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STUDIES ON PHOSPHATE ADSORPTION ISOTHERMS AND RESPONSE TO PHOSPHATE  
FERTILIZATION OF KENYA SOILS

by

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## 1. ABSTRACT

Three tropical soils from Kenya were involved in studies on phosphate adsorption isotherms. Calculations on the basis of the Langmuir equation gave phosphate adsorption maxima of 405, 52.6, and 91.7 ppm P for Katumani (1), Kikambala (2), and Kikambala (3) soil, respectively.

In a pot experiment with Kikambala (2) soil, the addition of 55 ppm P was already sufficient for maximum production of dry matter of maize plants.

In another pot experiment in which the high-phosphate Katumani soil (1) was mixed with sand, it was found that a soil:sand ratio of 2:6, corresponding with 3.250 kg of soil per pot, was already sufficient for optimum development of 3 maize plants.

## 2. INTRODUCTION

Most of the phosphate in many tropical soils is not readily available to plants. When phosphate fertilizer is applied, phosphate is "fixed". The amount of phosphate that is likely to be fixed by the soil is of great importance in making soil test interpretations and fertilizer recommendations. The information from this study will be used to determine the pattern of phosphate adsorption in relation to the phosphate concentration of the soil solution on the basis of the Langmuir equation. This does not imply that the Langmuir equation is the best in describing phosphate adsorption.

The phosphate adsorption approach for predicting phosphate fertilizer requirements is based on the principle that requirements are directly related to the amounts of phosphate adsorbed by soils depending on the phosphate concentration of the supernatant solution (Beckwith, 1965). Several factors may affect the relationship between phosphate adsorption and phosphate concentration, such as: ambient temperature and duration of contact between soil and solution, method of shaking, solution:soil ratio, kind of extractant, moisture content of the soil prior to shaking (Barrow and Shaw, 1979).

An adsorption isotherm describes the equilibrium relationship between the amounts of adsorbed and dissolved species at a given temperature. Constant temperature is essential, because the relationship is temperature-dependent. The term phosphate adsorption is used to describe any process in which phosphate ions in solution react with atoms on the surface of soil particles.

Olsen and Watanabe (1957), and Rennie and McKercher (1959) found that adsorption of phosphate by soils from dilute solutions showed a closer agreement with the Langmuir than with the Freundlich isotherm. Constants calculated from the Langmuir isotherm and interpretations based upon these constants permit a sound theoretical approach to some of the problems of phosphate retention in soils. According to Olsen and Watanabe (1957) the Langmuir equation is based on the kinetic theory of gases as to gas adsorption to solids; whether or not these equations may be

applied to adsorption of ions by the solids is still a questionable matter, but it may be possible to do so after further theoretical development.

The Langmuir isotherm equation is often written as:  $\frac{c}{x/m} = \frac{1}{K b} + \frac{c}{b}$ , where  $c$  = equilibrium P-concentration ( $\mu\text{g P/ml}$ ),  $x/m$  = amount of phosphate adsorbed ( $\mu\text{g P/g}$ ). The adsorption maximum  $b$  ( $\mu\text{g P/g}$ ) and the adsorption constant  $K$  ( $\text{ml}/\mu\text{g P}$ ) are derived from the slope and intercept values. The units of  $b$  are those of  $x/m$ . Regression analysis was used to compute all straight lines obtained with the conventional Langmuir equation as mentioned before. Where experimental data may be represented by the equation, plotting  $\frac{c}{x/m}$  against  $c$  yields a straight line with slope  $\frac{1}{b}$  and intercept  $\frac{1}{K b}$ . The Langmuir adsorption isotherm has the advantage that both the  $K$  and  $b$  values may be determined from relatively simple laboratory experiments. Once these values are known, the amount that will be adsorbed at any particular input may be estimated. The phosphate adsorption maximum and the equilibrium solution concentration of phosphate are important parameters, when studying the soil phosphate levels needed for optimum growth. Thus, the Langmuir equation can be used to give an approximate empirical description of the curves and to characterize them with two parameters which then allow ready comparison of adsorption characteristics among soils.

