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Phosphorus supplying capacity of heavily fertilized soils II. Dry matter yield of successive crops and phosphorus uptake at different temperatures

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Abstract

Nine heavily fertilized soils were collected from southern and central Norway. A greenhouse experiment in the phytotron was conducted to evaluate the P supplying capacities of these soils at different temperatures (9, 12 and 18 °C). The crops were grown in succession and the sequence was oat, rye grass (cut twice), oat, rape and oat. Effect of temperature on dry matter (DM) yield and P uptake was more marked up to the fourth crop but the effect varied among crops. The DM yields of oat and rape increased with increasing temperature but the opposite was the case with rye grass. The yield differences among soils at 12 °C were highly significant ($p < 0.01$) in contrast to 9 and 18 °C. The amount of P taken up by plants in these soils was highest at 18 °C. The P supplying capacity was highest in the soils with higher content of organic P. Generally, the soils of very fine and coarse texture classes failed to supply enough P to crops to avoid P deficiency in the successive crops. Soil P test (P-NH_4-lactate) values in most of the soils increased with increasing temperatures. The highest temperature effect was seen in the Særheim sand soil. Soil P test extractants P-AL, Bray-1 and Colwell-P were used to determine P in the soil after each harvest and the soil P test values were compared with P uptake by crops. Only the P-AL extractant was significantly correlated to cumulative P removal (CPR) by plants in most of the soils. Regression equation was calculated for each soil. The value of removed P per harvest (RPH) varied from 10.33 to 20.87 mg P kg^{-1} soil. Phosphorus drawdown slope was determined for each soil and the number of consecutive harvests necessary to reduce the P-AL value to a normal level (110 mg P kg^{-1} soil) was calculated. The drawdown slope varied widely (1.257-2.801) and this reflected the P buffer capacity and the number of crops required to lower the soil test P value to a normal level. The highest drawdown slope was found in the soils with higher P supplying capacities. The Bray-1 extractant was significantly correlated in the soils with higher buffer capacity but the Colwell-P method did not show significant correlation in any of the soils.

Introduction

Many soils in the intensively cultivated grain and grass growing regions in the southeastern, southwestern and central Norway, have high levels of residual phosphorus as a result of the application of liberal rates of inorganic fertilizers and large amounts of animal manure for many years. Rapidly rising prices of P fertilizers and the concern for pollution of terrestrial and aquatic ecosystems have stimulated interest in determining the availability of P in the heavily fertilized soils to both plants and runoff water. The relationship between plant uptake of P and its concentration in soil is important from the points of view of making fertilizer recommendations and for assessing the contamination of terrestrial and aquatic ecosystems.

Several investigators have studied behaviour of accumulated P in soils (Adepoju et al., 1982; Aquino & Hanson, 1984; Bowman et al, 1978; Brams, 1973; Novais & Kamprath, 1978; Yerokun & Christenson, 1990). Accumulation of P in the soil and its availability to plants are dependent on soil's P fixation characteristics (McLean & Logan, 1970). The P fixation in the soils depends on several soil characteristics such as pH, clay, $CaCO_3$, crystalline and amorphous Fe oxides, citrate extractable Al and Fe contents in soils (Borggaard, 1983; Brennan et al., 1994; López-Hermándes & Burnham, 1982; Moshi et al., 1974; Upadhyay et al., 1993). The best soil test method is one which gives values near to the actual quantities taken up by plants. Several extractants have been used to find the relationship between P uptake by plants and extracted P in the soil (Aquino & Hanson, 1984; Bowman et al., 1978; Holford, 1980), and the prediction varied widely depending upon the characteristics of the soils studied.

Climatic factors such as temperature and rainfall are reported to affect P uptake by plants (Bravo & Uribe, 1981; Cumbusi & Nye, 1982). Cumbus & Nye (1982) concluded that temperature effects on root growth, root morphology, and root/shoot ratio can become prominent factors in the regulations of ion uptake. Bravo & Uribe (1981) also observed that P uptake in plants was affected by temperature.

Several studies (Adepoju et al., 1982; Aquino & Hanson, 1984; Bowman et al., 1978; Brams, 1973; Novais & Kamprath, 1978) have shown that soils with high residual P concentrations may sustain crop production without P application for several years. Soil containing plant available P > 200 mg P kg^{-1} soil have greater and longer growth potential than the soils just adequately supplied with P, if N and other nutrients are not limited (Bowman et al., 1978). Residual P effects in relation to rates of initial application (100-400 kg P ha^{-1}) were studied by Read et al. (1973). Their results show that in all instances the soil available P decreased approximately to 10 mg kg^{-1} after 5-19 harvests. Only the lowest initial P (100 kg P ha^{-1}) application to the soil reached the critical level after five consecutive crops. Aquino & Hanson (1984) studied seven consecutive harvests of grain sorghum from Missouri soils and showed that the extracted P by different methods was significantly related to plant uptake of P in most of the soils.

Novais & Kamprath (1978) suggested that the information received from greenhouse cropping could be used to estimate the number of field crops that can be grown before fertilization is necessary. Yerokun & Christenson (1990) reported that each mg of plant removed P per kg soil decreased the Bray-Kurtz P to 0.13-0.31 mg P kg^{-1} soil in the cultivated Michigan soils.

The objectives of this study were (i) to evaluate the effects of residual and freshly applied P on DM yield and P uptake by successive crops grown at different temperatures, (ii) to study the P supplying capacity of different soils, (iii) to correlate soil test values of P with P uptake by plants, and (iv) to estimate the number of consecutive harvests necessary to reduce the P test values in soils to a normal level.

