat and barley) production decreased from a record 9.2 millions metric tons in 1994 to 1.6 in 1995 due to a devastating drought. Therefore, maximum profit must be achieved when rainfall is sufficient by optimizing growth conditions using proper fertilizer sources and rates as will as pest management control.

Improving productivity in a sustainable manner and adoption of modern agriculture practices should result in an economically and environmentally stable system. Mediterranean climates dominate Morocco with rainfall during the colder winter and dry and hot in the summer. The annual rainfall in arid and semiarid regions of Morocco ranges from 200 to 450 mm per year. About 59% of the total area is cultivated with cereals, and 55% of the country's total cereal production is in these regions.

The current farming system encompasses three main cropping systems: continuous cereal, cereal-legume, and cereal-follow. The productivity of these cropping systems can only be maintained through judicious use of fertilizers. It is imperative to consider direct and previous fertilizer applications as a strategy to better manage P in these rotations.

Fertilizer use by Moroccan farmers started in the 60's as a result of a program called "Fertilizer Operation". This project had the ultimate goal of generalizing the use of fertilizer by farmers. Since then farmers have become aware of the importance of fertilizer in their production systems. Furthermore, during this early time the Moroccan government subsidized fertilizer costs to encourage its use. However, by the end of the 80's, the government eliminated fertilizer subsidies and adopted a competitive pricing policy; resulting in a dramatic increase in fertilizer prices. The increased cost of fertilizer and its importance to production increased the number of farmers that started to look for more economical way to use fertilizers. Soil testing and fertilizer recommendation research began to develop a more scientific approach to fertilizer use.

Soil test calibration started in Morocco in the mid 80's by Soltanpour et al. (1986) who established the first P and N recommendations for the Chaouia region based on soil analysis. The validation of the $NaHCO_3$-P test as a reliable soil test method was accomplished by Azzaoui et al. (1989).

Fertilizer use efficiency, environmental impact, and economical cost are important issues in today's agricultural enterprise. Therefore, the question that arises regarding proper management of P fertilizer in the various cropping systems is how to optimize fertilizer use.

The first goal of soil science was to enhance fertilizer recommendation precision. In fact, the current P fertilizer recommendation procedures are subject to shortcoming, as described by earlier studies. Currently, soils with the same initial test P level are given the same amount of P fertilizer. Soils vary considerably in their characteristics. This variation can affect the soil test P calibration and plant response. Therefore, the amount of P fertilizer needed to increase the available P fraction varies with soil properties. The contribution of some P capacity factors such as maximum buffering capacity (MBC) has been reported to account for 74 to 86% of the variation in P uptake and 94% variation in grain yield (Dalal and Hallsworth, 1976). Cox (1994a) found that clay content was the most important factor that influenced P availability.

This dissertation is written in three chapters. The first chapter reports my progress in improving fertilizer P recommendations by discriminating among soils under greenhouse conditions. The second chapter covers my results on P management in different cropping systems by taking into account crop specificity, soil, and residual P affect. The third chapter covers my work on the first two years of a long-term experiment studying direct, residual, and cumulative effect of P fertilizers in different cropping systems in Morocco.

The general objectives of my research were to:

1 - Improve P soil test calibration

2 - Evaluate the impact of direct, residual, and cumulative P in different cropping systems.

The specific objectives of each chapter are given below:

Chapter I:

i) Determine P sorption indices and their relationship to soil characteristics

ii) Determine the availability of applied P with time in several soils

iii) Evaluate the variation of extractable P as a function of added P in different soils

iv) Determine the P critical level for wheat under greenhouse conditions

v) Evaluate P requirement using buffer indices.

Chapter II.

Evaluate the residual and cumulative fertilizer P affects on crop growth and P uptake in contrasting calcareous soils under greenhouse conditions.

Chapter III.

Evaluate the effect of direct, cumulative and residual P on wheat and chickpea yields in two cropping systems: continuous wheat and chickpea-wheat under field conditions.

CHAPTER I.

Improving Soil Test Calibration For Wheat In Moroccan Calcareous Soils

ABSTRACT

The increased concern about cost and environmental impact of fertilizers emphasizes the importance of improving fertilizer recommendations to be more accurate and soil specific. Buffering capacity is considered to be a key factor in understanding P availability in soil and crop response because it controls the rate at which P is supplied or depleted from soil solution. Phosphorus buffering indices were determined from sorption isotherms developed using 19 soils from Abda, Chaouia, and Ben Sliman zones of Morocco. Soil characteristics were also used to develop prediction equations of these buffer indices. To characterize the rate of increase of the available P ($NaHCO_3$-P) in different soils, the slope of the linear regression curve relating added P rates to actual soil test P is used. The greenhouse study consisted of growing wheat in 13 soils under four P rates treatments (0, 3.4, 6.7, and 13.4 mg P kg^{-1}). Critical soil test P levels for wheat under greenhouse conditions were determined. Maximum buffering capacity (MBC) of individual soils was incorporated into the Mitscherlich equation, which was modified to determine corrective P fertilizer requirement. In this study, my soils showed a contrasting ability to adsorb P. Maximum P adsorption (Xm) varied from 146 to 808 mg P kg^{-1} soil for the soils used in my study. Averaged across regions, soils from Chaouia adsorbed more P at maximum adsorption compared to Abda and Ben Sliman Soils, suggesting that each region has to have specific P recommendation norms. Maximum buffering capacities also showed large variation, the values ranged from 35 to 404 mg P kg^{-1}. This study showed that these buffer indices can be predicted using soil

characteristics determined by routine soil analysis especially using clay, calcium carbonate, and exchangeable calcium contents. The differences between soils to react with P is also demonstrated in a kinetic study. The amount of P fertilizer needed to increase $NaHCO_3$-P level in a given soil depends upon both time to maintain this increase and the soil itself. The rate of increase (b) varied widely among soils from 0.51 to 0.24 (kg P $kg^{-1})^{-1}$ after 15 days of incubation, after 380 days between 0.32 to 0.17 (kg P $kg^{-1})^{-1}$. It is also inferred from this study that P recovery declines with increasing time of contact between P fertilizer and soil particles, suggesting that it is better to apply P fertilizer at sowing time. The study showed that the critical soil test $NaHCO_3$-P level for wheat grown under greenhouse conditions would be between 10 and 14 mg kg^{-1} for a maximum yield that ranged between 90 and 99%. The inclusion of MBC in fertilizer P recommendations did not significantly increase the precision of current applied P at $\propto = 0.05$. However, the tentative calculations of P requirement, assuming a soil test in all our 13 soils of 3 mg kg^{-1}, showed that the need for 90% of maximum yields varied from 1 to 15 mg P kg^{-1} depending on the MBC = 26 or MBC = 404, respectively. However, the fertilizer P recommendation by the usual method was 12 mg P kg^{-1} for all soils with soil test P of 3 mg kg^{-1}. These results suggest that the incorporation of buffer indices into a P requirement model should increase the accuracy and overcome the problem of over-fertilization in sandy soils and under-fertilization in clayey soils.

INTRODUCTION

Since the early 60's, the Moroccan government has subsidized fertilizer costs for farmers to encourage its application. However, at the end of 80's, the government eliminated this policy and adopted a competitive pricing policy. Consequently, fertilizer prices increased drastically. Because of fertilizer cost and also environmental concerns, farmers have started to use soil testing to optimize fertilizer applications.

Soil P testing was an important first step in the rational use of fertilizer, but I believe that P recommendations can be improved by taking into account soil characteristics such as P supply capacity and availability index.

In the past century, the major goal of soil fertility research in many countries has been to remove the limitation of soil fertility in food production. However, the amount of fertilizer to be applied also must optimize economic return to fertilizer inputs. A properly calibrated soil P test is a crucial step in determining P requirement to reach and maintain available P level for a given cropping system. Three parameters need to be known to achieve this goal: (i) critical soil P test level, (ii) current P level in soil, and (iii) amount of P fertilizer needed to supply the plant with adequate amounts of P.

Usually, the same amount of P fertilizer is added to different soils with the same P soil test level to achieve a yield goal. Consequently, the third parameter mentioned above is not always satisfactory because the P requirement may be either under or overestimated. Fertilizer recommendations should take into account both supplying power of the soil and the nutrient requirement of the targeted crop yield. When applying fertilizers, the objective is to increase nutrient concentration in soil solution from a deficient to a sufficient level. However, the rate of increase differs between soils depending upon each soil's characteristics. These differences should be included in determining P fertilizer requirement.

In this literature review, I will discuss the shortcoming of the current P soil tests as outlined by Cox (1994a). The emphasis will be on two factors that contribute to the variation in P fertilizer requirement in relation to soil P test: (i) P soil sorption capacity, and (ii) P availability index.

Soil Sorption Capacity

Phosphorus soil chemistry is very complicated because the nature of reactions in the soil (Olsen and Khasawneh, 1980). Buffering capacity is considered to be a key factor in understanding crop response to P because it controls the rate that P is supplied or depleted from soil solution (Holford, 1980). Sorption poses a severe constraint on the ability of many soils to supply adequate amounts of P to plants. The contribution of some P capacity factors such as maximum buffering capacity was reported to account for about 74 to 86% variation in P uptake and 94% variation in grain yield (Dalal and Hallsworth, 1976). Peaslee (1978), proposed a response function that takes into account the index of P availability (slope of the linear relationship relating soil test level to applied P). In the latter study, the P availability index varied from 0.14 to 0.50 which results in 3-fold differences in fertilization rates for soils having similar levels of extractable P but different reaction properties with P. Kuo (1990) found that $NaHCO_3$-P test is highly dependent on P sorption capacity, and cannot be used to make specific interpretations of

P requirement across soil types without knowing the P sorption capacities of the soils. In his conclusion, he pointed out that the adjustment becomes necessary to improve the estimation of P requirements of soils.

Different critical levels, for the same crop and climate, have been reported in the literature for example: 5 mg kg^{-1} (Soltanpour et al. 1986), 24 mg kg^{-1} (Jackson et al., 1991), and 33 mg L^{-1} (Cox, 1996) are reported as a soil test P critical levels for wheat. Some researchers suggest that those differences may be related to soil properties. Holford (1976) has shown that phosphate requirement is a function of three parameters (i) quantity of P required by the plant for optimum yield, (ii) quantity of soil P required to maintain a non-limiting soil solution concentration, and (iii) quantity of labile soil P. He showed that for soils of similar quantity of labile P, phosphate requirement is positively correlated to phosphate buffer capacity. And he suggested that the phosphate buffer capacity must be taken into account when considering P fertilizer requirement of soil-plant system. Holford (1979) suggested that the P adsorption buffering capacity of the soil may be calculated from adsorption isotherms.

Holford (1980) found that the NaHCO$_3$-P test is more precise in predicting relative yield when the critical level is adjusted according to the buffer capacities. In the same study, the author reported that the higher the buffer capacity, the lower the relative yield at any given soil test value. Similarly, Kuo (1990) reported that NaHCO$_3$-P test is highly dependent on P sorption capacity and cannot be used alone in making specific interpretation of P requirements across soil types without knowing the P sorption capacity of the soil. He then suggested that adjustment becomes necessary to improve the estimation of P requirements of soils. He included, in the equation estimating P requirement, P sorption capacity, percentage clay, and soil P test level

McLean et al. (1982) developed a model, which measures P-fixing tendencies of individual soils to improve fertilizer P recommendations. In the model, they included the coefficient measuring the rate of increase in P availability as a function of added P. They concluded that this technique provides more accurate P fertilizer recommendations to allow soils to reach given sufficient levels.

Soils vary considerably in their characteristics. This variation can affect the soil test calibration and plant response. Therefore, the amount of P fertilizer needed to increase the extractable P concentration varies with soil properties. This point was well illustrated by Reuter et al. (1995) who collected data from 580 field experiments conducted in south Australia over the 30 past years. They found that when all data for a given plant species were compared, the relationship between yields and P status was variable. However, when data was grouped according to common soil types, soil surface texture, or sorption indices, better relationships were found. These results point out how important it is to group soils together according to their characteristics in order to accurately predict plant response to P fertilizer.

Phosphorus requirements were found to be different among soil types (Sahrawat and Warren, 1989), who found that a larger amount of P fertilizer was needed in Oxisols to obtain the same yield response found in Vertisols. Thus, 100 to 200 kg P ha^{-1} was required to achieve a good first crop in the Brazilian Cerrado Oxisols, whereas many Indian Vertisols give reasonable yields without fertilizer. This was mainly due to the higher capacity of Oxisols to adsorb P (100 to 405 kg kg^{-1}) than Vertisols (39 kg kg^{-1}). Similar results were found by Cox (1994a) who reported that the critical level found on sandy Ultisols in North Carolina was twice that found in Mollisols in Iowa. He suggested that this variation is mainly due to P sorption capacity.

Clay content has been reported to be as effective as P buffering capacity in determining P requirement (Lins and Cox, 1989). Therefore, clay content was used to predict P requirement (Johonson et al., 1991; Cox, 1994a and 1994b). Cox (1994b) found that the increase of Mehlich3-P concentration was 0.7 and 0.2 units per unit of applied P in sandy (10% clay) and clayey (40 to 50% clay) soils, respectively. Cox (1994a) considered clay as the most important factor influencing P requirement in relation to soil test. Therefore, he established a multiple regression equation giving the P rate (F) as a function of soil P test (M3P = Mehlich 3 test) and clay content:

$$F = 107 - 0.7(M3P) + 0.072(clay)^2 - 0.0073(M3P)(clay)^2 \qquad (1)$$

Another equation, developed by Lins (1987) for soybean in Brazilian soils, showed that the critical level (Pcl) varied from 6 to 23 mg P kg^{-1} when clay content decreased from 63 to 12 %:

$$Pcl = 26.6 - 0.303 * clay \qquad \text{adjusted } R^2 = 0.97 \qquad (2)$$

It is important to point out that these kinds of equations are specific to given soil conditions. Consequently, appropriate relationships have to be established for each crop-soil system.

The importance of soil clay content is probably due to its effect on P absorption. In fact, Moughli et al. (1993) showed that soil clay content is correlated to buffering capacity indices. In the same study they found that the ratio of CEC/clay also affects P sorption in most soils. The negative correlation indicates that when CEC decreases, the P sorption ability of the soil increases and applied P becomes less available. By comparing two contrasting soils in regard to their clay contents, Kato and Owa (1989) found that the slopes of P isotherm curves for clayey soils were less steep than for sandy soils. They suggested that clayey soils have less ability to maintain the P concentration in soil solution than do sandy soils.

In calcareous soils with pH less than 8.8, Brar and Cox (1991) found that availability of fertilizer P depends upon clay content, CEC, sample density, and calcium content. Whereas, in soils with pH above 8.8, P availability is mainly controlled by pH. Mahmood-ul-Hassan et al. (1993) found that soils with high clay and $CaCO_3$ contents have the highest P sorption capacity. The amounts of P fertilizer needed to increase soil P concentration to 0.2 mg P L^{-1}, considered as the adequate soil P concentration for most crops, vary among soils from 8 to 83 mg P kg^{-1} soil. To achieve the same goal for soils from Natal (South Africa), the P requirements vary from 5 to 1174 mg kg^{-1} (Bainbridge et al.. 1995). The greatest P requirements were obtained for highly weathered clay soils and the lowest for sandy soils.

Because the determination of sorption isotherms is tedious and does not lend itself to routine use, the association of P sorption indices with soil properties, mainly clay content, $CaCO_3$ content, CEC and exchangeable Ca in calcareous soils, enables the rapid and moderately accurate prediction of those indices.

Studies have been conducted on other important soil parameters that affect sorption and desorption of P in soil such as pH, Fe and Al compounds. Depending on soil, climate, and cropping system, the effect of one soil parameter may be greater than the other. In the case of soil oxides, hydroxides and oxyhydroxides of Fe and Al compounds are the major factors that influence P sorption (Pena and Torrent, 1990; Borggaard et al., 1990). Crystalline Fe has been found to be the form of Fe that has a greatest effect on P sorption in Mediterranean soils (Pena and Torrent, 1990). In other studies, amorphous Fe and Al (hydro-) oxides and clay were reported to describe P adsorption measured after 40 days of gentle shaking (Freese et al., 1992).

The relation between pH and P sorption was well documented by Borrow (1984). He showed that at least four factors influence this relationship. The first is pH. At low pH levels, an increase of pH decreases sorption but at high pH, a further increase in pH increases P sorption. The second is the difference among soils on the effect of pH on electrostatic potential in the adsorption surface. The third factor is the ionic medium in which the measurements are made. The fourth is release of P from the soil itself.

The kind of fertilizer could affect sorption and desorption of P in soil. In the study of Al-Kanani and MacKenzie (1991), it was shown that more orthophosphate (OP) is adsorbed in soil and goethite samples than pyrophosphate (PP), whereas kaolinite adsorbs less P but at the same amount regarding OP and PP. As far as desorption is concerned, more OP than PP is desorbed by both soil and goethite samples. However, kaolinite desorbs the same amount of OP and PP.

P Availability Index

Phosphorus availability index is defined as the rate of increase in soil P test leve as a function of added P rate:

$$NaHCO_3\text{-}P = a + b^*Padd \qquad (3)$$

$NaHCO_3$-P is soil P test

a and b are constant

Padd is P rate added

P availability index = rate of P increase = slope (b) of the equation (3).

The kinetics of P is another tool, besides sorption capacity, which plays an important role in optimizing P fertilization management. The kinetics give a continuous assessment of available P with time and has been reported to be useful as a tool for long-term P management by describing the fate of P in soil with time (Cooke, 1966; Olsen, 1975; Sharpley et al., 1989; Kato and Owa, 1989). The kinetics of P give important information about the decrease of P availability as caused by sorption. Calculation of optimum long-term profits from fertilizers requires carry-over functions that can evaluate nutrient concentration at any time especially for high-potential residual-effect nutrients such as P. As far as long-term management of a cropping system is concerned, not only information about the amount of fertilizer to be applied to increase P to sufficient level is needed, but also how long this increase will be maintained. Kinetic measurements on soil can also be used as a diagnostic technique for predicting crop response. Positive relationships were established between grain yield response of sorghum to applied P and the kinetics equation constant (Onken, 1992). Steffens (1994) reported that cumulative plant P uptake is related to slope of the Elovich kinetics equation. The rate coefficients for P desorption kinetics models also characterize the susceptibility of a given soil to release added P.

Different models have been developed to describe P kinetic in soils such as (i) first order equation (Amer et al., 1955; ElKhatib and Hern, 1988), (ii) two constant rate equation (Kuo and Lotse, 1974), (iii) Elovich equation (Chien and Clayton, 1980; Boukhal, 1989), (iv) polynomial equation (Harter and Foster, 1976), and (v) empirical equation (Enfield et al., 1976). The choice of a kinetics models is related to experimental conditions, duration of incubation, solution:soil ratio, and range of added P. Each of these models is valid only for a limited concentration range and reaction time. For instance, the reciprocal of the reaction rate, $z = 1/(dq/dt)$, gives convex, straight, or concave curves when z is plotted against time (t) for short, intermediate, and long reaction times, respectively.

Some models are preferable to others. For instance, a zero-order kinetics model was reported to be inadequate because its reaction rate is independent of reactant and product concentrations (Sharpley, 1982). The second-order kinetics are, however, indicative of P desorption at a rate proportional to both concentration of P in solution and the number of vacant sorption sites (Kuo and Lotse, 1972). The Elovich equation was established based on the assumption that the distribution of activation energies for sorption onto the adsorbent surface is heterogeneous. This assumption was latter shown to be true by Agbenin and Tiessen (1995). Another investigation demonstrated that, in general, integral-form models reflect adsorption pattern more accurately than the differential equations (Kato and Owa, 1989).

Another feature of P management that can be gained from kinetics studies is the time when P fertilizer should be applied. When phosphate fertilizer is added to soil, its fate is governed by both the soil and the plant. The rate in which P is removed from soil solution depends not only on soil properties but also on time (Garcìa-Rodeja and Gil-Sotres, 1995; Indiati et al., 1995). Indiati et al. (1995) found that the rate of P increase as a function of added P (P availability index) decreases with time: 0.55, 0.38, and 0.36 (mg P kg^{-1} increase in soil P test by 1 mg P kg^{-1} added) after 16 hr, 48 hr, and 60 days, respectively. The variation in the availability index among soils reported in the same study ranged from 0.25 to 0.75, 0.19 to 0.56, and 0.17 to 0.56 for the same periods of incubation mentioned above. The variation between soils is mainly explained by CEC. The practical implication of these results is crucial as far as economical and environmental issues are concerned. For instance, if the P test levels of these soils needed to be increased by one unit to a reach sufficiency level, the amount required to increase and maintain P level for 48 hr (1.8 mg kg^{-1}) is lower than for 60 days (2.6 mg kg^{-1}). The variation in the amount, among soils, is between 1.8 and 5.8 mg kg^{-1} for maintaining the one unit increase in P test level for 60 days.

Earlier results showed that the decrease of P availability with time is highly significant in the first days and less significant thereafter. There are some indications that the fixation of phosphorus in soil occurs within a few hours (Rennie and McKercher, 1959; DcDatta et al., 1963); however, the magnitude of P fixation is soil dependent.

The rate of increase of available P with added P was influenced by $CaCO_3$, silt plus clay contents and pH (Fuleky, 1978). The importance of soil characteristics in rate of P increase also was reported by Mclean et al. (1982) who found that the percentage recoveries varied from soil to soil.

An important point in determining P fertilizer requirement is the variation among soils regarding their rates of increase in extractable-P level as a function of added P. These differences usually are not taken into account when P recommendations are made. In fact, P soil test calibration procedures develop critical levels and P fertilizer recommendations ranges without discrimination among soils. This problem mainly occurs if (i) soils used in the soil test calibration study are heterogeneous in their P sorption capacities and/or (ii) the soils have a P sorption capacity value outside the range of the soils used for soil test calibration.

Little work has been conducted to overcome this problem. One technique is the "double calibration technique" (Peaslee, 1978, McLean et al., 1982) or a two point sorption curve (Dear et al., 1992). The double calibration technique takes into account both yield as a function of extractable P levels and the extractable P level as a function of added P (Fp).

$$\mathrm{Log}\ (A\text{-}Y) = \log(A) - C_1{*}P \qquad (4)$$

A = maximum relative yield (%)

Y = relative yield goal (%)

P = available soil P level

C_1 = factor for efficiency of use of soil available P

In the Mitscherlich equation, he substituted P by (P + PF/fp):

$$\mathrm{Log}\ (A\text{-}Y) = \log(A) - C_1{*}(P + PF/fp) \qquad (5)$$

PF = fertilizer P requirement (mg kg^{-1})

fp = 1/fraction of added P recovered by the used P extraction method

With these modifications, he found a difference equivalent to about 90 kg P_2O_5 ha^{-1} among species for soils containing virtually no extractable P, and 3-fold differences in fertilization rates for soils having the same P levels. Dear et al. (1992) found that a two point sorption curve was sensitive and efficient in predicting fertilizer requirement of clover pastures. In the model they developed, the yield was expressed as a function of initial soil P test (PS), P buffering capacity (PBC), and amount of P fertilizer (FP). They showed that the response to fertilizer was affected by the interaction of the PBC with the soil test. The P sorbed accounted for 89% of the variation in P required to achieve 90% of maximum yield in their field experiments.

The development of accurate methods for determining P recommendations is needed. Farmers must make more efficient use of P fertilizer to maximize net returns and reduce environmental pollution.

This review has attempted to show that P fertilizer requirement is a function of not only soil test, but also P sorption capacity which determines, along with the amount of added P, the soil P availability. The range in P requirements among soils, with the same P soil test levels, suggests that it may be useful to take into account P sorption capacities when determining P fertilizer recommendations. Phosphorus sorption indices can be derived from isotherm studies or indirectly by using soil properties determined by routine analyses. Many investigations showed that the association between P sorption indices and soil properties may be used as a first step approach to estimate those indices. From this review, an alternative solution to overcome the shortcomings of current P recommendation would be soil grouping. Phosphorus soil test calibration could be undertaken for homogeneous soils regarding their P sorption capacities.

The kinetics of P reactions has shown a strong potential for increasing the possibility to quantify various important relationships and factors influencing P reactions in soil and plant responses. The importance of kinetics of P in soils also may help answer question regarding long-term availability of P to plants and how P availability is influenced by soil parameters. Phosphorus kinetics also can be used as an important tool for determining the P availability index which in turn can be used to determine the amount of P to be added to increase initial P test level to a sufficient level for different soils. Kinetics studies also help in managing P fertilization for long-term rotations as well as for perennial crops .

The present study was conducted under greenhouse and laboratory conditions. The objectives are (i) to determine P sorption indices and their relationships with soil characteristics (ii) to follow the availability of applied P with time in several soils (iii) to evaluate the variation of extractable P as a function of added P in different soils, (iv) to determine the P critical level for wheat under greenhouse conditions, and (v) to evaluate P requirement using buffer indices..

MATERIALS AND METHODS

Soil Characteristics

Samples from eighteen calcareous soils were collected from main soil subgroups of arid and semi-arid zones of Morocco to get representative data for those zones. The top 20 cm of the < 2 mm fraction of soil samples was used in this experiment. This study covers three regions where mainly cereals are grown: Chaouia (10 samples), Abda (5 samples) and Ben Sliman (3 samples) (Table 1.1). The soils were chosen to give a wide range in clay content, exchangeable bases and calcium carbonate content. Other soil characteristics were determined: available P was extracted by 0.5 M $NaHCO_3$ solution (Olsen et al., 1954) and analyzed by the ascorbic acid method of Murphy and Riley (1962); pH was measured by glass electrode using a soil:water ratio of 1:2; organic matter by wet oxidation (Walkley and Black, 1934); CEC by a method by Chapman (1965); exchangeable cations were extracted using 1N NH_4OAC solution (pH = 7) with Ca and Mg being determined by atomic adsorption and K by flame photometer; and total N by micro Kjeldahl method (Bremner, 1965). Some characteristics of these soils are given in Table 1.2.

Phosphorus Sorption Measurements

Phosphate sorption was measured by shaking soil samples (2 g) with an equilibrating solution of monocalcium phosphate (MCP) containing 0, 1.5, 3.0, 4.5, 6.0, 9.5, 13, 26, 36, 45, and 54 mg P L^{-1}. The equilibrating solution was 0.01 M $CaCl_2$ and the soil solution ratio was 1:20. Two drops of toluene were added to stop microbial activity. After 17 hours of shaking at 20°C, the solution was separated from the soil by centrifugation and filtration using Whatman N°4 filter paper. The P was then determined in the supernatant solution by the ascorbic acid method of Murphy and Riley (1962). All adsorption measurements were carried out in triplicate. The difference between initial added P and final solution P concentration is the amount adsorbed by the soil. These data were fitted to different models by relating the amount of P adsorbed to the equilibrium concentration.

The kinetic equations that express adsorption and desorption were given by Gerke and Dette (1993):

$$d\theta/dt = ka*C*Xm*(1-\theta) \qquad \text{adsorption} \qquad (6)$$

$$d\theta/dt = kd*Xm*\theta \qquad \text{desorption} \qquad (7)$$

Xm = adsorption maximum

θ = relative coverage = X/Xm

C = equilibrium solution

t = time

ka and kd = constants

In my study, the sorption data were fitted to five widely used models:

- Langmuir model:

This equation is derived from the equality of equation (1) and (2) (equilibrium state)

with $(ka/kb) = k$ and $\theta = kC/(kC+1)$ (8)

then $X = (Xm*k*C)/(1+k*C)$ (9)

X = amount of P adsorbed ($\mu g\ P\ g^{-1}$ soil)

C = equilibrium solution ($\mu g\ P\ cm^{-3}$ soil solution)

Xm = adsorption maximum (μg P/g soil)

k = binding energy ($cm^3\ \mu g^{-1}$)

- Freundlich model:

The model is described by the equation:

$$X = a*C^n \qquad (10)$$

The linearized form is:

$$Log(X) = Log(a) + n*Log(C) \qquad (11)$$

X = amount of P adsorbed (μg P g^{-1} soil)

C = equilibrium solution (μg P cm^{-3} soil solution)

a = amount of P adsorbed when $C = 1(ml\ g^{-1})$

n = describes isotherm slope

- Cooke model:

It is also known also as simple diffusion-kinetic equation,

$$X = a + b*\sqrt{C} \qquad (12)$$

X = amount of P adsorbed (μg P g^{-1} soil)

C = equilibrium solution (μg P cm^{-3} soil solution)

a and b = constants

- Temkin model:

The model is a semi-logarithmic equation:

$$X = a + b*Log(C) \qquad (13)$$

X = amount of P adsorbed (μg P g^{-1} soil)

C = equilibrium solution (μg P cm^{-3} soil solution)

a and b = constants

- Linear model:

$$X = a + b*C \qquad (14)$$

X = amount of P adsorbed (μg P g^{-1} soil)

C = equilibrium solution (μg P cm^{-3} soil solution)

a and b = constants

Phosphorus Availability Measurements

Soil samples were sieved with a 2-mm screen. Dilute solutions of monocalcium phosphate were mixed with 400 g of each soil. The solution concentrations varied to deliver 0, 3.4, 6.7, 13.4 and 53.8 mg P kg^{-1} of soil. The volume used was sufficient to raise the water content of the soils to the sticky consistency. Samples were carried out in triplicate and incubated at 30°C for 0, 0.25, 0.5, 1, 2, 7, 15, 21, 28, 35, 65, 130, and 380 days. Large surface containers were filled with water and placed in the incubator to assure a humid environment and prevent excess evaporation. Every three days, soil moisture content of the incubated soils was brought to sticky consistency (90 to 95% of field capacity). Drops of toluene were added to dilute solution to prevent algae growth. At the end of every incubation time, samples were taken and analyzed for available P using 0.5 M $NaHCO_3$

Pot Experiment

Thirteen of the soils in Table 1.1 (soils 1 through 13) were air dried, crushed and sieved through a 2 mm screen. Five-kg portions of each soil were placed in polyethylene plastic pots that allowed drainage. The drain solution was captured and periodically returned to the pot. Fertilizer solutions were prepared using reagent-grade monocalcium phosphate mixed with the soils at rate of 0, 3.4, 6.7 and 13.4 mg P kg^{-1} soil in four replications. Nineteen wheat seeds (*cv.* Merchouch) were planted, on January the 5th 1995, at a depth of 2 to 3 cm in each pot and thinned to 9 seeds 12 days after sowing.

Supplements fertilization added to each pot consisted of 100 mg N kg^{-1} from NH_4NO_3, one half at sowing and the other at tillering, 50 mg K kg^{-1} from K_2SO_4, 3.5 mg Zn kg^{-1} from $ZnSO_4.7H_2O$, 8 mg Fe kg^{-1} from Fe-Chelate (10%), 4.5 mg Cu kg^{-1} from $CuSO_4.5H_2O$, and 8 mg Mg kg^{-1} from $MgSO_4.7H_2O$. Pots were regularly watered with enough deionized water to bring them to approximately 90% of field capacity during plant growth. The greenhouse was maintained at 24 °C day and 15 °C at night.

At harvesting, on 24 June 1995, above ground dry matter production and grain yields were determined. Plant materials were dried in an oven at 70 °C for 48 hr, then ground and sieved to pass a 0.5-mm mesh, and were analyzed for total P. Differences in dry matter production, grain yield, and total P uptake for individual soils were determined using a Duncan's test by SAS (1985). Critical levels were computed by using a Mitscherlich model using non linear (NLIN) regression by SAS, linear regression and plateau models, using linear regressions, and the graphical and statistical methods by Cate and Nelson (1965) and (1971).

RESULTS AND DISCUSSION

Phosphorus Isotherms

The soils used in this study were markedly different with respect to their P sorption behaviors (Fig. 1.1). The adsorption rate was extremely high for small concentrations of added P. At P rate of 3 mg L^{-1}, the amounts of P adsorbed were between 29.0 (50% of added P) to 59.7 mg kg^{-1} (99% of added P) for soils 13 and 1, respectively. At the high P rate (54 mg L^{-1}), however, the amounts of P adsorbed were

146 (14%) to 808 mg kg^{-1} (75%) for soil 14 and 7, respectively. This suggest that more P adsorption occurs at low P concentrations. Rajan and Fox (1975) explained that there are adsorption sites that are highly reactive at low P concentrations. However, with increasing P concentration, the energy of adsorption becomes low, and P adsorption is less. The magnitude of P sorption exhibited by different soils varied greatly. Three soil groups have been classified based on their maximum adsorption (Fig. 1.1). The first group, with maximum P adsorption (Xm) less than 300 mg P kg^{-1} soil, included soils 8, 10, 11, 13, 14, 15, 16, and 17. The second group with Xm between 300 and 500 mg P kg^{-1} included soils 2, 4, 9 and 18. The third group had Xm values ranging from 500 to 800 mg P kg^{-1}. The soils of this group were 1, 3, 5, 6, 7, and 12. These soils have different P adsorption capacities, therefore, the P application rates required to increase and maintain the P concentration at a given level would probably be different. For instance, the P rates needed to increase soil P concentration to 0.2 mg P kg^{-1} (considered as the optimum external concentration for the many crops) in soils 2 and 16, which have the same initial P level (7.6 and 7.8 mg P kg^{-1}, respectively), were 24 and 14 mg P kg^{-1}. Consequently, the P requirement for different soils with the same P level would be different.

In order to characterize soil adsorption capacity of specific soils, the experimental data were fitted to five kinetic equations: Langmuir, Freundlich, Cooke, Timken, and Linear models, by relating P adsorption to equilibrium P concentration using linear and non-linear regression analysis (Table 1.3). Timken and linear models were omitted because of their relatively low coefficients of determination and high coefficients of variation. Generally, the Cooke model resulted in a closer fit for P sorption followed by the Langmuir model then the Freundlich model, respectively as indicated by both high coefficients of determination (R^2) and small coefficients of variation (CV). In fact, the Cooke model accounted for 97 to 99% of the variation in P adsorption with an average CV of 11% compared to 92% of the variation and a CV of 26% for the Langmuir model. The Freundlich had the poorest coefficient of determination, which was around 90% (Table 1.3).

The observed data and the isotherm curves developed from the Cooke, Langmuir, and Freundlich models were plotted for each soil (Fig. 1.2). The graphic presentations confirmed that our data were best fitted by the Cooke and Langmuir models but not by Freundlich model; especially at high equilibrium concentration ranges. This result confirmed the findings by Polyzopoulos and Pavlatou (1992) who showed that the Freundlich model did not predict adsorption surfaces at intermediate or high concentration ranges. The Freundlich model described the adsorption at the low range of P concentrations. Soil 2 (Fig. 1.2) showed that, at low P concentrations (i.e. 18 mg P L^{-1}), the amounts of predicted P adsorption by the Freundlich model (202 mg P kg^{-1}soil) were close to the actual adsorbed P values (215 mg P kg^{-1}soil). However, at higher P concentrations, the prediction and observed values by the Freundlich model varied. For instance, at a P rate of 54 mg P L^{-1}, the predicted value was 536 mg P kg^{-1} compared to the observed value of 338 mg P kg^{-1} soil. The shape of the curve of Freundlich model predicts a high rate of increase in sorption at high concentrations compared to Cooke model. It is obvious from these results that Freundlich model may be suitable where the adsorption sites are saturated slowly and the differences between P adsorption at low and high concentrations are not large. Figure 1.2 also showed that the fit of the Langmuir model was better at low concentration ranges than the Cooke model; especially for soils 2, 12, 15, 16, 18, which were characterized by low adsorption capacities. In fact, it has been reported that the Langmuir model is more suitable to fit data generated from low concentration experiments (Gerke and Dette, 1993).