Fried and Shapiro (1956) concluded that the ability of a soil to continue supplying phosphate to the soil solution is an important factor in evaluating the phosphate status of a soil. They have found that soils with a high phosphate adsorption maximum apparently are able to supply sufficient phosphate for growth at a lower saturation than the soils with a low phosphate adsorption maximum. According to Woodruff and Kamprath (1965), soils with a low phosphate adsorption capacity require a higher saturation of the adsorption capacity and thus, a higher equilibrium solution concentration for maximum growth. Olsen and Watanabe (1963) pointed out that diffusion might become a limiting process in uptake more rapidly in sandy soils than in clay soils; therefore, sandy soils require a much higher equilibrium phosphate concentration of the solution to supply adequate amounts of phosphate for plant growth.

There was a wide range in the phosphate adsorption maxima, which was

to be expected in view of the differences in soil properties (Woodruff and Kamprath, 1965). These authors found high phosphate adsorption maxima in soils with high clay and high organic-matter contents. They have shown that neutralization of exchangeable aluminum markedly reduced the phosphate adsorption maximum.

It is known that phosphate adsorption takes place on the surface of clay colloids and on the surface of hydroxides and oxides of aluminum and iron (Muljadi *et al.*, 1966). The isotherm results from at least three types of adsorption sites (region I, II, and III) of widely different reactivities. The number of adsorption sites increases to a limit with a decrease in pH for region I and II. Thus, the regions I, II, and III are related to the affinity of phosphate for at least three energetically different reactive sites. Muljadi *et al.* (1966) described the three different reactivities as follows:

*Region I.* At low phosphate concentration (less than  $10^{-4}$ M), the adsorption isotherm rises steeply and remains close to the y-axis. This region represents sites with a very high affinity for phosphate.

*Region II.* The second region commences approximately at  $10^{-4}$ M, when the isotherm becomes convex to the y-axis.

*Region III.* The third part of the isotherm is linear and occurs at medium to high concentrations ( $10^{-3}$  to  $10^{-1}$ M).

Chen *et al.* (1973), in studying the reaction of phosphate with aluminum oxide, suggested the adsorption process to consist of a rapid adsorption on a reactive surface and of the formation of a new solid phase. The new solid phase formed in the reaction of phosphate ions with  $\text{Al}(\text{OH})_3$  as sterrettite has been identified by Van Riemsdijk *et al.* (1975).

Inorganic phosphate sorption of strongly weathered acidic soils is due to the sesquioxide fraction (Bache, 1964). A sorption reaction involves the removal of a component from solution by its accumulation in a solid phase. This may be physical sorption, which is reversible and involves a small decrease of energy or it may be chemical sorption, which is partly or completely irreversible and involves a larger decrease in energy. Wild (1950) considered that the distinction between precipitation and chemisorption is a narrow one, and difficult to resolve. Those differences were resolved by Bache (1964); a high energy chemisorption of small amounts of phosphate by both Al and Fe hydrous oxides occurs

over a wide pH range without precipitation of  $\text{Al}^{3+}$  and  $\text{Fe}^{3+}$  ions. With larger amounts of phosphate,  $\text{Al}^{3+}$  and  $\text{Fe}^{3+}$  ions are precipitated as insoluble phosphates. When the activities of these ions are reduced to very low values, increasing amounts of phosphate are sorbed at low energy, which may be physical adsorption onto a phosphate-saturated surface, or exchange with phosphate ions which diffuse into the solid.

There are two stages of phosphate fixation, a rapid initial reaction followed by a relatively slow reaction. The initial reaction has been attributed to an exchange adsorption of phosphate ions against hydroxyl ions on the surface of the solid particles. The exchange adsorption of the initial reaction results in the phosphate ions becoming attached to exchangeable iron, aluminum, and calcium ions of the clay and hydrous oxide. The slow reaction continues by the gradual increase in crystal size of precipitated iron and aluminum phosphate, with metal ions being supplied by the gradual breakdown of clay minerals and hydrous oxides (Haseman *et al.*, 1950; Kurtz *et al.*, 1946; Low and Black, 1950).

The objective of the first experiment was to investigate the amount of phosphate fertilizer required on a tropical soil from Kikambala (2), Kenya, in a pot experiment with maize (variety LG-11) as the test crop during a 35-day growing period. In this experiment the relationships between phosphate uptake, dry-matter yield and phosphate fertilization were also studied. The second pot experiment was meant to investigate the relationship between phosphate uptake and the amount of soil per pot for a tropical soil from Katumani (1), Kenya. There is no relationship between the first and the second pot experiment.