Materials and methods

Soil characteristics

Nine bulk soil samples from the upper layer (0-20 cm) of the cultivated soils of varying physico-chemical properties were collected. The samples collected were three each from the counties of Akershus, Rogaland, and Trøndlag. The sampling sites had received heavy P fertilization, both in terms of inorganic P fertilizers and farmyard manures especially in the grassland areas for many years(> 40 years). The soil samples were air dried, ground and sieved through a 2 mm sieve. The important physico-chemical properties of these soils are presented in Table 1. The particle-size distribution was determined by the pipette method (Elonen, 1971). The soil pH was measured by a glass electrode at a soil-water ratio of 1:2.5 w/v. The organic carbon in soils was determined by combustion in an E-12 LECO carbon analyzer. Total P and inorganic P were determined by the method of Møberg & Pettersen (1982). In this method 1 g soil was ignited at 550 °C for 1 h and 5 ml of 12 *N* H_2SO_4 was added after ignition. The mixture was heated in a water bath at 70 °C for 10 min. After heating another 5 ml of 12 *N* H_2SO_4 was added and the mixture was allowed to cool for 1 h. The final solution was made to 250 ml with distilled water and the total P in the solution was determined by the Molybdenum blue method. In another set of 1 g soil the same procedure of digestion was followed as described above for the total P but the soil was not ignited prior to H_2SO_4 treatment. The final solution of the second set was used to determine inorganic P. The organic P was calculated by the difference between total P and inorganic P.

Greenhouse experiment

A completely randomized three factorial greenhouse experiment in a phytotron was conducted to evaluate the effects of residual soil P and freshly applied P on DM yields and P uptake by different crops grown consecutively at different temperatures (9,12 and 18 °C). Three kilogram of air-dried soil was mixed with required amounts of fertilizers and placed in plastic

Table 1. Selected physical and chemical characteristics, and textural classes of the soils used

Soil	pH	Sand %	Silt %	Clay %	Org. C%	P-AL	Bray-P mg P kg^{-1}	Col.-P
Stjørdal silt loam	5.8	30	67	4	34.2	320	124	150
Stjørdal sandy c. loam	5.8	71	24	4	2.9	390	300	166
Stjørdal silty clay loam	6.8	12	59	29	2.3	320	180	148
Årnes (Nysv.) silt	6.1	7	89	3	3.0	320	240	108
Særheim sand	7.6	99	1	0	1.3	440	73	142
Særheim loamy sand	6.8	74	21	4	6.0	490	340	192
Særheim clay loam	5.8	24	48	29	15.9	260	44	118
Råde (Delviken) sand	6.0	94	6	0	1.6	560	-	264
Bjørge (Stranger) silty clay loam	6.6	11	61	28	2.1	730	385	330

The soil names in the subsequent tables are according to their texture class.

pots. Phosphorus rates for each soil consisted of 0 and 15 mg P kg^{-1} (30 kg ha^{-1}), applied as a solution of $Ca(H_2PO_4)_2$. A basal dose of N and K, each at the rate of 120 mg kg^{-1}, and a mixture of micronutrients (Mg, Fe, Mn, Cu, B, Mo and Zn at the rate of 16, 15, 8, 6.3, 0.28, 0.26 and 1.3 mg kg^{-1} soil, respectively) were applied in liquid form to each pot. These basal dressings ensured that the growth of the plants in the two treatments was limited only by P. The cropping sequences was oat, rye grass (two cuts), oat, rape and oat. The rate of fertilization was the same as mentioned above for all the crops in succession. Moisture content in the pots was maintained at 70% of the field capacity by regular watering with deionized water. The value of moisture content is based on our experience from other greenhouse experiments in this department. The loss of water was determined by weighing the pots at the time of watering. The treatments were replicated twice. All the nine soils collected were used at 12 and 18 °C but at 9 °C only six soils were used due to space limitation. The crops were harvested at the initiation of heading or flowering growth stage at all temperatures but the number of days taken to reach this stage differed considerably among the temperatures used. For example, rye grass at 18 °C took about 96 days but this crop at 9 °C took 218 days to reach the heading growth stage. This implies that the same crop at different temperature was grown in different seasons (summer, autumn, and winter) of the year. All crops were harvested only once, except rye grass which was harvested twice. After each harvest the roots and other plant material in the soil were removed and fertilization and the procedure of crop planting was repeated in the same way as in the first crop.

Soil and plant analysis

Plants were harvested at about one cm above the soil surface level, and the DM yield per pot was determined by weighing plant shoots after oven drying them at 75 °C. Plant tissue was dry ashed at 500 °C, treated with 1:2 $HCl:HNO_3$ and diluted to 50 ml. Phosphorus in the digested solution was determined colorimetrically by complexing the orthophosphate ion with MoO_4 and Sr, reducing with ascorbic acid at an acidic pH, and reading the absorbance at 700 nm. The P uptake by the plants was calculated by multiplying the P concentration in the tissue and the DM yield per pot. The P concentration and P uptake data are presented on an oven dry weight basis.

Soil samples collected from each pot after each harvest (removing roots, stubbles and any dead material) were analyzed for easily soluble P using 0.1 *M* NH_4-lactate + 0.4*M* CH_3COOH, pH 3.75 (P-AL method of Egner et al., 1960), 0.03 *M* NH_4F + 0.025*M* HCl, pH 2.6 (Bray-I, Brown et al., 1977) and 0.5 *M* $NaHCO_3$, pH 8.5 (Colwell-P, Colwell et al., 1963). The Colwell method is a modification of the Olsen method by extending the shaking time to 16 hours.

Statistical analysis

The data of DM yield and P concentration in plants for each crop and each soil were subjected to one-way analysis of variance and the LSD test at different levels of significance. The relationship between DM yield and P uptake in the respective soils was analyzed with linear regression analyses. The regression analyses were also used to work out the relationship between the soil P extracted by different soil test methods and the cumulative plant P uptake. Relationships between removed P per harvest and soil properties were evaluated with pairwise correlations.

Results and discussion

Initial soil P status and soil tests methods

The initial soil P levels in different soils determined by the different extractions methods are presented in Table 1. All these values were considered very high, according to guidelines used to interpret soil results in Norway (Krogstad, 1992). P-AL values > 150 mg kg^{-1} are considered as very high. The corresponding values for the Bray-1 and Colwell-P methods are 20 mg kg^{-1} and 60 mg kg^{-1}, respectively.