This study showed that both the Cooke and Langmuir models can be used to fit P adsorption isotherms for Moroccan calcareous soils. For the rest of this study, the Langmuir and Cooke models will be used for generating buffer indices which will be used to illustrate the adsorption capacity of each specific soil. The buffer indices were calculated as follows:

- From the Langmuir model: equation (9):

i) Maximum P adsorption (Xm), defined as the amount of P adsorbed when surfaces are saturated (asymptote of the Langmuir model),

ii) P affinity or binding energy (K) is the reciprocal of the equilibrium P concentration at the saturation of the half of total available site (Olsen and Watanabe, 1957),

iii) Maximum buffering capacity (MBC) which is maximum slope of the Langmuir isotherm, calculated from K*Xm (Holford and Mattingly, 1976),

iv) Standard buffering capacity (SBC), determined as a slope of tangent to the Langmuir model at an equilibrium P concentration of 0.3 µg ml^{-1} (Ozanne and Shaw, 1967), and

v) Phosphorus requirement (PR), defined as the amount of P needed to achieve a soil concentration of 0.2 mg L^{-1}.

- From the Cooke model: equation (12):

i) Affinity constant (AC), which is the slope (b) of the Cooke model (equation 13),

ii) Theoretical P desorption (TPD), which is equal to the intercept (a) of the Cooke model (equation 13),

iii) Buffering constant (BC1) calculated from the equation (1 , for C =1 mg L^{-1}, and

iv) Standard buffering capacity (SBC), determined as a slope of the Cooke curvel at an equilibrium P concentration of 0.3 μg ml^{-1} (Ozanne and Shaw, 1967).

The magnitude of the values of P adsorption maxima (Xm) exhibited by different soils varied greatly (Table 1.4). The range of variation was between 141 (soil 14) and 837 mg P kg^{-1} (soil 7). These values are similar to those reported by Moughli et al. (1993), who found a range of from 68 to 521 mg kg^{-1} in Moroccan soils. In my study the K values were between 0.10 (soil 13) and 0.60 mg (soil 11). These values were similar to those reported by Moughli et al. (1993), but were low compared to those reported by Agbenin and Tiessen (1994) for Brazilian soils (K varied from 0.10 to 2.44) and Solis and Torrent (1989b) who found binding energy values ranging from 1.43 to 2.80 L mg^{-1}.

Maximum buffering capacity is an important index that evaluates the amount of change in available P upon fertilizer addition to soil. The increase in $NaHCO_3$-P level by adding P fertilizer will be lower in soils with high MBC compared to soils with low MBC. The MBC values, in my study, varied between 35 (soil 13) to 404 mg kg^{-1} (soil 12) (Table 1.4). These variations in MBC values showed that my soils reacted differently with regard to P applications. The greater the buffer capacity of the soil, the higher the P rate required to increase P concentration in soil solution. The variation in MBC in my soils explains our concern about the possible differences in each soil's ability to supply soil solution with available P.

The other buffer indices, SBC, ST, and PR follow the same trend as MBC (Table 1.4). The correlation matrix (Table 1.5) showed that buffer indices were highly correlated with each other suggesting that any of the indices could be used to contrast soils with respect to the variation of soil P concentration as a function of P applications.

Buffer indices values were averaged across soils within the same geographical origins: Chaouia, Abda and Ben Sliman. The result showed that there was a significant differences between Abda and Ben Sliman soils compared to Chaouia soils. On the average, the soils of Chaouia zone adsorbed 596 mg P kg^{-1} soil at the adsorption maxima (Xm), which is 1.7 and 2 times greater than Abda (340 mg P kg^{-1} soil) and Ben Sliman (284 mg P kg^{-1} soil) zone soils, suggesting that more P fertilizer would be adsorbed in Chaouia soils compared to the others. The average values of MBC were 259, 108 and 93 mg P kg^{-1} for Chaouia, Abda and Ben Sliman, respectively. The same tendency was followed by all other buffer indices. Those differences among zones were mainly due soil parameters such as clay, calcium carbonate, and exchangeable calcium contents which are different within these zones (Table 1.2). The average soil levels in Chaouia were 46, 11, and 4796 mg kg^{-1} for clay, calcium carbonate, and exchangeable calcium contents, respectively. The correspondent values for Abda and Ben Sliman zones were 31, 4, and 3000 mg kg^{-1} and 29, 5, and 2668 mg kg^{-1}, respectively. Therefore, because of their high adsorption capacities, the P requirement should be higher for Chaouia soils compared to Abda and Ben Sliman soils. Presently, the current P fertilizer recommendations are the same for all three regions.

My data shows that Moroccan calcareous soils have different P adsorption capacities. The buffering capacity of a specific soil can be evaluated by using the buffering index calculated from the Langmuir or Cooke models. The different buffer indices determined from the Langmuir model showed high correlations with each other (Table 1.5) suggesting that any of them could be used to contrast soils. The coefficients of correlation (r) determined for MBC were from 0.70 to 0.99. All correlation with MBC were highly significant. Because it is the most widely-used index in the literature, I used MBC to characterize P buffering capacity of each soil.

Effect of Soil Parameters on P Sorption

The determination of buffer indices requires the establishment of P sorption isotherms which are difficult to adapt to routine analyses. Therefore, regression relationships between buffer indices and soil properties possibly could be used to rapidly predict these indices. Stepwise regression analysis in SAS was used to relate different buffer indices to soil properties. Table 1.6 showed that clay and exchangeable Mg contents explain 87% of the variation in Xm. The soil parameters accounting for 98% of variation in MBC were clay, lime, and exchangeable Ca contents. These parameters were positively correlated with buffer indices, suggesting that they affect the ability of soil to replenish the soil solution with P. Partial correlations between P-sorption indices and soil parameters also were determined and are presented in Table 1.7. The importance of clay content in determining adsorption capacity of a specific soil is important because it reflects the amount of surface available for P adsorption. The implication of lime content is also expected because of the adsorption of P on calcite surface. However, the effect of exchangeable Ca and Mg contents probably is not just the formation of Ca-P and Mg-P compounds, but also the effect of cation saturation on electrostatic potential (Curtin et al., 1992). The significant effect of these parameters on P buffer indices is consistent with many earlier findings (Manikandan and Sastry; 1988; Shailaja and Sahrawat, 1990; Moughli et al., 1993). Strong correlations were exhibited between clay content and different indices as shown in Table 1.7. In fact, more than 85% of the variation in buffer indices was explained by clay content. The clayey soils such as 1, 3, 11, and 12 had higher MBC compared to the other soils. Moughli et al. (1993) suggested that clay content can be used to predict buffer indices as well as the Salmon index. They found that clay content accounted for 66 to 76% of the variation in buffer indices. Our results also are consistent with previous results (Bowman and Olsen, 1985; Novais and Kamprath, 1978). Owusu-Bennoha and Acquaye (1989) found that clay and organic matter accurately described the P sorption maximum.

Multiple regression analyses showed positive correlations between buffer indices and soil parameters, especially clay content , lime, and exchangeable calcium contents. This indicates that as the content of one or more of these three parameters increases, soil P buffering capacity increases, resulting in an increased ability of a soil to replenish the soil solution as P is withdrawn by any external sink. My results indicate that a soil's buffer index can be estimated by using only these three parameters, which are usually determined in routine soil analyses procedures.

Effect of Time on Soil P Availability

Applying correct amounts of fertilizer is one of the primary keys to optimizing profits from its use. The relationship between fertilizer rate and supplying capacity of a specific soil varies over time. Therefore, we must known which soil characteristics affect P availability with time.

The amount of extracted P by 0.5 M $NaHCO_3$ using different rates of applied P was plotted as a function of incubation time (Fig. 1.3). In general, the amounts of extractable-P decreased with time, and the rate of decrease depended on both the rate of added P and soil type. The decrease in the amounts of $NaHCO_3$-P for soil 1 were from 4.4 (6 hr) to 3.9 mg P kg^{-1} (15 days) and 26.5 (6 hr) to 17.4 mg P kg^{-1} (15 days) for P rates 0 and 53.8 mg P kg^{-1}, respectively. These changes were more pronounced in a sandy soil 13, the respective decreases were 18.0 to 17.3 mg kg^{-1} without P, and 72.6 to 43.7 mg kg^{-1} with P rate of 53.8 mg P kg^{-1}. These results confirmed those reported by Sharpley et al. (1989), Afif et al. (1993), and Garcìa-Rodeja and Gil-Sotres (1995). Garcìa-Rodeja and Gil-Sotres (1995) who found that the rate of increase of soil P test increased with P rates and decreased with increasing time.

The $NaHCO_3$-P values declined sharply for many soils during the first two days (soils 2, 7, 8, 11, and 13), and it took about a week for the others. This information should be valuable in managing the time of P fertilizer application to optimize its use. Therefore, the shorter the time between P application and uptake by root, the higher the amount of P recovered by plant.

After 140 days of incubation, all soils reached an apparent steady state level. The decrease of $NaHCO_3$-P content with time was large, particularly at high P application rates. Little or no change occurred in the amount of $NaHCO_3$-P accumulated at the lower P application rates (P rate $\leq$ 6.7 mg kg^{-1}). This is consistent with the findings of Afif (1993) who reported that, at 20 mg P kg^{-1}, the availability index (AI= ratio between the increase in $NaHCO_3$-P and P applied) changed relatively little after 60 days of incubation. At high levels of P application, nucleation and growth of Ca-P crystals was reported to take place until steady state occurred (Freeman and Rowell, 1981).

Five models were tested to determine which best described P availability with time. These models were: Elovich model, parabolic diffusion model, parabolic model, two constant-rate model, and linear model. The parabolic-diffusion, simple parabolic, and Elovich equations best described my data (Table 1.8). The linear model was not satisfactory (low R^2 and high CV) at high P application rates (P rate $\geq$ 13.4 mg P kg^{-1}). The two constant rate model produced low R^2 and high CV values relative to the other models and their performance varied with soil. Based on the R^2 and variation coefficients, the Elovich equation was the best model to fit my data (Table 1.8).

Variation in experimental conditions between studies can result in different kinetics models describing P availability. Solis and Torrent (1989a) reported that the parabolic diffusion model gave the best fit in their investigation. Garcìa-Rodeja and Gil-Sotres (1995) reported that the two-constant equation was the appropriate model. Many earlier studies reported different models for specific experimental conditions. The most important consideration is the significance of the correlation between model parameters and the soil and plant availability index. Therefore, to determine which soil parameters influenced the change in extractable-P over time, I correlated rates of decrease (slopes) for each soil with soil properties (clay content, lime content, exchangeable Ca content, exchangeable Mg content, initial $NaHCO_3$-P level, organic matter, and CEC) using stepwise regression analysis (Table 1.9). The results showed that the rate of decrease in $NaHCO_3$-P was mainly influenced by clay content, exchangeable Ca content, and initial P concentration. The positive correlations between slope of P decrease and clay content and exchangeable calcium content indicated that the decrease of $NaHCO_3$-P is very pronounced in sandy compared to clayey soils. Our findings are similar to the result reported by Kato and Owa (1989), who suggested that the ability of clayey soils to maintain the P concentration in solution is higher than that of sandy soils. The release of P in clayey soils occurs slowly. It is inferred from Table 1.9 that the initial P content influenced the rate of decrease of P with time only at low P applications. The slope of Elovich equation was highly correlated with clay content. where clay content explained 66 to 78% of the variation in slope (Table 1.9). Sharpley (1983) showed that the modified coefficients for the Elovich equation were highly correlated with the ratio of calcium carbonate to organic-C and with the ratio of clay to organic-C content.

The extractable $NaHCO_3$-P decreased with time in all soils, and the decrease was best described by the Elovich equation. The rate of decrease was mainly governed by clay content. Therefore, after applying P fertilizer, the rate of decrease in $NaHCO_3$-P was more pronounced in sandy as compared to clayey soils, suggesting that in clayey soils there is resistance against any external change in P as compared to sandy soils.

Effect of Added P on P Availability in soil

A simple linear regression model was used to establish the relationship between $NaHCO_3$-P and P application rates. The relationships were best described by simple linear equations. These equations accounted for more than 96% of variation except for soil 2 (89%) and soil 7 (70%). A linear relationship also has been reported in earlier studies (Fuleky, 1978; Sharpley, 1982). The rates of extractable $NaHCO_3$-P increase (slope b of equation 3) were reported for P rates of 13.7 and 53.8 mg P kg^{-1} for each soil (Table 1.10). For the low P rates, the kinetic models were unable to describe the fate of P in soils because of the small changes induced by these rates. The highest increase in $NaHCO_3$-P occurred in soil 13 (Table 1.10). In general, the rates obtained in clayey soils were less steep than those in the sandy soils. The latter soils have high capability to maintain relatively high soil P concentration (Kato and Owa, 1989). It is important to point out the differences in rates of increase (b), within the same soil, for different times of incubation. For instance, the rates of increase were reduced from 0.93 and 0.39 to 0.51 and 0.36 for soils 13 and 3, respectively after 15 days of incubation time, and to 0.32 and 0.19 after 380 days for the same soils, respectively (Table 1.10). These results clearly show how important it is to know the period during which high in P availability will be maintained, and then the P rate required can be adjusted accordingly.

At any incubation time, the rate of a $NaHCO_3$-P increase in different soils was in the order of: soil 13 > 2 > 11 > 7 > 8 > 6 > 4 > 5 >1 > 3 (Table 1.10). The soils also ranked in the same order in regard to their adsorption capacities (MBC) (Table 1.4). Therefore, the higher the P adsorption capacity of soil the higher the amount of fertilizer needed to increase the concentration of available P in soil solution.

Correlations were determined between soil buffer indices and rates of increase of $NaHCO_3$-P (b). The highest correlations were obtained with maximum buffering capacity (Table 1.11). The correlations were all negative. Therefore, when P fertilizer is applied, the increase in P availability will be greater in soils with low sorption capacity than soils with high sorption capacity. Consequently, the P requirement for bringing P level to a sufficient range should account for the sorption capacity of a particular soil.

The percentage of P recovered by the $NaHCO_3$-P method, reported in Table 1.12, decreased significantly with time of incubation. The differences among soils is mainly explained by their sorption capacities. The highest recovery occurred in soil 13 (MBC = 35): 100% at 6 hours to 49% and 35% after 15 and 380 days, respectively (Table 1.12). While the lowest recoveries were obtained in soils 1 (MBC = 346): 41% after 6 hours which decreased to 25% and 17% after 15 and 380 days, respectively. The variation among soils was due mainly to their P sorption capacities. More P is sorbed on soil particles and/or precipitated with time. These results confirm the findings of Barrow and Shaw (1975), who reported that one of their soils required 20 times as much P to produce the same solution concentration after one day of incubation as compared to another soil. It is important to point out in Table 1.12 that P recovery was both soil and time dependent. The practical application of this information is to take into account the period of time during which P level has to be maintained in a given range of concentration, when determining P requirement. This could help in long-term management of P fertilization.

High correlations were found between various soil properties and the rates of increase of $NaHCO_3$-P in soils (Table 1.13). The slopes (rates of P increase) were principally influenced by the clay, silt, exchangeable calcium, and organic matter contents, but not all the same at different incubation periods. The regression equations showed negative correlations with all soil parameters (Table 1.13). Pena and Torrent (1990) postulated that not only clay and $CaCO_3$ were involved in P sorption, but also the edge surfaces of the clay minerals provided P adsorption sites and adsorbed more than $CaCO_3$. On other hand, the effect of $CaCO_3$ content was reported to affect long-term sorption (Solis and Torrent, 1989b).

In current soil test calibration method, recommendations are given without accounting for the ability of a given soil to react to applied P fertilizer. The differences between soils can be tremendous. Data reported in Table 1.14 show the amount of P needed to increase extractable-P value by 1 mg P kg^{-1}. This amount varied from soil to soil (1 to 2 fold) and also with incubation time (1 to 3 fold). Thus, short-term and long-term analyses are required for assessment of carry-over effects of P fertilizer application.

Soil test calibration is a good tool to classify soils from deficient to sufficient in regards to their P levels, but does not determine P requirement. The discrimination between soils is based upon initial P soil test level. However, as shown here, the increase of $NaHCO_3$-P level from the initial level to a given level depended upon initial P content, P sorption capacity, and rate of increase of extractable P with fertilization. Consequently, soils with the same initial P level and different characteristics probably require different amounts of fertilizer P to insure the same increase in extractable $NaHCO_3$-P.

Wheat Response to P Fertilizer

The response of wheat, grown in the greenhouse, to P applications varied markedly among soils. Yields were affected by P rates, soils, and the interaction between fertilizer P and soils. Nine out of thirteen soils had a significant increase in grain yield as a result of P fertilization (Table 1 15). Maximum grain yields were obtained for soils 3 (13.3 g/pot) and 7 (14.4 g/pot), while, the lowest were obtained for soils 1 (3.0 g/pot) and 11 (6 g/pot). Averaged across P rates, soils showed different abilities to produce high grain yields (Table 1.15). The grain yield in unfertilized pots varied from 0.4 (soil 1) to 14.8 g/pot (soil 7). The same soils, 1 and 7, produced the lowest (3.8 g/pot) and the highest (33.0 g/pot) total dry matter production, respectively (Table 1.16). These yields were expected as the initial $NaHCO_3$-P levels of these two soils are 2.7 and 23.0 mg P kg^{-1}, respectively. Similar trends of variation among soils were generally found for dry matter production. The difference response of wheat to applied P for the various soils was mainly explained by initial $NaHCO_3$-P soil test levels. The amount of plant P uptake averaged across P rates, varied from 6.4 (soil 1) to 44.8 mg P kg^{-1} (soil 12) with 9 out of 13 soils showing significant increases in P uptake with increased P rate (Table 1.17). More response to P additions were obtained with P uptake (9 soils) than dry matter production, suggesting that luxury P uptake took place without effecting yield (Table 1.18).

In general, initial soil P test level predicted the way wheat responded to P fertilization in different soils. The lower the P soil test level the higher the response by wheat to applied P. The largest increase in wheat yields were obtained in soils 1, 4, and

13. The soil test P levels for these soils were 3, 6, and 9 mg kg^{-1}, respectively. The average yields, across P rates, varied among soils, suggesting that parent materials under which a specific soil was developed plays an important role in determining its production potential.

Critical Level Determination

Soil tests must be related to crop response in order to formulate fertilizer recommendations. To determine these relationships for my results, wheat grain yield was expressed as relative yield and then plotted against the initial $NaHCO_3$-P of the 13 soils used in this experiment. Four methods were chosen to describe this relationship: Mitscherlich equation, linear response and plateau model (Cox, 1996), Cate-Nelson graphical method (Cate and Nelson, 1965), and Cate-Nelson statistical method (Cate and Nelson, 1971).

The Mitscherlich model computed using a non linear procedure (NLIN) by SAS program resulted in a critical soil test P level of 11 mg kg^{-1} at 90% of maximum yield. The problem associated with this kind of asymptotic model is the high variation of critical level value as I shift within 90 to 100% of maximum yield (Fig. 1.4A). In fact, the P test critical level was nearly 20 mg kg^{-1} (2-fold) at 98% of maximum grain yield.

The linear response and plateau model showed a soil test P critical level of 11 mg kg^{-1} with the maximum yield of 99% (Fig. 1.4B). This model gives an immediate estimation of yield associated with the critical level which was, in my case, 99%. The associated maximum yield is not chosen arbitrarily as with other methods. Cox (1996), postulated that the estimation of the critical level from curvilinear and exponential functions is difficult because of continuous change in slope to a maximum or toward an asymptote.

The Cate-Nelson graphic method is plotted in Fig. 1.4C. This method identified a soil P test critical level of 10 mg kg^{-1} associated with 90% of maximum yield. The Cate-Nelson statistical method, however, resulted in soil P test critical level of 14 mg kg^{-1} ($R^2 = 0.85$) (Fig. 1.4D). Therefore, the choice of the model and the relative associated yield are crucial in order to generate more precise critical levels to develop fertilization recommendations. These results showed some differences in critical levels values. For wheat grown on calcareous soils of Morocco, the $NaHCO_3$-P soil P critical level in the greenhouse study was between 10 and 14 mg kg^{-1} for a maximum yield range of 90 to 99%.

My critical level is very similar to that reported by Azzaoui et al. (1989) (10 mg kg^{-1}) and Moughli (1991) (9 mg kg^{-1}) in Morocco under greenhouse conditions. The variation among critical levels may be because they used early season dry matter productions as their data base. However, in my study, I used grain yield at maturity.

The P soil test critical levels found in the greenhouse were much higher than the critical level established from field study by Soltanpour et al. (1989), which was 5 mg kg^{-1}. These results are expected because of the vastly different environmental and rooting volume that occurs in the greenhouse as compared to the field.

Results from earlier studies conducted by Azzaoui et al. (1989) and Moughli (1991), as well as my study suggested that the soil P test critical level of 9 to 14 mg kg^{-1} is the cutoff point beyond which crop response to added P is not likely for wheat grown in the greenhouse.

Fertilizer P Requirement as Influenced by P Sorption

The relationship between wheat yield and soil P parameters was generally described as an exponential function. The widely used equation was based on the well known Mitscherlich equation:

$$RY = a - b*\exp(-c*P) \qquad (15)$$

RY = relative yield (yield at P=0 over maximum yield at non limiting P plot, expressed as %).

a , b and c = constants.

P = initial $NaHCO_3$-P level (mg P kg^{-1}).

Earlier studies (Holford 1980; Dear et al., 1992, Moughli et al., 1993) showed that P soil test, itself, did not explain all the variation in yield observed in the field. Therefore, other parameters should be included in the model to increase the accuracy of P recommendations. In fact, it has been reported that the critical P level increases with increasing P buffering capacity of the soil (Holford, 1980, Holford and Crocker, 1988). Therefore, the P requirement is inversely proportional to P buffering capacity. Based on that, equation (15) becomes:

$$RY = a - b*\exp[c*P + d*(Pad/BI)] \qquad (16)$$

a, b and c = constant

P = initial $NaHCO_3$-P level (mg P kg^{-1})

Pad = amount of added P (mg P kg^{-1})

BI = buffer indices (Xm, K, MBC, ST, or PR)

The modified Mitscherlich equations (16) were computed using yield data from the greenhouse experiment (13 soils) and buffer indices from the sorption study. The NLIN procedure of SAS was used to compute the Mitscherlich-equation coefficients involving: initial $NaHCO_3$-P, P added, yields, and buffering indices. Because of high correlations among various buffer indices (Table 1.5), I chose to use only MBC to illustrate the effect of buffer index on P requirement.

The computed constants of equation (16) after using MBC as a buffer index, were: a = 95.6; b = 208.9; c = 0.32; and c = 71.6 (equation 18). The coefficient of determination was significant and very high ($R^2 = 0.75$**). Initial soil P, amount of added P and buffer index explain about 75% of the variation in relative grain yield.

$$RGY = 95.6 - 208.9*\exp[-(0.32*P+71.6*(Pad/MBC))] \qquad R^2 = 0.75^{***} \qquad (17)$$

For RGY = 90%, the P requirement (mg P kg^{-1}) will be:

$$PR = (505 - 45*P)*MBC*10^{-4} \qquad (18)$$

The predicted values of RGY using equation (17) were then compared to actual values in Table 1.18. In general, the values were very comparable, the differences between predicted and observed were within 10%. The importance of the model given by equation (19) is the fact that it gives P requirement not only as a function of initial soil P test level (P), but also takes into account the increase in P availability by adding P fertilizer to a specific soil. Therefore, at the same initial soil P test, soils with different adsorption capacities will have different P recommendations (equation 19). Actual and predicted P applications to obtain 90% of maximum grain yield are given in Table 1.19. The model predicted P requirement fairly well (within 2 mg P kg^{-1}) for all soils except for soil 6. No explanation can be offered for this exception. The variation between predicted and observed P requirement (Δ) showed that accounting for MBC reduced the deviation from the actual required amount of P (Table 1.19). Over all soils, the mean P requirement for all thirteen soils was equal to the predicted value when MBC was used (2.6 mg P kg^{-1}). Whereas, without MBC, the average P requirement among soils were underestimated by 1.4 mg P kg^{-1} (Table 1.19).

To illustrate the importance of the discrepancv between soils regarding the P requirement, equation (18) was plotted for two rates of P added (Pad) of 1.7 ($\approx$ 10 kg P_2O_5 ha^{-1}) and 5.2 mg P kg^{-1} ($\approx$ 30 kg P_2O_5 ha^{-1}) for different soils. It is obvious from Figure 1.5 that, at any initial $NaHCO_3$-P soil test level, the same rate of added P resulted in different yield responses for different soils. For instance, assuming our soils had the same initial $NaHCO_3$-P level of 4 mg P kg^{-1}, the application of a P rate of 1.7 mg P kg^{-1} resulted in predicted relative grain yields of 78, 62, and 50% in soils 2 (MBC=131), 4 (MBC=184), and 12 (MBC= 404), respectively (Fig. 1.5). However, when 5.2 mg P kg^{-1} was applied, the correspondent RGY were 92, 88, and 72% for soils 2, 4, and 13, respectively. The effect of soil sorption indices seemed to be more pronounced in low P soils. That is, the inclusion of such soil parameters in fertilizer recommendation equations is highly suitable. This finding supports the results of Dear et al. (1992). In their study they postulated that soil P test combined with P buffering capacity measurement was a better approach to estimating yields in soils with low P test levels.

To show how buffer indices could affect P requirements for soils having the same initial soil P test level, relative grain yields were calculated using model (17) assuming that all soils had the same initial $NaHCO_3$-P (P = 3 mg P kg^{-1}). For each soil, the response curve was developed by giving its MBC value in equation (17) and varying P added (Pad) in the range 0-15 mg P kg^{-1}. Relative grain yield curves, fitted to each soil were plotted in Fig. 1.6. The results showed that, when using current soil test recommendation, the amount of P needed to achieve 90% of the maximum grain yield was 12 mg P kg^{-1} for soils having soil test P of 3 mg kg^{-1} (Fig. 1.6A). However, using my modified Mitscherlich model, the amounts of P needed to achieve 90% of the maximum grain yield were: 5 and 16 mg P kg^{-1} for soils 9 and 13 having low (MBC = 101) and high (MBC = 404) buffering capacities, respectively (Fig. 1.6B). Therefore, when a recommendation is made without considering buffer indices, the amount of P required for a given yield goal is overestimated for soils with low buffering capacities and underestimated in the case of high buffering capacitv soils.

It is clear from these results that buffer indices have significant effects on predicting yields especially in low P soil in the greenhouse. Holford (1980) found that buffer capacity had a very significant effect ($p<0.01$) on the relationships between the $NaHCO_3$-P test and relative yield. He explained this by the greater negative effect of buffering on the extraction of labile phosphate by the $NaHCO_3$-P tests.

The P requirements for achieving 90% of maximum yield were calculated for soil P contents of 0, 3, 6, 8 and 10 mg P kg^{-1} using equation (14) at the actual buffering capacities of my soils (Table 1.20). Phosphorus requirement varied as a function of both initial P level and MBC (Table 1.20). It ranged from 1 to 15 mg P kg^{-1} for soil 13 (sandy soil) and soil 12 (clayey soil) respectively. The difference disappeared at high soil P levels (greater than 10 mg/kg). This clearly shows how soil sorption capacities can affect fertilizer P requirement.

This study suggests that buffer indices could improve the estimation of P requirement for achieving maximum yield under greenhouse conditions. In general, clayey soils were under-fertilized and sandy soils over-fertilized using current P recommendation. To overcome this problem, soil P adsorption capacities can be used to adjust P fertilizer requirement.

SUMMARY AND CONCLUSION

Langmuir and Cooke equations were found to accurately describe P sorption isotherms in calcareous soils of Moroccan arid and semiarid zones. These soils range from medium to high in P fixing capacity. The range of MBC was between 35 and 404 mg P kg^{-1}. The variation in soil buffer indices was explained mainly by clay, calcium carbonate, and exchangeable calcium contents. These three parameters can be used to predict MBC as well as other indices with a satisfactory coefficient of determination.

One of the most important results of this study was the identification of the variation in soil P adsorption capacities between geographical zones. Soils from Chaouia adsorbed more P compared to Abda and Ben Sliman Soils. This emphases the importance of developing recommendations specific for each region, which is not currently the case in Morocco.

The information regarding kinetics of P in soil may be used to manage P fertilizer use regarding both the amount and time of application. The maximum increase in

$NaHCO_3$-P level was obtained when the contact time between soil particles and P fertilizer was shortest. Phosphate recovery declines when fertilizer contact time with a soil increases, suggesting that it is better to apply P fertilizer at sowing time.

The increase in P availability was found to be significantly correlated to P adsorption capacity ($r=-0.65$ to -0.77). It is important to point out that the correlations were all negative. Therefore, when P fertilizer is applied, the increase in P availability will be larger in soil with low sorption capacity than with high sorption capacity.

The practical use of the equations describing variation of extractable P as a function of added P is to calculate the amount of P to be added, not only to reach a sufficient level of P concentration in the soil, but also to maintain this level as long as it is needed. This study showed that the fate of P with time can be described by the Elovich equation. The shape of the curve was mainly governed by the soil, especially its clay and exchangeable calcium contents.

The variation in amount of available P with P rates was consistently described by linear relationships. The rate of increase (b) varied widely among soils from 0.51 (soil 13) to 0.24 (soil 1) after 15 days of incubation and between 0.32 (soil 13) to 0.17 (soil 3) after 380 days of incubation. In general, sandy soils had a higher rate increase than clayey soils. The implication of these results is that the amount of P required to reach a given available P level differs among soils, and the linear regression equations could be used for these predictions.

As far as P critical level is concerned, the choice of the model and the associated relative yield are crucial in order to generate more precise soil test critical level to guide fertilization recommendations. For wheat grown under greenhouse conditions in Moroccan calcareous soils the $NaHCO_3$-P critical level would be between 10 and 14 mg kg^{-1} for yield between 90 and 99% of the maximum.

Although the inclusion of buffer indices did not significantly increase grain yield prediction, my findings from hypothetical soils showed a greater utility of these indices in the improvement of P fertilizer recommendations. In fact, calculations of P requirement, assuming a soil test P of 3 mg kg^{-1}, showed that the need for 90% of maximum yields ranged from 1 to 15 mg P kg^{-1} for soils 13 (MBC = 26) and 12 (MBC = 404), respectively. The main conclusion from this study was that the incorporation of buffer indices in determining P requirement would increase the accuracy of P fertilizer recommendations and overcome the problem of over-fertilization in sandy soils and under-fertilization in clayey soils.

The next logical step is to test the use of buffer indices under field conditions and develop recommendation norms accordingly.

Table 1.1. Classification of soils used in study and their geographic locations.

Soil	Soil great group	Location
1	Palexerolic Chromoxerets	Chaouia
3	Calcic Argixerolls	"
4	Typic Chromoxererts	"
5	Typic Rendolls	"
6	Xerochrepts	"
7	Xerochrepts	"
8	Argiustolls	"
10	Aridic SG of Ustolls	"
12	Xerochrepts & Ustochrepts	"
18	Palexerolic Chromoxerets	"
2	Vertic Calcixerollic	Abda
9	Typic Rendolls	"
11	Chromoxererts	"
13	Arguistolls	"
14	Orthents	Ben Sliman
15	Torrifluvents	"
16	Typic Rendolls	"
17	Typic Calciaquolls	"

Table 1.2. Selected physical and chemical characteristics of surface (0-20 cm) soils used in study.

Soil	Clay	Silt	Sand	pH water	CEC	Organic matter	Lime	NO_3-N	K	Na	Ca	Mg	P
	---------	%	----------		mS/cm	-------- %	--------	----------------------------	----------	mg kg^{-1}	----------	----------	----------
1	56	20	23	7.9	56	1.6	7	4	198	294	6450	411	3
2	42	8	48	8.1	39	2.3	1	44	112	280	4150	414	8
3	51	28	22	8.2	50	1.9	15	4	319	154	8040	351	10
4	48	8	39	7.9	39	2.2	6	3	210	58	6310	289	6
5	56	14	27	7.7	26	4.6	4	10	238	85	7170	171	7
6	47	23	27	8.0	28	1.6	21	10	167	70	5730	273	8
7	49	9	39	8.0	28	2.3	37	6	78	72	4430	103	23
8	26	8	64	7.7	10	2.8	1	5	125	82	1390	97	14
9	28	15	67	8.2	27	3.7	14	10	152	43	3430	178	8
10	27	7	66	8.1	13	2.5	1	6	117	41	1530	171	9
11	45	10	43	7.6	43	1.4	1	4	186	445	3860	375	9
12	53	8	37	7.5	28	2.6	1	4	152	84	3860	288	26
13	10	2	87	7.9	1	0.6	1	6	82	22	570	57	9
14	25	7	68	7.5	8	1.7	1	15	192	980	1090	782	9
15	11	27	62	7.8	27	1.3	8	9	271	74	3130	331	7
16	50	23	27	8.1	43	1.8	1	10	300	137	3520	703	8
17	30	7	63	8.0	23	1.6	10	15	133	85	2930	265	8
18	43	19	28	8.3	49	2.3	16	22	413	73	3050	513	17

Table 1.3. Statistical Parameters computed for Langmuir, Freundlich, and Cooke models expressing P sorption for 18 soils used in study.

	Models											
	Langmuir				Freundlich				Cooke			
Soil	Int	Coef	R^2	CV	Int	Coef	R^2	CV	Int	Coef	R^2	CV
1	0.00289	0.00157	0.92	28.4	2.23	0.51	0.87	14.0	35.9	139	0.98	10.4
2	0.00761	0.00289	0.98	13.7	1.79	0.60	0.88	13.2	33.7	57	0.96	13.9
3	0.00276	0.00149	0.94	25.7	2.24	0.53	0.89	13.1	36.3	147	0.99	6.6
4	0.00543	0.00190	0.95	22.3	2.15	0.37	0.84	15.5	26.2	97	0.99	7.3
5	0.00301	0.00159	0.92	33.0	2.35	0.31	0.91	12.3	36.1	132	0.99	9.7
6	0.00285	0.00133	0.95	20.8	2.17	0.76	0.89	12.7	10.8	181	0.99	10.3
7	0.00273	0.00120	0.93	22.4	2.24	0.75	0.88	13.3	6.5	220	1.00	3.1
8	0.01009	0.00361	0.85	40.5	1.66	0.56	0.99	3.8	12.9	46	0.96	13.3
9	0.00986	0.00207	0.92	23.9	1.79	0.69	0.93	10.5	-1.3	86	1.00	3.6
10	0.00978	0.00348	0.80	51.1	1.24	1.01	0.69	33.8	4.1	50	0.99	9.4
11	0.00575	0.00342	0.99	12.9	1.86	0.50	0.76	19.1	43.2	47	0.93	19.1
12	0.00248	0.00136	0.98	18.9	2.23	0.77	0.85	15.9	35.1	174	0.95	22.2
13	0.02884	0.00422	0.79	39.4	0.86	1.17	0.80	29.6	-6.9	38	0.95	18.9
14	0.01817	0.00707	0.92	29.0	1.55	0.41	0.97	5.9	22.6	19	0.93	15.6
15	0.01416	0.00340	0.97	15.3	1.54	0.68	0.77	18.4	17.7	45	0.97	13.0
16	0.00520	0.00234	0.97	20.2	2.16	0.32	0.86	14.1	41.4	72	0.98	11.0
17	0.00710	0.00368	0.87	42.7	1.75	0.48	0.99	4.0	17.9	45	0.98	9.6
18	0.00543	0.00164	0.96	18.4	1.97	0.69	0.90	12.5	9.9	118	0.98	11.1

Int = intercept

Coef = coefficient

CV= coefficient of variation

Table 1.4. Buffer indices of the 18 soils used in study calculated for Langmuir and Cooke isotherm models.