### 3. MATERIALS AND METHODS

#### 3.1. *Laboratory experiment*

Equilibration of soil and phosphate solutions was performed under conditions of the Pw-determination (Sissingh, 1971). The average weight of 1.2 ml of soil, scooped five times, is determined in quadruplicate. The weights of the 1.2 ml of the three Kenya soil samples were: 1.2250, 1.4820, and 1.4170 g for Katumani (1), Kikambala (2), and Kikambala (3), respectively. Topsoils of Katumani (1) and Kikambala (2) and subsoil of Kikambala (3) were used in this experiment. 1.2 ml of each soil was given 2 ml  $\text{Ca}(\text{H}_2\text{PO}_4)_2$  solutions containing different amounts of phosphate per ml of soil: 0-886  $\mu\text{g P}$  for Katumani (1), 0-885  $\mu\text{g P}$  for Kikambala (2), and 0-755  $\mu\text{g P}$  for Kikambala (3). The addition of 2 ml of the phosphate solutions served at the same time to premoisten the soils. After standing for 22 hours at 20 °C, 70 ml of water was added and the soil suspensions were equilibrated by shaking with a end-over-end mechanical shaker for 1 hour at a constant temperature (20 °C). After equilibration with the soil, the suspensions were filtered and the filtrates analyzed for phosphate by the Murphy and Riley method (1962). The difference between the initial quantity of soil phosphate + added phosphate in the solution and the quantity present after equilibration was taken to be the quantity adsorbed from the added phosphate.

#### 3.2. *Potted plant studies*

Topsoil of Kikambala (2) was placed in 10-liter plastic pots, corresponding with 13 kg of moist soil. Five levels of P were supplied: 0, 55, 110, 165 and 220 ppm P, as  $\text{Ca}(\text{H}_2\text{PO}_4)_2 \cdot \text{H}_2\text{O}$ .

Topsoil of Katumani (1) sandy clay loam was placed in 10-liter plastic pots, corresponding with 13 kg moist soil, or mixtures of quartz sand and soil, containing 1/8, 2/8, 4/8, 6/8 parts of soil. One treatment consisted of quartz sand only.

The soils belong to the subgroup Oxic Paleustalf for Katumani (1) soil



and Typic Eutrostoxx for Kikambala (2) soil (Soil Survey Staff, 1975).

Both experiments received 2.4 g N (urea), 2.4 g K<sub>2</sub>O (KCl), 2.5 g MgSO<sub>4</sub>.7H<sub>2</sub>O, 0.1 g CuSO<sub>4</sub>.5H<sub>2</sub>O, 0.1 g ZnSO<sub>4</sub>.7H<sub>2</sub>O, 0.05 g Na<sub>2</sub>B<sub>4</sub>O<sub>7</sub>.10H<sub>2</sub>O, thoroughly mixed with the soil. Randomized block design was used in this experiment with two replications. After the soil and added nutrient solutions had equilibrated for 7 days, maize (variety LG-11) was sown on 2 April and thinned to three plants per pot. Soil moisture was maintained at 60-80% of the maximum water holding capacity. The maize plants were harvested at the soil surface level 5 weeks after emergence. The plants were weighed and dried at 70 °C for 4 days, weighed again, ground and stored for P analysis.

#### 4. RESULTS AND DISCUSSION

##### 4.1. Laboratory experiment

The amount of phosphate adsorbed, in  $\mu\text{g P/g}$  of soil, has been plotted against the equilibrium phosphate concentration ( $\mu\text{g P/ml}$ ) to give the adsorption isotherm (table I). In this experiment the final phosphate solution concentrations were less than  $14 \mu\text{g P/ml}$ . This is in agreement with Olsen and Watanabe (1957), who reported that adsorption data did not conform to the Langmuir isotherm where final solution concentrations greater than  $18\text{--}20 \mu\text{g P/ml}$  were used. Thus, the Langmuir equation only describes adsorption over a limited range of concentrations. The Langmuir equation tends to increase the variance of the observations at high concentrations and these observations then have a disproportionate effect on the value of the coefficient (Barrow, 1978).