There were wide variations among soils in the amount of P extracted by different soil test methods. The amount of the P-AL extractable P was generally higher than that extracted either by the Bray-1 or Colwell methods. There were weaker correlations between the Bray-1 P and the P extracted by the P-AL or Colwell methods ($r = 0.70$, $p < 0.1$ for both extractants), as compared to that between P-AL and Colwell-P ($r = 0.95$, $p < 0.001$). The reaction mechanism of the P-AL method is that the lactate ions in the extractant form complexes with Al, Fe and Ca ions which are fixed to P and thus bringing the soil adsorbed P into the soil solution. All the extractants showed positive correlations with Al-P, but only Colwell-P was found to be positively correlated to Ca-P. None of the extractants was significantly correlated to Fe-P.

Effect of temperature on crops

Dry matter yields and plant uptake of P for each crop at different temperatures are presented in Tables 2 and 3, respectively. The first crop of oat produced the same amount of DM yield at a shorter period (46 days) at 18 °C as compared to that at 9 °C (89 days), in the same growing season (Table 2). In spite of a rapid growth rate at 18 °C, the P uptake by the plants was 2.5 times higher at this temperature than at 9 °C. Case et al. (1964) observed that roots of oat plants at 25 °C were concentrated in the top 5 cm and the majority of roots were in the soil-pot interface, while at 15 °C it was distributed throughout the soil.

Relatively lower O_2 diffusion at higher temperature may be the cause for the differences in root distribution systems between temperatures. Root distribution played a major role in P uptake, especially in soils with poor soil structure. The effect of temperature on DM yield and P uptake was more marked up to the fourth crop (oat 2) than in the following crops of rape and oat (Tables 2 and 3). Similar trends were also observed by Case et al. (1964). Higher uptake of P at higher temperature is a result of both higher P concentration in plants and higher DM yield. This effect of temperature may be perceived in two ways: (i) a direct effect on the physiology of the oat plants, due mainly to increased translocation of P from the well developed root systems to the tops and (ii) an indirect effect due to an increase in the rate of mineralization of organic P with increasing soil temperature.

The P uptake by rape also increased significantly with temperature but the differences in P uptake between 12 and 18 °C were not significant (Table 3). The DM yield of this crop was not affected by temperature (Table 2). Cumbus and Nye (1982) observed that DM yield of rape was clearly temperature dependent at a range of 10-35 °C. A narrow temperature range in the present experiment may explain why the temperature effect was not so pronounced as reported in the literature. Moorby & Nye (1984) observed that the rate of root growth in rape plants increased with temperature, but the P uptake was independent of temperature within the range of 10-23 °C. However, both root growth and P uptake were reduced by 50% when the temperature dropped to 5 °C. The results indicate that the lowest P uptake at 9 °C in this study may have been caused by low ion transport and reduced root growth. The lowest ion uptake at low temperature was more closely related to active transport systems than to either respiration or membrane permeability (Bravo & Uribe, 1981).

In this experiment, rye grass was harvested twice. The highest DM yield was at 9 °C in the first harvest and at 12 °C in the second harvest. The P uptake was not consistently affected by temperature. The highest

Table 2. Ranges and mean values of the dry matter yields as affected by temperatures (g/pot)

Crop sequences	9°C*		12°C**		18°C**	
	Range	Mean	Range	Mean	Range	Mean
Oat-1	8.7-37.2	23.6a	4.6-11.9	9.1b	19.3-34.2	25.6a
Rye grass-1	18.8-50.1	32.0a	4.6-11.9	9.1b	4.5-10.8	8.1b
Rye grass-2	1.7-18.6	8.7a	12.8-22.5	16.6b	7.7-10.6	9.2a
Oat-2	2.3- 5.4	4.0a	4.6-11.9	9.1b	19.3-34.2	25.6c
Rape	1.1-11.9	7.3a	0.3-21.1	9.7a	0.3-21.6	8.7a
Oat-3	4.7-23.4	12.1a	6.1-38.5	20.2b	2.2-17.5	6.8a

The mean values followed by the same letter in the same row (crop) are not significantly different at p=0.05. *number of observations 12 and ** number of observations 18.

Table 3. Ranges and mean values of the P uptake at different temperatures (mg/pot)

Crop sequences	9°C*		12°C**		18°C**	
	Range	Mean	Range	Mean	Range	Mean
Oat-1	8.1- 84.2	46.4a	8.2-45.8	21.7b	52.2-230.0	112.2c
Rye grass-1	31.5- 50.0	38.0ab	26.5-58.8	43.6a	17.0- 51.0	33.8b
Rye grass-2	49.4-122.3	70.2a	8.4-27.4	19.1b	35.7- 76.1	54.0c
Oat-2	8.3- 22.5	15.7a	11.9-57.7	30.4b	41.5-144.6	64.7c
Rape	7.8- 27.8	18.9a	1.4-62.0	31.5b	1.7- 50.8	21.5ab
Oat-3	14.9- 30.5	23.0a	23.1-49.3	32.7b	11.0- 56.0	29.9ab

The mean values followed by the same letter in the same row (crop) are not significantly different at p=0.05. *number of observations 12 and ** number of observations 18.

P uptake was observed at 9 °C. At this temperature rye grass took much longer (218 days) to reach the flowering stage than at 18 °C (96 days). This resulted in a more compact plants showing higher DM percentage at lower than at higher temperature (Singh, 1991). In contrast to oat and rape crops, the DM yield and P uptake by rye grass decreased at higher temperatures.

Effect of temperature on dry matter yield and P uptake in different soils

Average DM yield and P uptake per pot at different temperatures were determined for the nine soils used and are presented in Tables 4 and 5, respectively. There was no significant difference on DM yields among the temperatures in any of the soils. Similarly, no significant differences in the DM yields among the soils were observed at 9 °C. However, the yield differences among the soils at 12 °C were statistically significant ($p = 0.01$). The Stjørdal silty clay loam, Årnes silt and Råde sand soils generally produced lower DM yields as compared to other soils (Tables 4 and 6). Table 6 shows that the yield reduction in these soils was very drastic in crops 5 and 6.

