Placement of Phosphate Leads to a More Efficient Use of a Finite Resource

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Abstract

In a desk study and in a climate chamber experiment we explored the rationale behind the low or even negative correlation between recommended P(hosphorus)-application rates and P-off-take in the Netherlands. We hypothesized that especially for short growing vegetable crops it will be necessary to maintain in the early growth stages a high P-concentration in the soil solution, despite the relatively low P-off-take at harvest. Although the daily P-demand of the crop is low immediately after germination, actual P-uptake might be limited by root length. Placement of P is then a strategy to achieve a more efficient P-fertilization. The fact that P-resources in the future will become scarce will encourage such a strategy.

The interaction between soil P-fertility, rooting, P-demand and placement of P was explored with a simulation model. Placement turned out to be very effective to realize the required P-uptake in the early growth stages, more effective than increasing the P-soil fertility status.

The effect of placement of P-fertilizer was verified in a climate chamber experiment. In a pot experiment P-fertilization by placement (0, 4, 13 kg P ha^{-1} in 3% of the soil volume) was compared with 87 kg P ha^{-1} mixed homogeneously through the entire soil volume. Placement stimulated juvenile growth to a great extent in several crops (including carrots, spinach, onion). Placement was equally or even more effective than the broadcasted treatment indicating that P-placement can potentially lead to a large reduction in the use of P-fertilizer. It opens the possibility to maintain crop productivity and quality at lower P-fertility levels of the soil, thereby saving valuable P-resources for the future.

INTRODUCTION

Phosphate (P) is a finite resource, depending on the increase in global use of rock phosphate a severe shortage of phosphate fertilizer is to be expected within 50-300 years.

In many parts of the world phosphorus is the limiting nutrient for crop growth, achieving profitable yields depends highly on the input of P-fertilizer.

In contrast, in the Netherlands in regions with a concentration of livestock raising (hogs, poultry) a surplus of organic manure has led to a more than sufficient P-fertility status of the soil. In these regions environmental concerns about the quality of ground water and surface water have forced the national government (endorsed by the European Union) to regulate the N and P input on land used by farmers. For nitrogen, crop-specific application rates were developed to meet the EU nitrate directive (<50 mg nitrate/L groundwater). For P a maximum input of 35 kg P kg ha^{-1} y^{-1} (80 P_2O_5) is now allowed (at farm level) but further reductions (to 26 kg P (60 kg P_2O_5)) are to be expected in the near future. This will force growers to reduce their P-input.

A shortage on P in the near future will have consequences for the maintenance of quality and yield of most agricultural crops, although the consequences will be much worse in regions like Africa with a general low P-status of the soil. We should realize that phosphorus is a valuable, essential, non-replaceable nutrient and that we should use it efficient. For a sustainable agriculture we should recycle P wherever possible and prevent losses by erosion or leaching. At this moment large quantities of phosphorus end up at the bottom of the oceans or in the ashes of incinerators, contaminated with heavy metals which prevent reuse of the phosphorus.

The Dutch government aims at an equilibrium fertilisation strategy for P, to be reached in 2015. This implies that P-application rates have to be proportional to maximum P-uptake and P-off take. Considering the Dutch recommendations there seems to be, unlike nitrogen, no relationship between the recommended P-application rates and the P-off-take (Neeteson et al., 2006). Following economic principles Dutch recommended P-application rates for some short growing crops are even higher than for longer growing crops, in spite of higher P-uptake and off-take for the latter. Therefore especially farms with intensive vegetable growing are expected to have difficulties in realizing the equilibrium fertilisation mentioned above.

What is the background of the bad (or even negative) correlation between recommended phosphorus application rates and phosphorus uptake? It is well known that due to the immobile character of the phosphate ion, root length determines to a great extent the potential phosphorus uptake capacity (de Willigen and van Noordwijk, 1987). Although relatively large differences in rooting pattern and root proliferation have been observed among crops (Smit and Groenwold, 2005) inherent crop rooting characteristics cannot explain this phenomenon. However, it can be hypothesized that sufficient root length will be a crucial factor particularly in the juvenile phase of growth. Obviously, the daily crop demand for phosphorus is then low, but so is the root length.