The soils can be arranged in sequence of decreasing adsorption of phosphate: Katumani (1), Kikambala (3), and Kikambala (2). The maxima of phosphate adsorption were 405, 91.7, and  $52.6 \mu\text{g P/g}$  of dry soil for Katumani (1), Kikambala (3), and Kikambala (2), respectively (table II). The ability of these soils to sorb added phosphate depends on the percentage of sesquioxide (table III). But it was not studied which component makes the largest contribution to the sorption of phosphate by those soils. Even though the  $P_w$ -value of Katumani (1) was already high ( $= 120 \mu\text{g P}_2\text{O}_5/\text{ml}$  of dry soil), the phosphate adsorption maximum was very high, undoubtedly caused by the high  $\text{Al}_2\text{O}_3$  and  $\text{Fe}_2\text{O}_3$  contents. The content of  $\text{Al}_2\text{O}_3$  in Katumani (1) soil was 5 and 3 times that of Kikambala (2) and Kikambala (3) soils, while the content of  $\text{Fe}_2\text{O}_3$  was 7 and 5 times that of Kikambala (2) and Kikambala (3) soils. The soil with a high phosphate adsorption maximum apparently was able to supply sufficient phosphate for growth at a lower degree of saturation than the soils with a low phosphate adsorption maximum. In phosphate studies conducted on Katumani (1) soil in pot experiments, no response to phosphate was found (Sissingh, personal communication).

TABLE I. Equilibrium concentration and adsorbed P in three Kenya soils.

Soil series	P applied in solution* ( $\mu\text{g P}/60 \text{ ml}$ of solution)						
	C = Equilibrium concentration ( $\mu\text{g P}/\text{ml}$ of filtrate)						
	$C_0$	$P^{**}$					
Katumani (1)	0.85	1.31	1.81	2.90	6.16	9.19	12.30
Kikambala (2)	0.05	0.59	1.27	2.59	6.67	10.35	13.98
Kikambala (3)	0.01	0.37	0.85	1.88	5.29	8.16	11.16
	P-ad- sorbed at 0 P	P adsorbed ( $\mu\text{g P}/\text{g}$ of soil) = x/m					
Katumani (1)	32.60	48.97	62.98	85.72	152.76	193.44	227.66
Kikambala (2)	0	9.63	12.46	20.06	37.03	37.57	40.53
Kikambala (3)	0	13.67	21.24	32.82	51.30	65.26	72.61

\*

44.31, 88.61, 177.22, 443.06, 664.59, 886.12  $\mu\text{g P}/60 \text{ ml}$  sol. for Katumani (1)44.29, 88.59, 177.17, 442.93, 664.40, 885.86  $\mu\text{g P}/60 \text{ ml}$  sol. for Kikambala (2)37.74, 75.48, 150.95, 377.37, 566.06, 754.74  $\mu\text{g P}/60 \text{ ml}$  sol. for Kikambala (3)

\*\* Derived from Pw-values of the soils.

The amount of phosphate adsorbed ( $\mu\text{g P}/\text{g}$  of soil) has been plotted against the equilibrium concentration ( $\mu\text{g P}/\text{ml}$ ), and the curves are presented in figure 1.

As the reaction period increased, the adsorption maximum increased slightly. Possibly an increase in the growth of microorganisms interfered with inorganic phosphate reaction during a 3-day period. A reaction time of 22 hours was selected for subsequent studies on the basis of these data. According to Davis (1935) and Langmuir (1918), the effect

TABLE II. The adsorption maximum, adsorption constant and the Langmuir equation for three Kenya soils.

Soil series	Adsorption maximum ( $\mu\text{g P/g}$ of soil)	Adsorption constant ( $\text{ml}/\mu\text{g P}$ )	Regression equation according to Langmuir	r
			$\frac{c}{x/m} = \frac{c}{b} + \frac{1}{K b}$	
Katamani (1)	405.0	0.1008	$Y = 0.00247X + 0.0245$	0.994
Kikambala (2)	52.6	0.2414	$Y = 0.01900X + 0.0787$	1.000
Kikambala (3)	91.7	0.2995	$Y = 0.01090X + 0.0364$	0.992

TABLE III. The chemical characteristics of tropical soils from Kenya.