Phosphorus uptake by crops at different temperatures was significantly affected in most of the soils. The amount of P taken up by plants in these soils was highest at 18 °C and it differed significantly with that taken up by plants at 9 or 12 °C. However, there were no significant differences in P uptake by crops at 9 and 12 °C. Since the DM yields among temperatures were not different, it seems that the improved root development and increased mineralization in the soils may have stimulated the P uptake at higher temperature.

Increased root development at higher temperature was also observed by several investigators (Anderson & Kemper, 1964; Mackay & Barber, 1984; Moorby & Nye, 1984). Increased root growth increases the root surface area for P absorption. This is particularly important for P, since P diffusion in the soil even at high residual P is often low. Moorby & Nye (1984) investigated the effect of temperature on rape root and observed that there was no reduction in the number of laterals per cm when temperature was reduced from 23 ° to 10 °C and hence the total effects of temperature could be attributed to root extension. At 5 °C there was little root extension, but root weight per unit length was about 54% greater than that found at all other

Table 4. The average Dm yield (g/ pot) pr crop in different soils and at different temperatures

Soil name	9 °C*		12 °C		18 °C	
	Range	Mean	Range	Mean	Range	Mean
Stjørdal silt loam	2.5-37.2	17.4	10.0-38.5	17.6	10.4-32.3	19.6
Stjørdal sandy loam	3.8-50.1	14.6	10.6-25.2	15.0	9.6-25.4	17.1
Stjørdal silty c. loam	1.1-34.5	10.6	0.6-15.2	8.5	0.3-22.6	10.4
Årnes silt	1.7-32.9	12.6	0.3-13.5	8.7	0.5-25.6	11.1
Særheim sand	3.5-29.4	16.2	7.2-32.8	14.1	3.3-26.8	15.7
Særheim l. sand	4.4-34.5	16.2	6.6-20.3	12.2	3.0-21.4	12.0
Særheim clay loam			8.3-31.8	15.0	2.7-33.1	14.7
Råde sand			3.2-22.5	10.2	1.4-25.3	10.9
Bjørge silty c. loam			4.1-16.8	9.2	1.0-34.2	14.5

*Temperature effect was not found to be signficant. Number of observations 12.

Table 5. Average plant P uptake (mg P /pot) per crop in different soils and at different temperatures

Soil name	9 °C		12 °C		18 °C	
	Range	Mean	Range	Mean	Range	Mean
Stjørdal silty loam	17.0- 84.2	39.8 a	16.4-62.0	35.7 a	37.1-151.7	67.1 b
Stjørdal sandy l.*	8.1- 81.2	27.5 ab	10.8-46.5	26.5 a	21.1- 83.1	39.6 b
Stjørdal silty c. l.*	7.8- 92.5	39.4 a	2.7-48.7	28.6 a	1.7-136.4	49.2 b
Årnes silt	9.7-122.3	40.2 a	1.4-49.8	25.3 a	2.8- 83.4	39.0 a
Særheim sand	8.3- 54.3	33.0 ab	11.1-52.3	27.1 a	11.0-114.8	51.1 b
Særheim l. sand	14.7- 64.7	32.3 a	18.4-56.9	32.7 a	14.6- 76.1	47.4 b
Særheim clay loam			8.2-48.2	25.8 a	6.6- 79.1	36.1 a
Råde sand			8.4-46.9	28.9 a	9.1-146.8	57.5 b
Bjørge silty c. loam			16.2-57.7	38.0 a	7.3-230.0	87.1 b

The mean values followed by the same letter in the same row (soil) are not significantly different at p=0.05.
*means significant difference at p=0.1. Number of observations 12.

temperatures. They also found that the P uptake per unit length of root decreased consistently from 10 to 5 °C.

Phosphorus uptake by plants in soils depends on morphological characteristics of the root, such as root length, distance between roots, root radius and root: shoot ratio (Anderson & Kemper, 1964; Cumbus & Nye, 1982; Schenk & Barber, 1979). It was observed that temperature had a major role on root morphology but the amount of organic matter, pH, aggregation and changes in density of soils may also have some influences (Schenk & Barber, 1979). Plants growing in soils with poor structure needed a higher P availability because of poor root development (Prummel, 1975). In this study, the soils with higher content of fine particles and lower organic C were most prone to low DM yield and reduced P uptake. These soils were heavy textured and hence the root development and morphology may have been affected by these physical conditions. A weaker contact between soil particles and root surfaces also affects the P uptake as is in the case of Råde sand. Shoot : root ratio is another important factor which affects the DM yield. At 9 °C, P uptake by rye grass was very high due to a well developed root system over an eight months period but DM yield was poor at this temperature. This high root : shoot ratio resulted in a higher amount of carbohydrates and other compounds to be transported to the root. Reduced ion uptake at lower temperatures may also be caused by low metabolic activities. At a lower temperature, membranes lose lateral compressibility and fluidity, and decrease the mobility of membrane phospholipids (Bravo & Uribe, 1981). These changes in the membranes may have caused reduced P uptake at lower temperatures.

Table 6. The DM yield and P uptake by six crops in different soils

Soil No.	DM yield (g/pot soil) 1	2	3	4	5	6	P uptake (g/pot soil) 1	2	3	4	5	6
1	25.5	15.8	13.2	14.8	16.2	23.8	78.6	46.9	49.5	34.2	41.8	34.7
2	14.9	22.8	11.9	13.4	16.4	13.9	31.1	30.4	45.2	24.4	30.7	25.5
3	17.1	14.1	8.1*	12.3	1.2*	7.4*	70.6	39.4	46.1	41.4	7.5*	29.3*
4	21.2	16.4	8.2*	12.1	1.3*	5.7*	49.3	40.9	58.2	33.3	6.3*	21.0*
5	18.1	14.4	13.1	12.7	15.1	18.7	59.4	36.7	36.7	25.7	40.7	23.0*
6	18.8	17.9	1.4*	12.3	6.4*	12.2	41.3	44.9	50.4	34.5	23.7*	30.4*
7	18.2	7.7	13.6	18.2	13.0	18.3	37.6	26.5	30.8	38.6	27.2	25.3
8	14.8	5.7*	14.9	14.8	3.8*	9.4*	82.6	33.1	36.8	52.4	22.1*	32.1*
9	20.3	7.7*	12.5	20.3	2.9*	7.5*	126.3	44.0*	43.0	94.0	19.8*	48.4*

*Indicates that significant difference at p=0.05.