	Model									
	Langmuir						Cooke			
Soil	Xm	K	MBC	SBC	ST	PR	AC	TPD	BC1	SBC
1	637	0.54	346	256	89	62	139	35.9	69	127
2	346	0.38	131	106	35	24	57	33.7	28	52
3	672	0.54	363	269	94	66	147	36.3	73	134
4	527	0.35	184	151	50	34	97	26.2	49	89
5	631	0.53	332	248	86	60	132	36.1	66	120
6	750	0.47	351	270	92	64	181	10.8	91	165
7	837	0.44	367	287	97	68	220	6.5	110	201
8	277	0.36	99	81	27	19	46	12.9	23	42
9	484	0.21	101	90	29	20	86	-1.3	43	78
10	287	0.36	102	84	28	19	50	4.1	25	46
11	292	0.60	174	125	44	31	47	43.2	24	43
12	736	0.55	404	298	104	73	174	35.1	87	159
13	237	0.15	35	32	10	7	38	-6.9	19	34
14	141	0.39	55	44	15	10	19	22.6	10	17
15	294	0.24	71	62	20	14	45	17.7	22	41
16	428	0.45	192	149	51	35	72	41.4	36	66
17	272	0.52	141	106	37	26	45	17.9	22	41
18	608	0.30	184	155	51	35	118	9.9	59	107

Langmuir:
Xm = adsorption maxima (mg kg^{-1} soil)
K = binding energy
MBC = maximum buffering capacity
SBC = standardized buffering capacity
ST = standardized test
PR = phosphorus requirement

Cooke
AC = Affinity constant
TRD = theoretical P desorption
BC = buffering constant at C = 1
SBC = standardized buffering capacity

Table 1.5. Matrix given Pearson correlation coefficients between buffer indices computed from Langmuir and Cooke models.

	Buffer indices from									
	Langmuir model						Cooke model			
	Xm	K	MBC	SBC	ST	PR	AC	TRD	BC1	SBC
Xm		0.38 NS	0.91 **	0.93 **	0.92 **	0.92 **	0.98 **	0.14 NS	0.98 **	0.98 **
K			0.70 **	0.66 **	0.68 **	0.69 **	0.40 NS	0.75 **	0.40 NS	0.40 NS
MBC				0.99 **	0.99 **	0.99 **	0.92 **	0.42 NS	0.92 **	0.92 **
SBC					0.99 **	0.99 **	0.94 **	0.38 NS	0.94 **	0.94 **
ST						0.99 **	0.92 **	0.40 NS	0.93 **	0.93 **
PR							0.92 **	0.41 NS	0.92 **	0.92 **
AC								0.09 NS	0.99 **	0.99 **
TRD									0.09 NS	0.09 NS
BC1										0.99 **
SBC										

Langmuir:
Xm = adsorption maxima (mg kg^{-1} soil)
K = binding energy
MBC = maximum buffering capacity
ST = standardized test
PR = phosphorus requirement

Cooke
AC = Affinity constant
TRD = theoretical P desorption
BC = buffering constant at C = 1
SBC = standardized buffering capacity

NS and ** non significant and significant at p=0.01, respectively.

Table 1.6. Multiple regression analysis relating selected soil properties and buffer indices for Langmuir and Cooke models.

Model	Multiple regression	
Langmuir		
	$Xm = 36.23 + 15.50*CL - 0.38*Mg$	$r^2=0.87$**
	$K = 0.26 + 3.90*10^{-5}\cdot(Ca+Mg)$	$r^2=0.60$*
	$MBC = -38.10 + 3.34*CL + 3.70*L + 0.024*Ca$	$r^2=0.98$**
	$STC = -9.81 + 0.94*CL + 1.00*L + 0.006*Ca$	$r^2=0.98$**
	$PR = -6.92 + 0.64*CL + 0.69*L + 0.004*Ca$	$r^2=0.98$**
	$SBC = -28.18 + 2.96*CL + 2.97*L + 0.014*Ca$	$r^2=0.98$**
Cooke		
	$AC = 139.24 - 1.52*S + 3.62*L$	$r^2=0.93$**
	$TRD = 4.01 + 0.96*CL$	$r^2=0.94$**
	$SBC = 79.89 - 0.90*CL$	$r^2=0.80$**
	$BC1 = 20.93 - 0.02*Mg$	$r^2=0.45$*

* and ** significant at p=0.05 and 0.01, respectively.

Langmuir:
Xm = adsorption maxima (mg kg^{-1} soil)
K = binding energy
MBC = maximum buffering capacity
SBC = standardized buffering capacity
ST = standardized test
PR = phosphorus requirement
Cooke:
AC = Affinity constant
TRD = theoretical P desorption
BC = buffering constant at C = 1
SBC = standardized buffering capacity

CL = clay content (%)
L = lime content (%)
Ca = exchangeable calcium (mg kg^{-1})
Mg = exchangeable magnesium (mg kg^{-1})
S = sand content (%)

Table 1.7. Correlation matrix between selected soil parameters of 18 soils used in study and P buffer indices for Langmiur and Cooke models.

Soil Properties	Models	Indices					
	Langmuir	Xm	K	MBC	SBC	ST	PR
Clay		0.76**	0.54*	0.87**	0.87**	0.87**	0.87**
Silt		0.49*	0.32NS	0.59*	0.58*	0.58*	0.58*
Sand		0.75**	0.40NS	0.78**	0.79*	0.79*	0.79*
CEC		0.49*	0.34NS	0.55*	0.54*	0.55*	0.55*
Lime		0.59*	0.19NS	0.57*	0.59*	0.60*	0.58*
Ca		0.63*	0.58*	0.86* *	0.83**	0.84* *	0.85**
K		0.07NS	0.01NS	0.04NS	0.04NS	0.04NS	0.04NS
Na		0.17NS	0.01NS	0.08NS	0.08NS	0.08NS	0.08NS
Mg		0.04NS	0.04NS	0.02NS	0.02NS	0.02NS	0.02NS
$NaHCO_3$-P		0.18NS	0.03NS	0.04NS	0.06NS	0.05NS	0.04NS
	Cooke	AC	TRD	BC1	SBC		
Clay		0.70**	0.94**	0.12NS	0.80**		
Silt		0.38NS	0.60*	0.30NS	0.40NS		
Sand		0.64**	0.86**	0.18NS	0.70**		
CEC		0.36NS	0.77**	0.15NS	0.63*		
Lime		0.72**	0.33NS	0.02NS	0.50*		
Ca		0.65*	0.77**	0.12NS	0.68**		
K		0.02NS	0.17NS	0.34NS	0.05NS		
Na		0.14NS	0.03NS	0.12NS	0.07NS		
Mg		0.06NS	0.01NS	0.45*	0.01NS		
$NaHCO_3$-P		0.22NS	0.02NS	0.09NS	0.07NS		

* and ** significant at p=0.05 and 0.01, respectively. NS = non significant at p=0.05.

Ca, K, Na, Mg = exchangeable calcium, potassium, sodium, magnesium, respectively. (Mg kg^{-1})

Langmuir:
Xm = adsorption maxima (mg kg^{-1})
K = binding energy
MBC = maximum buffering capacity
ST = standardized test
PR = phosphorus requirement
SBC = standardized buffering capacity

Cooke
AC = Affinity constant
TRD = theoretical P desorption
BC = buffering constant at C = 1

Table 1.8. Coefficients of Elovich, parabolic-diffusion, and simple parabolic kinetics models relating $NaHCO_3$-P (P) to time (t) when P was added at rate of 53.4 mg P kg^{-1} soil.

		Coefficients				
Soil	Model	a	b	c	R^2	CV
	Elovich : $P = a + b*\ln(t)$					
1		23.3	-1.98		0.95**	5.8
2		50.9	-4.07		0.95**	5.6
3		36.1	-2.41		0.91**	6.2
4		31.5	-1.50		0.93**	3.7
5		30.5	-2.08		0.97**	3.9
6		37.2	-2.96		0.91**	7.6
7		62.0	-4.74		0.93**	6.6
8		50.4	-3.37		0.77*	11.1
11		40.8	-3.81		0.82*	13.9
13		64.3	-7.60		0.93**	11.5
	Parabolic-diffusion : $P = a + b*(t)^{0.5}$					
1		23.6	-0.98		0.69*	15.2
2		51.7	-2.05		0.72*	13.4
3		37.0	-1.30		0.80*	9.4
4		31.6	-0.73		0.66*	8.3
5		30.9	-1.06		0.75*	10.6
6		38.7	-1.72		0.92**	7.2
7		63.8	-2.62		0.84**	9.7
8		50.0	-1.46		NS	17.4
11		40.9	-1.78		NS	22.4
13		66.2	-3.93		0.94**	21.5
	Simple Parabolic : $P = a + b*t + c*t^2$					
1		24.3	-0.380	0.0024	0.91*	9.6
2		52.8	-0.756	0.0047	0.90*	9.1
3		37.4	-0.450	0.0027	0.97**	4.4
4		32.3	-0.303	0.0019	0.93*	4.5
5		31.4	-0.378	0.0023	0.91*	7.3
6		38.1	-0.432	0.0023	0.95*	6.7
7		64.3	-0.826	0.0048	0.96**	5.7
8		52.8	-0.798	0.0054	0.88*	9.3
11		42.1	-0.689	0.0043	NS	21.0
13		68.4	-1.458	0.0090	0.93*	12.5

* and **significant at p=0.05 and 0.01, respectively; NS= non significant at p=0.05

CV = coefficient of variation.

Table 1.9. Relationship between rate of decrease of NaHCO$_3$-P (b) and selected soil parameters.

Applied P	Regression equation	R^2
Stepwise regression using all soil parameters:		
13.7 mg P kg^{-1}		
Model 1	b = -11.04 + 0.16*CL + 0.36*Pi	0.91**
Model 2	b = -5.27 + 0.07*CL + 0.17*Pi	0.94**
54.8 mg P kg^{-1}		
Model 1	b = -7.77 + 0.10*CL	0.66**
Model 2	b = - 4.04 + 0.00042*Ca	0.84**
Regression using only clay content:		
13.7 mg P kg^{-1}		
Model1	b = -6.22 + 0.11 CL	0.69*
Model2	b = -2.99 + 0.05 CL	0.71*
53.8 mg P kg^{-1}		
Model1	b = -7.77 + 0.10 CL	0.66**
Model2	b = -4.59 + 0.07 CL	0.78**

Model 1= Elovich equation
Model 2 = parabolic-diffusion equation
b = rate of decrease (slope of the model)
Pi = soil P test before incubation (mg kg^{-1})
CL = clay content (%)
Ca = exchangeable calcium (mg kg^{-1})
* and ** = significant at p=0.05 and 0.01, respectively

Table 1.10. The rates of $NaHCO_3$-P increase as a result of P applications for 10 soils and for different times of incubation.

	Soils									
Incubation time	1	2	3	4	5	6	7	8	11	13
-- day----	increase in $NaHCO_3$-P by 1 unit added P									
0.25	0.42	0.72	0.39	0.48	0.44	0.49	0.67	0.65	0.69	0.93
0.5	0.41	0.71	0.38	0.47	0.40	0.47	0.63	0.61	0.46	1.00
1	0.36	0.62	0.32	0.47	0.39	0.42	0.56	0.60	0.42	0.91
2	0.32	0.48	0.37	0.40	0.41	0.39	0.51	0.47	0.38	0.98
7	0.30	0.49	0.34	0.42	0.37	0.38	0.46	0.41	0.38	0.74
15	0.24	0.44	0.36	0.37	0.33	0.34	0.43	0.38	0.30	0.51
21	0.23	0.44	0.21	0.36	0.29	0.32	0.40	0.40	0.34	0.33
28	0.21	0.30	0.17	0.34	0.24	0.21	0.21	0.25	0.21	0.36
35	0.21	0.29	0.16	0.34	0.23	0.21	0.20	0.24	0.21	0.36
65	0.23	0.31	0.16	0.29	0.22	0.15	0.24	0.27	0.29	0.34
130	0.21	0.34	0.21	0.36	0.23	0.17	0.26	0.46	0.24	0.32
380	0.17	0.35	0.19	0.26	0.26	0.19	0.29	0.30	0.29	0.32

The rate of increase represents the slope b of the following equation:

$NaHCO_3\text{-}P = a + b*Padded$

all computed regressions were significant at $p = 0.01$.

Table 1.11. Correlation coefficients between buffer indices (BI) and rates of P availabilities (b).

Avialability Indices	Buffer Indices					
	Xm	K	MBC	SBC	ST	PR
b15	-0.67*	-0.74*	-0.76*	-0.75*	-0.76*	-0.76*
b380	-0.65*	-0.55NS	-0.75*	-0.73*	-0.74*	-0.74*

* significant at p=0.05
NS = non significant at p=0.05
b15 = rate of $NaHCO_3$-P increase after 15 days of incubation
b385 = rate of $NaHCO_3$-P increase after 385 days of incubation
Xm = adsorption maxima (mg kg^{-1} soil)
K = binding energy
MBC = maximum buffering capacity
SBC = standardized buffering capacity
ST = standardized test
PR = phosphorus requirement

Table 1.12. Percentage P recovered by $NaHCO_3$-P soil test method for different times of incubation with P added of 53.8 mg P kg^{-1}.

	Incubation time (days)											
Soil	0.25	0.50	1	2	7	15	21	28	35	65	130	380
	%											
1	42	40	35	32	31	25	24	21	21	23	21	17
2	75	73	64	50	50	46	45	30	31	31	34	36
3	41	39	33	38	32	32	20	14	13	15	20	19
4	50	49	48	42	43	39	39	36	36	31	39	26
5	45	39	38	46	36	33	30	24	24	24	24	25
6	49	47	42	39	38	34	32	24	24	15	18	19
7	68	62	53	49	42	21	38	22	21	28	30	31
8	64	58	59	45	40	41	37	26	26	27	46	32
11	71	45	42	36	39	29	32	23	22	32	24	30
13	100	100	93	96	74	49	32	34	34	34	32	35

Table 1.13. Multiple regressions equation between the rate of P increase (b) and soil parameters.

Incubation time	Regression Equation	R^2
------ day ------		
0.25	b = 0.896-6.41*10^{-5}Ca	0.82**
0.50	b = 1.05 - 0.0096*CL - 0.0069*SL	0.82**
1	b = 0.806 - 6.41*10^{-5}Ca	0.75*
2	b = 0.951 - 0.0116*CL	0.73**
7	b = 0.736 - 0.006*CL - 0.004*SL	0.77**
15	b = 0.63 - 0.0052*CL	0.53*
21	b = 0.40 -0.0048*SL	0.41*
28	b = 0.37 -0.0052*SL	0.50*
35	b = 0.31- 0.0045*SL	0.47*
65	b = 0.36 - 0.0055*SL - 0.0155*OM	0.96**
130	b = 0.34 - 0.0065*SL	0.51*
380	b = 0.34 - 0.0054*SL	0.74**

The rate of increase represents the slope b of the following equation:

NaHCO$_3$-P = a + b*Padded

CL = clay content (%)
SL = silt content (%)
Ca = exchangeable calcium content (mg kg^{-1})
OM = organic matter content (%)
* and ** = significant at p=0.05 and 0.01, respectively

Table 1.14. Amount of P needed to increase $NaHCO_3$-P in different soil by 1 mg P kg^{-1}.

Increase maintained for	Soils									
	1	2	3	4	5	6	7	8	11	13
-- days---	mg P kg^{-1}									
0.25	2.4	1.4	2.6	2.1	2.3	2.0	1.5	1.5	1.4	1.1
0.5	2.4	1.4	2.6	2.1	2.5	2.1	1.6	1.6	2.2	1.0
1	2.8	1.6	3.1	2.1	2.6	2.4	1.8	1.7	2.4	1.1
2	3.1	2.1	2.7	2.5	2.4	2.6	2.0	2.1	2.6	1.0
7	3.3	2.0	2.9	2.4	2.7	2.6	2.2	2.4	2.6	1.4
15	4.2	2.3	2.8	2.7	3.0	2.9	4.5	2.6	3.3	2.0
21	4.3	2.3	4.8	2.8	3.4	3.1	2.5	2.5	2.9	3.0
28	4.8	3.3	5.9	2.9	4.2	4.8	4.8	4.0	4.8	2.8
35	4.8	3.4	6.3	2.9	4.3	4.8	5.0	4.2	4.8	2.8
65	4.3	3.2	6.3	3.4	4.5	6.7	4.2	3.7	3.4	2.9
130	4.8	2.9	4.8	2.8	4.3	5.9	3.8	2.2	4.2	3.1
380	5.9	2.9	5.3	3.8	3.8	5.3	3.4	3.3	3.4	3.1

Table 1.15. Effect of fertilizer P rates on grain yield of wheat under greenhouse conditions.

	Applied P (mg P kg^{-1})					
Soil	0.0	3.4	6.7	13.4	Mean	Sign.
	g/pot					
1	0.4 c	2.4 b	3.9 a	5.1 a	3.0	**
2	9.5 c	9.0 b	10.3 b	12.2 a	10.3	**
3	13.0 b	12.8 b	13.4 b	14.0 a	13.3	*
4	6.3 c	8.7 bc	9.6 ab	9.9 a	8.6	**
5	8.7 c	9.7 b	10.3 b	11.9 a	10.2	**
6	10.5 a	10.6 a	10.7 a	10.2 a	10.5	NS
7	14.8 a	14.3 a	14.1 a	14.3 a	14.4	NS
8	11.0 a	10.7 a	10.9 a	10.7 a	10.8	NS
9	9.5 b	9.7 b	10.5 a	11.0 a	10.2	**
10	8.4 c	8.6 c	9.6 b	10.6 a	9.3	**
11	5.2 b	6.0 a	6.3 a	6.6 a	6.0	**
12	11.4 a	11.3 a	11.5 a	11.4 a	11.4	NS
13	6.1 c	7.7 bc	8.6 ab	11.1 a	8.4	**

sign.= significance

Means with the different letters, in row, were significatively different ($P = 0.05$)

* and ** significant at $p=0.05$ and 0.01, respectively.

NS = non significant at $p=0.05$

Table 1.16. Effect of fertilizer P rates on dry matter production of wheat under greenhouse conditions.

	Applied P (mg P kg^{-1})					
Soil	0.0	3.4	6.7	13.4	Mean	Sign.
	g/pot					
1	3.8 c	8.6 b	12.8 a	14.8 a	10.0	**
2	24.6 b	23.8 b	25.9 b	29.5 a	26.0	**
3	32.1 b	33.5 ab	35.5 ab	36.4 a	34.4	NS
4	20.9 b	22.9 ab	25.0 a	25.9 a	23.7	*
5	26.9 b	27.5 b	32.5 a	31.7 a	29.7	*
6	25.0 a	26.9 a	27.9 a	26.8 a	26.6	NS
7	33.0 a	33.2 a	32.8 a	30.4 a	32.4	NS
8	27.8 a	28.2 a	28.4 a	29.5 a	28.5	NS
9	25.3 a	25.3 a	26.6 a	27.2 a	26.1	NS
10	22.2 b	25.5 a	25.2 a	26.1 a	24.8	*
11	16.7 a	17.7 a	18.1 a	18.4 a	17.7	NS
12	26.2 a	27.2 a	26.6 a	26.7 a	26.7	NS
13	17.0 c	20.4 b	22.8 ab	24.6 a	21.2	***

sign.= significance

Means with the different letters, in row, were significatively different (P = 0.05)

* and ** significant at p=0.05 and 0.01, respectively

NS = non significant at p=0.05

Table 1.17. Effect of fertilizer P rate on total P uptake by wheat under greenhouse conditions.

	Applied P (mg P kg^{-1})					
Soil	0.0	3.4	6.7	13.4	Mean	Sign.
	mg/pot					
1	1.1 d	4.9 c	7.9 b	11.5 a	6.4	**
2	20.0 c	22.2 bc	27.8 ab	35.4 a	26.4	**
3	32.8 b	35.1 b	34.8 b	40.9 a	35.9	**
4	14.8 c	20.6 bc	23.9 b	35.5 a	23.7	**
5	14.9 c	20.4 b	24.5 b	35.9 a	23.9	**
6	26.1 a	23.5 a	28.1 a	30.6 a	27.1	NS
7	33.6 b	42.7 b	35.1 a	43.5 a	38.7	**
8	30.9 b	30.4 b	37.9 b	30.6 a	32.5	*
9	17.6 b	22.3 b	22.7 b	29.9 a	23.1	**
10	20.9 a	22.8 a	24.6 a	25.3 a	23.4	NS
11	22.6 a	26.6 a	27.2 a	27.9 a	26.1	NS
12	51.6 a	39.2 a	41.1 a	47.4 a	44.8	NS
13	14.0 b	16.4 ab	22.9 a	34.1 a	21.9	*

sign.= significance

Means with the different letters, in row, were significatively different (P = 0.05)

* and ** significant at p=0.05 and 0.01, respectively.

NS = non significant at p=0.05

Table 1.18. Observed and predicted relative grain yield (RGY) for check plot using computed models.

Soil	Soil $NaHCO_3$ P	Observed RGY	Predicted RGY Using P only	Predicted RGY Using MBC and P
	mg kg^{-1}	%		
1	3	8	8	7
4	6	64	66	68
5	7	73	71	73
2	8	78	75	77
9	8	86	75	77
6	8	98	78	80
10	9	79	80	81
13	9	55	81	82
11	9	79	83	84
3	10	93	87	87
8	14	100	95	93
7	23	100	99	95
12	26	99	99	96

RGY = relative grain yield (%)
P = soil initial $NaHCO_3$ level (mg kg^{-1})
MBC = maximum beffering capacity
Computed model using P only:

$$RGY = 99.1 - 187.5*\exp[-(0.27*P)]$$

Computed model using P and MBC:

$$RGY = 95.6 - 208.9*\exp[-(0.32*P + 71.6*(Pad/MBC))] \quad \text{with } Pad = 0$$

Table 1.19. Comparison of observed and predicted P requirement for 90% of maximum grain yield in greenhouse with and without taking into account soil buffering capacities.

Soil	MBC	$NaHCO_3$-P	Current applied P rate	Predicted P rate			
				with MBC	Δ	without MBC	Δ
		mg P kg^{-1}					
1	346	3	10	13	+3	7	-3
2	131	8	0	2	+2	3	+3
3	363	10	0	2	+2	0	0
4	184	6	4	4	0	3	-1
5	332	7	9	6	-3	3	-6
6	351	8	0	5	+5	0	0
7	367	23	0	0	0	0	0
8	99	14	0	0	0	0	0
9	101	8	4	2	-2	3	-1
10	102	9	7	1	-6	0	-7
11	174	9	3	2	-1	0	-3
12	404	26	0	0	0	0	0
13	35	9	1	0	-1	0	-1
Mean			3	3	0	1	-2

MBC = maximum buffering capacity

The recommendations without MBC were made based on the critical soil P test level of 10 mg P kg^{-1}

Δ = variation between predicted and current P requirement

Table 1.20. Phosphorus requirement to achieve 90% of maximum yield for 5 hypothetical values of soil test P for thirteen Moroccan soils.

Soil	MBC	NaHCO$_3$-P (mg kg^{-1})				
		3	5	8	10	11
		mg P kg^{-1}				
13	26	1.3	1.0	0.5	0.2	0.0
10	57	3.8	2.9	1.5	0.6	0.1
8	58	3.7	2.8	1.5	0.6	0.1
9	101	3.8	2.9	1.5	0.6	0.1
2	131	4.9	3.7	1.9	0.8	0.2
11	174	6.5	4.9	2.6	1.0	0.2
4	184	6.8	5.2	2.7	1.1	0.3
5	275	12.3	9.4	4.9	1.9	0.5
1	346	12.9	9.8	5.1	2.0	0.5
6	351	13.0	9.9	5.2	2.1	0.5
3	363	13.5	10.2	5.4	2.1	0.5
7	367	13.6	10.3	5.4	2.1	0.5
12	404	15.0	11.4	6.0	2.4	0.6

MBC = maximum buffering capacity

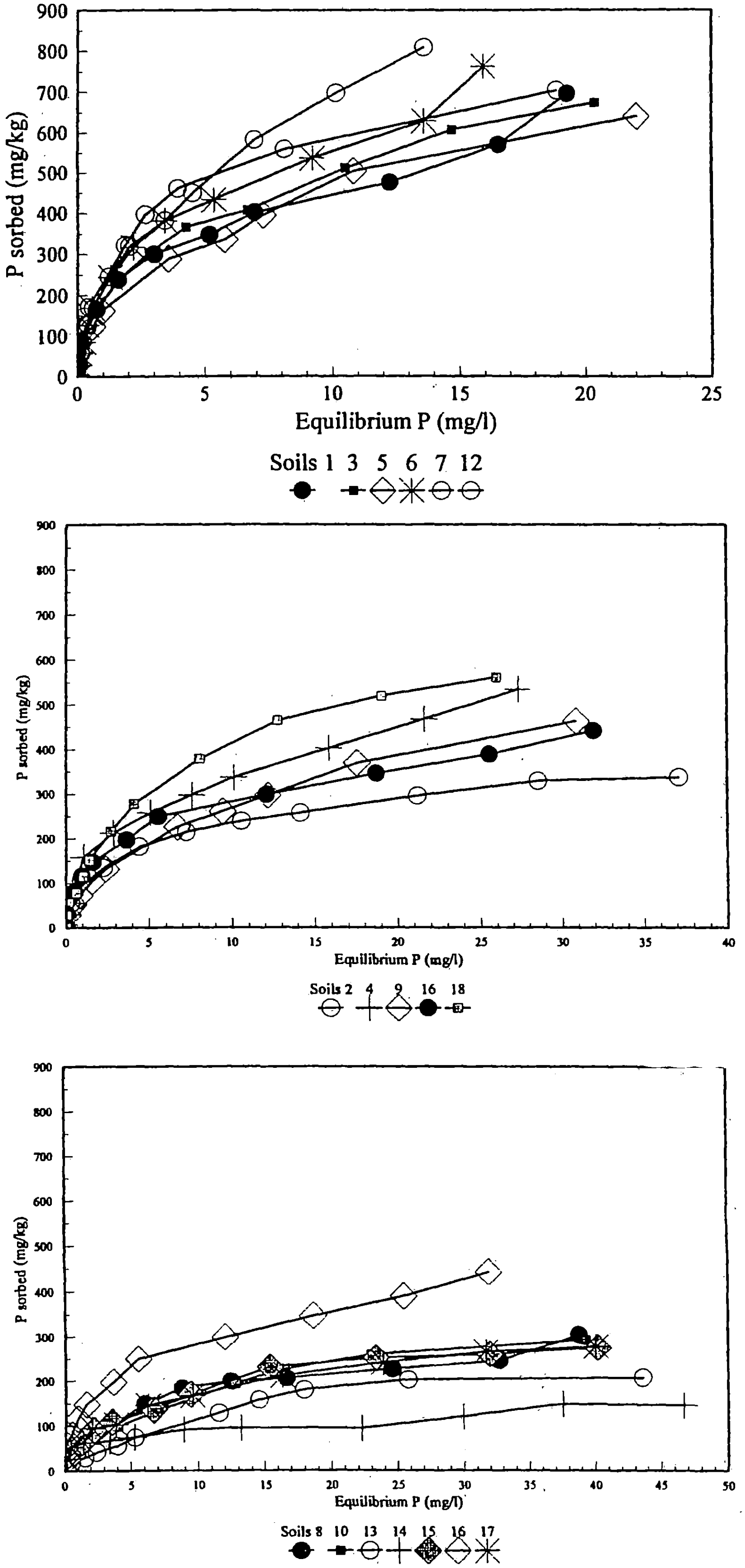


Figure 1.1. Phosphorus adsorption isotherms for 18 calcareous Moroccan soils.

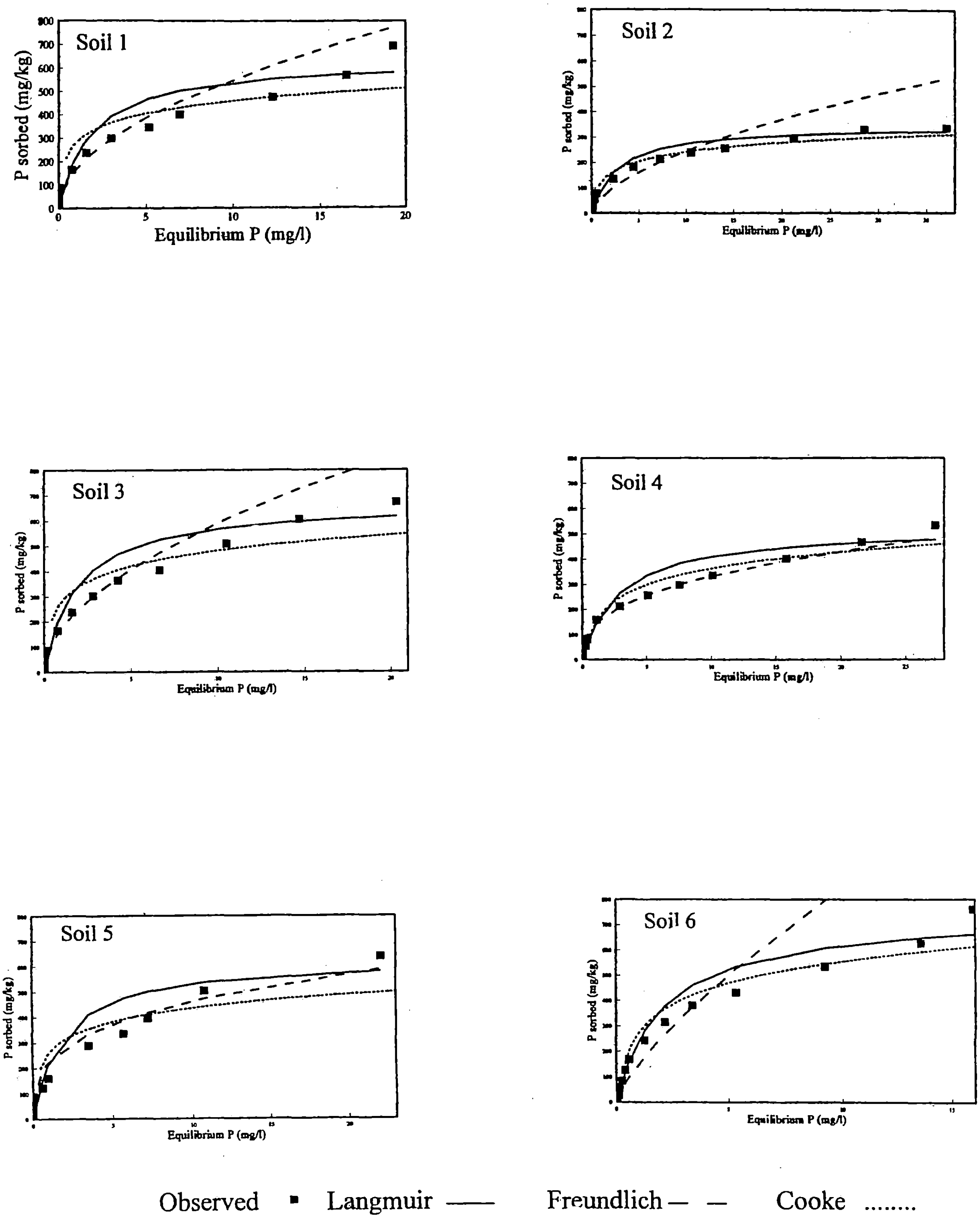


Figure 1.2. The P adsorption isotherms as described by the Langmuir, Freundlich, and Cooke models.

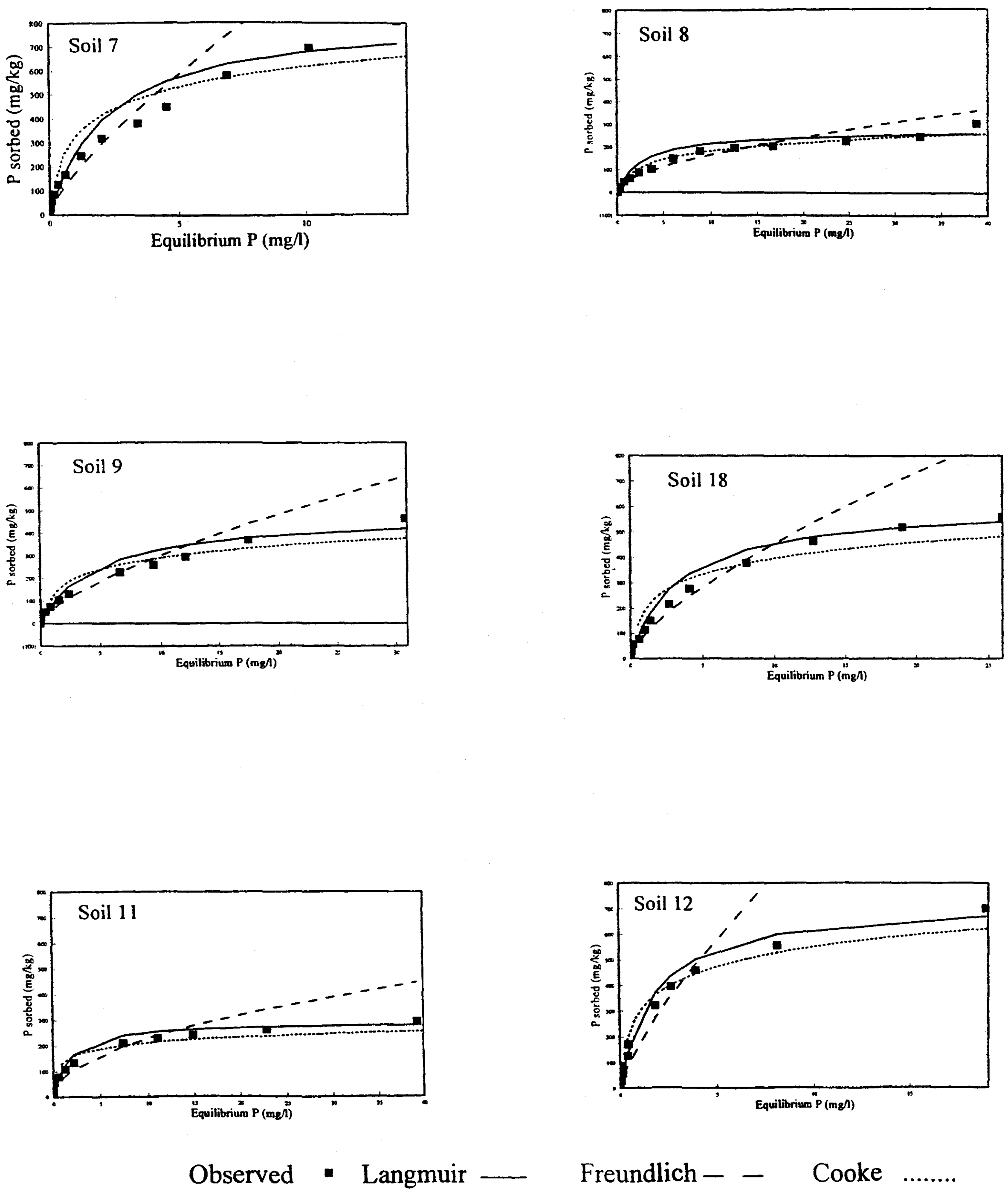


Figure 1.2. The P adsorption isotherms as described by the Langmuir, Freundlich, and Cooke models (continued).