Soil series	P-total (%)	$\text{Fe}_2\text{O}_3$ (%)	$\text{Al}_2\text{O}_3$ (%)	pH	
				KCl	$\text{H}_2\text{O}$
Katamani (1)	0.233	3.266	5.59	5.6	6.8
Kikambala (2)	0.025	0.454	1.13	5.3	6.3
Kikambala (3)	0.022	0.724	1.89	4.9	6.4

of soil:solution ratio on the isotherm is small. Therefore, this variable was not investigated further.

By extrapolation of the adsorption curve in figure 1 to the intersection with the y-axis, the phosphate adsorbed in soil without addition of phosphate could be estimated. For Katamani (1) soil, phosphate adsorbed by the soil without addition of phosphate was found to be about 30 g P/g of soil. A correction for the initial phosphate adsorbed can be made by withdrawing phosphate from the soil with  $\text{Fe}(\text{OH})_3$ -paper, as suggested by

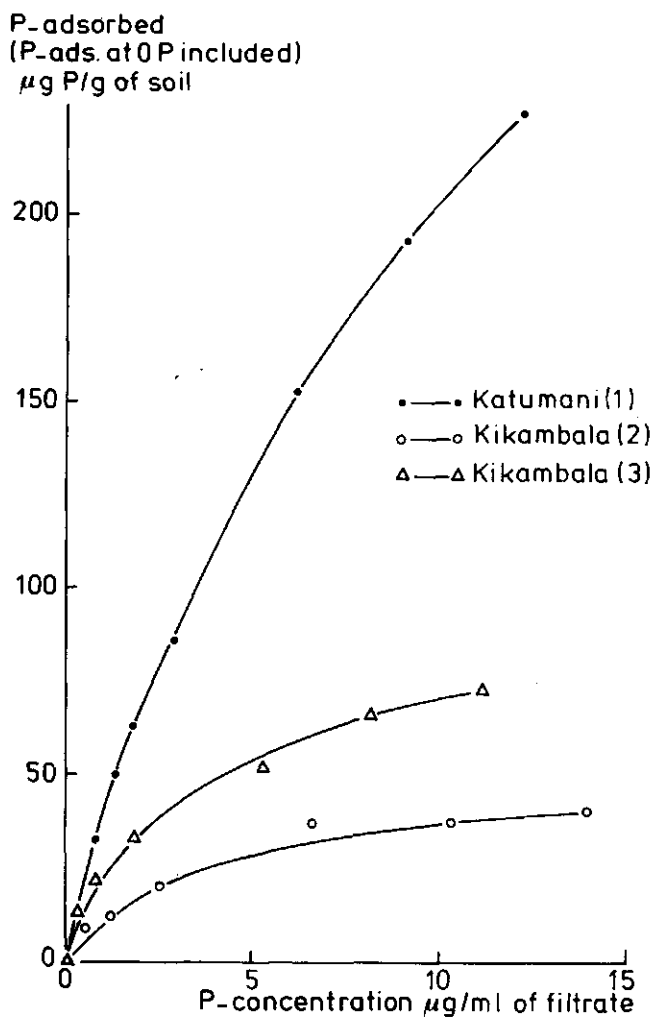


Figure 1. Phosphate adsorption curve for Katumani (1), Kikambala (2) and Kikambala (3) soil.

Sissingh (personal communication). Phosphate adsorbed in the soil without addition of phosphate proved to be small in the Kikambala (2) and Kikambala (3) soils as shown by extrapolation of the curves, so that these amounts of adsorbed phosphate were neglected. In the experiment with the Katumani (1) soil, the sum of the phosphate in the filtrate and in the  $\text{Fe}(\text{OH})_3$ -paper was about  $74.7 \mu\text{g P/g}$  of soil. The amount of phosphate in the filtrate of this soil without addition of phosphate was

42.1  $\mu\text{g P/g}$  of soil. Thus, phosphate adsorbed by the solid phase, if no phosphate had been added, and under the conditions of the  $P_w$  determination, was  $74.7 - 42.1 = 32.6 \mu\text{g P/g}$  of soil.

The adsorption maxima for the three Kenya soils were 405, 52.6, and 91.7  $\mu\text{g P/g}$  of soil for Katumani (1), Kikambala (2), and Kikambala (3), respectively (Table II).