Effect of temperature on P-AL in different soils

The effect of temperature on plant available P measured by the P-AL extractant is shown in Figure 1. The P-AL values in most of the soils increased with increasing temperatures, but only the Særheim sand (no. 5), Særheim clay loam (no. 7) and Stjørdal clay loam (no. 2) soils showed the significant differences among the temperatures. Increased microbial activities and chemical mineralization of P in the soils at higher temperatures should be responsible for this increase. Barrow & Shaw (1975) incubated different amounts of P at 25 °C and measured solution P concentrations at different temperatures. They observed that higher temperatures gave rise to high P concentration in the solution but P incubation at higher temperatures lead to low P concentration in the solution. These results show that both adsorption and desorption of P are temperature dependent. Furthermore, the desorbed and released P by increased mineralization and microbial activities at higher temperatures, may be re-adsorbed by other soil components at higher temperatures. This suggests that temperature is one of the crucial factors affecting the plant available P through its effect on the behaviour of P in soil.

High temperature increases the rate of transfer to the specifically adsorbed form and thus decrease the concentration in solution (Barrow & Shaw, 1975). It seems that the effect of temperature on the equilibrium between P in solution and that adsorbed on soil particles is in the opposite direction. Thus under conditions in which the transfer to the firmly-held form is slow, high temperatures increase the concentration in solution. Barrow & Shaw (1975) suggested that adsorption is an exothermic process and this is the most probable reason for significant increase in P-AL values in the Særheim sand soil at higher temperatures.

High content of organic C in the Stjørdal silt loam soil released adequate amount of P through increased desorption and increased mineralization at higher temperatures. But no significant increase in the P-AL values among temperatures was observed in this soil. The highest drawdown slope for P-AL (Table 8) implies that the released P in the soil was removed from the solution in two ways; (i) P uptake by plants (two-fold higher uptake at 18 °C than that at 12 °C, and (ii) converted to insoluble form as Fe-P (Fe was the major sink for P in these soils (Subramaniam & Singh, 1997).

The net effect of temperature will also depend on the soil's physical and chemical characteristics. Low effects of temperature in soils may probably be caused by the increased re-adsorption (endothermic reaction) at higher temperature by fine silt and clay particles and Ca, Al and Fe ions. Mehadi & Taylor (1988) observed that the quantity of adsorbed P in soils increased at higher temperatures and they suggested that the adsorption was an endothermic reaction.

The effect of temperature on the Bray-1 extractable P in the soils showed that temperature was inversely related to Bray-1 P. A significant reduction in the Bray-1 P was observed in the soils with higher content of Al-P i.e. Særheim loamy sand, Råde sand and Bjørge silty clay loam soils (Subramaniam & Singh, 1997). A higher correlation found between Al-P and Bray-1 P in the soils implies that the main cause for the reduced Bray-1 P may be due to reduced Al-P fractions at higher temperature. A similar tendency was also observed in

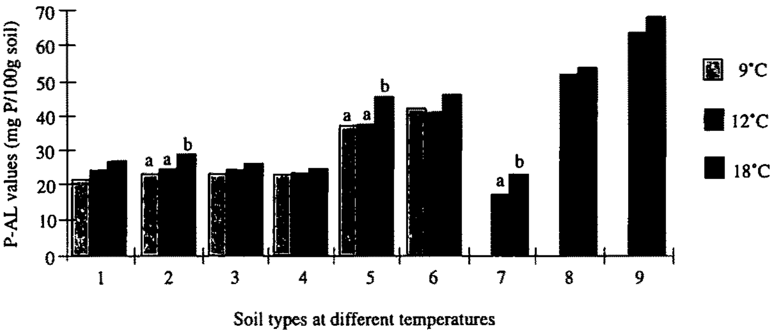

Figure 1. Effect of temperature on P-AL values in different soils. Treatment means that are significantly different (p<0.05) are indicated with different letters.

Table 7. Correlations between cumulative P removed and extractable P by the three P extraction methods and [1] relationship between DM yield and P uptake in different soils

Soil name	P-AL	Bray-P	Colwell-P	[1]r-values
Stjørdal silt loam	0.89*	0.67^{ns}	0.58^{ns}	0.49^{ns}
Stjørdal sandy loam	0.83*	0.76^{ns}	0.61^{ns}	0.23^{ns}
Stjørdal silty c. loam	0.94**	0.88*	0.36^{ns}	0.89*
Årnes silt	0.96**	0.69^{ns}	0.51^{ns}	0.99**
Særheim sand	0.86*	-0.22^{ns}	0.61^{ns}	0.27^{ns}
Særheim loamy sand	0.79^{ns}	0.93**	0.35^{ns}	0.96**
Særheim clay loam	0.90*	-0.53^{ns}	0.71^{ns}	0.55^{ns}
Råde sand	0.86*	0.69^{ns}	0.66^{ns}	0.71^{ns}
Bjørge silty c. loam	0.88*	0.91*	0.54^{ns}	0.92**

*, ** are signficant at p=0.05 and p=0.01, respectively.

the Colwell-P, but the reduction was not significant (data not shown).

Effect of phosphorus supplying capacity

Phosphorus supplying capacity of the soils was investigated by comparing the DM yield, with (15 g P per pot) and without P for the six crops grown in sequence and the results are shown in Figure 2. In this study reduced DM yield in the control pots was observed in many crops and P deficiency observed initially in the Bjørge silty clay loam already in the second crop and it was followed by the Stjørdal silty clay loam, Årnes silt, Særheim loamy sand and Råde sand (Figure 2). These results indicate that soil texture has significantly affected the P uptake or P supplying capacity. It implies that the soils with very fine and coarse texture classes have failed to supply enough P. Baldovinos & Thomas (1967) observed that clay content in the soil affected both P uptake and DM yield. The lowest P uptake was observed in the soil with highest clay content (63.5%), and the highest P uptake was observed in the soil with intermediate level (22.5%) of clay content. But the highest response to added P was observed in the soil with lowest clay content (10%). These observations along with soil test values (Table 1) indicate that the P supplying capacity depended not only on the initial P levels but also on the capacity of plants to adsorb P and soil physical properties such as aggregate stability and pore size distribution.