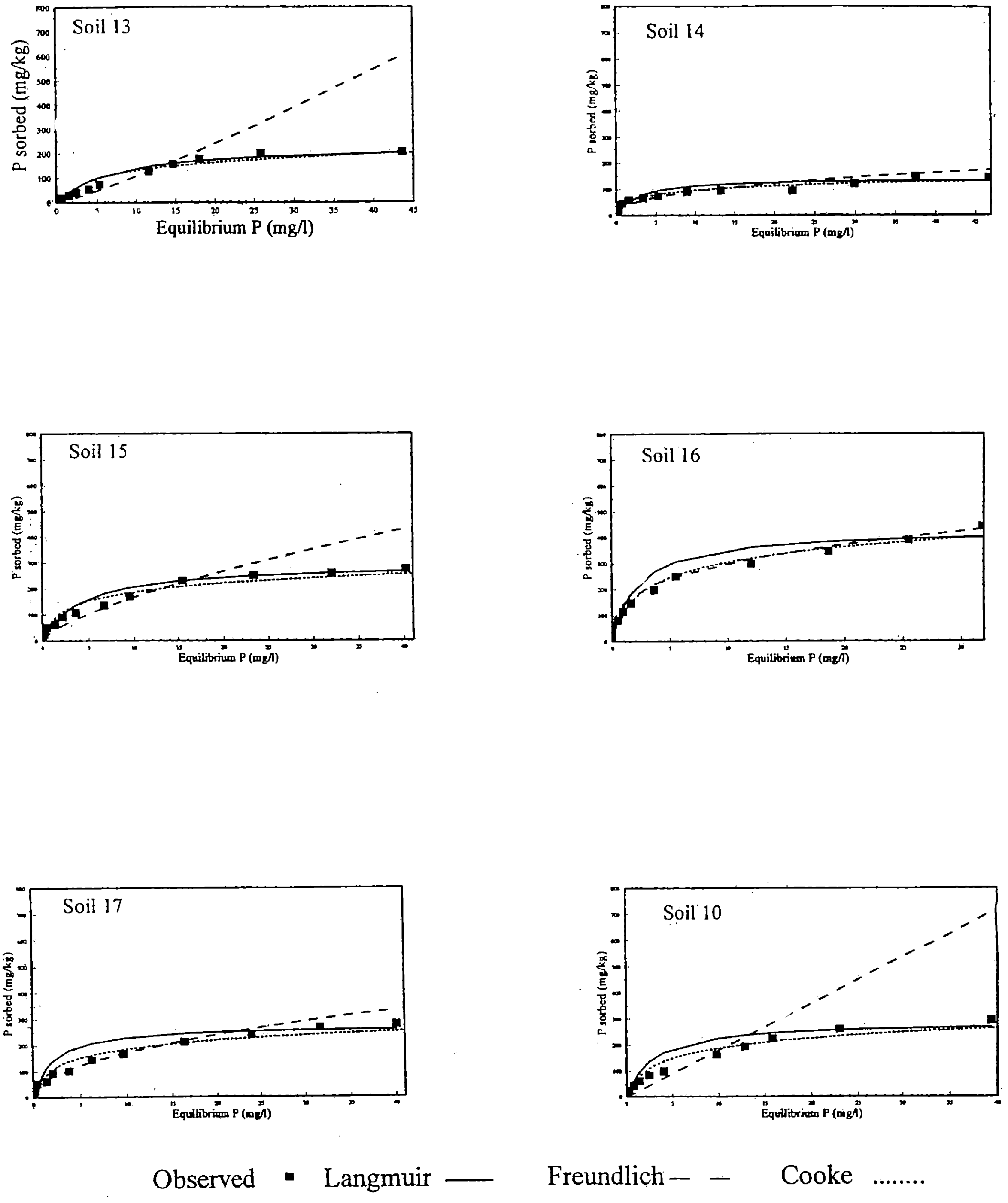


Figure 1.2. The P adsorption isotherms as described by the Langmuir, Freundlich, and Cooke models (continued).

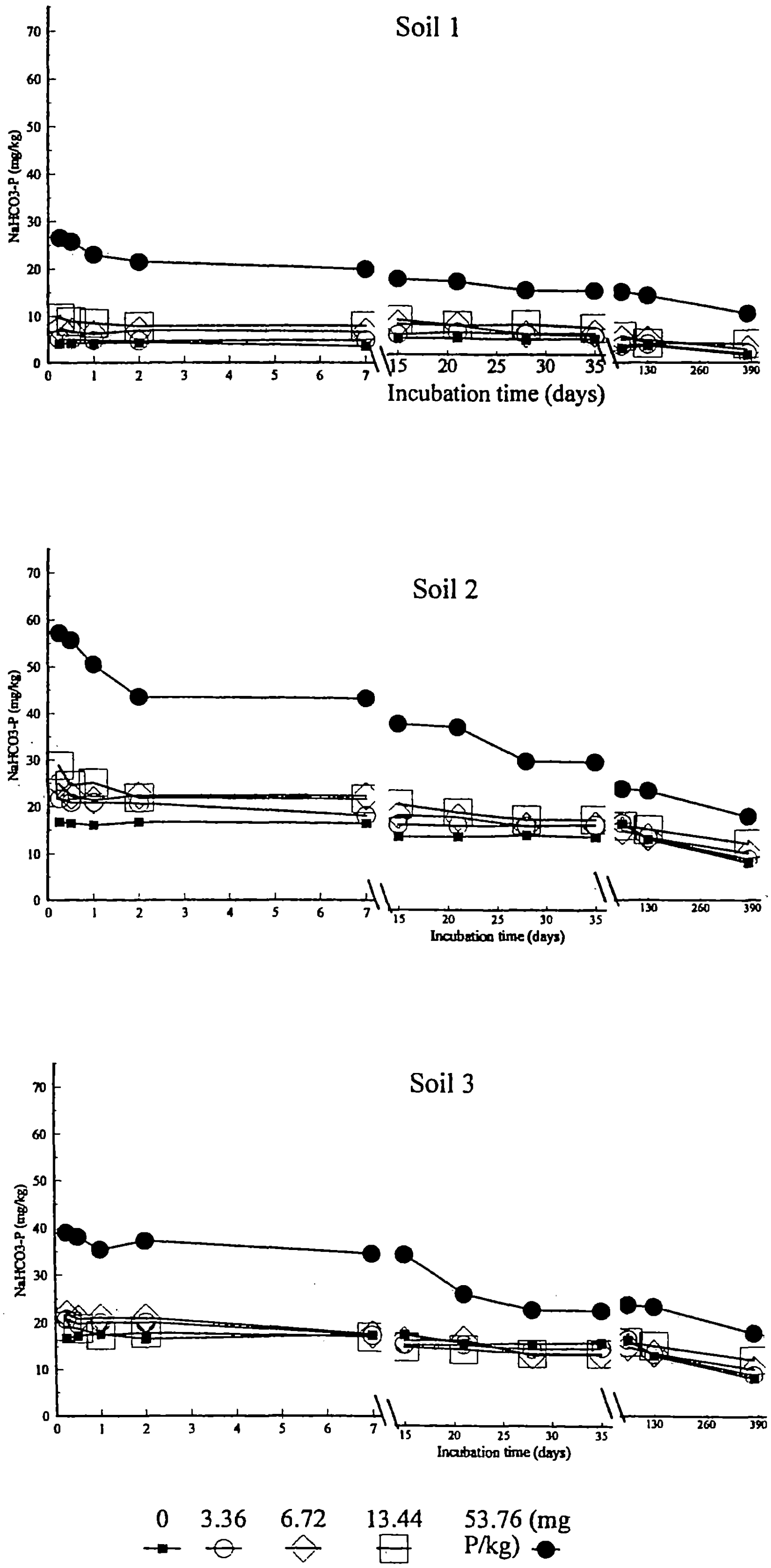


Figure 1.3. The concentration of extractable NaHCO3-P in soils that were incubated with 5 rates of applied P as a function of time after P addition.

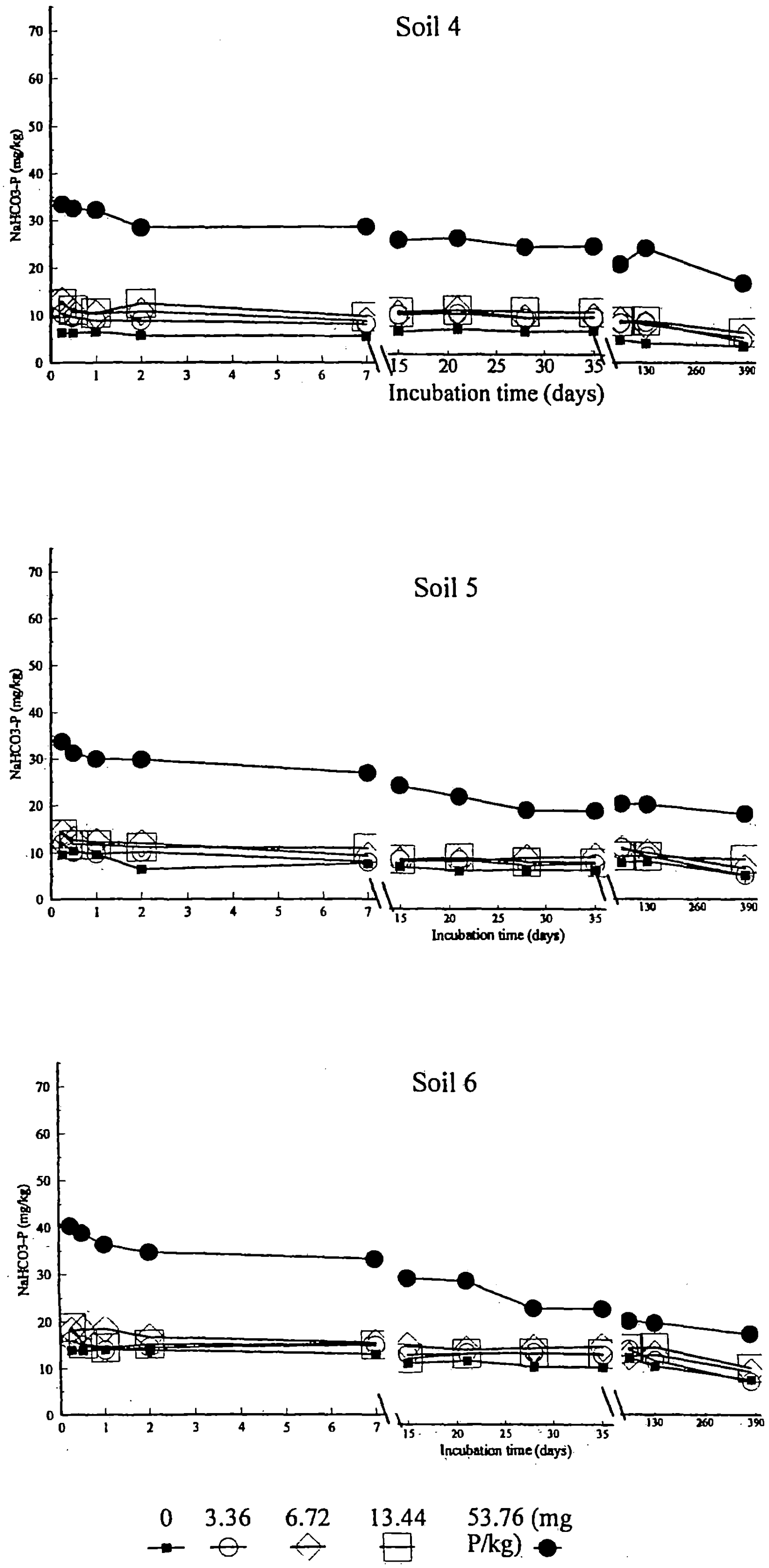


Figure 1.3. The concentration of extractable NaHCO3-P in soils that were incubated with 5 rates of applied P as a function of time after P addition (continued).

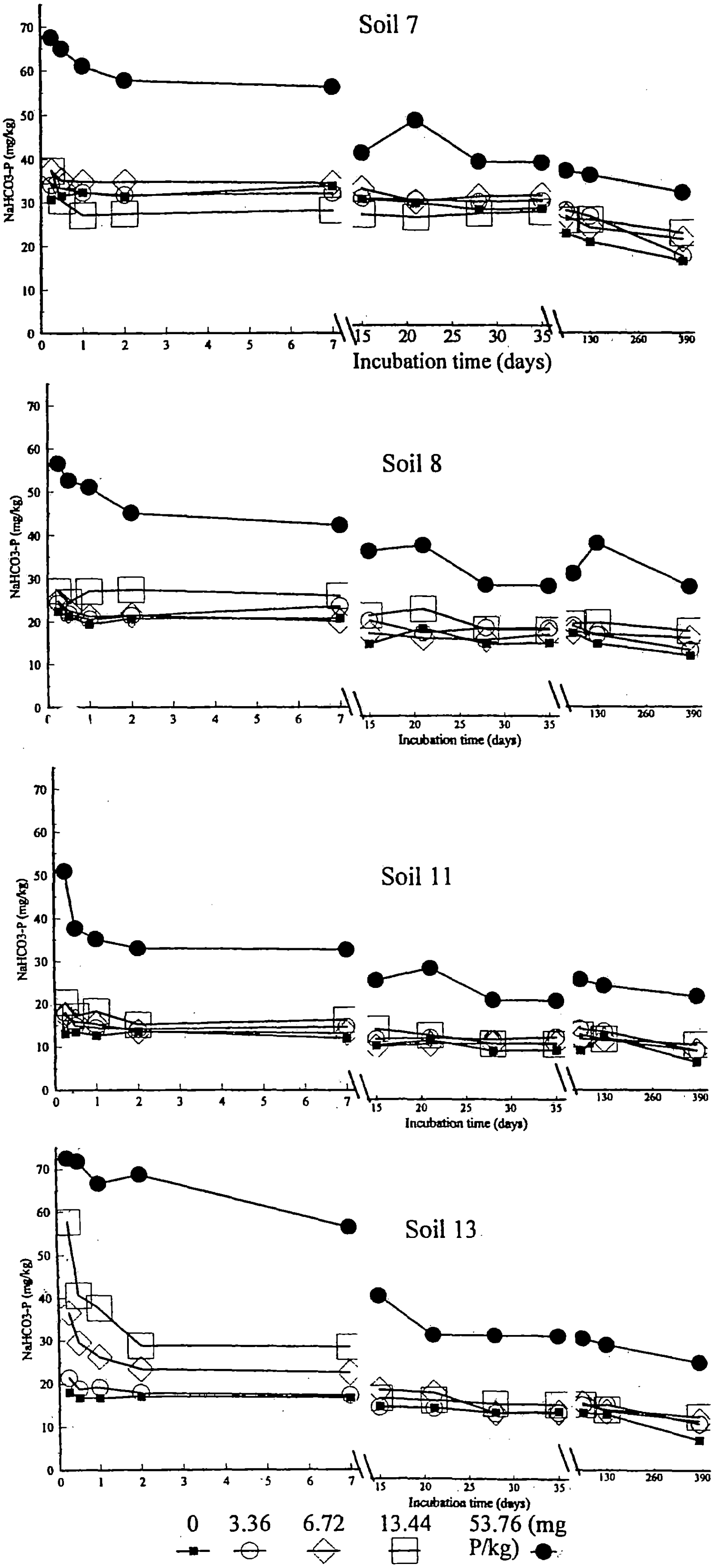


Figure 1.3. The concentration of extractable NaHCO3-P in soils that were incubated with 5 rates of applied P as a function of time after P addition (continued).

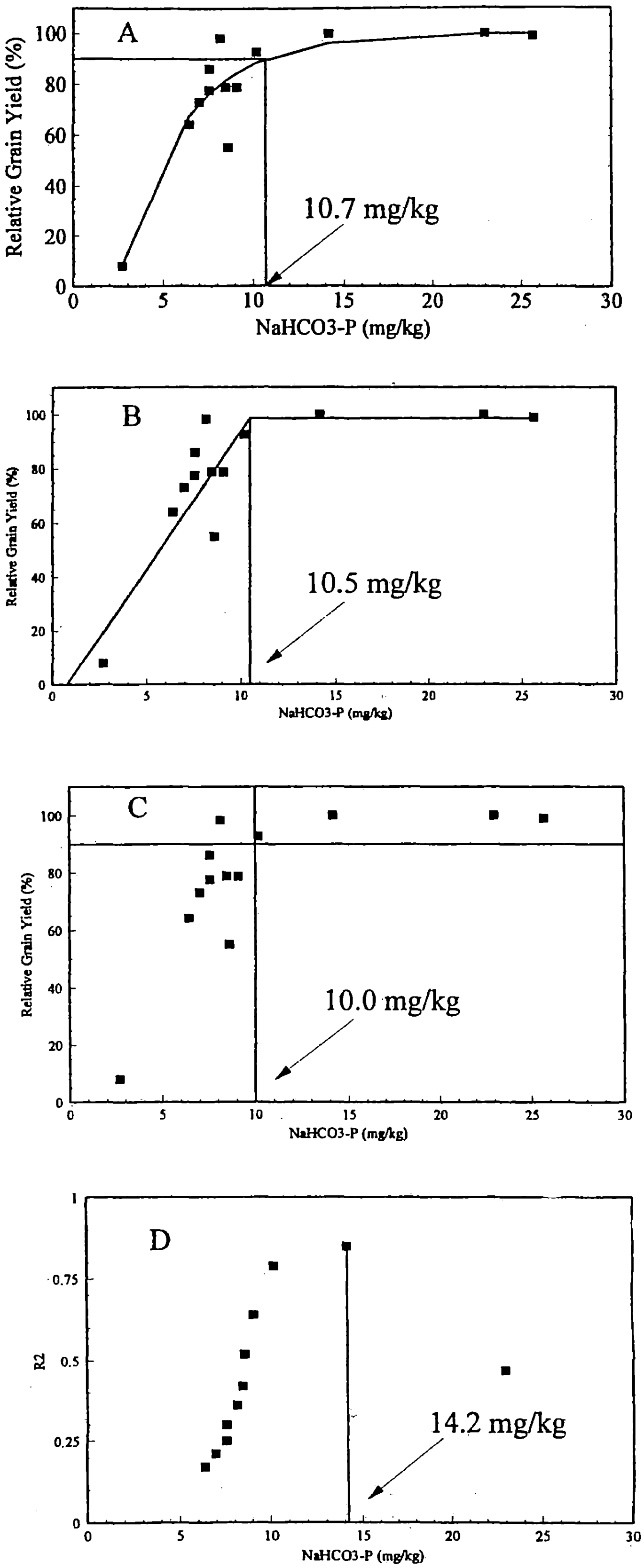


Figure 1.4. Critical soil test P levels for greenhouse experiment for wheat using A=Mitscherlich model B= Linear and plateau model, C=Cate -Nelson graphic method, and D=Cate-Nelson statistical method.

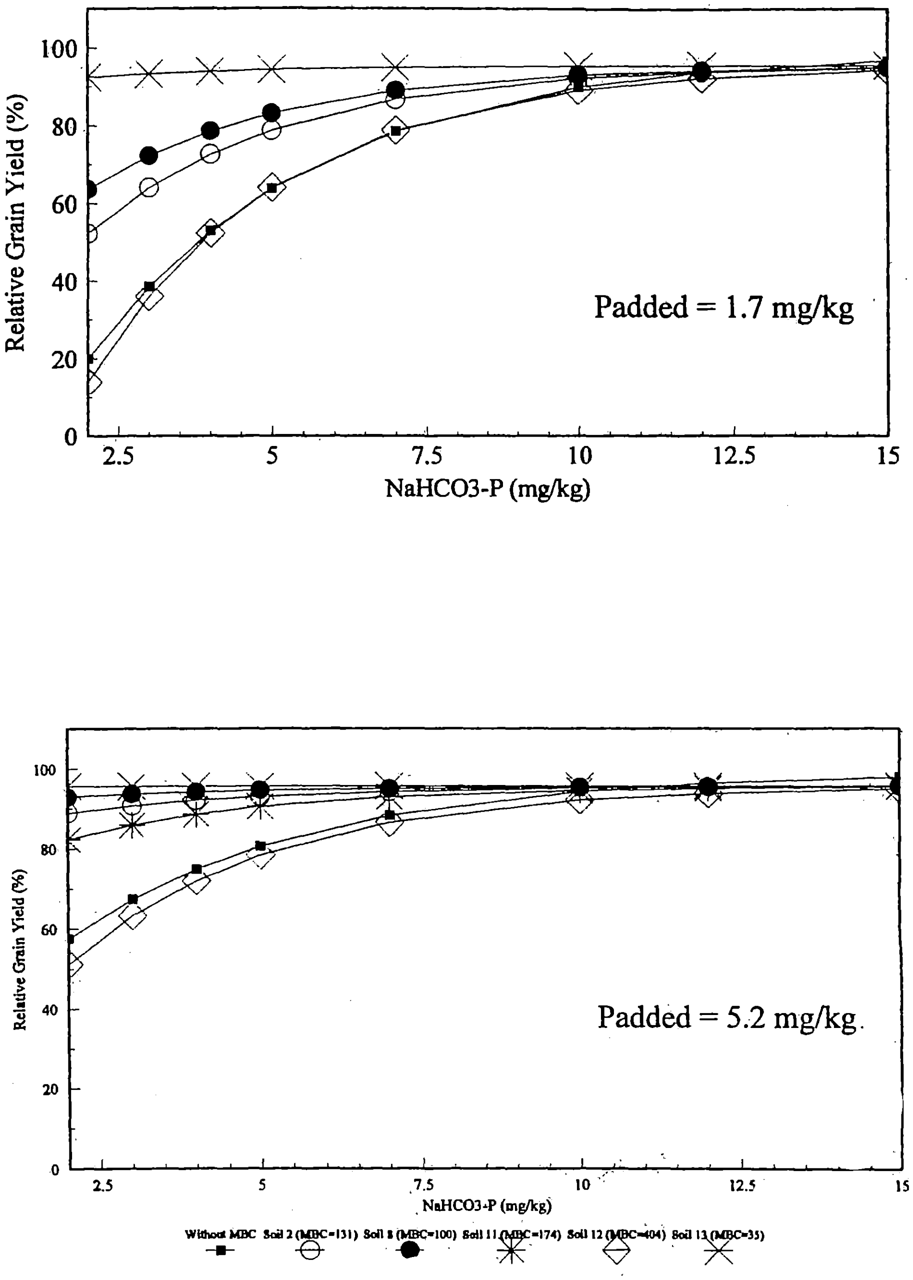
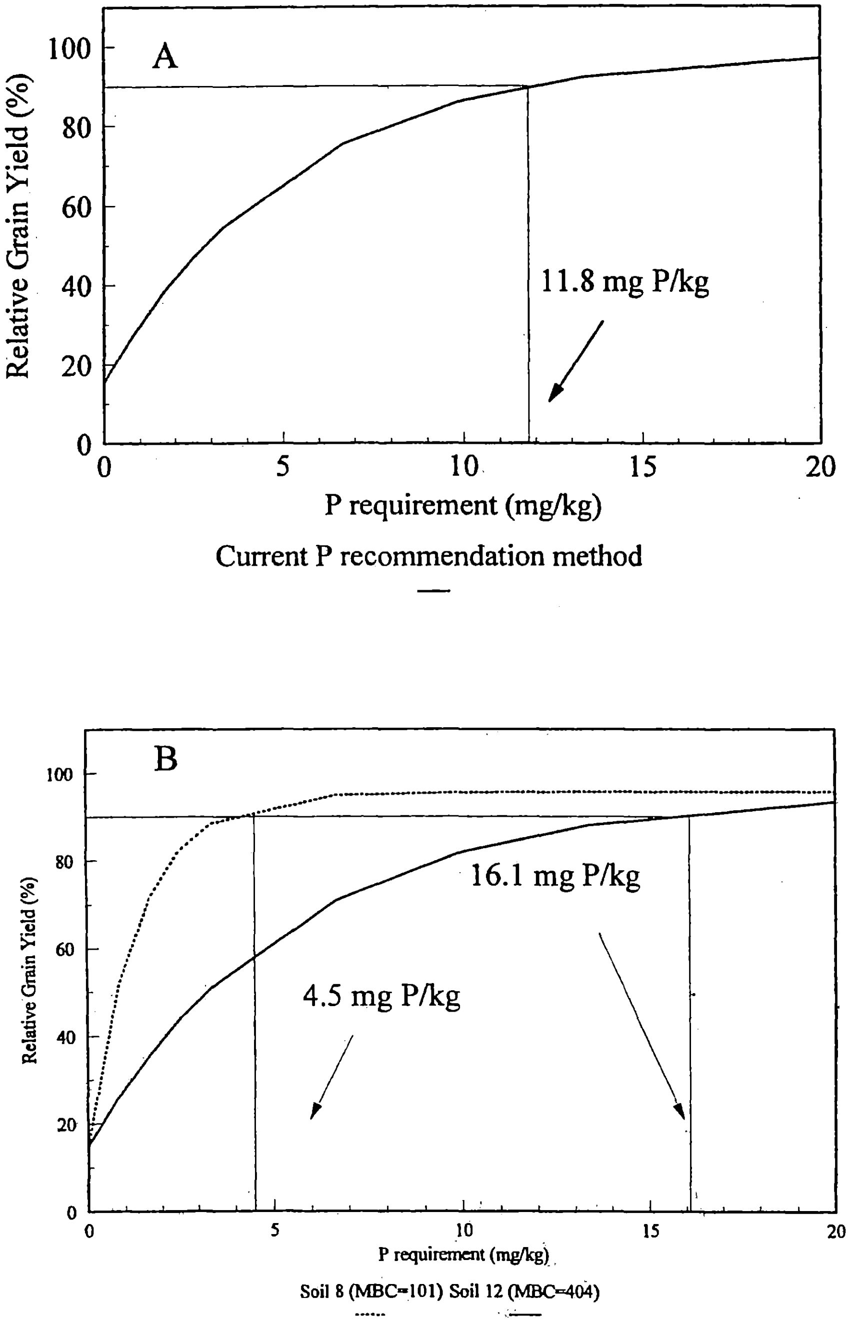


Figure 1.5. Hypothetical relative grain yield as a result of two P application rates (1.7 and 5.2 mg P/kg) in contrasted soils with different adsorption capacities.
(curves developed from equation 18)



RGY = 95.6 -
208.9*exp[-(0.32*P+71.6*(Pad/MBC))]

Figure 1.6. The P requirement determined with ordinary method (without MBC)(A) and with modified Mitscherlich model (with MBC)(B).

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CHAPTER II.

Residual And Cumulative Effect Of P Fertilizer In Selected Moroccan Soils

ABSTRACT

Evaluation of the factors affecting the availability of applied P in soils could improve P fertilization recommendations. Little information is available on the continuous effect of P fertilizer application under cropping systems in Morocco. A greenhouse study was conducted to evaluate the residual and cumulative P effects on crop growth and P uptake on wheat and corn in contrasting calcareous soils from the arid and semiarid zones of Morocco. Thirteen soils from Abda, Chaouia, and Ben Sliman locations were chosen for this study. Three succeeding crops were grown: wheat (to maturity), corn (60 days), and wheat (to maturity). After harvesting wheat, corn was planted in the same pots with no further P fertilization applications (residual P). The third crop (wheat) was grown after splitting pots into two parts (i) cumulative P: the P fertilizer was added to two replicates; each treatment received the same amount of P as was applied to the first crop: 0, 3.4, 6.7, or 13.4 mg P kg^{-1} soil and (ii) residual P: no additional fertilizer P was added to the two remaining replicates. The residual P effect was statistically significant for grain yield, dry matter production, and total P uptake Less response was observed in corn (residual P) (5 out of 13 soils) compared to wheat (6 and 9 soils for dry matter and grain yield, respectively) (direct P). The average increase in dry matter production of corn ranged from 1 (5%) to 11 g/pot (105%). Across P rates, the maximum percentage increases in wheat grain yield due to residual and cumulative P varied from 97 to 265% for residual and cumulative P, respectively. At the same P fertilizer rate, the single applications (6.7 plus 0 and 13.4 plus 0 mg P kg^{-1}) produced less

grain than repeated applications (3.4 plus 3.4 and 6.7 plus 6.7 mg P kg^{-1}). These results showed that if we want to take into consideration residual P in P fertilizer recommendations, the critical soil test P level should be lower than the one normally determined by soil test calibration method. The P uptake was governed by initial $NaHCO_3$-P soil level, rate of P application, and MBC. In general, when the same amount of P was added, more uptake occurred in soils having low P buffering capacity. Also, soils with low initial $NaHCO_3$-P levels had the lowest residual value, inferring that a large portion of added P is sorbed or fixed in these soils. This study showed that a significant response of corn to residual P would occur in soils with initial $NaHCO_3$-P test levels less than 6 mg P kg^{-1}, the response would be inconsistent between 6 and 10 mg P kg^{-1}, and no response is expected above a soil test P level of 10 mg P kg^{-1}. In general, soils with more than 14 mg kg^{-1} $NaHCO_3$-P could provide adequate P for maximum yield for three succeeding crops under greenhouse conditions.

INTRODUCTION

Soils of arid and semiarid zones of Morocco are calcareous with a pH greater than 7.5. The application of P fertilizers to these soils has been problematic mainly due to P fixation (Olsen et al., 1954; Ridley and Tayakepisuth, 1974; Sample et al., 1980). When P is applied to the soil, only a small percentage is taken up by the plant; the remainder is either permanently or temporarily fixed in forms varying in plant availability. The temporary fixed P, called also residual P, becomes available with time, but at slow rates.

Fertilizer P is an expensive production input and it is essential to know the effect of the P application rate on the current crop as well as the long-term effect of the added P on the succeeding crops. Residual P effects on crop growth should be taken into consideration when making decisions regarding fertilizer recommendations.

Residual P can increase yields of succeeding crops (Singh and Singh, 1989; Bolland, 1992a). The magnitude of residual P effect depends upon time after P application, soil properties, crop, management, and climate (Morel and Fardeau, 1990; Mendoza, 1992). The availability of residual P in the soil is related to the rate of P application and the amount of P taken up by the plant. Wendt et al. (1996) found that when the amounts of P applied were equal to those removed by the crop at harvest, the soil test values remain unchanged. A decrease in the soluble P levels was observed only if the soluble soil P content was much higher than necessary for plant growth. Wendt et al. (1996) concluded that the rate of P application required to maintain the P status of the soil constant is equal to the quantity of P removed by the plant. These results are, however, contradictory with the finding by Bolland (1992a) who showed that residual P is mainly governed by soil characteristics. Using contrasting soils, Gianquinto and Borin (1996) also pointed out the importance of the effect of soil type on residual P levels. They showed different responses to residual P in sandy and clayey soils. Lettuce yield was significantly increased in sandy soil by residual P, while the effect was less evident in clayey and peat-clay soils. These differences could be explained by the variations between sorption and desorption between soils. McKean and Warren (1996) reported that, in some soils, P desorption reached the asymptotic state more quickly than in others. These differences between soils are mainly explained by iron oxides associated with organic matter. This infers that there is continued release of adsorbed P which could play an important role with respect to residual P effect. They concluded that the differences between soils could be explained by both Fe oxides and organic matter contents.

The effects of soil factors on residual P are likely a result of natural differences in the soil's capacity to adsorb and desorb P. The most significant soil physical and chemical properties affecting P release are principally: kind and amount of clay, CEC, $CaCO_3$, exchangeable Ca, and organic matter. Chapter 1 showed that the rate of decrease in P availability was primarily influenced by clay content (66 to 78% of variation) and exchangeable Ca content. In a study conducted by Sharpley (1996), the rate of soil P release decreases rapidly followed by a more gradual decline. Phosphorus sorption maxima described 76% of the variability in the rate of decrease in P release. The P release from soils treated with poultry litter varied from 111 (Gallion soil) to 544 mg P kg^{-1} (Carnasaw soil). Another investigation reported that the relationship between the rates of P desorption from the soils and P uptake were soil specific (Raven and Hössner, 1994). In their study, the desorption rate of 0.08 mg P kg^{-1} h^{-1} was sufficient to support corn plant growth in an Aridic Calcuistoll soil (31.9% clay) to achieve 95% of maximum relative P uptake. In contrast, it required 0.25 mg P kg^{-1} h^{-1} (3-fold) to obtain the same result in Psammentic Paleudult soil (6.2% clay).

Cropping system has been reported to influence residual P levels in soils. When P was applied to soybeans, the residual P affect was found in two succeeding crops. Whereas when P was applied on wheat, the residual P affect was only found in one succeeding crop (Rao et al., 1995). The amount of P taken up by plants from native soil P and fertilizer P may play an important role in this cropping-system effect.

The time of P application is crucial in determining the residual P effect on crops. Thus, the longer the time between P application and plant uptake, the higher the P adsorption by soil particles, and the lower residual P levels. The accumulation of residual P in soil is generally the result of low P recovery by plants. Only 5 to 33% of freshly applied P is recovered in a crop the first year. The remaining is partially recovered but slowly. Bolland (1992b) reported that the effectiveness of superphosphate P decrease by about 70 to 80% between the year of application and the first and the second years after application.

Another important variable that affects residual P level is P rate. McPharlin et al. (1994) reported that the effectiveness of residual P on carrots (yield on residual plots divided by yield on freshly applied plots x 100) increased from 46% of freshly applied P at 20 kg P ha^{-1} to 95% at 320 kg P ha^{-1} applied 9 months earlier. This was explained by low adsorption capacity of the sandy soil, used in this study, as well as by the higher level of residual P induced by the application of high P rate of 320 kg P ha^{-1}. In fact, the P application rate of 320 kg P ha^{-1} increased $NaHCO_3$-P soil level to 75 mg P kg^{-1}, sufficient for maximum yields for carrots in sandy soils.