The slope of the line relating adsorbed phosphate and concentration of phosphate in solution in Katumani (1) soil was greater than in Kikambala (2) and Kikambala (3) soils (figure 1). Rennie and McKercher (1959) observed that the relationship between adsorbed phosphate and concentration of phosphate in solution depends on particular soil characteristics. The slope of the line relating these two variables is greater as the clay content rises. The texture of Katumani (1) soil was sandy clay loam, while Kikambala (2) and Kikambala (3) soils were sandy. Rennie and McKercher also pointed out that the available phosphate would become a limiting factor more quickly on a sandy soil than on clay soil, if they had initially the same concentration of phosphate and if plant uptake rates were the same.

Indeed, when  $\frac{c}{x/m}$  was plotted against  $c$  according to the Langmuir equation, linear relationships were obtained (figure 2). At lower  $c$ -values, one or two of the plots suggest the presence of a second linear relationship for both of the Kikambala soils. But the number of observations in this part is too small for quantitative interpretation. Two markedly diverging data of the Kikambala (2) soil and one of the Kikambala (3) soil were not included in the calculation of the relating slopes, intercept values and correlation coefficients.

#### 4.2. Potted plant studies

The Katumani (1) soil was so rich in phosphate that no response to P-fertilization could be expected.

The most common type of relationships between phosphate uptake, yield (dry matter) and phosphate fertilization is shown in figure 3, as suggested by De Wit (1953). In this diagram the rate-uptake curve is given in the quadrant bounded by the axis marked R (rate) and U (uptake). The

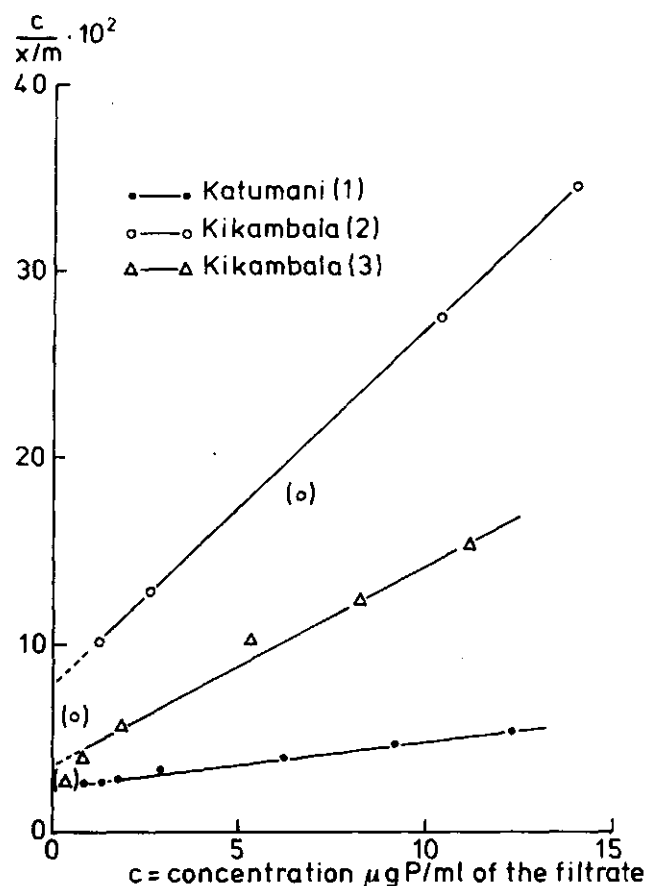


Figure 2. Linear relationships for equilibrium P concentrations versus  $\frac{c}{x/m}$  according to the conventional Langmuir equation.

uptake-yield curves are represented in the quadrant bounded by the axis marked U (uptake) and Y (yield). The fertilization rate-yield curves have been constructed from the rate-uptake and uptake-yield curves and are represented in the quadrant bounded by the axis marked Y (yield) and R (rate). The part of the curve in which the yield increase markedly with increasing uptake is called the region of increase, and the part of the curve in which there is little or no increase in yield with increase in uptake is called the region of luxury consumption.