Holford & Mattingly (1976) suggested that the available P is inversely related to the P affinity constant (P bonding energy to soil particles) and buffer capacity of the soil. Adsorption studies (Subramaniam & Singh, 1997) of these soils show that the soils showing P deficiency had relatively higher affinity constant and/ or higher adsorption maximum. Both silty clay loam soils are identical to each other in most of the soil characteristics except the amount of residual P. The Bjørge s. c. loam soil contained 1.6 times higher residual P than that in the Stjørdal s. c. loam soil. But no significant differences on the DM yield to added P between the two soils were observed.

The relationships between the DM yield and P uptake in different soils presented in Table 8 show that the soils with higher P supplying capacity have weaker correlation to P uptake. In the soils with higher r-values DM yield depended on P uptake. A similar relationship is also depicted in Figure 2. Since the amount of removed P per harvest (RPH) is a function of DM yield, the P deficiency in these soils did not follow the same pattern as the amount of RPH. For example, crops in the Særheim clay loam did not show any P deficiency in spite of its lowest RPH value. On the other hand, the Bjørge silty clay loam soil showed the highest RPH value but the crop suffered from severe P deficiency.

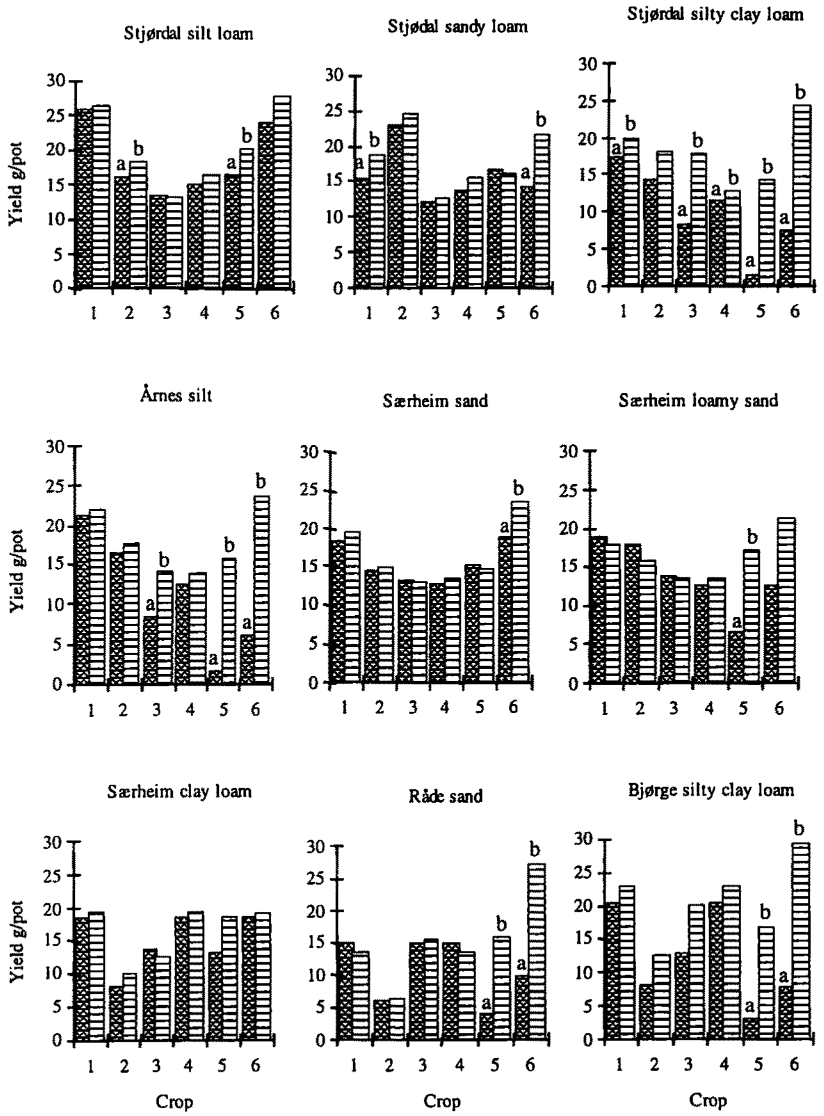

Figure 2. Comparison of dry matter yield for six crops with 15 mg P kg^{-1} (lines) and without P (dots) grown in different soils. Treatment means that are significantly different ($p<0.05$) are indicated with different letters.

Phosphorus uptake by oat plants in the latter soil was very high and this may be a possible explanation for the highest average RPH value. A higher uptake of P by a previous crop may have caused P deficiency in the following crops.

In spite of a very high amount of residual P in the Bjørge silty clay loam soil, relatively low P supplying capacity was observed in this greenhouse experiment by successive crops. Soil P test values measured by different extractants after each harvest showed that the soil possesses higher amount of plant available P. A possible explanation for this contradiction between soil test values and P uptake by plants may be a competition between growing plants and re-adsorbing processes in the soils. Higher amount of inorganic P fractions in the soil implies that it could have a high potential for re-adsorption of soluble P by active Ca^{2+}, Al^{3+} and Fe^{3+} ions. Soil test values may have underestimated such processes. The P affinity constant (k) determined by the classical Langmuir isotherm was relatively high in this soil but it was compensated by the lower adsorption maximum (Subramaniam & Singh, 1997). A high

Table 8. Regression equation, P removed per harvest and the number of harvests necessary to decrease P in the soil to a normal level