Different methods have been used to evaluate residual effects of P fertilizers on crop growth. Unfortunately there is no standardized method which can be used successfully under all conditions. Each method has its advantages and disadvantages. In this study I adopted the "increase in crop yield" as the criterion for evaluating the residual P affect. Fixen and Ludwick (1982) demonstrated the advantage of using the regression equation developed for estimating the residual available P in Colorado soils. They found that residual P correlated with initial soil P level and clay content.

The general consensus is that, residual P is mainly governed by soil, crop, rate of P, and time. It seems that any estimation of residual P effect on plant growth should account all these factors.

Accurate P fertilizer recommendations are important for maximizing productivity and profit, while minimizing adverse environmental impacts. One of the important questions relating to P fertilizer efficiency is what fertility management practices should be adopted on soils with different levels of nutrient availability. The emphasis of the work reported here will be on P rate and timing. The response of wheat to previous and repeated application of P fertilizer is not known for Moroccan calcareous soils. It is important to identify the soil factors that influence the residual P levels in soils of this region. Therefore, the project was undertaken under greenhouse conditions with the objective of evaluating the residual and cumulative P effects on crop growth and P uptake in contrasting calcareous soils from the arid and semiarid zones of Morocco.

MATERIAL AND METHODS

Soils

Thirteen calcareous soils were collected from three regions of arid and semi-arid zones of Morocco: Abda, Chaouia and Doukkala. The soils were air dried, crushed and sieved through a 2-mm screen. Soil taxonomy and some selected characteristics of these soils are given in Tables 2.1 and 2.2 respectively. Available P was extracted by 0.5 M $NaHCO_3$ solution (Olsen et al., 1954) and analyzed by the ascorbic acid method of Murphy and Riley (1962); pH was measured by glass electrode using a soil:water ratio of 1:2; organic matter by wet oxidation (Walkley and Black, 1934); CEC by a method by Chapman (1965); exchangeable cations were extracted using 1N NH_4OAC solution (pH = 7) with Ca and Mg being determined by atomic adsorption and K by photometer; and total N by micro Kjeldahl method (Bremner, 1965).

Greenhouse Experiment

Five kg of each soil were placed in polyethylene plastic pots. Three successive crops were grown as follows.

- First Crop : Wheat

A fertilizer P solutions were prepared using reagent-grade monocalcium phosphate and mixed with soil at rates of 0, 3.4, 6.7 and 13.4 mg P kg^{-1} soil in four replications. Nineteen wheat seeds (*cv.* Merchouch) were placed at a depth of 2 to 3 cm in each pot and thinned to 9 seeds, 12 days after sowing. Supplemental fertilization added to each pot consisted of 100 mg N kg^{-1} from NH_4NO_3, one half at sowing and the other at tillering; 50 mg K kg^{-1} from K_2SO_4; 3.5 mg Zn kg^{-1} from $ZnSO_4.7H_2O$; 8 mg Fe kg^{-1} from Fe-Chelate (10%); 4.5 mg Cu kg^{-1} from $CuSO_4.5H_2O$; and 8 mg Mg kg^{-1} from $MgSO_4.7H_2O$. Pots were regularly watered (each 3 days) with enough deionized water to bring them to 90% of field capacity. The greenhouse was maintained at 24°C day and 15°C at night. At harvesting, on June the 24th 1995, above ground dry matter production and grain yields were determined.

- Second Crop : Corn

After harvesting wheat, corn (cv Kamla) was planted on July 27th, 1995 and was grown for 50 days at a density of two plants per pot. For this second crop, no further P fertilizer was added. Nitrogen was added at 100 mg N kg^{-1} as NH_4NO_3 and K was added at 50 mg K kg^{-1} as. Pots were watered each 2 days with enough deionized water to bring soils to 90% of field capacity. At harvesting, above ground dry matter production was determined.

- Third Crop : Wheat

In order to evaluate cumulative effect and residual effect of P on crop growth, the four replicates were split into two treatments:

(i) Cumulative P (With P): Phosphorus fertilizer was added to two replicates. Each treatment received the same amount of P as was applied to the first crop: 0, 3.4, 6.7, or 13.4 mg P kg^{-1} soil.

(ii) Residual P (Without P): No additional fertilizer P was added to the two remaining replicates.

Fifteen seeds of wheat (*cv.* Merchouch) were sown on December 10, 1995 and thinned to seven plants per pot after emergence. To ensure adequate nutrient conditions, nutrients were added for each pots as follows: N was added as NH_4NO_3 at 60 and 40 mg N kg^{-1} soil at sowing and at tillering, respectively, and K as K_2SO_4 was added at the rate of 60 mg K kg^{-1} soil at sowing. Micronutrients also were added at rates half of those used for the first crop. The watering procedure was the same as for the first crop. The greenhouse was maintained at 24°C day and 15°C at night. At harvesting, on June 4th 1996, above ground dry matter production and grain yields were determined.

Measurement And Analysis

Soil samples were taken before sowing each crop and analyzed for P using the $NaHCO_3$-P extraction method (Olsen et al. 1954). Dry matter production, grain yield, number of head (ears), and number of grains per pot were recorded at harvest of each crop. The plant materials were dried in an oven at 70°C for 48 hours. Plant samples were ground to pass 0.5-mm sieve and a 0.25 g of plant sample was analyzed for P after digestion in H_2SO_4. The P recovery (PR) was calculated by dividing total P uptake in treated pots minus total P uptake in check pots by the amount of fertilizer P added. Total P uptake expressed in percentage was calculated by dividing P uptake in the check pot over the maximum P uptake in fertilized pots.

Experimental Design And Data Analysis

The greenhouse experiments were conducted as completely randomized factorial designs with:

(i) Two factors for the first crop (wheat): soil (13) and rate of P (4) (direct effect of P fertilizer) with four replicates.

(ii) Two factors for the second crop (corn): soil (13) and residual P (4), with four replicates, and

(iii) Three factors for the third crop (wheat): soils (13), P management (2: either residual or cumulative P applications), and P rate (4) with two replicates.

The residual P treatments were those treatments where fertilizer was applied only once to the first crop (0, 3.4, 6.7 and 13.4 mg P kg^{-1}). The cumulative P treatment was where both the first (wheat) and the third crops (wheat) received the same amounts of fertilizer.

An analysis of variance was performed on measured and calculated variables using the SAS package (SAS Institute, 1985).

RESULTS AND DISCUSSIONS

The response of greenhouse wheat and corn to direct, residual and cumulative P applications was soil and P rates dependent (Table 2.3). The significant effect of soil types, P rates, and the interaction soils x P rates on direct, residual, and cumulative P may be explained by the contrasting soils used in this experiment. In fact, initial $NaHCO_3$-P soil test levels varied from 3 to 26 mg kg^{-1}, and clay content varied from 10 to 56% (Table 2.2). These interactions indicate that P management should consider soil, and time of application.

Direct Effect of P on the first Crop (Wheat)

The response of greenhouse wheat to direct P applications varied markedly among soils. The analysis of variance showed that yields of wheat, grown as a first crop, were affected significantly by P rates, soils, and the interaction between fertilizer P and soils (Table 2.3). The interaction soil x P rate suggested that P rate was not the only factor that determine the magnitude of crop response to P fertilizer, but that soil factors played an important role; especially initial soil test P level, as it will be shown later. Nine out of thirteen soils (1, 2, 3, 4, 5, 9, 10, 11, and 13) showed a significant increase in first crop grain yield as a result of P fertilization (Table 2.4). In general, dry matter production showed similar trends of variation among soils (Table 2.5). Dry matter production increased significantly, as a result of direct P application, in only 6 soils (1, 2, 4, 5, 10, and 13). The highest grain yields and dry matter production were obtained on soils 3 (13.3 and 34.4 g/pot) and 7 (14.4 and 32.4 g/pot), while the lowest were found on soils 1 (3.0 and 10.0 g/pot) and 11 (6 and 17.7 g/pot). Averaged across P rates, soils showed different abilities to produce dry matter and grain yields (Tables 2.4 and 2.5). The grain yield of unfertilized pots varied from 0.4 (soil 1) to 14.8 g/pot (soil 7). The same soils, 1 and 7, produced the lowest (3.8 g/pot) and the highest (33.0 g/pot) dry matter production respectively. These yields were expected because of the initial $NaHCO_3$-P levels of these two soils (3 and 23 mg P kg^{-1}, respectively). The response of wheat to applied P was mainly explained by initial $NaHCO_3$-P soil test levels; it explained about 75% of the relative grain yield variation ($p=0.01$).

Residual Effect of P on the Second Crop (Corn)

Corn was grown as a second crop after wheat without any additional P application. Dry matter production of corn was increased on 5 out of 13 soils (soils 1, 5, 7, 11, and 13) due to residual P effects (Table 2.5). Averaged across P rates, soils 1, 2, 3, 4, 5, 6, and 9 yielded the lowest dry matter production. Typical symptoms of P deficiency in corn were observed on soils 1 and 2 with P rates of 0 and 3.4 mg P kg^{-1}.

The response by corn to residual P was obtained only in 5 soils with initial NaHCO$_3$-P test level less than 9 mg kg^{-1}. Less response was observed in corn (5 out of 13 soils) compared to wheat (6 and 9 soils for dry matter and grain yield, respectively). This was expected because wheat is more sensitive to low soil test P levels than corn. The higher the amount previously applied P, the greater the residual effect. These results confirmed the previous findings by McPharlin et al. (1994) who found that the relative effectiveness of the residual P was increased by increasing the rate of P. A very large response in corn dry matter was obtained on soil 1. The increase in dry matter production was 225% above a check. This was expected because of the very low initial soil test P level (3 mg kg^{-1}). The NaHCO$_3$-P test levels for soil 1 after harvesting the first crop (wheat) were 3 and 6 mg kg^{-1} for previously applied P rates of 0 and 13.4 mg P kg^{-1}, respectively. Even the increase in soil NaHCO$_3$-P level was not large due to the high P buffering capacity of this soil (MBC = 346, Chapter I). No response in corn yield was obtained in soil 2. In this soil, the NaHCO$_3$-P levels after wheat harvest were between 7 to 10 mg kg^{-1} for all P rate treatments. Corn requires less P compared to wheat (Westfall, 1997, personal communication). This may explain the lower number of soils where corn responded to residual P. However, because of significant response by wheat (1st crop) on soil 2, the response by corn to residual P was expected. The reason for this discrepancy in this specific soil was probably due to its low P buffering capacity (MBC = 131, Chapter I). In fact, low P sorption capacity soils showed large increases in $NaHCO_3$-P levels after P application. On the other hand, in the same soil (2), the $NaHCO_3$-P level decreases rapidly with time compared with high P sorption capacity soils, which led to a decrease in residual P effect. In soil 4, the soil residual P level was between 5 and 7 mg kg^{-1} after wheat harvest as a result of previously applied P rates of 0 and 13.4 mg P kg^{-1}, respectively. However, there was no significant increase in corn dry matter production. The response of corn to both direct and residual P in soils 5 and 13 was mainly due to low initial $NaHCO_3$-P test levels (7 and 9 mg kg^{-1}). The highest response by corn to residual P was obtained in soil 13 (81% increase in dry matter above the check) which may be explained by the course texture of this soil (10% clay). Gianquinto and Borin (1996) reported that the increase in lettuce yield as a result of residual P was more important in sandy soil compared to clayey and peat-clay soils because of differences in adsorption and desorption kinetics of P. Because of high initial $NaHCO_3$-P levels for soils 7 and 11 (9 and 23 mg kg^{-1}), the response of corn to residual P in these soils was not expected. No explanation can be given for this discrepancy.

In general, soils with initial $NaHCO_3$-P test levels, greater than 10 mg kg^{-1}, did not show a significant response in my study, suggesting that this level would be a critical level for maximum dry matter by corn grown as a second crop in the greenhouse.

The response by corn to residual P was soil dependent. Initial $NaHCO_3$-P soil test played an important role in determining the magnitude of residual P effect. The lower the soil P test, the higher the residual effect. Besides soil test P level, the rate of P application had an important effect on the quantity of residual P available for subsequent crop use. The highest increase in dry matter production by corn was obtained from the highest rate of previously applied P. This greenhouse study showed that a significant response of corn to residual P would occur in soils with initial $NaHCO_3$-P test levels less than 6 mg P kg^{-1}, the response would be inconsistent between 6 and 10 mg P kg^{-1}, and no response is expected above a soil test P level of 10 mg P kg^{-1}.

Residual And Cumulative P Effect On The Third Crop (Wheat)

Cumulative P

Grain yield and dry matter production were increased significantly with the cumulative P treatments (P applied on both the 1st and the 3rd crops). The analysis of variance showed that P rates, soils, and the interaction soil x P rate affected yields significantly (Table 2.3). Wheat dry matter responses to cumulative P were only observed in 4 of the 13 soils (Table 2.6). Dry matter production was low in the unfertilized treatments (0 rate) for almost all soils. The differences between unfertilized and fertilized treatments at the highest P rate were only significant in soils 1, 2, 4, and 10 (Table 2.6). Grain yield in the unfertilized pots varied from 3.7 (soil 2) to 28 g/pot (soil 12) (Table 2.4). Eight soils out of thirteen showed a significant increase in grain yield as influenced by cumulative P. The largest increases were found in soils with low initial $NaHCO_3$-P levels. The percentage increases over a check treatments were 580, 627, and 239% in soils 1, 2, and 4, respectively.

The highest response of wheat dry matter production to cumulative P was observed in soil 1 where the increase was from 8.6 to 40.2 g/pot (367%) as a result of P application rate of 13.4 mg kg^{-1} (Table 2.6). In soils 1 and 2, the highest P rate application (13.4 mg kg^{-1}) on the first crop increased $NaHCO_3$-P levels, after harvesting corn, to 5 mg kg^{-1}. At this soil test P level the response by wheat was expected in these two soils. The responses by wheat to cumulative P in soils 4 and 10 were also explained by their low $NaHCO_3$-P levels reached after growing two crops. The soil $NaHCO_3$-P levels before planting the third crop varied from 4 to 8 mg kg^{-1} and from 4 to 6 mg kg^{-1} for soils 4 and 10, respectively. Wheat grain yield responses to cumulative P were obtained in soils 3, 6, 9, and 13 because of their $NaHCO_3$-P levels (10, 8, 8, and 9 mg kg^{-1}, respectively) which are lower than the critical level determined in Chapter I (10 to 14 mg kg^{-1}).

Residual P

Grain yield, dry matter production and total P uptake were significantly affected by residual P, soil types, and the interaction residual P x soils (Table 2.3). Significant responses of wheat to residual P were found in most soils with the P rates up to 13.4 mg kg^{-1}(Tables 2.4 and 2.6). In soil 1, the grain yield was increased by 5.6 g/pot (135%) as a result of previous P rate application of 13.4 mg P kg^{-1} (Table 2.4). However, other soils such as soil 7 showed no significant increase due to residual P. Significant increases in wheat dry matter production were observed in soils 1, 2, 4, 5, 9, and 10 (Table 2.6). After corn harvest, the $NaHCO_3$-P soil test levels in soils 1, 2, 4, 5, 9, and 10, resulting from the highest P rate application (13.4 mg P kg^{-1}), were 5, 8, 7, 8, 14, and 8 mg kg^{-1}, respectively. These low soil P values explained the positive responses to residual P in these soils.

The average percentage grain yield increase over the control due to residual effects were 27, 86, and 142%, with 3.4, 6.7 and 13.4 mg P kg^{-1}, respectively. Over all P rates, the mean increase ranged from 0 in soils 7 and 8 to 97% in soil 2. The larger the increase in soil $NaHCO_3$-P level by previous application, the higher was the residual P effect. Therefore, residual P is more likely controlled by the parameters that govern the P availability of soil such as: initial $NaHCO_3$-P level, soil P buffering capacity, and rate of P application. My results showed that the average increases due to residual P effects were more pronounced in soils initially lower in $NaHCO_3$-P content (soils 1, 2, 4, 5, 10, and 11) than in soils with high $NaHCO_3$-P levels (soils 3, 6, 7, 8, 12, and 13) (Table 2.4). The only exception to this rule was soil 13 which had a relatively low increase in grain yield with residual P (18% of increase over check). In this sandy soil, P may have been leached by repeated irrigations in the greenhouse. Mare and Leaon (1990) also reported that the residual effect of P is different among soils and it is influenced by the mineralogy of the soils.

These results suggested that soils that have more than 14 mg kg^{-1} as initial soil $NaHCO_3$-P level could provide adequate P for maximum yield for three succeeding crops under greenhouse conditions. As shown for corn, the effect of residual P on wheat was soil dependent. The effect was mainly due to the initial $NaHCO_3$-P levels which in turn reflect the amount of previous P applications and adsorption capacity of soil. The maximum residual effect of P generally occurred when high P rates were applied to soils.

Direct vs Residual And Cumulative P Effects

The maximum percentage increases in wheat grain yield due to residual and cumulative P, across P rates, varied from 97 to 265% for residual and cumulative P, respectively. In soils with initial $NaHCO_3$-P levels less than 10 mg kg^{-1}, the increases in grain yields were the highest with both residual and cumulative. For example, soils such as 1, 2, and 4 showed the highest increases of 264, 256 and 89%, respectively, as a result of cumulative P applications. Both cumulative and residual P treatments produced higher grain yields compared to the check (unfertilized) in all soils. At the same P fertilizer rate, the single applications (6.7 plus 0 and 13.4 plus 0 mg P kg^{-1}) yielded less grain than repeated applications (3.4 plus 3.4 and 6.7 plus 6.7 mg P kg^{-1}). Paynter (1990) showed that the most recent application had a significantly greater effect than other timings. The increasing contact time between soil particles and P fertilizer granules accelerates P fixation which in turn reduces P availability. Consequently, the residual P effect is negatively affected by time, suggesting tnat repeated P applications seemed to be better than the single application.

Because of increasing fixation of P in soil with time, the efficiency of P fertilizer use was much better when P was split (cumulative treatment). This does not support the results reported by Dhillon and Dev (1986), Fixen and Ludwick (1983), and Benbi and Gilkes (1987). These authors concluded that the residual P has the same effect as freshly applied P. Fixen and Ludwick (1983) found that 75 kg P ha^{-1} applied prior to planting did not differ significantly from splitting the same amount into three applications regarding P concentration or P uptake by alfalfa. The reason for these different results may be due to the variation of range of P application rates between studies.

Relative wheat grain yields were plotted as a function of initial $NaHCO_3$-P levels using the Mitscherlich equations (Fig. 2.1). It is obvious from these correlations that initial $NaHCO_3$-P can be used to predict relative grain yield for different succeeding crops. Figure 2.1 showed that the P critical level could be established based on many scenarios:

(i) fertilization management based on one crop: in this case, the critical level had to be determined from Fig. 2.1A. For 90% of maximum yield, the critical soil test P level was 11 mg kg^{-1} under greenhouse conditions and (ii) fertilization management based on the system: if the objective is to adopt single P application for the whole rotation, Fig. 2.1B may be an alternative to determine critical soil P test level. In this case, the critical soil test P level is 9 mg kg^{-1} for 90% of maximum yield under greenhouse conditions.

No significant difference was found between the critical levels of the two scenarios in this study. Whereas, it can be inferred that when residual P has to be taken into consideration, the critical soil test P level may be lower than the critical soil test P level determined by ordinary soil test calibration studies. This may be an important issue especially for perennial crops such as alfalfa where P incorporation is difficult after planting.

Direct, residual, and cumulative P effect on P uptake are shown in Table 2.7. The number of soils where P fertilizer enhanced P uptake decreased with increasing time after P application. The general trend was for an increase in total P uptake by wheat with P application rate. Cumulative P treatment increased total P uptake significantly ($p=0.10$, in all soils except for soils 3, 7, 11 and 12 (Table 2.7). However, residual P had a significant effect on 8 soils for the second crop (corn) and only on 5 soils for the third crop (wheat). With increasing time after P application, P becomes less available to the plant, and its effectiveness drops drastically. The large response due to cumulative P may be explained by luxury P uptake. The P uptake, expressed as the maximum P uptake in fertilized pots over the yield in check plot, was best related to initial $NaHCO_3$-P levels (Fig. 2.2) suggesting that initial $NaHCO_3$-P level can be used to predict P requirement for maximum P uptake in different soils.

Total P uptake for the whole rotation was determined for different treatments (Table 2.8). Phosphorus uptake increased with an increase in initial soil test P level. Fertilization, compared to no fertilization, increased P uptake by almost 7 times for very low P soils, 2 to 3 times for medium P soils, and less than one time for high P soils. The increases were more pronounced in cases of cumulative compared to residual P treatments. Split application of P fertilization seemed to be more efficient than one large application. The single application of P fertilizer at a rate of 13.4 mg P kg^{-1} to soil 1 resulted in a total P uptake of 37 mg P/pot, whereas, splitting the same amount of P into two applications resulted in a total P uptake of 43 mg P/pot.

Stepwise regression analysis were performed to determine the factors that governed total P uptake for the whole rotation by relating total P uptake to the rates of P application and soil parameters using stepwise regression:

Single P application (residual P):

$$TPup = 18.9 + 4.9*P + 89.0*(Pad/MBC) \qquad r^2 = 0.77^{***} \quad (1)$$

Two P applications (cumulative P):

$$TPup = 29.0 + 4.3*P + 24.5*(Pad/MBC) \qquad r^2 = 0.70^{***} \qquad (2)$$

TPup = total P uptake for the whole rotation (mg P/pot)

P = initial $NaHCO_3$-P level (mg kg^{-1})

Pad = rate of P added (mg kg^{-1})

MBC = maximum buffering capacity

Texture did not significantly affect total P uptake. However, its effect was probably indirect through MBC. Regression equations (1) and (2) showed that the P uptake was governed by initial $NaHCO_3$-P soil level, rate of P application, and MBC. In general, with the same amount of P added, more uptake was found in soils having low P buffering capacity.

Residual P Value

A concept of residual value, developed by Barrow and Campbell (1972), was used to compare residual and cumulative effects in different soils. A residual value is calculated by dividing the slope value (b from regression equation (3 or 4)) computed for residual P by the slope for the cumulative P treatment.

A linear relationships was established between either wheat grain yield or soil $NaHCO_3$-P, measured after harvesting the 3rd crop, and P application rates.

$$P = a + b*Pad \qquad (3)$$

Or:

$$Y = a + b*Pad \qquad (4)$$

P = soil test $NaHCO_3$-P (mg kg^{-1})

Y = grain yield (g/pot)

Pad = P application rate (mg P kg^{-1})

The regression equations developed for soil P are given in Table 2.9. The correlations were highly significant. The rates of increase (b values) were soil dependent and were higher for the cumulative P treatment than for the residual P treatment. The correlations of b values with MBC values for the same soils were highly significant (R^2 = 0.87** for residual P and R^2 = 0.71** for cumulative P). This result confirmed our earlier findings that the rate of increase in $NaHCO_3$-P in soil was related to the MBC of the soil. The residual values calculated for each soil using equation (3) are presented in Table 2.10. These results show that residual value of P dropped by 10 to 50% compared to cumulative P after only three crops.

The residual value of P also was determined using regression equations relating wheat grain yield to P application rates (equation 4) in soils where wheat responded to P (Table 2.11). The average grain yield increase was higher with cumulative P (0.53) than with residual P (0.38) (Table 2.11). The difference was accentuated in soils with low initial $NaHCO_3$-P. This inferred that repeated P applications were more efficient in increasing wheat grain yield than single application in the range of P rates used in this study.

The residual value, using grain yield ranged from 0.49 to 1.13. The residual value of P in soil 1 dropped by 51% from the first crop to the third crop. While the decrease was only 25% in soil 5 (Table 2.12). In general, soils with low initial $NaHCO_3$-P had the lowest residual value (soil 1: RV = 0.49; soil 2: RV=0.52) inferring that in those soils the largest part of the added P was sorbed on soil particles. While in soils with high initial P, the sites may be saturated, leading to less fixation of applied P.

Effect of $NaHCO_3$-P On Subsequent Yields

The $NaHCO_3$-P values measured before sowing each crop were related to the yield of the next crop. The relationships were established for corn, as the second crop and wheat, third crop. Data were fitted to the Mitscherlich model using the non linear (NLIN) procedure in SAS.

Soil $NaHCO_3$-P, measured before planting each crop, described some of the yield variation for both the second (Fig. 2.3) and the third crop (Fig. 2.4). The predicted models showed that the variation accounted for was lower for the second crop ($R^2 = 0.61$) than for the third crop ($R^2 = 0.88$), indicating that soil $NaHCO_3$-P test seemed to be less accurate in evaluating residual P effects. More accurate evaluation of residual P affects were obtained when measurements were made after more complete equilibrium between added and native soil P was reached, as was the case for the third crop.

SUMMARY AND CONCLUSION

The effect of residual P on succeeding crops was evident in our study. The response of both corn (second crop) and wheat (third crop) to previously applied P supported the observation that much of the P applied to a crop in fertilizer may not be used by that crop. The average increase in dry matter production of corn, in our greenhouse study, ranged from 1 (5%) to 11 g/pot (105%) in soils 12 and 11 respectively. Both cumulative and residual treatments resulted in higher wheat grain yields (third crop) as compared to the unfertilized treatments. Averaged across P rates, the maximum increase in yield varied from 97 to 265% for residual and cumulative P, respectively.

The increase in yield was closely related to the amount of P applied to the previous crop, initial $NaHCO_3$-P, and soil P buffering capacity (MBC). In fact, the residual P effect was very pronounced in soils with low $NaHCO_3$-P content. That does not exclude the possibility that there was a residual effect in soils with high P test, but the effect was masked because of our short-time study. Beside soil test, the rate of P application had an important effect on the magnitude of response to residual P. The largest increase in corn dry matter production was obtained with the highest rate of P application.

When comparing equal total P application rates, the single applications produced less grain than repeated applications. It was clear from these results that because ot increasing contact time between fertilizer P and soil particles, the P fertilizer use efficiency was higher for split applications (cumulative P treatment) than for a single P application.

This greenhouse study showed that the response of corn to residual P would be significant for soils with initial $NaHCO_3$-P test levels less than 6 mg kg^{-1}, the response is likely between 6 and 10 mg P kg^{-1}, and no response above 10 mg P kg^{-1}.

My results suggested that soils that have more than 14 mg kg^{-1} of $NaHCO_3$-P could provide adequate P for maximum yield for three succeeding crops under greenhouse conditions. For corn, the effect of residual P on wheat was soil specific, and mainly due to the initial $NaHCO_3$-P levels which in turn reflected the amount of previous P applications and adsorption capacity of soil.

The regression equations relating soil $NaHCO_3$-P at harvest of the third crop, to the rates of P application showed that the rate of increase in P availability (b values) were soil dependent and seemed to be higher for cumulative than for residual P treatment. Similarly, the rate of grain yield increase was generally lower for residual than for cumulative treatment. The average rates of grain yield increases were 0.53 and 0.38 per unit of P added for cumulative and residual P respectively.

In general, soils with low initial $NaHCO_3$-P levels had the lowest residual value (soil 1: RV = 0.49; soil 2: RV=0.52) inferring that in those soils a large part of the added P is sorbed or fixed. A high P soil test, the sorption sites may already be saturated leading to less adsorption of the added P.

Table 2.1. Classification of soils used in study and their geographic locations.

Soil	Soil great group	Location
1	Palexerolic Chromoxerets	Chaouia
3	Calcic Argixerolls	"
4	Typic Chromoxererts	"
5	Typic Rendolls	"
6	Xerochrepts	"
7	Xerochrepts	"
8	Argiustolls	"
10	Aridic SG of Ustolls	"
12	Xerochrepts & Ustochrepts	"
2	Vertic Calcixerollic	Abda
9	Typic Rendolls	"
11	Chromoxererts	"
13	Arguistolls	"

Table 2.2. Selected physical and chemical characteristics of surface (0-20 cm) soils used in study.

Soil	Clay	Silt	Sand	pH water	CEC	Organic matter	Lime	NO_3-N	K	Na	Ca	Mg	P
	-------- %	--------	--------		mS/cm	-------- %	--------	--------	--------	mg kg^{-1}	--------	--------	--------
1	56	20	23	7.9	56	1.6	7	4	198	294	6450	411	3
2	42	8	48	8.1	39	2.3	1	44	112	280	4150	414	8
3	51	28	22	8.2	50	1.9	15	4	319	154	8040	351	10
4	48	8	39	7.9	39	2.2	6	3	210	58	6310	289	6
5	56	14	27	7.7	26	4.6	4	10	238	85	7170	171	7
6	47	23	27	8.0	28	1.6	21	10	167	70	5730	273	8
7	49	9	39	8.0	28	2.3	37	6	78	72	4430	103	23
8	26	8	64	7.7	10	2.8	1	5	125	82	1390	97	14
9	28	15	67	8.2	27	3.7	14	10	152	43	3430	178	8
10	27	7	66	8.1	13	2.5	1	6	117	41	1530	171	9
11	45	10	43	7.6	43	1.4	1	4	186	445	3860	375	9
12	53	8	37	7.5	28	2.6	1	4	152	84	3860	288	26
13	10	2	87	7.9	1	0.6	1	6	82	22	570	57	9

Table 2.3. Analysis of variance of the direct, cumulative, and residual effect of P on succeeding crops grown under greenhouse conditions.

			Crops			
			Wheat (1st crop)	Corn (2nd crop)	Wheat (3rd crop)	
			Direct P	RP	CP	RP
Variable	Source	DF				
			P			
Grain yield	Soils	12	0.01	-	0.01	0.01
	Prates	3	0.01	-	0.01	0.01
	Soils X Prates	35	0.01	-	0.01	0.01
Dry matter	Soils	12	0.01	0.01	0.01	0.03
	Prates	3	0.01	0.01	0.01	0.01
	Soils X Prates	35	0.01	0.01	0.13	0.01
Total Puptake	Soils	12	0.01	0.01	0.01	0.01
	Prates	3	0.01	0.01	0.01	0.01
	Soils X Prates	35	0.01	0.01	0.02	0.04

- only corn dry matter was harvested
P is probability
PR = residual P
CP = cumulative P

Table 2.4. Effect of direct, cumulative , and residual P on wheat grain yield in a succession wheat-corn-wheat under greenhouse conditions.

	Applied P (mg P kg^{-1})					
Soil	0.0	3.4	6.7	13.4	Mean	Sign.
	grain yield (g/pot)					
	Wheat (1st crop): direct effect of P application					
1	0.4 c	2.4 b	3.9 a	5.1 a	3.0	**
2	9.5 c	9.0 b	10.3 b	12.2 a	10.3	**
3	13.0 b	12.8 b	13.4 b	14.0 a	13.3	*
4	6.3 c	8.7 bc	9.6 ab	9.9 a	8.6	**
5	8.7 c	9.7 b	10.3 b	11.9 a	10.2	**
6	10.5 a	10.6 a	10.7 a	10.2 a	10.5	NS
7	14.8 a	14.3 a	14.1 a	14.3 a	14.4	NS
8	11.0 a	10.7 a	10.9 a	10.7 a	10.8	NS
9	9.5 b	9.7 b	10.5 a	11.0 a	10.2	**
10	8.4 c	8.6 c	9.6 b	10.6 a	9.3	**
11	5.2 b	6.0 a	6.3 a	6.6 a	6.0	**
12	11.4 a	11.3 a	11.5 a	11.4 a	11.4	NS
13	6.1 c	7.7 bc	8.6 ab	11.1 a	8.4	**
	Wheat (3rd crop): cumulative effect of P (P applied to first and third crops)					
1	4.0 c	9.2 c	16.8 b	27.2 a	14.3	**
2	3.7 c	10.5 bc	13.0 b	26.9 a	13.5	**
3	16.7 b	24.5 ab	25.2 ab	28.9 a	23.8	*
4	7.2 c	11.7 bc	15.5 b	24.4 a	14.7	**
5	9.9 b	15.7 ab	17.9 ab	24.4 a	17.0	NS
6	16.6 c	21.2 bc	22.6 b	27.7 a	22.0	*
7	26.3 a	26.4 a	28.9 a	22.5 a	26.0	NS
8	21.9 a	21.3 a	19.5 a	27.4 a	22.5	NS
9	9.9 b	15.1 b	20.7 a	23.5 a	17.3	**
10	7.6 c	13.3 b	15.4 ab	17.7 a	13.5	**
11	15.7 a	23.6 a	21.6 a	25.3 a	21.6	NS
12	28.0 a	27.6 a	28.0 a	26.6 a	27.6	NS
13	12.2 d	14.3 c	16.3 b	20.9 a	15.9	***
	Wheat (3rd crop): residual effect of P (P applied only to first crop)					
1	4.0 c	5.0 bc	7.4 ab	9.6 a	6.5	*
2	3.7 c	5.9 b	6.3 b	9.8 a	6.4	**
3	16.7 b	17.9 ab	21.7 ab	22.7 a	19.8	NS
4	7.2 b	9.8 ab	11.1 a	11.7 a	10.0	NS
5	9.9 c	12.0 bc	14.8 ab	16.4 a	13.3	*
6	16.6 b	17.9 ab	19.4 ab	21.8 a	18.9	NS
7	26.3 a	22.1 a	22.6 a	27.3 a	24.6	NS
8	21.9 a	24.4 a	19.7 a	20.0 a	21.5	NS
9	9.9 c	12.1 b	13.1 ab	14.1 a	12.3	*
10	7.6 b	8.9 ab	9.7 ab	11.9 a	9.53	NS
11	15.7 b	22.8 a	22.1 a	22.5 a	20.8	*
12	28.0 a	27.9 a	26.7 a	30.0 a	28.2	NS
13	12.2 b	13.3 ab	14.4 ab	15.5 a	13.9	NS

Means with the different letters, in row, were significatively different (P = 0.05)
sign.= significance, * and ** significant at p=0.05 and 0.01, respectively.
NS = non significant at p=0.05

Table 2.5. Effect of fertilizer P rates applied to wheat (1st crop) on dry matter production by wheat-corn succession under greenhouse conditions.