Maximum dry-matter yield of maize plants grown on the Kikambala (2) soil occurred at 110 ppm applied P (table IV). When phosphate was applied

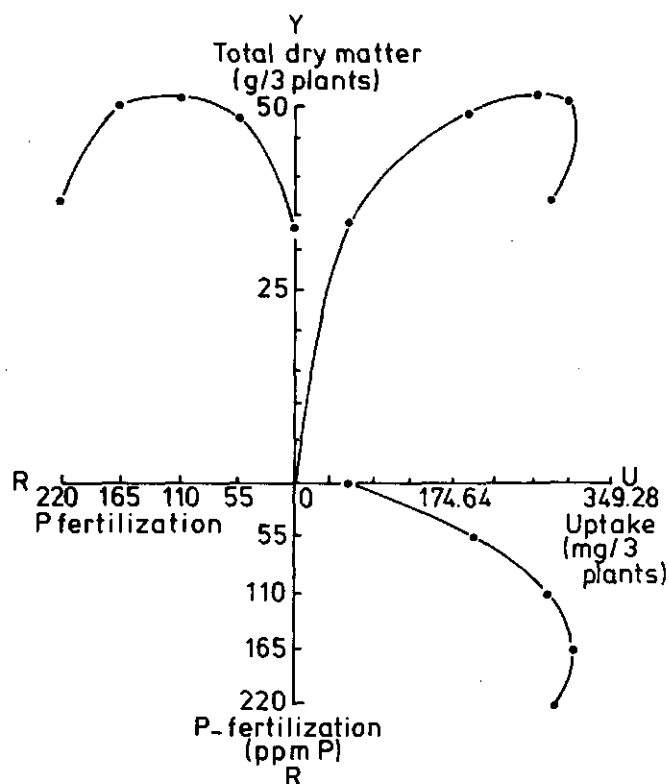


Figure 3. Rate of fertilization, phosphate uptake and dry-matter yield in a phosphate fertilization experiment on Kikambala (2) soil with maize as indicator crop during a 35-day growing period.

at a rate greater than 110 ppm P, the Kikambala (2) soil gave no, or a slightly negative, response. Dry-matter yield at 110 ppm P did not differ significantly from that at 55 ppm P.

According to Woodruff and Kamprath (1965), soils with a low adsorption capacity require a higher saturation of the adsorption capacity and a higher equilibrium solution concentration for maximum growth. For a proper classification of the adsorption maximum into low, medium, and high values, many soil types are needed.

The relationship between the phosphate added to the soils and the phosphate uptake by the plants is presented in table V. The phosphate uptake by the maize plants showed an increase with the addition of phosphate up to 165 ppm P. At the higher rate, phosphate uptake decreased. The



TABLE IV. Dry-matter yield and relative yield of maize plants at varied P-applications to Kikambala (2) soil\*.

	ppm P applied				
	0	55	110	165	220
dry-matter (g/pot)	33.73	48.23	50.68	49.81	36.65
treatment code	W1	W2	W3	W4	W5
relative yield**	-	0.30	0.33	0.32	0.08

\* available phosphate content: 6.81  $\mu\text{g P/l}$  of dry soil

\*\*  $\frac{W_2 - W_1}{W_2}$  for 55 ppm P, or  $\frac{W_n - W_1}{W_n}$  for the n-rate of P

TABLE V. Phosphate uptake by maize grown on the Kikambala (2) soil.

	ppm P applied				
	0	55	110	165	220
uptake (mg P/3 plants)	56.31	194.34	272.70	304.39	282.18
relative P-response	-	0.71	0.79	0.82	0.80

rate-uptake curve also shows that maximum phosphate uptake occurred at 165 ppm P (figure 3). With an increase in phosphate uptake there was not always a corresponding increase in dry-matter yield. Yield decreased with an addition of phosphate greater than 110 ppm P. Possibly the availability of microelements in the soil decreased.