Soils	Regression equation	RPH mg P kg soil	No. of harvests
Stjøordal silt loam	SEP = 43.11 - 2.801 ·CPR	15.9	7
Stjøordal sandy loam	SEP = 38.01 - 2.730 ·CPR	10.4	10
Stjøordal silty c. loam	SEP = 35.07 - 1.660 ·CPR	13.0	11
Årnes silt	SEP = 34.66 - 1.957 ·CPR	11.6	10
Særheim sand	SEP = 47.70 - 1.708 ·CPR	12.3	17
Særheim loamy sand	SEP = 51.08 - 1.633 ·CPR	12.5	20
Særheim clay loam	SEP = 27.86 - 1.946 ·CPR	10.3	8
Råde sand	SEP = 59.68 - 1.257 ·CPR	14.4	27
Bjørge silty c. loam	SEP = 79.81- 1.586 ·CPR	20.9	21

SEP + (P-AL) Soil extractable P (mg P 100 g^{-1} soil); CPR = Cumulative P removal by crops (μg P/pot soil); RPH = removed P per harvest (mg P kg^{-1} soil).
In this calculation the plant available P was estimated between the initial concentration of P and when the P-AL concentration dropped to 110 mg P kg^{-1} soil (normal P level).

amount of inorganic-P (84.2%) in the soil reflects its adsorption and P supplying capacities.

The most dominant P fraction in the Råde sand was Al-P (49%). In this soil relatively lower crop yield and P deficiency were observed. The lowest P affinity constant in the soil should indicate an adequate amount of available P (Subramaniam & Singh, 1997). Furthermore, the number of harvests necessary to decrease P to a normal level (110 mg kg^{-1} soil) were calculated to be 27. This suggests that only a small portion of the P present in the soil was removed by each harvest. A possible explanation for this contradiction between low k and low plant removed P by each harvest may be a re-adsorption of mineralized P by active Al components in the soil. The low k-value may also be due to low content of clay in this soil. The P uptake is probably low due to the poor soil structure and the soil P test methods may have overestimated the plant available P.

The relative contribution of the various P fractions to the P removed by each harvest (RPH) was determined by using a linear multiple regression analysis for these soils. The equation shows that both Ca-P and Al-P were significantly and positively correlated to RPH. However, Fe-P did not show any significant correlation with RPH.

$$RPH = 0.397 + 0.0016 \times Ca - P$$
$$+0.0012 \times Al - P \qquad (r = 0.84) \qquad (1)$$

Multiple regression with Ca-P and Al-P as X-variables showed that these two fractions explained 71% ($p \leq$ 0.05) of the variation in RPH. The simple correlation coefficient values between these P fractions and some soil properties show that Fe-P was bonded to organic P and clay particles (Subramaniam & Singh, 1997). The Al-P and Ca-P showed no relationships to any of the soil properties. This observation further substantiated the earlier statement that Fe played a greater role in adsorbing P in these soils.

Relationship of soil tests to plant phosphorus uptake

The cumulative plant uptake of P for each soil was compared to the P extracted by P-AL, Bray-1 and Colwell-P extractants and the relationship is presented in Table 7. Only the P-AL extractant gave highly sensitive and significant correlations with the cumulative P uptake in most of the soils. However, the P-AL extractant failed to show a significant correlation in the Særheim loamy sand. The latter soil showed the highest adsorption maximum and a high maximum buffer capacity among the soils studied (Subramaniam & Singh, 1997). Since the P-AL is the strongest extractant among the extractants used in this study, it probably overestimated the plant available P in the soil. The Bray-1 extractant known as a weaker reagent especially in the soil with higher content of Ca-P and at high pH did not result in significant correlation with P uptake in most of the soils. It however, showed significant correlation in the high buffered soils such as the Særheim loamy sand and silty clay loam soils from Stjørdal and Bjørge, respectively (Table 7). The Colwell-P method did not show any correlations with P uptake in any of the soils. According to these results the P-AL extractant is the best soil test method which gives better indices of plant available P in the Norwegian soils.

The number of consecutive harvests necessary to reduce P-AL values to a normal level (110 mg kg^{-1} soil) was calculated by regression equations. The number varied from 7 for Stjørdal silt loam to 27 for Råde sand (Table 8). The lower organic P and higher initial P concentration (P-AL = 56) in the Råde sand may be responsible for its capacity to supply P to 27 consecutive harvests. In practice, however, the soil suffered with strong P deficiency in 5^{th} and 6^{th} crops grown in the soil. This means that the regression equation in Table 9 overestimated the P supplying capacity of this soil. These results may imply that the increase in soil P buffer capacity will result in a corresponding decrease in the proportion of P taken up by plants.

In general, the P drawdown slope (change in P-AL values with cumulative plant removal) varied considerably. Because the P-AL values decreased with each crop harvest, the predicted slopes had a negative value. A greater negative slope indicated a greater P drawdown per unit of crop P removal (Table 8). The highest drawdown slope was for the Stjørdal silt loam soil and the lowest slope for the Råde sand soil. This drawdown slope sequence reflects the P supplying capacities of these soils but it was not related to RPH. The P drawdown slopes were highly correlated to organic-P ($r=0.82$, $p=0.01$) but they were inversely related to Al-P. Soil texture, initial P or other P-fractions did not have much effect on this parameter.

Conclusion

The results from this study show that the P uptake and DM yield of crops were significantly affected by temperature and soil type. Phosphorus uptake and DM yield of oat and rape crops increased with increasing temperature but opposite was the case with rye grass. The highest P uptake was at 18 °C and it differed significantly with that taken up by plants at 9 and 12 °C. Soil temperature affects plants P uptake in several ways. Both adsorption and desorption are affected by temperature. The net temperature effect also depended on the content of organic P in the soil. Generally desorption was higher than adsorption in the soils with higher organic C (Særheim clay loam and Stjørdal sand loam soils). Increased chemical mineralization with higher microbial activities at higher temperatures may be the main cause for this increase. Soil types also affected the DM yield and P uptake. In general, heavy textured and coarse textured soils were more prone to reduced P supplying capacity caused probably by changed root morphological characteristics. Soils with higher buffer capacity possess lower supplying capacities.