	Applied P (mg P kg^{-1})					
Soil	0.0	3.4	6.7	13.4	Mean	Sign.
	----dry matter (g/pot)----					
	Wheat (1st crop)					
1	3.8 c	8.6 b	12.8 a	14.8 a	10.0	**
2	24.6 b	23.8 b	25.9 b	29.5 a	26.0	**
3	32.1 b	33.5 ab	35.5 ab	36.4 a	34.4	NS
4	20.9 b	22.9 ab	25.0 a	25.9 a	23.7	*
5	26.9 b	27.5 b	32.5 a	31.7 a	29.7	*
6	25.0 a	26.9 a	27.9 a	26.8 a	26.6	NS
7	33.0 a	33.2 a	32.8 a	30.4 a	32.4	NS
8	27.8 a	28.2 a	28.4 a	29.5 a	28.5	NS
9	25.3 a	25.3 a	26.6 a	27.2 a	26.1	NS
10	22.2 b	25.5 a	25.2 a	26.1 a	24.8	*
11	16.7 a	17.7 a	18.1 a	18.4 a	17.7	NS
12	26.2 a	27.2 a	26.6 a	26.7 a	26.7	NS
13	17.0 c	20.4 b	22.8 ab	24.6 a	21.2	**
	Corn (2nd crop)					
1	1.0 b	1.0 b	1.6 b	3.2 a	1.7	**
2	4.7 a	4.1 a	5.8 a	7.5 a	5.5	NS
3	3.5 a	5.8 a	4.3 a	4.2 a	4.4	NS
4	2.1 a	3.3 a	3.3 a	4.7 a	3.3	NS
5	4.4 b	6.6 ab	5.8 b	6.6 a	5.9	*
6	3.3 a	3.5 a	3.0 a	4.1 a	3.5	NS
7	9.4 c	9.9 c	11.6 b	13.1 a	11.0	**
8	10.5 a	12.3 a	13.2 a	14.9 a	12.5	NS
9	5.1 a	6.0 a	5.4 a	5.7 a	5.5	NS
10	6.1 a	7.0 a	7.6 a	8.1 a	7.2	NS
11	6.4 c	9.5 bc	12.5 b	17.2 a	11.4	**
12	13.1 a	12.6 a	14.5 a	14.0 a	13.6	NS
13	6.1 b	7.4 b	9.6 a	11.1 a	8.6	**

sign.= significance

Means with the different letters, in row, were significatively different (P = 0.05)

* and ** significant at p=0.05 and 0.01, respectively.

NS = non significant at p=0.05

Table 2.6. Effect of cumulative and residual P on dry matter production of wheat grown as a third crop under greenhouse conditions.

Soil	Applied P (mg P kg^{-1}) 0.0	3.4	6.7	13.4	Mean	Sign.
	dry matter (g/pot)					
	Wheat (3rd crop): cumulative P effect (P applied to first and third crop)					
1	8.6 c	18.3 b	23.9 b	40.2 a	22.8	**
2	10.5 c	21.6 b	26.5 b	41.2 a	25.0	**
3	25.6 a	36.1 ab	41.3 ab	45.1 a	37.0	NS
4	16.3 c	23.9 b	28.3 b	37.7 a	26.6	**
5	19.3 b	27.8 ab	30.7 ab	38.7 a	29.1	NS
6	30.0 a	36.3 a	33.9 a	41.9 a	35.5	NS
7	38.3 a	41.1 a	37.2 a	43.5 a	40.0	NS
8	36.6 a	33.8 a	31.5 a	39.1 a	35.3	NS
9	23.4 a	31.4 a	30.8 a	38.6 a	31.1	NS
10	15.0 b	24.6 a	27.1 a	27.3 a	23.5	**
11	32.7 a	45.5 a	44.5 a	37.7 a	40.1	NS
12	43.5 a	40.4 a	42.5 a	37.9 a	41.1	NS
13	23.4 a	25.1 a	23.7 a	25.6 a	24.5	NS
	Wheat (3rd crop): residual P effect (P applied only to first crop)					
1	8.6 c	11.5 b	13.2 b	19.4 a	13.2	**
2	10.5 c	14.7 b	15.1 b	18.4 a	14.7	*
3	25.6 a	31.0 a	35.9 a	37.3 a	32.5	NS
4	16.3 c	17.3 bc	23.1 ab	24.0 a	20.2	*
5	19.3 c	23.9 bc	28.3 ab	30.2 a	25.4	*
6	30.0 a	33.6 a	35.5 a	36.6 a	33.9	NS
7	38.3 a	33.5 a	35.4 a	34.3 a	35.4	NS
8	36.6 a	33.6 a	33.3 a	33.1 a	34.2	NS
9	23.4 b	24.4 b	27.8 ab	31.1 a	26.7	*
10	15.0 c	15.6 bc	19.7 ab	21.8 a	18.0	*
11	32.7 a	35.3 a	31.4 a	37.6 a	34.3	NS
12	43.5 a	39.1 a	40.8 a	44.0 a	41.9	NS
13	23.4 b	24.5 ab	28.3 a	22.4 a	24.7	NS

sign.= significance

Means with the different letters, in row, were significatively different (P = 0.05)

* and ** significant at p=0.05 and 0.01, respectively.

Table 2.7. Effect of direct, cumulative, and residual P on P uptake by different crops in a wheat-corn-wheat succession under greenhouse conditions.

Soil	Applied P (mg P kg^{-1})					
	0.0	3.4	6.7	13.4	Mean	Sign.
	P uptake (mg/pot)					
	Wheat (1st crop): direct effect of P application					
1	1.1 d	4.9 c	7.9 b	11.5 a	6.4	**
2	20.0 c	22.2 bc	27.8 ab	35.4 a	26.4	**
3	32.8 b	35.1 b	34.8 b	40.9 a	35.9	**
4	14.8 c	20.6 bc	23.9 b	35.5 a	23.7	**
5	14.9 c	20.4 b	24.5 b	35.9 a	23.9	**
6	26.1 a	23.5 a	28.1 a	30.6 a	27.1	NS
7	33.6 b	42.7 b	35.1 a	43.5 a	38.7	**
8	30.9 b	30.4 b	37.9 b	30.6 a	32.5	*
9	17.6 b	22.3 b	22.7 b	29.9 a	23.1	**
10	20.9 a	22.8 a	24.6 a	25.3 a	23.4	NS
11	22.6 a	26.6 a	27.2 a	27.9 a	26.1	NS
12	51.6 a	39.2 a	41.1 a	47.4 a	44.8	NS
13	14.0 b	16.4 ab	22.9 a	34.1 a	21.9	*
	Corn (2nd crop): residual effect of P application					
1	0.4 c	0.5 c	1.6 b	3.6 a	1.5	**
2	2.2 b	3.3 b	6.2 ab	9.6 a	5.3	**
3	3.4 a	6.8 a	5.1 a	5.5 a	5.2	NS
4	1.5 b	2.6 ab	3.6 ab	5.7 a	3.3	*
5	2.9 c	5.1 bc	6.2 ab	8.5 a	5.7	*
6	2.6 a	3.3 a	3.2 a	4.5 a	3.4	NS
7	13.3 c	12.1 bc	15.7 b	20.0 a	15.3	**
8	4.6 b	12.2 a	14.0 a	15.6 a	11.6	**
9	2.8 a	7.4 a	5.5 a	6.2 a	5.5	NS
10	5.7 a	6.0 a	5.8 a	5.4 a	5.7	NS
11	3.5 b	6.3 b	7.2 b	12.6 a	7.4	**
12	9.0 a	11.9 a	12.2 a	10.8 a	11.0	NS
13	3.6 b	5.2 b	10.4 a	13.1 a	8.1	**
	Wheat (3rd crop): residual effect of P application					
1	8.9 b	10.5 b	15.0 ab	22.2 a	14.2	*
2	8.5 c	14.7 b	15.6 b	20.2 a	14.8	**
3	45.4 a	46.5 a	53.3 a	60.6 a	51.5	NS
4	15.0 a	18.9 a	25.7 a	29.2 a	22.2	NS
5	16.0 b	21.8 b	33.3 a	38.2 a	27.3	*
6	39.3 b	49.3 a	55.1 a	50.4 a	48.5	*
7	74.9 a	54.2 a	59.0 a	80.4 a	67.1	NS
8	59.1 a	67.6 a	63.0 a	57.6 a	61.8	NS
9	23.6 a	32.2 a	28.5 a	32.2 a	29.1	NS
10	16.9 a	22.6 a	21.2 a	26.5 a	21.8	NS
11	37.2 a	50.4 a	44.1 a	51.2 a	45.7	NS
12	78.2 a	94.9 a	79.8 a	93.4 a	86.6	NS
13	28.1 b	33.4 ab	38.4 a	37.1 a	34.3	*

Means with the different letters, in row, were significatively different (P = 0.05)

Sign.= significance; * and ** significant at p=0.05 and 0.01, respectively.

NS = non significant at p=0.05

Table 2.7 (continued). Effect of direct, cumulative , and residual P on P uptake by different crops in a wheat-corn-wheat succession under greenhouse conditions.

	P added (mg P kg^{-1})					
Soil	0	3.4	6.7	13.4	Mean	sign
	P uptake (mg/pot)					
	Wheat (3rd crop): cumulative effect of P application					
1	8.9 b	18.8 b	33.6 b	69.1 a	32.6	*
2	8.5 c	26.7 bc	32.6 b	65.3 a	33.3	**
3	45.4 b	63.8 ab	56.2 ab	76.2 a	60.4	NS
4	15.0 c	31.4 b	34.9 b	53.9 a	33.8	**
5	16.0 b	28.2 b	34.8 ab	56.9 a	34.0	*
6	39.3 b	54.9 ab	66.6 a	70.4 a	57.8	*
7	74.9 c	62.5 a	70.7 a	70.5 a	69.7	NS
8	59.1 b	53.1 ab	47.3 ab	76.9 a	59.1	*
9	23.6 c	29.0 bc	50.5 ab	55.2 a	39.6	*
10	16.9 b	29.8 ab	39.6 a	41.8 a	32.0	*
11	37.2 b	53.8 ab	55.2 ab	74.2 a	55.1	NS
12	78.2 a	100.6 a	99.6 a	80.4 a	89.7	NS
13	28.1 b	36.9 b	41.8 ab	52.8 a	39.9	*

sign.= significance

Means with the different letters, in row, were significatively different (P = 0.05)

* and ** significant at p=0.05 and 0.01, respectively.

NS = non significant at p=0.05

Table 2.8. Effect of cumulative and residual P on total P uptake in the whole rotation by the three crops under greenhouse conditions.

	P added (mg P kg^{-1})					
Soil	0	3.4	6.7	13.4	Mean	sign
	P uptake (mg/pot)					
Cumulative P						
1	10.5 c	24.3 cb	43.1 b	84.2 a	40.5	**
2	30.7 c	52.2 cb	66.6 b	110.3 a	65.0	**
3	81.5 b	105.7 ab	96.1 b	122.6 a	101.5	*
4	31.4 c	54.6 b	62.4 b	95.1 a	60.9	**
5	33.8 b	53.8 b	65.4 b	101.3 a	63.6	*
6	68.0 b	81.7 ab	97.9 a	105.4 a	88.3	*
7	121.8 a	117.3 a	121.5 a	134.0 a	123.7	NS
8	94.6 a	95.8 a	134.0 a	123.1 a	111.9	NS
9	44.0 c	58.6 bc	78.7 ba	91.3 a	68.2	*
10	43.5 b	58.5 a	70.0 a	72.4 a	61.1	*
11	63.2 c	86.8 bc	89.7 b	114.7 a	88.6	*
12	138.8 a	151.7 a	153.0 a	138.6 a	145.5	NS
13	45.7 c	58.5 c	75.1 b	100.1 a	69.9	**
Residual P						
1	10.5 c	16.0 cb	24.5 b	37.3 a	22.1	**
2	30.7 c	40.2 cb	49.7 b	65.2 a	46.5	**
3	81.5 b	88.5 b	93.3 ba	107.0 a	92.6	*
4	31.4 c	42.1 b	53.2 b	70.3 a	49.3	**
5	33.8 b	47.3 b	64.0 b	82.7 a	57.0	*
6	68.0 b	76.0 ab	86.4 a	85.5 a	79.0	*
7	121.8 a	109.0 a	109.8 a	143.9 a	121.1	NS
8	94.6 a	110.2 a	143.9 a	103.9 a	113.2	NS
9	44.0 c	61.9 bc	56.7 ab	68.3 a	57.7	*
10	43.5 b	51.3 a	51.5 a	57.1 a	50.9	*
11	63.2 b	83.3 ab	78.5 ab	91.7 a	79.2	NS
12	138.8 a	146.1 a	133.1 a	151.6 a	142.4	NS
13	45.7 c	55.1 c	71.6 b	84.3 a	64.2	**

sign.= significance

Means with the different letters, in row, were significatively different (P = 0.05)

* and ** significant at p=0.05 and 0.01, respectively.

NS = non significant at p=0.05

Table 2.9. Linear regression coefficients for the relationship between $NaHCO_3$-P level in soils (mg P kg^{-1}) after three crops and amount of applied P (mg P kg^{-1}).

Soil	P management	a	b	r^2
1	RP	2.73	0.13	0.61*
	CP	2.04	0.21	0.93**
2	RP	2.72	0.36	0.96**
	CP	2.20	0.43	0.95**
3	RP	7.49	0.20	0.91**
	CP	7.34	0.34	0.95**
4	RP	4.45	0.25	0.96**
	CP	4.71	0.31	0.86**
5	RP	5.21	0.15	0.69*
	CP	5.15	0.19	0.93**
6	RP	5.59	0.18	0.92**
	CP	5.80	0.23	0.94**
7	RP	16.84	0.14	0.59*
	CP	17.88	0.23	0.87**
8	RP	8.38	0.29	0.95**
	CP	8.28	0.35	0.96**
9	RP	6.11	0.32	0.61*
	CP	6.23	0.37	0.88**
10	RP	4.16	0.32	0.93**
	CP	4.22	0.34	0.93**
11	RP	5.07	0.30	0.93**
	CP	4.28	0.37	0.89**
12	RP	21.84	0.17	0.63*
	CP	22.70	0.21	0.84**
13	RP	5.53	0.36	0.86**
	CP	5.12	0.42	0.97**

RP = residual P.

CP = cumulative P.

* and ** significant at $p = 0.05$ and 0.01, respectively.

Table 2.10. Residual value (RV) calculated using $NaHCO_3$-P soil test in the thirteen soils used in this study.

Soil	RV
1	0.64
2	0.84
3	0.60
4	0.81
5	0.75
6	0.77
7	0.62
8	0.83
9	0.88
10	0.94
11	0.80
12	0.83
13	0.85

Table 2.11. Linear regression coefficients for the relationship between wheat grain yield (g/pot) and applied P (mg P kg^{-1}) in soils where wheat responded significantly to P applications.

Soil	P management	a	b	r^2
1	RP	3.93	0.43	0.89**
	CP	3.97	0.88	0.96**
2	RP	3.85	0.43	0.94**
	CP	3.63	0.84	0.94**
3	RP	16.95	0.47	0.67*
	CP	19.06	0.40	0.71**
5	RP	10.39	0.48	0.82**
	CP	10.89	0.51	0.68*
6	RP	16.61	0.39	0.76**
	CP	17.40	0.39	0.88**
9	RP	10.55	0.30	0.79**
	CP	11.40	0.50	0.84**
10	RP	7.66	0.31	0.81**
	CP	9.36	0.35	0.80**
13	RP	12.37	0.24	0.75**
	CP	12.09	0.33	0.99**

RP = residual P.

CP = cumulative P.

* and ** significant at $p = 0.05$ and 0.01, respectively.

Table 2.12. Residual P values (RV) calculated using grain yield in soils where wheat responded significantly to P applications.

Soil	RV
1	0.49
2	0.52
3	1.17
5	0.94
6	1.00
9	0.59
10	0.90
13	0.75

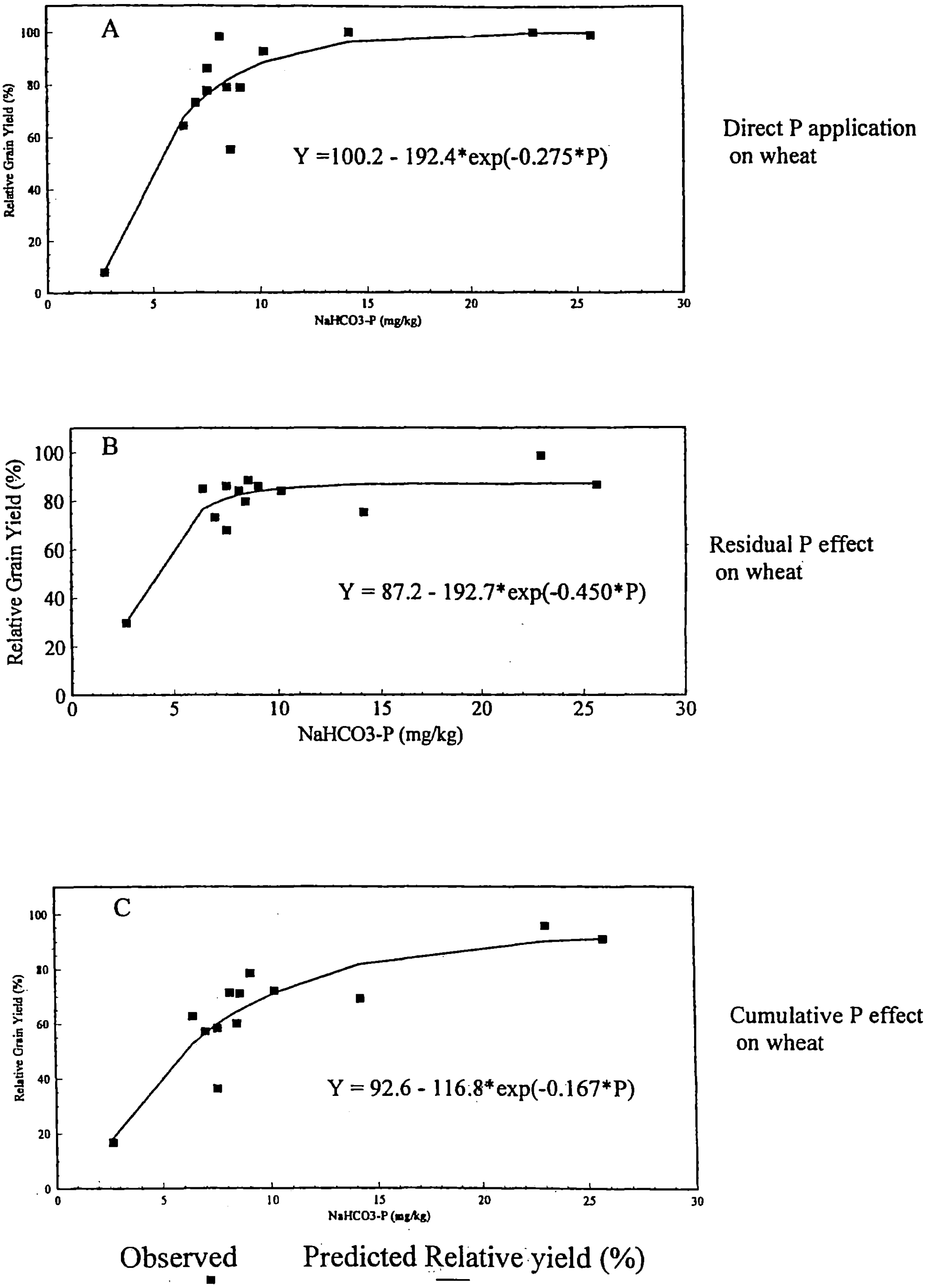

Figure 2.1. Observed and predicted relative grain yield by wheat as a function of initial NaHCO3-P soil test (P)

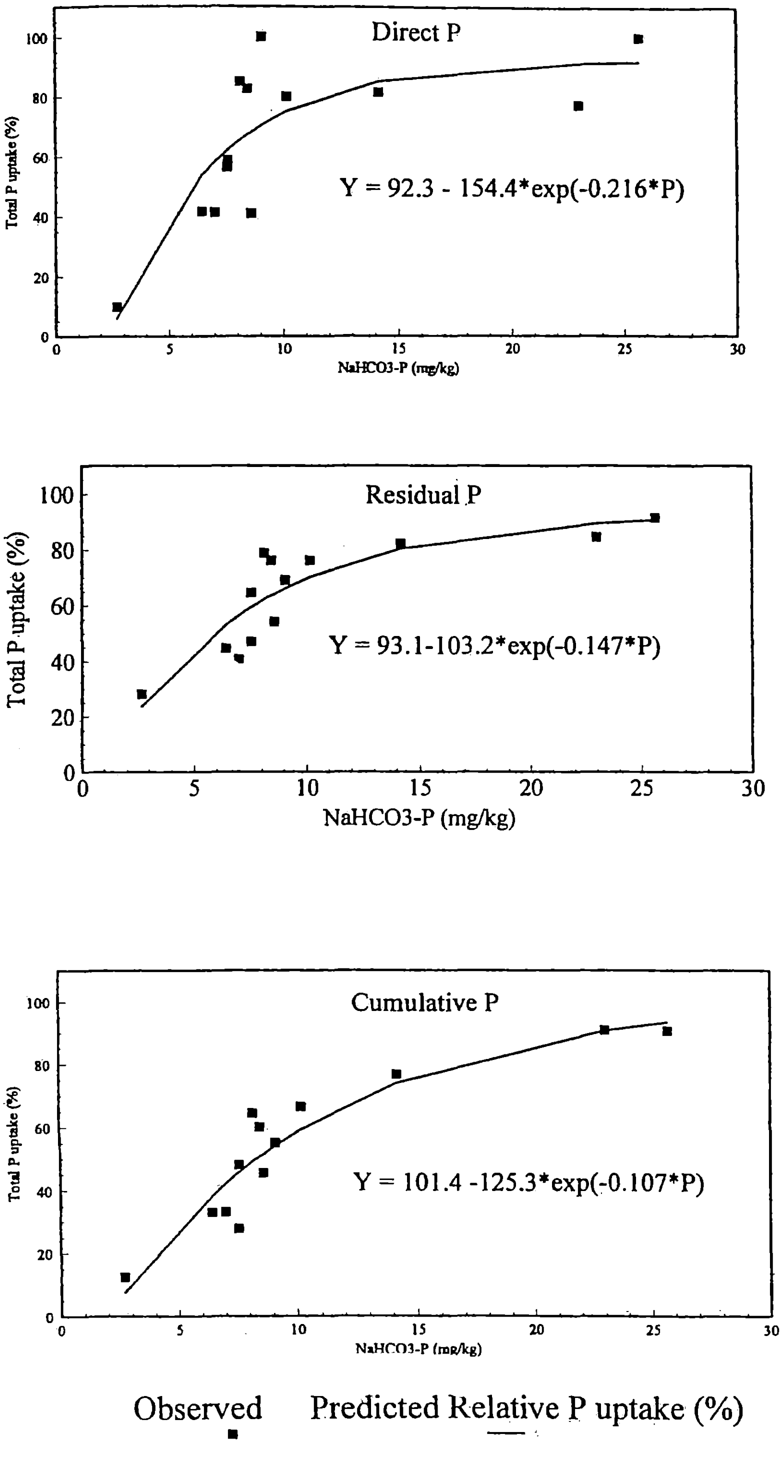

Figure 2.2. Observed and predicted relative total P uptake by wheat as a function of initial NaHCO3-P soil test (P)

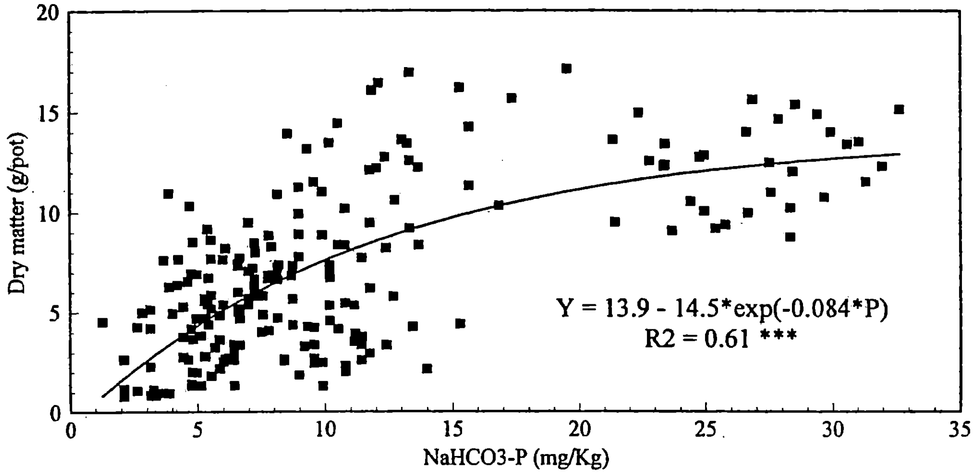

Figure 2.3. Relationship between corn dry matter production (second crop) and soil NaHCO3-P measured after first wheat crop

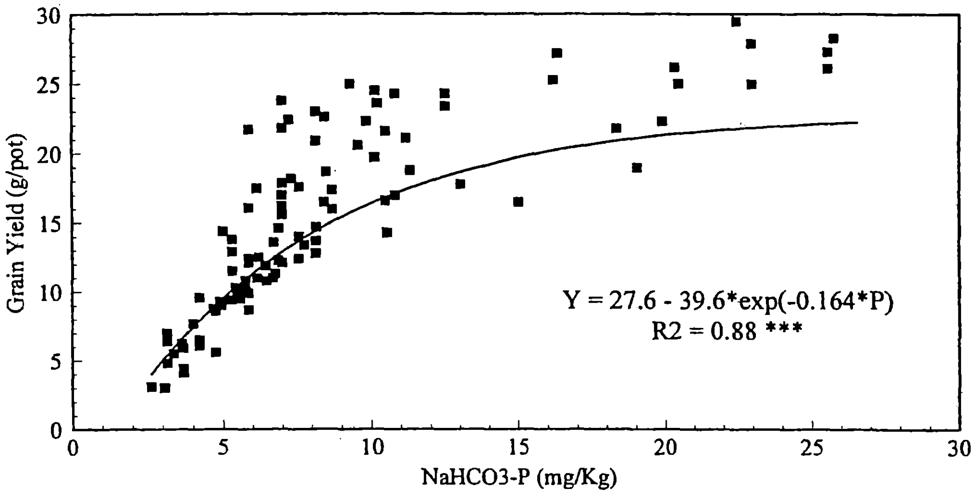

Figure 2.4. Relationship between wheat grain yield (third crop) and soil NaHCO3-P measured after corn harvest

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CHAPTER III.

Direct, Cumulative, And Residual P Management In Continuous Wheat and Wheat-Legume Rotations

ABSTRACT

Continuous wheat and wheat-legume are of the most dominant cropping systems in arid and semi-arid zones of Morocco. The sustainability of these systems is closely related to judicious use of fertilizers. Little research has been conducted on the management of P in the rotations. The purpose of this study was to determine the effect of direct, cumulative, and residual P on wheat and chickpea yields under field conditions in two cropping systems: continuous wheat and chickpea-wheat.

Experiments were conducted in 1994-96 at three locations in the arid and semiarid regions of Morocco. Phosphorus was applied the first year at a rates of 0, 8.9, 17.8, and 26.7 kg P ha^{-1} on both wheat and chickpea. The second year, plots were split to treatments of with (applied the same amount as previous year) and without P fertilizer. The changes in $NaHCO_3$-P in soil showed that, after 2 years of cropping, P rates of 8.9, 17.8, and 53.4 kg P ha^{-1} were needed to increase and maintain soil test P level in the range where a third successive crop could be grown at Khmis Zemamra, Sidi El Aydi, and Khmis Sidi Rhhal, respectively. Also, soils with the same initial test P levels required different amounts of fertilizer P to produce maximum yields. The first year, wheat grain yields averaged 2.6 and 2.9 Mg ha^{-1} at Sidi El Aydi and Khmis Zemamra, respectively. These yields are high, compared to the region-wide average of 2.2 Mg ha^{-1}. The maximum average grain yields in 1994-95 for chickpea were 1.8 and 2.1 at the Sidi El Aydi and Khmis Zemamra locations, respectively. Inclusion of chickpea in the rotation resulted in a greater response to residual P by wheat at Khmis Zemamra. At Khmis

Zemamra, the average grain yields, for the highest P rates, were 2.4 and 2.6 Mg ha^{-1} for wheat after wheat and wheat after chickpea, respectively. The differences in wheat grain yield between rotations were not significant at Sidi El Aydi. The corresponding grain yields were 2.3 and 2.4 Mg ha^{-1}. The maximum increase in yield above the check due to the highest residual P rate was 1.3 Mg ha^{-1} obtained in continuous wheat at Khmis Zemamra. The highest average dryland wheat grain yields were 2.6, 3.1 and, 3.4 Mg ha^{-1} as the at the three locations. These yields were much higher than the national average of about 1.6 Mg ha^{-1}. After two years, the effect of cropping system was not consistent. The residual P effect was evident in this study, but it was not able to produce maximum yield. Based on the range of P rates used in this study, a single P application is not a suitable practice in our soils. Current wheat prices suggest that the application of 18 kg P ha^{-1} each year or 9 kg P ha^{-1} the first year plus 18 kg P ha^{-1} the second year would be the recommendation for continuous wheat and chickpea-wheat rotations, respectively.

INTRODUCTION

Continuous wheat and wheat-legume are the most dominant cropping systems in arid and semi-arid zones of Morocco. The sustainability of these systems is closely related to judicious use of fertilizers. Wheat and chickpea are generally grown in soils deficient in phosphorus (P). The yield response to P fertilizer differs among species (Itoh, 1987). In general, cereals respond more to P fertilizers than do chickpea (Saxena, 1984).

It has been reported that about 80 to 90% of arid and semi-arid soils of the world are deficient in P (Sanders, 1986). Phosphorus chemistry in the soils is very complex. When P fertilizer is applied, less than 1/3 is used in the current growing season, the remaining is either sorbed or precipitated. Some of the P fertilizer can be used by succeeding crops; this part is called 'residual P'. Since the early 20th century, the concept of residual effect on plant growth of some nutrients has been reported in many investigations (Volk, 1945; Halvorson and Black, 1985a; McPharlin et al., 1994). Phosphorus has an important residual effect. Phosphorus residual effects could be used as part of the economic return (Black, 1994). However, that was not always the case. Miladinovic et al. (1977) studied the economic effect of residual P, which they called reserve P, and concluded that economics favoring reserve fertilization were not apparent in their investigation.

Phosphorus fertilization in calcareous soils has been found to have a residual effect on plants for many years (Olsen et al., 1954a; Halvorson and Black, 1985a and 1985b; Bolland, 1993). Fixen and Ludwick (1982) obtained yield increases from residual P for six greenhouse crops. In Morocco, Loudyi (1989) found that repeated applications of fertilizer P led to an increase of soil test P levels over time. Azzaoui et al. (1990), on a Petricalcic Palexeroll soil of Chaouia region, found that after 11 month $NaHCO_3$-P was increased by about 15.5 mg P kg^{-1} soil as the result of an application of 40 kg P ha^{-1}. The rate of fertilizer P application, time, and crop management influenced residual effect of P. Sharma et al. (1995) reported that inoculation and P application on chickpea had a significant effect on maize and sorghum grown of succeeding crops.

The decrease in P availability with time has always caused decreased yields. Bolland (1993) found that the residual value of superphosphate was reduced by about 60%, relative to fresh P application, between the first and the second year and by 25% in the fourth year.

The evaluation of residual effects of fertilizer P has generally been based upon variation of either soil test P (Fixen and Ludwick, 1982; Halvorson and Black, 1985a; Pothuluri et al., 1991) or crop yields (Ridley and Tayakepisuth, 1974; Read et al., 1977; Singaram and Kothandaraman, 1992; Bolland, 1992a). However, evaluations of residual affect have produced wide variations in results due to differences in experiments and environmental conditions such as soil type, rates of P, and fertilizer type. Kumar et al. (1991a) reported that P compounds differ considerably in their solubility. Therefore, it is expected that the relationships between plant and soil test P may differ depending upon what P fertilizer residues are present in the soil. In their second paper, Kumar el al. (1991b) postulated that there was a strong influence of types of P compounds on the solubility of P in soil test reagents. On the other hand, Aulakh and Pasricha (1991) found, in a study concerning transformations of residual P under peanut-wheat rotation, that the increase of rate and frequency of P application tended to enhance the conversion of residual P to stable forms that were less available to the plant.

The residual effect of P could be very large and it should be taken into account for succeeding fertilizer recommendation programs, especially when high amounts of fertilizer are used. McPharlin et al. (1992) reported that 80% of applied P was not used by carrots in sandy soils. These authors evaluated the remaining P five years after application of to 1200 kg P ha^{-1} to the carrots. Therefore, fertilizer P application should take into consideration the effect of previous P applications to minimize the buildup of P in the soil.

Fertilizer P can be a contributor to surface water pollution bodies. Therefore, proper use is not only of agronomic and economic concern, but also of environmental concern.

Prediction models have been developed to evaluate cost and economic profit from residual and cumulative P fertilizer application (Saroa and Biswas, 1989; Cox et al. 1981; Probert, 1985; Cox, 1996). Cox (1996) studied yield data from a 13 years residual-P experiment including corn, soybean, and wheat grown on a sandy soil. He found that, by taking into consideration current crop prices and fertilizer costs, the economic critical levels were between 31 and 35 mg P L^{-1} (mean = 33 mg P L^{-1}). His economical critical P level was about 14% greater than the critical P level found by linear regression and plateau model. Probert (1985) found that the model he used to predict residual P provided a basis for predicting residual P beyond the three year experimental period. However, the semi-descriptive model used by Saroa and Biswas (1989) showed good predictions for some soils, but not for others because of other sources of available P (mineralization from organic P) that were not considered in the model.

The P requirement based on soil test P in Morocco has been measured in a few field experiments (Soltanpour et al. 1986, Moughli, 1991) as well as under controlled conditions (Azzaoui et al., 1989). However. there is still a lack of information regarding P management under Moroccan cropping systems. This aspect is becoming of more interest because of the increase in fertilizers costs.

The purpose of this study was to determine the effect of direct, cumulative, and residual P on wheat and chickpea yields under field conditions in two cropping systems: continuous wheat and chickpea-wheat.

MATERIAL AND METHODS

Soil

Field experiments were conducted for two growing seasons (1994-95 and 1995-96) on three different sites in the Moroccan arid and semiarid zone: Sidi El Aydi Agricultural Experiment Station at 15 km north Settat, Khmis Zemamra Agricultural Experiment Station 100 km from Casablanca to the south, and an on-farm experiment at Khmis Sidi Rhhal (37 km south Settat). The soils at the three sites were deep and classified as Calcic Argixerolls (Sidi El Aydi), Vertic Calcixerollic (Khmis Zemamra) and Palexerolic Chromoxerets (Khmis Sidi Rhhal). All three sites are on flat topography with no appreciable micro-relief. Some of the important physical characteristics of the experimental sites are reported in Table 3.1. Available P was extracted by 0.5 M

$NaHCO_3$ solution (Olsen et al., 1954b) and analyzed by the ascorbic acid method of Murphy and Riley (1962); pH was measured by glass electrode using a soil:water ratio of 1:2; organic matter by wet oxidation (Walkley and Black, 1934); CEC by a method by Chapman (1965); exchangeable cations were extracted using 1N NH_4OAC solution (pH = 7) with Ca and Mg being determined by atomic adsorption and K by flame photometer; and total N was found by micro Kjeldahl method (Bremner, 1965).

Climate

The three sites are located in arid and semiarid zones of Morocco. The long-term average annual rainfall is about 380 mm at Sidi El Aydi, 308 for Khmis Zemamra and 280 mm at Khmis Sidi Rhhal. These averages are subject to large yearly variation (Watts and El Mourid, 1988). The long-term minimum and maximum temperature in these zones range from about 1°C in December to a maximum of 47°C in July.