The phosphate concentrations as determined by Pw-extraction in the Kikambala (2) soil after the addition of 0, 55, 110, 165 and 220 ppm P,

respectively, were 0.11, 0.81, 1.71, 2.49, and 3.37  $\mu\text{g P/ml}$ . Maximum growth of maize was reached at the Pw-phosphate concentration of 0.81  $\mu\text{g P/ml}$ . These phosphate concentrations may not be considered equilibrium concentrations. This could be the reason that they are much higher than those reported by other investigators. Aslyng (1954) concluded that, to avoid phosphate deficiency, a phosphate concentration of about  $2 \cdot 10^{-6}$  M (= 0.062  $\mu\text{g P/ml}$ ) was needed. Olsen (1950) found in nutrient solution experiments that the phosphate uptake by rye and some other species depended on phosphate ion concentration only when it was below  $3 \cdot 10^{-6}$  M (= 0.093  $\mu\text{g P/ml}$ ). Woodruff and Kamprath (1965) found that sandy soils with a low phosphate adsorption capacity required a higher saturation of the adsorption capacity and a higher equilibrium phosphate concentration for maximum growth.

The Katumani soil, rich in phosphate, was used for the second pot experiment.

Dry-matter yield and phosphate uptake, presented in table VI, should be regarded in two groups, as a consequence of some problems apparently related to the water supply of the plants. The plants of group I with low amounts of soil: 0, 1.625, and 3.250 kg per pot died at the first stage of the development. It was supposed that the system of water supply, mainly based on capillary rise, was not favourable, particularly when high amounts of sand were present in the soil/sand mixture. Again seeds were sown and the water supply was raised. Now the plants developed well, as was shown by the dry-matter production and the uptake of phosphate in 35 days. The development of the plants of group II was moderate. Sowing was not repeated. Results show that both the dry-matter yields and the P-uptake values were low. They were of the same level as those for the treatment 1.625 kg of soil per pot of group I, and no response to increasing amounts of soil was apparent. In this study on the relationship between the amount of soil per pot and the dry-matter yield or phosphate uptake, it was found that a soil:sand ratio of 2/6 (corresponding with 3.250 kg of soil) was already sufficient for complete development of the maize plants. The Pw-value of that mixture, 53.9 mg  $\text{P}_2\text{O}_5$ /1 of dry soil, was about the critical value for Dutch conditions.

TABLE VI. Dry-matter yield and phosphate uptake of maize plants and P<sub>w</sub>-values at different soil: sand ratios of Katumani (1) soil.

Groups	Amount of soil/10 l pots (kg)	Soil:sand ratio	Dry-matter yield (g)	P-uptake (mg P/3 plants)	P <sub>w</sub> -value (mg P <sub>2</sub> O <sub>5</sub> /l soil)
Group I	No soil+sand	0/8	1.18	1.41	2.3
	1.625 + sand	1/7	56.60	120.84	25.1
	3.250 + sand	2/6	65.52	155.74	53.9
Group II	6.500 + sand	4/4	55.24	128.69	92.7
	9.750 + sand	6/2	57.41	118.36	115.5
	13.000 of soil	8/0	56.66	121.36	125.6

## 5. CONCLUSIONS

From studies of the phosphate adsorption isotherm with the Langmuir equation, it was found that the phosphate adsorption maxima were 405, 52.6, and 91.7  $\mu\text{g P/g}$  of soil for the Katumani (1), Kikambala (2), and Kikambala (3) soil, respectively. Phosphate adsorption maximum for the subsoil sample of Kikambala (3) was higher than that of the topsoil samples of Kikambala (2) by a factor of 1.74. The ability of the three Kenya soils to sorb added inorganic phosphate was proportional to the increase in the content of sesquioxides.

When the  $\frac{c}{x/m}$  data and the P-concentrations  $c$  were plotted according to the Langmuir equation, linear relationships were obtained. At P-concentrations lower than 1  $\mu\text{g P/ml}$  the presence of a second straight line for both the Kikambala soils was suggested, but the number of observations in this part of the curves was insufficient for mathematical treatment.

The addition of 55 ppm P was already sufficient for complete development of maize plants on Kikambala (2) soil.

Phosphate uptake by maize grown on Kikambala (2) soil increased with the addition of phosphate up to 165 ppm P. Increased phosphate uptake by the plant was not always accompanied by a corresponding increase in dry-matter yield.

As to the relationship between the amount of soil per pot and the dry-matter yield or phosphate uptake, it was found that a soil:sand ratio of 2/6 (corresponding with 3.250 kg of soil) was already sufficient for complete development of maize plants grown on Katumani (1) soil which was rich in phosphate.

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