The rate of decline (drawdown slope) in extractable soil P (only P-AL) was significantly related to plant P removal. The buffer capacity of the soils seems to have affected the drawdown slopes. Low drawdown slopes were generally in the soils with higher P supplying capacities. Highly significant correlations between P-AL and the plant removed P in the soils suggest that the P-AL extractant is a better extractant to predict the P removal by crops in the Norwegian soils especially those with lower buffer capacity.

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References

Adepoju AY, Pratt PF & Mattigod SV (1982) Availability and extractability of phosphorus from soils having high residual phosphorus. Soil Sci Soc Am J 46: 583–588

Anderson W B & Kemper WD (1964) Corn growth as affected by aggregate stability, soil temperature and soil moisture. Agron J 56: 453–456

Aquino BF & Hanson RG (1984) Soil phosphorus supplying capacity evaluated by plant removal and available phosphorus extraction. Soil Sci Soc Am J 48: 1091–1096

Baldovinos F & Thomas GW (1967) The effect of soil clay content on phosphorus uptake. Soil Sci Soc Am Proc 31: 680–683

Barrow NJ & Shaw TC (1975) The slow reactions between soil and anions. 3. The effect of time and temperature on the decrease in phosphate concentration in the soil solution. Soil Sci 119: 167–177

Borggaard OK (1983) The influence of iron oxides on phosphate adsorption by soil. J Soil Sci 34: 333–341

Bowman RA, Olsen SR & Watanabe FS (1978) Greenhouse evaluation of residual phosphate by four phosphorus methods in neutral and calcareous soils. Soil Sci Soc Am J 42: 451–454

Brams E (1973) Residual soil phosphorus under sustained cropping in the humid tropics. Soil Sci Soc Am Proc 37: 579–583

Bravo PF & Uribe EG (1981) Temperature dependence of the concentration kinetics of adsorption of phosphate and potassium in corn roots. Plant Physiol 67: 815–819

Brennan RF, Bolland MDA, Jeffery RC & Allen DG (1994) Phosphorus absorption by a range of western Australian soils related to soil properties. Commun Soil Sci Plant Anal 25: 2785–2795

Brown JR, Garrett J & Fisher TR (1977) Soil testing in Missouri. EC 923. Extension Division, Univ. of Colombia

Case VW, Brady NC & Lathwell DJ (1964) The influence of soil temperature and phosphorus fertilizers of different water-solubilities on the yield and phosphorus uptake by oats. Soil Sci Soc Am Proc 28: 409–412

Colwell JD (1963) The estimation of the phosphorus fertilizer requirements of wheat in southern New South Wales by soil analysis. Aust J Exp Agric Anim Husb 3 : 190–197

Cumbus IP & Nye PH (1982) Root zone temperature effects on growth and nitrate absorption in rape (*Brassica napus* cv. Emerald). J Exp Bot 33: 1138–1146

Egner H, Riehm H & Domingo WR (1960) Investigations of the chemical soil analysis as a basis for the evaluation of nutrient status in soil. II. Chemical extraction methods for phosphorus and potassium determination. K Lantbruks Høgsk Ann 26: 199–215 (*In German*)

Elonen P (1971) Particle-size analysis of soil. Acta Agric Fenn 122, 1–122

Holford ICR & Mattingly GEG (1976) A model for behavior of labile phosphate in soil. Plant Soil 44: 219–229

Holford ICR (1980) Greenhouse evaluation of four phosphorus soil tests in relation to phosphate buffering and labile phosphate in soils. Soil Sci Soc Am J 44: 555–559

Krogstad T (1992) Methods of soil analysis. Report 6/92. Dept. of Soil and Water Sciences, Agric. Univ. of Norway. 32 p (*In Norwegian*)

López-Hermández D & Burnham CP (1982) Phosphate retention in some tropical soils in relation to soil taxonomic classes. Commun Soil Sci Plant Anal 13: 573–583

Mackay AD & Barber SA (1984) Soil temperature on root growth and phosphorus uptake by corn. Soil Sci Soc Am J 48: 818–823

McLean EO & Logan TJ (1970) Sources of phosphorus for plants grown in soils with differing phosphorus fixation tendencies. Soil Sci Soc Am J 34: 907–911

Mehadi AA & Taylor RW (1988) Phosphate adsortion by two highly-weathered soils. Soil Sci Soc Am J 52: 627–632

Moorby H & Nye PH (1984) The effect of temperature variation over the root system on root extension and phosphate uptake by rape. Plant Soil 78: 283–293

Moshi AO, Wild A & Greenland DJ (1974) Effect of organic matter on the charge and phosphate adsorption characteristics of Kikuyu red clay from Kenya. Geoderma 11: 275–285

Møberg JP & Pettersen L (1982) Øvelsesvejledning til geologi og jordbunnslære. KVL Part 2, København. 136 p.

Novais R & Kamprath EJ (1978) Phosphorus supplying capacity of previously heavily fertilized soils. Soil Sci Soc Am J 42: 931–935

Prummel J (1975) Effect of soil structure on phosphate nutrition of crop plants. Neth J Agric 33: 62–68

Read DWL, Spratt ED, Baily LD, Warder FG & Ferguson WS (1973). Residual value of phosphatic fertilizer on chemozemic soils. Can J Soil Sci 53: 389–398

Schenk MK & Barber SA (1979) Phosphorus uptake by corn as affected by soil characteristics and root morphology. Soil Sci Soc Am J 43: 880–883

Singh BR (1991) Annual research report. Fertilizer research programme. Dept of Soil and Water Sci. Agri Univ of Norway, Aas. pp 92–112

Subramaniam V & Singh BR (1997) Phosphorus supplying capacity of heavily fertilized soils I. Phosphorus adsorption characteristics and phosphorus fractination. Nutr Cycl Agroecosystems (this issue)

Upadhyay GP, Singh K & Bandari AR (1993) Phosphate-adsorption in some representative soil groups of north-west Himalayas. J Indian Soc Soil Sci 41: 434–439

Yerokun OA & Christenson DR (1990) Relating high soil test phosphorus concentrations to plant phosphorus uptake. Soil Sci Soc Am J 54: 796–799