Experimental Designs

The experimental design was a randomized complete design with common treatments for the two sites conducted at the experiment stations. The treatment arrangement consisted of a split-plot with cropping system (chickpea-wheat and continuous wheat) as main plote and P rates (0, 8.9, 17.8, and 26.7 kg P ha^{-1}) as subplots. The treatments were carried out with four replicates. All plots of every rotation were present each year, wheat (continuous), wheat after chickpea, and chickpea after wheat. This experiment consisted of 3 main plots. In the 1994-95 growing season, each main plot (36 x 10 m at Sidi El Aydi and 40 x 10 m at Khmis Zemamra) was divided into 4 sub-plots (either 4.5 x 10 m at Sidi El Aydi or 5 x 10 m at Khmis Zemamra).

Basal N and K fertilizers were applied to wheat at the rates of 70 kg N ha^{-1} and 42 kg K ha^{-1}. Nitrogen was splited into two applications 40 kg N ha^{-1} as $(NH_4)_2SO_4$ at sowing and 30 kg N/ha as NH_4NO_3 at tillering. Only K was added to chickpea at a rate of 42 kg K ha^{-1} as K_2SO_4.

In the second year (1995-96), the sub-plots were split into two sub-sub-plots. One received no additional P (Residual P) and the second sub-subplot was given the same rate of P as was applied in the first year (Cumulative P). The basal N rates applied the seconc year were: 100 and 50 kg N/ha for continuous wheat and wheat after chickpea, respectively. These amounts were split into two applications, one half at sowing and the other at tillering. Potassium was added as K_2SO_4 at a rate of 25 kg K ha^{-1}.

On-Farm Experiment

This experiment was carried out as a randomized factorial design with two P timings (residual or cumulative P) and four rates (0, 8.9, 17.8, and 26.7 kg P ha^{-1}) with three replicates. The cropping system was wheat-follow.

Each plot was 10 x 10 m size and the P fertilizer was applied in November 1994. The site was not cropped in 1994-95 season because of extreme drought (the field was sown but good germination did not occur). Twelve months later each plot was divided into two subplots (5 x 10 m each). One subplot received the same amount of P application as was applied 12 months earlier (cumulative P). The second subplot received no further P application (residual P).

Fertilizer Application

Triple superphosphate (45% P_2O_5) was used in all field experiments. Phosphorus fertilizer was broadcasted before sowing, together with N as ammonium sulfate and K as potassium sulfate. Fertilizer incorporation was done with an off set desk to a depth of 15 cm.

Crop Management

Wheat (cv Merchouch) was sown at a rate of 120 kg ha^{-1} at all sites each year except in 1995 at Sidi El Aydi where the rate was 150 kg ha^{-1}. Chickpea was sown at 80 kg ha^{-1} (around 60,000 plant ha^{-1}). Wheat and chickpea sowing occurred on 15 December the first year (1994) and 19 November the second year (1995) at Khmis Zemamra. The corresponding sowing time at Sidi El Aydi were 19 December and 22 November for the first and the second year, respectively. Harvest took place in June each year at all sites.

During the 1994-95 season, because of drought, the experiments conducted at the agricultural stations were irrigated. The total amount of irrigation water added equaled long-term average rain for each location.

Weed control consisted of application of Logran (Amber or Triansulfuron) 2-(2-chloroethoxy)-N-[[(4-methoxy-6-methyl1,3,5-triazin-2yl)amino]carbonyl]benzenesulfonamide at 3 kg a.i ha^{-1} on wheat 20 days after emergence. Weed control in chickpea was accomplished with a pre-emergence application of "Igran" (terbutryn) at a rate of 3 kg a.i ha^{-1}.

Measurement And Analysis

Soil samples were collected prior to fertilizer application in 1994 and 1995, at tillering in 1995 and 1996, and after harvest (August) in 1995 and 1996 (The pre-sowing soil sampling took place from August to September). Each sample was taken as a composite of three replicates in the same plot (treatment). After air-drying, they were ground and sieved to pass a 2-mm mesh, and analyzed for extractable P using the $NaHCO_3$ method (Olsen et al., 1954b).

The number of plants per m^2 was determined each year one month after sowing. Plant samples were collected at tillering and at harvesting in all experiments. Plant materials were dried in an oven at 70 °C for 48 hr, then ground and sieved to pass a 0.5-mm screen, and were analyzed for total P and N. At harvesting, dry matter production and grain yield were determined. Twenty random ears per plots were used to determine the average grain number per ear and the 1000-grain weight.

RESULTS AND DISCUSSION

Plant density was measured one month after sowing, and seedling emergence was not affected by rate of P application. An average of 223 ± 32 wheat plant per m^2 was found in 1994-95, compared to 267 ± 26 plants per m^2 in 1995-96.

The total rainfall in the first season (1994-95) was below a long-term average at all locations (Fig. 3.1). The total precipitation was the lowest this region had received in the past 50 years. The amount of rainfall received at Khmis Zemamra in 1994-95 was normal until November, after that time it dropped below the long-term average (curve D5). Statistical data from the past 60 years showed that this low amount of rainfall at Khmis Zemamra in the 1994-95 season was recorded less than one time every 10 years (cumulative curve was below D1) (Fig. 3.1). The deficit for the entire year was about 50% of the average. The same tendency was observed at Sidi El Aydi, the drought was extreme and the deficit reached 67% compared to the long term average. In the 1995-96 season, the precipitation amount was higher than the average. The amount received in 1995-96 normally occurs only once in 10 years (cumulative rainfall curve over D9) at Khmis Zemamra and three out of 10 years (cumulative rainfall curve over D1) at Sidi El Aydi (Fig. 3.1). The annual rainfall at Khmis Sidi Rhhal in the 1995-96 season was about 322 mm, which is higher than the average.

Bicarbonate-P Changes In Soil

The changes in soil $NaHCO_3$-P at different sites during the two growing seasons are shown in Figs. 3.2, 3.3, and 3.4. The values were affected by both rate and time of P application. At the end of 1994-95 season, the $NaHCO_3$-P levels were 8, 9, 10, and 12 mg P kg^{-1}soil at Sidi El Aydi and 7, 8, 9, and 10 mg P kg^{-1}soil at Khmis Zemamra as a result of application of 0, 8.9, 17.8, and 26.7 kg P ha^{-1}, respectively.

In general, the same trend was observed in the second season. But, more evidence of buildup of P was shown in the second season (Figs. 3.2, 3.3, and 3.4). The $NaHCO_3$-P was generally increased by repeated applications and high P rates (26.7 kg P ha^{-1}). The average increases in $NaHCO_3$-P levels as a result of P application of 53.4 kg P ha^{-1} were about 5, 6, and 7 mg P kg^{-1} at Sidi El Aydi, Khmis Sidi Rhhal, and Khmis Zemamra, respectively. The variation among locations was probably due to the variation in soil characteristics, especially initial soil P level and the ability of soil to respond to applied P. The main factor explaining this variation was the difference in the rates of $NaHCO_3$-P increase between soils. In fact, rates of $NaHCO_3$-P increase measured in the laboratory study for our three soils are 0.17, 0.19, and 0.35 (mg P $kg^{-1})^{-1}$ for Khmis Sidi Rhhal, Sidi

El Aydi, and Khmis Zemamra, respectively. This order matched the order found in the greenhouse study.

The norms of soil test calibration established for dryland wheat in Morocco by Soltanpour et al. (1986) classified soils into three categories: (i) soils with less than 5 mg kg^{-1} extractable $NaHCO_3$-P are considered as deficient (ii) between 5 and 7 mg kg^{-1}, the response is unlikely, and (iii) greater than 7 mg kg^{-1} no response is expected. The present experiment showed that a response was obtained with soils with 7 mg P kg^{-1}. The reason might be due to the irrigation. Under irrigation Moughli (1991) found that wheat responded at a level up to 12 mg P kg^{-1}. The other reason could be that the new genotype used in this study required a high amount of nutrient.

At Khmis Sidi Rhhal location, which had a low soil test P level (3 mg kg^{-1}), only the application of 53.4 kg P ha^{-1} (26.7 kg P ha^{-1} per year) was able to maintain the $NaHCO_3$-P level, after wheat harvest in 1996, greater than 8 mg P kg^{-1}. Therefore, no further P application would be required for the 1996-97 growing season. This led to the conclusion that in soils with a high adsorption capacity and very low soil test P level, large amounts of fertilizer P (>53.4 kg P ha^{-1}) would be needed to maintain high yield for three succeeding crops. However, at Khmis Zemamra and Sidi El Aydi (initial $NaHCO_3$-P = 7 mg kg^{-1}) 8.9 to 17.8 kg P ha^{-1} were sufficient to raise the soil test P level to a range where no P addition was recommended for either the 1995-96 or 1996-97 seasons.

At Khmis Sidi Rhhal, the $NaHCO_3$-P value resulted from the largest P rates, applied in 1994, did not exceed 7 mg kg^{-1} at sowing time of the next crop (Fig. 3.4). The results of our incubation study reported in chapter I, showed that the amount needed to increase $NaHCO_3$-P by 1 mg P kg^{-1} was 35 kg P ha^{-1}. Thus, neither 26.7 or 17.8 kg P ha^{-1} applied only the first year were able to increase soil test P sufficiently for the succeeding year's crop.

On the other hand, $NaHCO_3$-P values were not affected by crop. This leads to the conclusion that P transformations were mainly affected by soil characteristics and not crop roots. This result is consistent with the findings of Bolland (1992b).

As far as soil test P level is concerned, fertilizer P rates of 8.9, 17.8, and 53.4 kg P ha^{-1} were needed to increase and maintain soil test P level, after 2 years of cropping, in the range where a third succeeding crop could be grown without further P fertilizer.

Direct Effect Of P Fertilizer (1994-95)

Wheat and chickpea showed a significant response to direct application of P fertilizer in the first growing (1994-95) season at Sidi El Aydi and Khmis Zemamra locations (Tables 3.2 and 3.4). A significant increase in wheat grain yield was observed up to 26.7 kg P ha^{-1} at both locations. The percentage increase over the check was 116 and 61% at Sidi El Aydi and Khmis Zemamra, respectively, and averaged 2.6 and 2.9 Mg ha^{-1}. These yields are higher than the region-wide average of 2.2 Mg ha^{-1}.

The same trend was observed in dry matter production (Table 3.3). The response was significant up to the highest P rate at both locations except at Khmis Zemamra where no significant difference was obtained between 17.8 and 26.7 kg P ha^{-1}

There was a significant increase of chickpea yields due to a direct effect of P fertilizer application (Tables 3.4 and 3.5). The application of P at a rate of 17.8 kg P ha^{-1} increased grain yield as well as dry matter production to its maximum at the Sidi El Aydi location. However, a significant increase was only produced by the application of 8.9 kg P ha^{-1} at Khmis Zemamra. The average maximum chickpea grain yields in 1994-95 were 1.8 and 2.1 Mg ha^{-1} at Sidi El Aydi and Khmis Zemamra, respectively. The higher yield at Sidi El Aydi may have been due to the fact that chickpea was grown the previous years at this site which could lead to an increase of native rhizobium strains that are beneficial to chickpea. The small response to P fertilizer by chickpea compared to wheat has been reported in the literature (Seklani, 1983; Saxena, 1984). Seklani (1984) postulated that larger seed reserve of P in chickpea stimulates early development as well as increases P availability by solubilizing Ca-P surrounding seeds as a result of a lower rhizosphere pH.

Phosphorus Uptake

Annual and cropping system total P uptake by wheat and chickpea are plotted in Figs 3.5, 3.6, and 3.7. In 1994-95 season, the annual P uptake by either wheat or chickpea was significantly affected by P application. The increase of total P uptake by wheat with 26.7 kg P ha^{-1} was about 63% greater than the check plot at Khmis Zemamra and 142% at Sidi El Aydi. This was mainly due to the difference in yields obtained from the check plots. There was no significant difference in annual total P uptake by chickpea between 17.8 and 26.7 kg P ha^{-1} at any location in the 1994-95 growing season. The application of 17.8 kg P ha^{-1} of fertilizer P was sufficient to supply adequate P at Khmis Zemamra, while, 26.7 kg P ha^{-1} was required at Sidi El Aydi. This was mainly related to the crop stand which was better at Khmis Zemamra than at Sidi El Aydi.

In the 1995-96 season the P uptake by wheat was significantly affected by both residual and cumulative P as well as by cropping system (Table 3.6). For the continuous wheat rotation at Khmis Zemamra, annual P uptake by wheat was 9 and 10 kg P ha^{-1} in the check plots (Fig. 3.5). Whereas, in continuous wheat, P uptake increased to 13 and 19 kg P ha^{-1} for residual (application of 26.7 kg P ha^{-1} in the first year) and cumulative P (application of 26.7 kg P ha^{-1} each year), respectively. At Khmis Zemamra, P uptake by wheat varied between 11 kg P ha^{-1} in unfertilized plot (0-0, continuous wheat) to 19 kg P ha^{-1} with the application of 26.7 kg P ha^{-1} each year (CP-W). At Sidi El Aydi, P uptake by wheat was two times higher for the annual P application rate of 26.7 kg P ha^{-1} in the CP-W rotation (21 kg P ha^{-1}) as compared to the unfertilized plots (9 and 10 kg P ha^{-1}).

The 1994-95 plus 1995-96 P uptake was affected by P rate but not by cropping system at Khmis Zemamra. Cropping system probably needs more cycles to express an effect. The total P uptake by wheat in the check plot at Khmis Zemamra was as low as 9 kg P ha^{-1} in 1995-96 and 18 kg P ha^{-1} over a 2 year rotation (Fig. 3.5). The application of 26.7 kg P ha^{-1} on the first crop increased P uptake to 13 kg P ha^{-1} for wheat in 1995-96 and to 27 kg P ha^{-1} for the whole rotation. On the other hand, the cumulative P treatment of 26.7-26.7 kg P ha^{-1} resulted in a P uptake of 19 and 33 kg P ha^{-1} for the wheat and the cropping system in 1995-96, respectively.

In general, P uptake was lower in 1994-95 as compared to 1995-96 season. This was attributed to the low precipitation in 1994-95 as well as the high evapotranspiration (Fig. 3.1). Olsen and Watanabe (1970) also reported that P uptake was greater in a wet year as compared to a dry year. This was postulated to be due to the increase in P diffusion to plant roots under high soil moisture.

In the 1995-96 season, when no fertilizer P was applied (8.9-0, 17.8-0, 26.7-0 kg

P ha^{-1} treatments), P uptake was increased by P rates. Figures 3.5 and 3.6 show that P uptake from residual P fertilizer was lower as compared to cumulative P application. This shows that applied P becomes less plant available over time, probably due to sorption of P by the soil.

Residual Effect of P fertilizer

The residual effects of P fertilizer applied the previous year were measured by either the second crop of wheat or chickpea depending on cropping sequence. Wheat grain yield increased with previous application of P fertilizer at all locations. In the 1994-95 season, both the wheat and chickpea receiving the highest amount of P (26.7 kg P ha^{-1}) responded consistently in all three locations (Tables 3.2 and 3.7).

There was no significant effect of cropping system by residual P on grain yield (Fig. 3.6). However, a more pronounced effect of residual P was observed in the chickpea-wheat (CP-W) as compared to continuous wheat. This result is probably explained by the nature of crop residues and mineralization that take place in the legume-wheat system as compared to continuous wheat. In the CP-W rotation, the acidification of rhizosphere and formation of NH_4^+ (first product of mineralization) could increase the availability of residual P. The effect of NH_4^+ in increasing residual P was also reported by Fan and MacKenzie (1994) who found that banded low rates of urea with P fertilizer resulted in greater residual effects of P on grain yield and P uptake. On other hand, it was reported that legumes relying on symbiotic N fixation can acidify the soil (Mengel and Staffens, 1982) which in turn may increase P availability. Hanson and Westfall (1985) found that NH_4OH injected with ammonium polyphosphate resulted in higher extractable

P caused by the high pH in the injection zone.

At Khmis Zemamra, wheat grain yield was significantly increased by P fertilizer. The maximum yield obtained by 26.7 kg P ha^{-1} was 2.4 Mg ha^{-1} in the continuous wheat rotation compared to 2.6 Mg ha^{-1} in CP-W rotation (Table 3.2). In the continuous wheat rotation, the response to residual P was significant up to a P application rate of 17.8 kg P ha^{-1} . In the CP-W rotation all P rates had a significant effect on grain yield (Table 3.2).

At Sidi El Aydi, there was a significant difference in grain yields between continuous wheat and CP-W rotations. Averaged across P rates, grain yield was greater for CP-W (2.3 Mg ha^{-1}) compared to the continuous wheat rotation (2.1 Mg ha^{-1}). The response of wheat grain yield to residual P at this location was up to 17.8 kg P ha^{-1} (Table 3.2). The maximum yield obtained was 2.4 Mg ha^{-1} with 26.7 kg P ha^{-1} in the CP-W rotation (Table 3.2).

Wheat was grown at Khmis Sidi Rhhal the second season in plots that received P fertilizer 12 months previously. The residual P effects on wheat grain yield were markedly higher at this location due to its lower initial $NaHCO_3$-P level (2.7 mg P kg^{-1}). The increase in grain yield over the check plot was about 0.9 Mg ha^{-1} with 26.7 kg P ha^{-1} (Table 3.7). These results indicated that there was enough residual P available from previous P application to raise yield of the succeeding crop even in low soil test P situations. However, residual P did not result in maximum yields. In fact, even the lowest rate of 8.9 kg P ha^{-1} significantly increased wheat grain yield in 1995-96 season (Table 3.7). This result however, is not consistent with the findings of Prasad et al. (1985) and Venugopalan and Prasad (1989) who reported that low rates had no residual effects on succeeding crops probably due to differences in soil properties.

The maximum yield was not obtained by any rate of residual P. Therefore, the residual effect of previous applications of P at rates less than 26.7 kg P ha^{-1} were not able to provide sufficient P level for maximum grain yield. It is evident that in soils with low soil test P level, the residual P affect was present, but not sufficient to produce maximum yields. Therefore, P management should account for the amount of fertilizer P to be applied, soil test P level, and cropping system.

Differences in dry matter production among cropping systems were significant for wheat only at the Sidi El Aydi location (Table 3.6). The data given in Tables 3.3, 3.5, and 3.7 showed that in general, residual P significantly increased dry matter production at all sites. The larger the amount of applied P the higher the dry matter produced. At Sidi El Aydi, the effect of residual P was not significant. The average dry matter production of 4.7 Mg ha^{-1} was obtained with 26.7 kg P ha^{-1} (continuous wheat) at Sidi El Aydi (Tables 3.3). However, at Khmis Zemamra, only 8.9 kg P ha^{-1} was sufficient to increase dry matter production significantly to 4.6 Mg ha^{-1} in a continuous wheat rotation; on the other hand, no fertilizer P was needed for CP-W to maximize dry matter at 4.6 Mg ha^{-1} in 1995-96.

In 1995-96, chickpea grain yields were 2.1 and 1.8 Mg ha^{-1} and dry matter averaged 4.2 and 3.5 Mg ha^{-1} at the highest residual P rate of 26.7 kg P ha^{-1} at Khmis Zemamra and Sidi El Aydi, respectively (Tables 3.4 and 3.5). These grain yields values were much higher than the national average yield of 0.8 Mg ha^{-1}. No significant difference in grain yields was found at rates greater than 17.8 kg P ha^{-1}, and the effect on dry matter production was only significant up to a rate of 8.9 kg P ha^{-1} applied on the first crop.

Inclusion of chickpea in the rotation resulted in greater response to residual P by wheat at both locations. The average grain yields, for the highest P rates, were 2.4 and 2.6 Mg ha^{-1} for wheat after wheat and after chickpea, respectively at Khmis Zemamra. The differences in wheat grain yield between rotations were less pronouced at Sidi El Aydi. The corresponding grain yields were 2.3 and 2.4 Mg ha^{-1} (Table 3.2) The maximum increase in yield due to the highest residual P rate was 1.3 Mg ha^{-1}, obtained in continuous wheat at Khmis Zemamra.

Cumulative Effect of P Fertilizer

Differences in yields among cumulative P rates were significant for wheat at all sites (Table 3.6). However, the effect of cropping system seemed to be inconsistent. At Sidi El Aydi, the highest grain yield (3.1 Mg ha^{-1}) was obtained by the application of 26.7 kg P ha^{-1} each year for both rotations (Table 3.2) while no significant differences were obtained between rotations. However, at Khmis Zemamra, wheat grain yield was higher in the CP-W rotation as compared to continuous wheat. The chickpea-wheat rotation increased the average wheat yield, across P rates, by 0.3 Mg ha^{-1}.

At Khmis Sidi Rhhal, the effect of cumulative P on wheat grain yield was very high. The P rate of 26.7-26.7 kg P ha^{-1} produced an increase of 2 Mg ha^{-1} over a check plot (Table 3.7). This large response was expected because of the low initial P level at this location (2.7 mg P kg^{-1}). At Khmis Zemamra, the average grain yield (1.8 Mg ha^{-1}) was lower compared to the other locations.

Wheat dry matter production was affected significantly by both cumulative P rates and cropping systems at Sidi El Aydi location (Table 3.3). Maximum dry matter production obtained in 1995-96 was 6.4 and 7.0 Mg ha^{-1} for continuous wheat and CP-W rotations, respectively (Table 3.3). On the other hand, no significant difference was found between rotations at Khmis Zemamra. The average dry matter production across P rates was 6.1 Mg ha^{-1} in all treatments except in continuous wheat rotation at Khmis Zemamra where the average yield was 5.6 Mg ha^{-1}.

Similarly as was found for grain yield, the highest increase in dry matter production over the check was found at Khmis Sidi Rhhal with an increase of 4.1Mg ha^{-1} (Table 3.7). Also, there was no significant difference between dry matter production obtained by P application rates of 17.8-17.8 kg P ha^{-1} (5.1 Mg ha^{-1}) and 26.7-26.7 kg P ha^{-1} (5.5 Mg ha^{-1}). The average dry matter production across P rates was lower (4.1 Mg ha^{-1}) compared to the other locations.

Chickpea grain yield and dry matter production showed a significant increase as a result of the cumulative P effect (Table 3.4 and 3.5). In 1995-96, averaged across P rates, the grain yields obtained were 2.2 Mg ha^{-1} at both Sidi El Aydi and Khmis Zemamra (Table 3.4). The yields obtained in my study are higher that the national average yield of about 0.8 Mg ha^{-1}. This is mainly due to the fact that farmers are not using P fertilizers on legumes. Larger differences in dry matter production were recorded at the two locations where production was 3.3 and 4.4 Mg ha^{-1} at Sidi El Aydi and Khmis Zemamra, respectively (Table 3.5). While the application of 17.8-17.8 kg P ha^{-1} was sufficient to obtain maximum chickpea grain yield, only 8.9-8.9 kg P ha^{-1} was needed to maximize dry matter production at both locations.

Maximum dryland wheat grain yields production were 2.6, 3.1 and, 3.4 Mg ha^{-1} for Khmis Sidi Rhhal, Sidi El Aydi, and Khmis Zemamra, respectively. These yields were higher than national average of 1.6 Mg ha^{-1}. After two years, the effect of cropping system was not consistent.

A residual P effect was evident in this study, but residual P did not produce maximum yield. Based on the range of P rates used in this study, a single application would not maximize yields of the following crop in my soils.

Residual vs Cumulative P Effects

The percentage increase in yields was high with increasing rates of P, applied either as residual or cumulative P. When comparing both P rates combinations, cumulative P produced higher yields than residual P at all sites and under both cropping systems.

The increase in grain yield obtained with 8.9-8.9 kg P ha^{-1} was greater compared to a single P application of 17.8 kg P ha^{-1}, or even 26.7 kg P ha^{-1} on the first crop (either wheat or chickpea). This is due to a decrease in the availability of P with time. Bolland (1992a) found that the effectiveness of P applied three years previously was 30% as compared to fresh application. This value dropped to 13% four years after application.

These results suggest that in chickpea-wheat rotations, from 0 to 8.9 kg P ha^{-1} is needed on chickpea in soils with $NaHCO_3$-P less than 7 mg kg^{-1}. However, higher rates are needed for wheat in the same rotation.

It is clear that the residual P was not as effective in correcting P deficiencies as annual P application in low soil test P. The increases in wheat yields obtained with two annual application of 8.9 kg P ha^{-1} each were greater than those obtained by a single application of 17.8 kg P ha^{-1}. The same results were obtained at both locations and both rotations. Therefore, annual application of P is recommended in managing P fertilization.

Current wheat and fertilizer prices suggested that the combination 17.8-17.8, 26.7-0, and 8.9-17.8 kg P ha^{-1} would be needed for continuous wheat W-CP, and CP-W rotations, respectively, at the soil test levels present in my experiments.

Phosphorus P Recovery

Annual and total fertilizer P recovery are shown in Tables 3.7, 3.8, and 3.9. The % P recovery was always higher at lower P rates. This is consistent with the findings of earlier studies (Read et al., 1977; Baily et al., 1977; Alessi and Power, 1980; Halvorson and Black, 1985b; Pothuluri et al., 1991). The P recovery always decreased the second year in the residual treatments, while total P recovery for both years was generally lower as compared to annual P application treatments.

In 1994-95 at Khmis Zemamra, when averaged across P rates, % P recoveries were 22 and 18 % for wheat and chickpea, respectively (Table 3.8). The % P recovery from residual P by wheat in 1995-96, averaged across P rates, were 11% (Continuous wheat) and 14.2% (CP-W) at Sidi El Aydi (Table 3.9). The correspondent values at Khmis Zemamra were 15.2 and 15.3%, respectively. Larger % P recovery was found at Khmis Sidi Rhhal (16.0%) compared to other locations suggesting that P recovery is higher at low soil test P levels.

Percentage P recovery values found in this study were higher, but within the range of those reported in literature (Read et al. 1977; Halvorson and Black, 1985b; Fan and MacKenzie, 1994). Alessi and Power (1980) reported the P recovery value of 30% with broadcast application of 8.9 kg P ha^{-1} and about 5% with 160 kg P ha^{-1}.

Application of P to both the first and second crop resulted in significantly more P uptake as compared to P application to only the first crop. In general, the P uptake from 17.8-17.8 kg P ha^{-1} treatments was statistically greater or equal to other combinations. Among the two crops, P uptake by wheat was higher than in chickpea. This was due to higher biomass and grain yield of wheat as compared to chickpea.

SUMMARY AND CONCLUSION

The response of wheat and chickpea to direct, residual, and cumulative fertilizer P application in calcareous soils of dryland Moroccan zones was investigated at three locations. Cumulative P rates of two annual application of 8.9, 17.8, and 26.7 kg P ha^{-1} each resulted in increasing NaHCO$_3$-P level by about 1.8, 3.5, and 5.5 mg P kg^{-1}, respectively, at the end of 1995-96 growing season. However, the increase in NaHCO$_3$-P produced by a single application of the three above rates to the first crop were 0.4, 1.0, and 2.0 mg P kg^{-1}.

At low soil test P levels, high amounts of fertilizer were needed to increase soil NaHCO$_3$-P in soil to a sufficient level. In our study, the amounts needed to maintain the NaHCO$_3$-P level above the critical level during two years were 8.9, 17.8, and 53.4 kg P ha^{-1} at Khmis Zemamra, Sidi El Aydi, and Khmis Sidi Rhhal, respectively. In fact, an annual application of 17.8 kg P ha^{-1} was sufficient to maintain the yields of wheat and chickpea near the optimum level for the entire rotation.

The NaHCO$_3$-P levels were not affected by cropping system or crop. Therefore, the P availability is mainly governed by soil factors rather than crop. The data reported in this study lead to the conclusion that residual effects of P fertilizer are governed by the amount of P application, time, and initial soil test P level. While the residual effects of P was evident, they are not adequate to maximize yields of wheat or chickpea.

In the 1994-95 season, the maximum wheat yields were obtained with 26.7 kg P ha^{-1}. The grain yield was increased from 1.2 to 2.6 Mg kg^{-1} at Sidi El Aydi and from 1.8 to 2.9 Mg ha^{-1} at Khmis Zemamra. In the 1995-96 season, the increase in wheat grain yield over a check plot varied among location and ranged from 0.5 to 1.8 Mg ha^{-1} at Khmis Sidi Rhhal and Khmis Zemamra, respectively.

The average increases in wheat grain yield, across P rates, were 19, 30, and 151% at Sidi El Aydi, Khmis Zemamra, and Khmis Sidi Rhhal, respectively. These data suggest that not only initial soil P affected residual P but also other soil characteristics were involved. The increase in yields due to cumulative P was 2 to 3 fold higher than residual P.

Dryland wheat yields were very good at all locations, producing a maximum of about 2.6, 3.1 and, 3.4 Mg ha^{-1}. These yields were higher than national average of about 1.6 Mg ha^{-1}. After two years, the effect of cropping system was not consistent. The results of this study show that annual application of fertilizer P is best because fertilizer P rates applied by Moroccan farmers rarely exceed 26.7 kg P ha^{-1} on wheat and 8.9 kg P ha^{-1} on chickpea. The P requirement for legumes, grown in rotation with wheat can be met by residual P application to wheat. Therefore, no or little (8.9 kg P ha^{-1}) P fertilizer is needed for chickpea in this rotation.

The average amount of P uptake by the plant increased with residual P rates. The ranges at both locations were 11 to 12 kg P ha^{-1} (continuous wheat), 12 kg P ha^{-1} (CP-W), and 10 to 11 kg P ha^{-1} (W-CP) at Khmis Zemamra and Sidi El Aydi, respectively. The amount of P recovered at Khmis Sidi Rhhal was lower (4 kg P ha^{-1}) compared to other locations. However, cumulative P increased the total amount of P uptake by the plant by about 4 kg P ha^{-1}, as compared to residual P at all locations.

The P recovery was reduced by more than 50% in the second year after application. Over all rotations, the total P recovery from the cropping system was always higher when P was applied first to wheat, as compared to applying P to a first crop of chickpea. Continuous wheat recovered more P than the other rotations. My results also showed that at the same P rate, P recovery was lower with residual P than with cumulative P (35% with 17.8-0 kg P ha^{-1} compared to 41% with 8.9-8.9 kg P ha^{-1}).

If we assume that a chickpea grain yield of 2 Mg ha^{-1} is a satisfactory yield in a CP-W rotation where wheat is the principal crop, P requirement for chickpea can be met by residual P. Current wheat and fertilizer prices suggested that the combinations of 17.8-17.8, 26.7-0, and 8.9-17.8 kg P ha^{-1} would be the recommended for continuous wheat, W-CP, and CP-W rotations, respectively. This study showed that farmers should consider soil P availability, previous P applications, and succeeding crops requirement for better P management in rotations.

Table 3.1. Selected physical and chemical characteristics of surface (0-20 cm) soils used in study.

Soil	Clay	Silt	Sand	pH water	CEC	Organic matter	Lime	NO_3-N	K	Na	Ca	Mg	P
	%				mS/cm	%		mg kg^{-1}					
K. S. Rhhal	56	20	23	7.9	56	1.6	7	4	198	294	6450	411	3
K Zemamra	42	8	48	8.1	39	2.3	1	44	112	280	4150	414	8
Sidi El Aydi	51	28	22	8.2	50	1.9	15	4	319	154	8040	351	10

Table 3.2. Effect of direct, residual and cumulative P on wheat grain yield at Sidi El Aydi (SA) and Khmis Zemamra (KZ).

	P applied kg P ha^{-1}		Locations SA		KZ	
Rotation	1st Y.	2nd Y.	1994-95	1995-96	1994-95	1995-96
			grain yield (Mg ha^{-1})			
W-W	0	0	1.2	1.9	1.8	1.7
	8.9	0	1.8	2.1	2.2	2.1
	17.8	0	2.3	2.3	2.6	2.3
	26.7	0	2.6	2.3	2.9	2.4
		mean	2.0	2.1	2.4	2.1
		LSD (0.05)	0.3	0.2	0.2	0.2
	0	0	1.2	1.8	1.8	1.7
	8.9	8.9	1.8	2.5	2.2	2.6
	17.8	17.8	2.3	2.8	2.6	2.8
	26.7	26.7	2.6	3.1	2.9	3.1
		mean	2.0	2.6	2.4	2.5
		LSD (0.05)	0.3	0.2	0.2	0.2
CP-W	0	0	-	2.0	-	1.8
	8.9	0	-	2.2	-	2.2
	17.8	0	-	2.4	-	2.4
	26.7	0	-	2.4	-	2.6
		mean	-	2.3	-	2.2
		LSD (0.05)	-	0.2	-	0.2
	0	0	-	1.9	-	1.9
	8.9	8.9	-	2.5	-	2.8
	17.8	17.8	-	2.8	-	3.3
	26.7	26.7	-	3.1	-	3.4
		mean	-	2.6	-	2.8
		LSD (0.05)	-	0.2	-	0.3

CP=chickpea; W=wheat; Y=year

- Chickpea was grown

Table 3.3. Effect of direct, residual and cumulative P on wheat dry matter production at Sidi El Aydi (SA) and Khmis Zemamra (KZ).

	P applied kg P ha^{-1}		Locations			
			SA		KZ	
Rotation	1st Y.	2nd Y.	1994-95	1995-96	1994-95	1995-96
			dry matter (Mg ha^{-1})			
W-W	0	0	3.9	4.3	3.8	4.0
	8.9	0	4.8	4.6	4.9	4.6
	17.8	0	5.6	4.8	5.6	5.0
	26.7	0	6.2	4.9	6.2	5.3
		mean	5.1	4.7	5.1	4.7
		LSD (0.05)	0.4	0.6	0.4	0.7
	0	0	3.9	4.2	3.8	4.6
	8.9	8.9	4.8	5.7	4.9	6.2
	17.8	17.8	5.6	6.3	5.6	6.5
	26.7	26.7	6.2	6.4	6.2	7.0
		mean	5.1	5.6	5.1	6.1
		LSD (0.05)	0.4	0.6	0.4	0.7
CP-W	0	0	-	4.3	-	4.6
	8.9	0	-	4.8	-	4.6
	17.8	0	-	5.2	-	5.4
	26.7	0	-	5.4	-	5.4
		mean		4.9		5.0
		LSD (0.05)	-	0.4	-	1.1
	0	0	-	4.3	-	4.6
	8.9	8.9	-	6.2	-	5.7
	17.8	17.8	-	6.8	-	7.1
	26.7	26.7	-	7.0	-	7.1
		mean	-	6.1	-	6.1
		LSD (0.05)	-	0.5	-	0.2

CP=chickpea; W=wheat; Y=year

- Chickpea was grown

Table 3.4. Effect of direct, residual and cumulative P on grain yield of chickpea at Sidi El Aydi (SA) and Khmis Zemamra (KZ).

Rotation	P applied kg P ha^{-1} 1st Y.	2nd Y.	Season 1994-95 SA	KZ	1995-96 SA	KZ
			grain yield (Mg ha^{-1})			
W-CP	0	0	1.3	1.4	1.4	1.6
	8.9	0	1.7	1.6	1.6	1.8
	17.8	0	2.0	1.7	1.7	2.0
	26.7	0	2.1	1.8	1.8	2.1
		mean	1.8	1.6	1.6	1.9
		LSD (0.05)	0.2	0.3	0.2	0.2
	0	0	1.3	1.4	1.4	1.6
	8.9	8.9	1.7	1.6	2.1	2.2
	17.8	17.8	2.0	1.7	2.4	2.5
	26.7	26.7	2.1	1.8	2.4	2.6
		mean	1.8	1.6	2.1	2.2
		LSD (0.05)	0.2	0.3	0.2	0.3

CP=chickpea; W=wheat; Y=year

Table 3.5. Effect of direct, residual and cumulative P on dry matter production of chickpea at Sidi El Aydi (SA) and Khmis Zemamra (KZ).

	P applied kg P ha^{-1}		Season			
			1994-95		1995-96	
Rotation	1st Y.	2nd Y.	SA	KZ	SA	KZ
			dry matter (Mg ha^{-1})			
W-CP	0	0	2.1	2.6	2.6	3.6
	8.9	0	2.8	3.1	3.1	3.9
	17.8	0	3.0	3.4	3.4	4.1
	26.7	0	3.1	3.5	3.5	4.2
		mean	2.7	3.2	3.2	3.9
		LSD (0.05)	0.3	0.3	0.3	0.4
	0	0	2.1	2.7	2.7	3.5
	8.9	8.9	2.8	3.5	3.5	4.6
	17.8	17.8	3.0	3.5	3.5	4.6
	26.7	26.7	3.1	3.5	3.5	4.8
		mean	2.7	3.3	3.3	4.4
		LSD (0.05)	0.3	0.3	0.3	0.3

W=wheat, CP=chickpea; Y=year

Table 3.6. Analysis of variance of the effect of residual and cumulative P on wheat at Khmis Zemamra and Sidi El Aydi in 1995-96.

Variable	Source	Khmis Zemamra	Sidi El Aydi
		----------------Probability	------------------
Residual P treatment			
Grain yield	CS	0.025	0.011
	P	0.001	0.001
	CS x P	0.876	0.985
Dry matter	CS	0.223	0.039
	P	0.004	0.001
	CS x P	0.705	0.646
Total Puptake	CS	0.002	0.026
	P	0.001	0.001
	CS x P	0.995	0.826
Cumulative P treatment			
Grain yield	CS	0.001	0.738
	P	0.001	0.001
	CS x P	0.163	0.929
Dry matter	CS	0.576	0.003
	P	0.001	0.001
	CS x P	0.180	0.573
Total Puptake	CS	0.620	0.011
	P	0.004	0.001
	CS x P	0.934	0.604

CS = cropping system
P = P rates

Table 3.7. Effect of residual and cumulative P on grain yield , dry matter production, total P uptake and P recovery of wheat at Khmis S. Rhhal in 1995-96.

Rotation	P applied kg P ha^{-1} 1st Y.	2nd Y.	Dry matter	Grain Yield	Total P uptake	P recovery
			Mg ha^{-1}		kg ha^{-1}	%
F-W	0	0	1.6	0.5	2.0	-
	8.9	0	2.0	1.0	3.6	18
	17.8	0	3.1	1.2	4.7	16
	26.7	0	3.4	1.4	5.6	14
	mean		2.5	1.0	4.0	16
	LSD(0.05)		0.3	0.2	0.7	5
	0	0	1.4	0.6	2.1	-
	8.9	8.9	4.4	1.7	7.1	29
	17.8	17.8	5.1	2.2	9.6	22
	26.7	26.7	5.5	2.6	12.3	20
	mean		4.1	1.8	7.8	23
	LSD(0.05)		0.8	0.3	1.0	8

F=follow; W=wheat; Y=year

Table 3.8. The fertilizer P recovery by wheat as affected by rate and time of P application at Khmis Zemamra (KZ).

	P applied kg P ha^{-1}		Season		
Rotation	1st Y.	2nd Y.	1994-95	1995-96	Total
			% P recovery		
W-W			Wheat	Wheat	
	8.9	0	24	17	41
	17.8	0	21	15	37
	26.7	0	20	13	33
		mean	22	15	37
		LSD (0.05)	7	10	11
	8.9	8.9	24	29	41
	17.8	17.8	21	23	33
	26.7	26.7	20	18	28
		mean	22	23	34
		LSD (0.05)	7	7	6
CP-W			Chickpea	Wheat	
	8.9	0	24	18	42
	17.8	0	16	16	31
	26.7	0	14	13	27
		mean	18	15	33
		LSD (0.05)	19	9	23
	8.9	8.9	24	25	37
	17.8	17.8	16	22	30
	26.7	26.7	14	18	25
		mean	18	21	30
		LSD (0.05)	19	9	16
W-CP			Wheat	Chickpea	
	8.9	0	24	13	37
	17.8	0	21	11	33
	26.7	0	20	11	31
		mean	22	11	33
		LSD (0.05)	7	7	11
	8.9	8.9	24	25	38
	17.8	17.8	21	19	29
	26.7	26.7	20	14	24
		mean	22	19	30
		LSD (0.05)	7	8	8

CP=chickpea; W=wheat; Y=year.

Table 3.9. The fertilizer P recovery by wheat as affected by rate and time of P application at Sidi El Aydi (SA).

Rotation	P applied kg P ha^{-1} 1st Y.	2nd Y.	Season 1994-95	1995-96	Total
			% P recovery		
W-W			Wheat	Wheat	
	8.9	0	28	12	40
	17.8	0	25	10	35
	26.7	0	22	12	33
		mean	25	11	36
		LSD (0.05)	18	20	19
	8.9	8.9	28	27	41
	17.8	17.8	25	20	32
	26.7	26.7	22	19	30
		mean	25	22	34
		LSD (0.05)	18	7	14
CP-W			Chickpea	Wheat	
	8.9	0	22	15	37
	17.8	0	17	15	32
	26.7	0	12	14	27
		mean	17	14	32
		LSD (0.05)	23	10	26
	8.9	8.9	22	31	42
	17.8	17.8	17	25	34
	26.7	26.7	12	20	26
		mean	17	25	34
		LSD (0.05)	23	16	14
W-CP			Wheat	Chickpea	
	8.9	0	28	14	42
	17.8	0	25	13	38
	26.7	0	22	10	32
		mean	25	12	37
		LSD (0.05)	18	11	13
	8.9	8.9	28	20	34
	17.8	17.8	25	16	29
	26.7	26.7	22	11	22
		mean	25	16	28
		LSD (0.05)	18	4	11

CP=chickpea; W=wheat; Y=year.

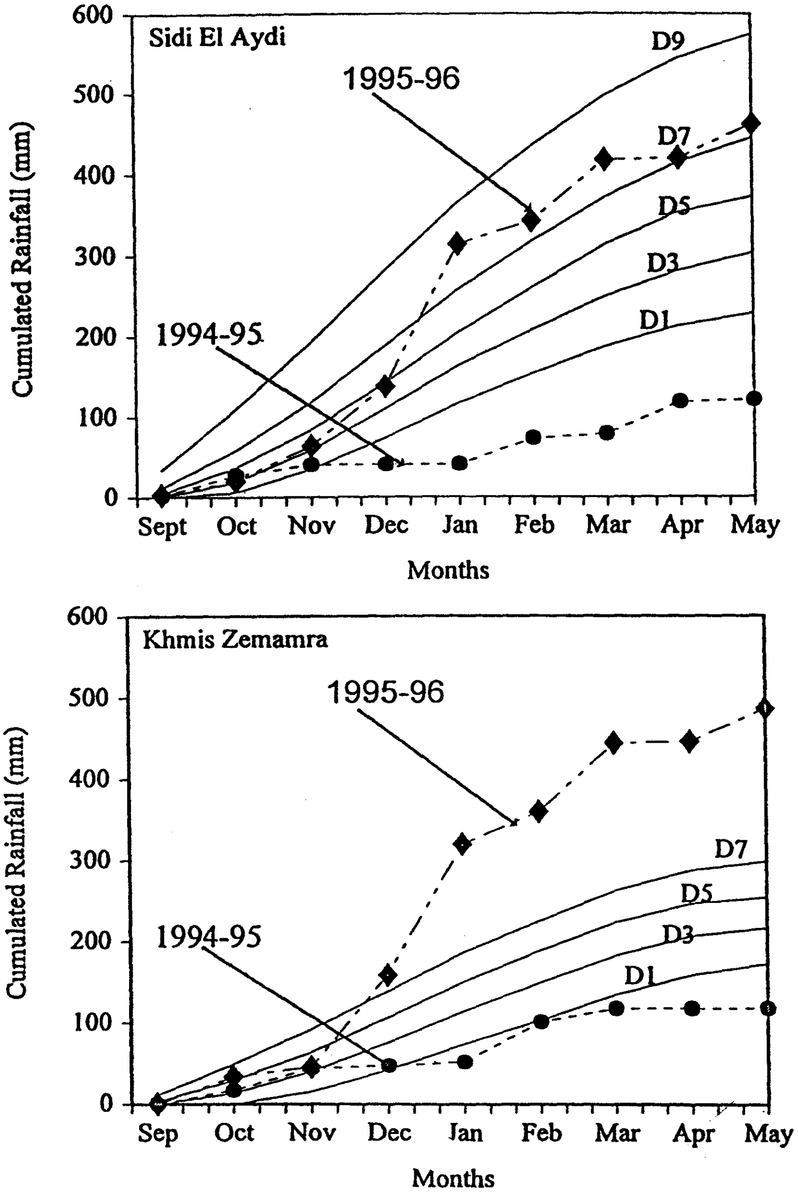

Figure 3.1. Accumulated seasonal rainfall at Khmis Zemamra and Sidi El Aydi locations in 1994-95 and 1995-96 growing seasons. D1, D3, D5, D7, and D9 are the probabilities of 90, 70, 50, 30, and 10%, respectively, to get more than a given amount of rain for a given period.

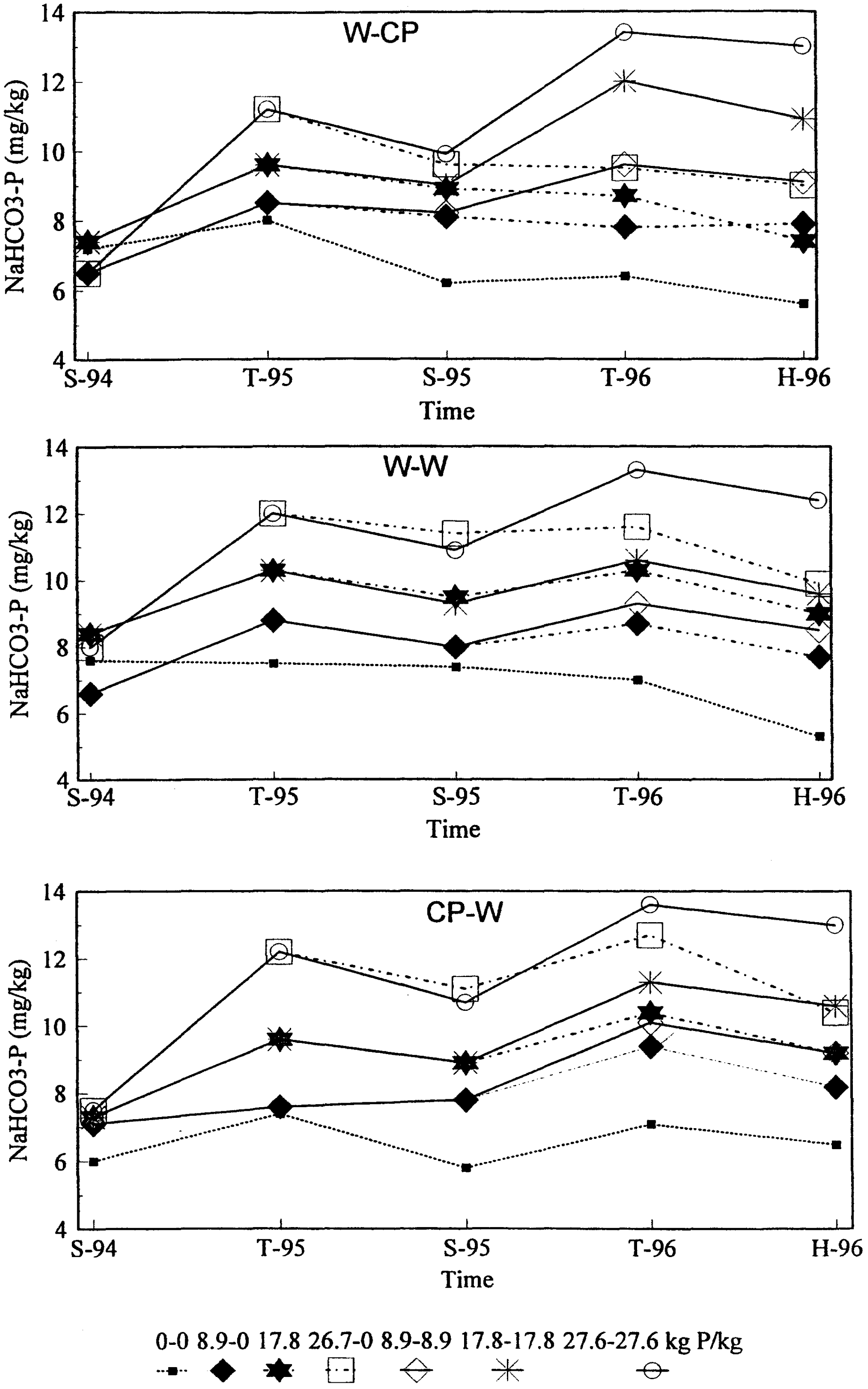

Figure 3.2. Soil test P level at Khmis Zemamra during 1994-95 and 1995-96 growing seasons for wheat-chickpea (W-CP), continuous wheat (W-W) and chickpea - wheat (CP-W) rotations (S = sowing, T = tillering, and H = harvesting times).

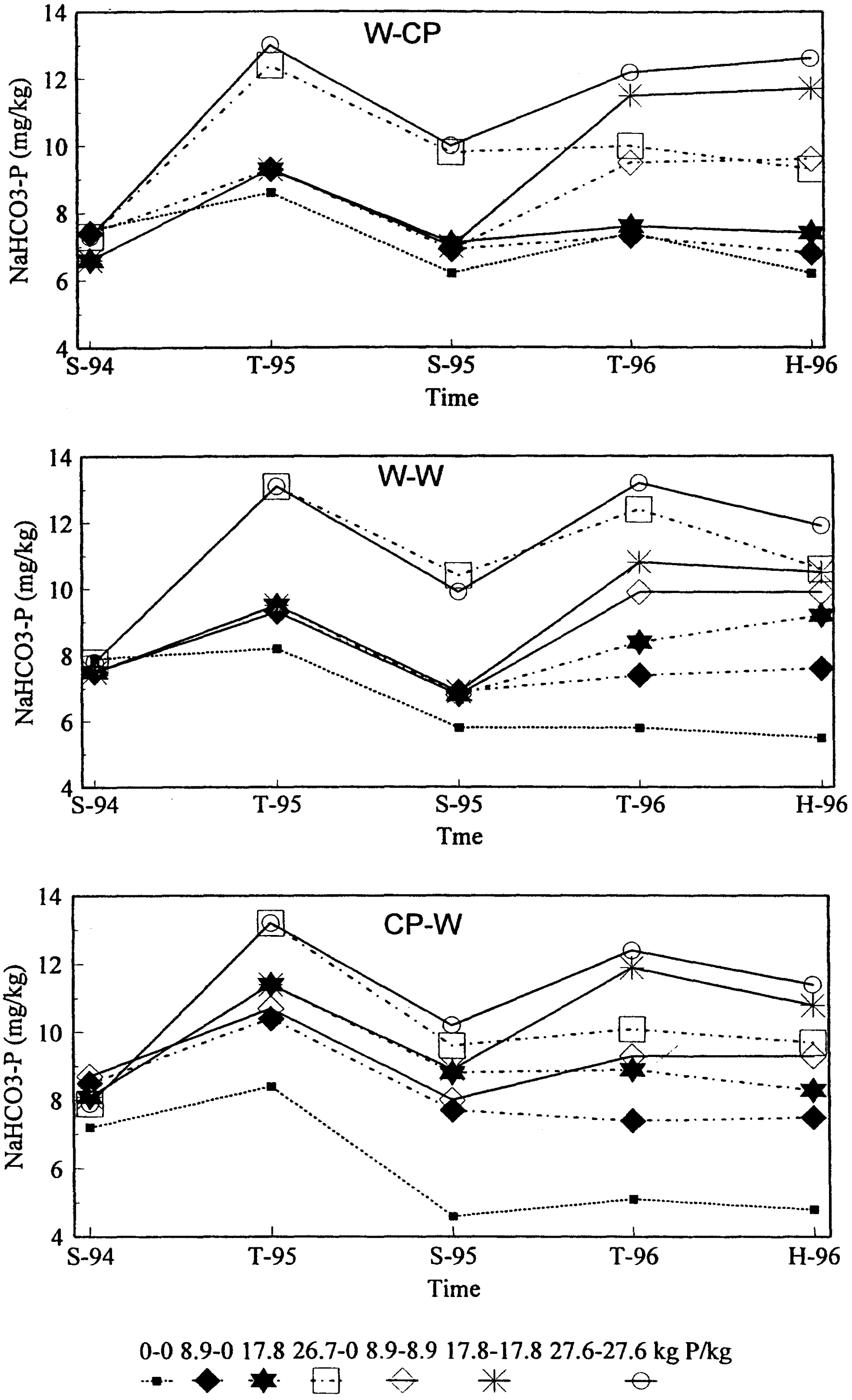

Figure 3.3. Soil test P level at Sidi El Aydi during 1994-95 and 1995-96 growing seasons for wheat-chickpea (W-CP), continuous wheat (W-W) and chickpea - wheat (CP-W) rotations (S = sowing, T = tillering, and H = harvesting times).

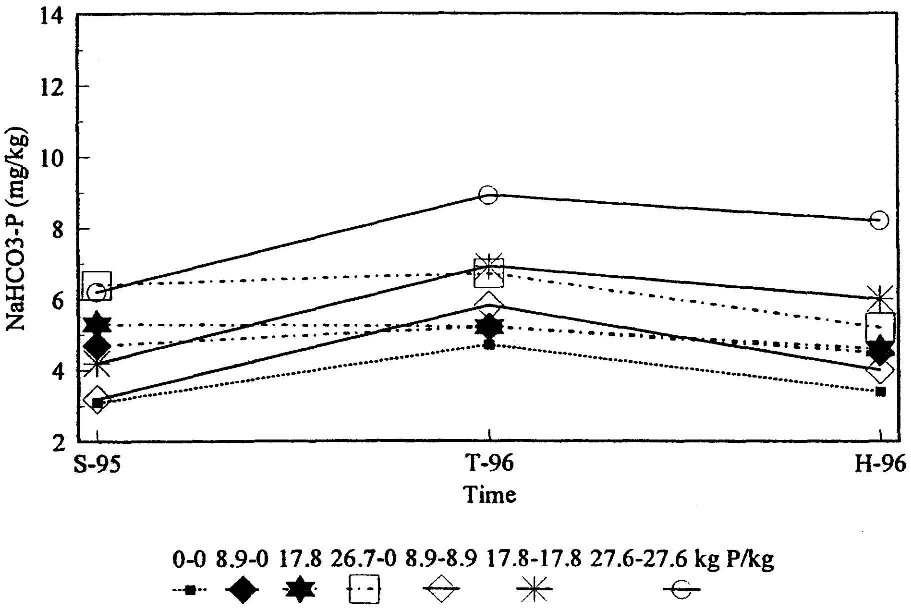

Fig.ure 3.4. Soil test P level at Khmis S. Rehhal during 1995-96 growing season (S = sowing, T = tillering, and H = harvesting times).

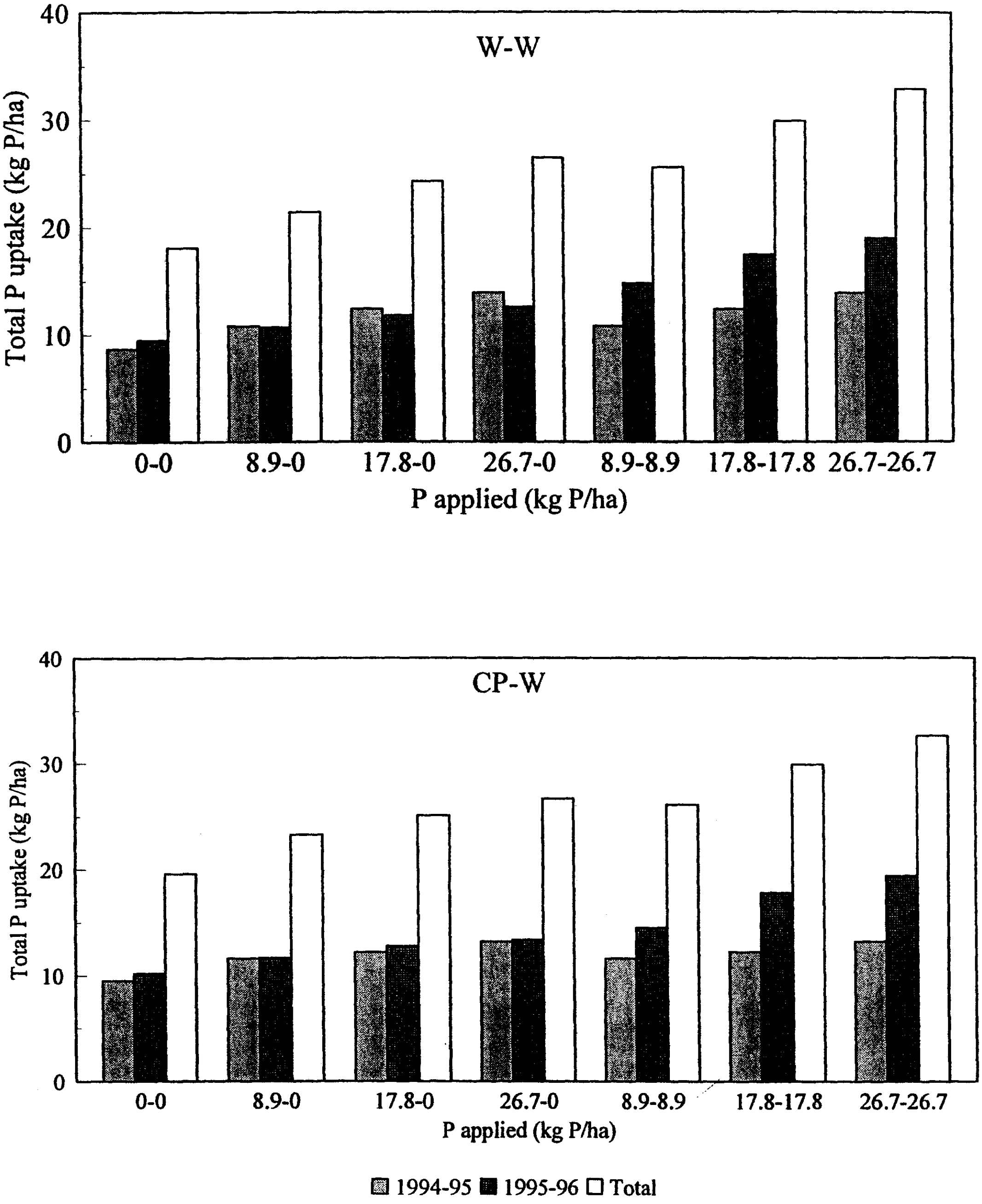

Figure 3.5. Total P uptake in 1994-95 and 1995-96 as influenced by P rate and timing in continuous wheat (W-W) and chickpea -wheat (CP-W) cropping systems at Khmis Zemamra. (0-0 = 0 kg P/ha first year plus 0 kg P/ha second year)

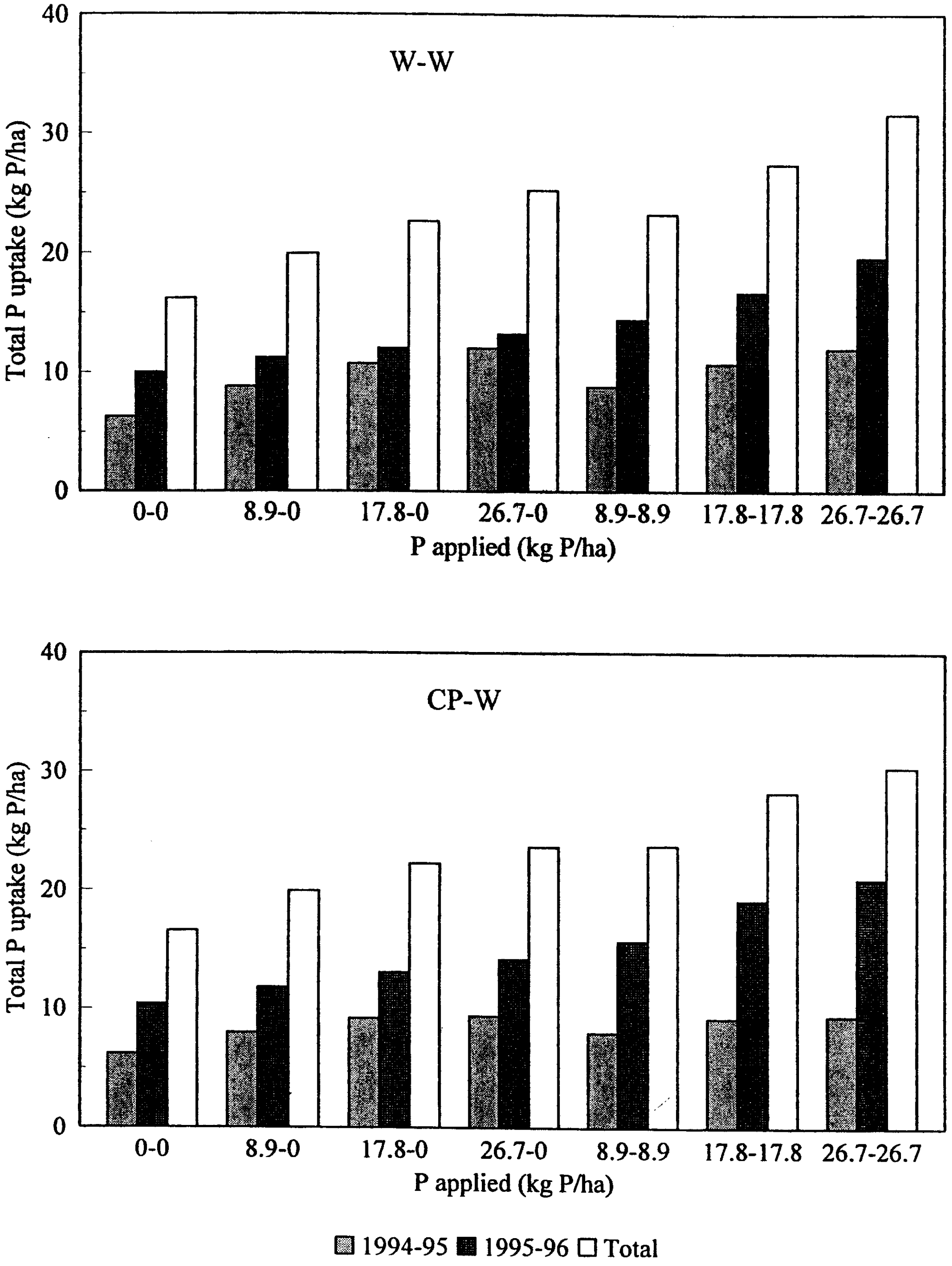

Figure 3.6. Total P uptake in 1994-95 and 1995-96 as influenced by P rate and timing in continuous wheat (W-W) and chickpea -wheat (CP-W) cropping systems at Sidi El Aydi. (0-0 = 0 kg P/ha first year plus 0 kg P/ha second year)

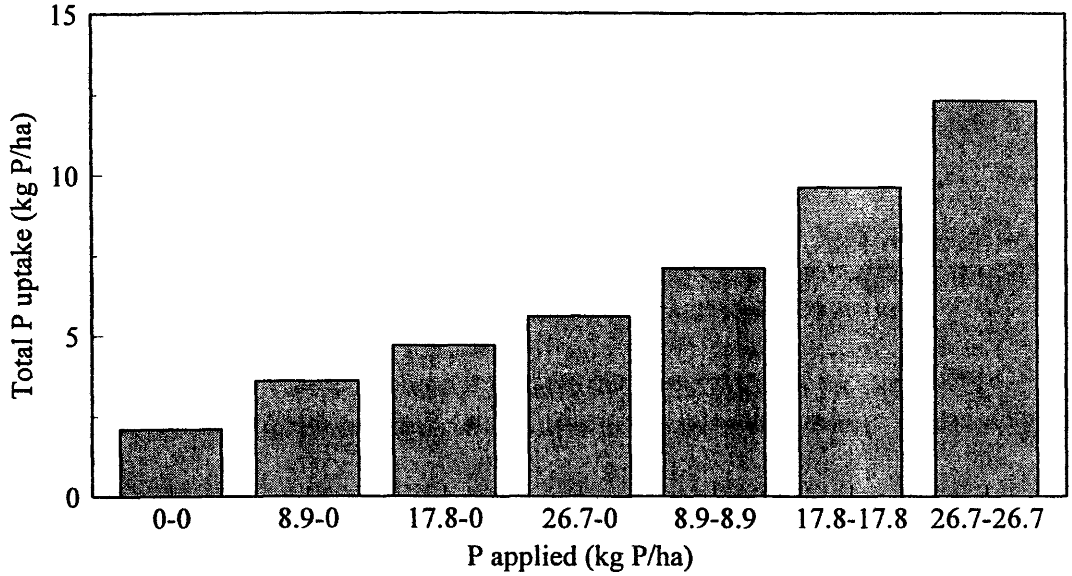

Figure 3.7. Total P uptake in 1995-96 as influenced by P rate and timing in wheat-follow system at KhmisSidi Rhhal. (0-0 = 0 kg P/ha first year plus 0 kg P/ha second year)

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APPENDIX

Appendix Table 1 The soil P adsorption data from the 18 soils used in this study.

Soil	Padd	Ceq	Ps	Soil	Padd	Ceq	Ps
	--mg P L^{-1} --		mg kg^{-1}		--mg P L^{-1} --		mg kg^{-1}
1	0.0	0.0	0	4	0.0	0.0	0
1	1.5	0.0	30	4	1.5	0.0	30
1	3.0	0.0	60	4	3.0	0.2	55
1	4.5	0.1	88	4	4.5	0.4	82
1	9.0	0.8	165	4	9.0	1.1	159
1	13.5	1.6	238	4	13.5	2.9	213
1	18.0	3.0	300	4	18.0	5.1	258
1	22.5	5.2	347	4	22.5	7.6	298
1	27.0	6.9	401	4	27.0	10.1	337
1	36.0	12.3	475	4	36.0	15.9	403
1	45.0	16.5	569	4	45.0	21.6	468
1	54.0	19.3	694	4	54.0	27.3	534
2	0.0	0.0	0	5	0.0	0.0	0
2	1.5	0.1	28	5	1.5	0.0	30
2	3.0	0.3	54	5	3.0	0.0	60
2	4.5	0.5	80	5	4.5	0.0	90
2	9.0	2.3	135	5	6.8	0.6	123
2	13.5	4.4	182	5	9.0	0.9	161
2	18.0	7.3	215	5	18.0	3.6	289
2	22.5	10.5	239	5	22.5	5.8	335
2	27.0	14.1	257	5	27.0	7.3	395
2	36.0	21.2	296	5	36.0	10.8	503
2	45.0	28.5	330	5	54.0	22.0	639
2	54.0	37.1	338	6	0.0	0.0	0
3	0.0	0.0	0	6	1.5	0.1	28
3	1.5	0.0	30	6	3.0	0.1	57
3	3.0	0.0	60	6	4.5	0.3	85
3	4.5	0.1	88	6	6.8	0.4	127
3	9.0	0.8	164	6	9.0	0.6	169
3	13.5	1.6	238	6	13.5	1.3	244
3	18.0	2.8	304	6	18.0	2.2	316
3	22.5	4.2	365	6	22.5	3.4	382
3	27.0	6.7	407	6	27.0	5.4	433
3	36.0	10.5	510	6	36.0	9.2	536
3	45.0	14.7	606	6	45.0	13.6	628
3	54.0	20.4	673	6	54.0	15.9	761

Padd = P added (mg P L^{-1}) Ceq = concentration at equilibrium (mg P L^{-1})

Ps = P adsorbed (mg P kg^{-1}soil)

Appendix Table 1. (continued).

Soil	Padd	Ceq	Ps	Soil	Padd	Ceq	Ps
	--mg P L^{-1} --		mg kg^{-1}		--mg P L^{-1} --		mg kg^{-1}
7	0.0	0.0	0	10	0.0	0.0	0
7	1.5	0.0	29	10	1.5	0.3	25
7	3.0	0.1	58	10	3.0	0.8	45
7	4.5	0.2	86	10	4.5	1.4	62
7	6.8	0.3	128	10	6.8	2.5	85
7	9.0	0.6	168	10	9.0	4.1	99
7	13.5	1.2	245	10	18.0	9.8	163
7	18.0	2.0	319	10	22.5	12.8	193
7	22.5	3.4	382	10	27.0	15.9	223
7	27.0	4.5	450	10	36.0	23.0	259
7	36.0	6.9	581	10	54.0	39.3	293
7	45.0	10.1	697	11	0.0	0.0	0
7	54.0	13.6	808	11	1.5	0.0	30
8	0.0	0.0	0	11	3.0	0.2	57
8	1.5	0.3	24	11	4.5	0.6	79
8	3.0	0.7	45	11	6.8	1.3	109
8	4.5	1.4	62	11	9.0	2.2	135
8	6.8	2.4	87	11	18.0	7.5	211
8	9.0	3.8	105	11	22.5	11.1	228
8	13.5	6.1	149	11	27.0	14.9	241
8	18.0	8.8	183	11	36.0	22.9	263
8	22.5	12.6	199	11	54.0	39.3	294
8	27.0	16.7	206	12	0.0	0.0	0
8	36.0	24.7	227	12	1.5	0.1	28
8	45.0	32.7	245	12	3.0	0.2	57
8	54.0	38.8	304	12	4.5	0.1	88
9	0.0	0.0	0	12	6.8	0.4	127
9	1.5	0.1	28	12	9.0	0.4	171
9	3.0	0.5	51	12	18.0	1.9	323
9	4.5	0.8	73	12	22.5	2.7	397
9	6.8	1.6	103	12	27.0	3.9	461
9	9.0	2.4	132	12	36.0	8.1	558
9	18.0	6.7	226	12	54.0	18.9	703
9	22.5	9.4	261				
9	27.0	12.2	297				
9	36.0	17.5	370				
9	54.0	30.8	463				

Padd = P added (mg P L^{-1}) Ceq = concentration at equilibrium (mg P L^{-1})
Ps = P adsorbed (mg P kg^{-1}soil)