If the plant in this stage cannot realize the required P uptake it will be especially harmful for crops having a short growing period (most vegetable crops). The observation that a P-deficiency is in particular visible in the younger plant stages is in agreement with the above. Experiments with maize showed that yield differences due to lower P-inputs were created in the first part of the growing season (Plénet et al., 2000) and not after closure of the canopy at the time that growth rate (and P-uptake) would be much higher.

The consequence of this could be that for a good yield and quality a relative high phosphorus status of the soil is needed just to help the plant through the (early) growth phase when root length is limiting phosphorus uptake. After all, in that case a high concentration of phosphorus in the soil solution would alleviate the negative effect of insufficient root length. On the other hand it also means that relative small amounts of phosphorus, provided that they are applied in the vicinity of the young plant roots, are sufficient to maintain productivity at a lower soil phosphorus status. It is obvious that this results in opportunities to reduce the P-input, especially for leafy vegetables known for their high P-recommendation rates.

We therefore explored the effects of P-placement with special emphasis on vegetables with a desk study using a simulation model (a combination of a plant growth model and a soil model) to study interactions between P-fertility status, rooting and P-demand. In addition we carried out a climate chamber experiment in which we assessed the effect of P-placement on various vegetables focusing on early growth. An interesting research question is also whether a lower P-status can be accepted provided P-fertilization is done as a placement.

MATERIALS AND METHODS

Model Study

In a desk study, a cylindrical simulation model for water uptake, nutrient uptake and crop production (de Willigen et al., 2007) was used. The model used was a combination of two models: a Light INTerception and UtiLisation model LINTUL (van Ittersum et al., 2003) to simulate the aboveground processes and a three dimensional water balance and nutrient model FussimR to simulate the belowground processes (Heinen and de Willigen, 2001).

LINTUL calculates potential dry matter production using radiation, the leaf area index and a "Light Use Efficiency" (LUE). When the potential dry matter production is known, a "Water Use Efficiency" (WUE) is used to estimate potential transpiration. The actual dry matter production and actual transpiration is assessed after FussimR has indicated whether the demand for water can be met (see Pronk et al. (2005) for a short description). The actual dry matter is distributed between different sinks. N-demand is based on optimal N-concentrations in the dry matter, whereas the P-demand is based on a fixed ratio to the N-demand. FussimR modifies the dry matter available for root growth into root length density and root length distribution in the soil profile. Root development is simulated with a non-linear diffusion model (de Willigen et al., 2002). In the soil model P-transfer between soil and solution is described by a Langmuir equation, and assumed to be instantaneous (P available = P in solution and P reversibly adsorbed.

The simulation study was done with several "designed" crops, differing in rooting intensity and P-demand. Rooting intensity, characterized as weak, moderate and strong, was varied by changing the diffusion parameters for root growth (de Willigen et al., 2002), resulting in a root length density after 30 days of either 0.43, 0.84 and 1.72. P-demand was varied as 10, 20 and 30 kg P ha^{-1} (after 75 days of growth).

Several combinations of rooting and P-demand were simulated. In the model we attributed to each plant a cylinder of soil with a radius of half the plant/row distance (rectangular plant distribution) and a height of 1 m. The cylinder is horizontally divided in 11 rings and vertically in layers (6 layers of 5 cm and 7 layers of 10 cm) (Fig. 1).

Placement was simulated by applying P to a small volume (around 1% of the upper 30 cm of the profile). In this volume P-status was raised to 100, 200, 300, 400 and 500 mg water-extractable P_2O_5/L (after extraction in a 1:60 v/v ratio soil:water solution, this figure is called Pw in the Netherlands). The rest of upper 30 cm of the soil profile had a P-status of either 25 or 35 mg P_2O_5/L. A Pw of 35 is considered to be an average fertility status in the Netherlands. Below 30 cm a Pw of 15 was assumed. On a hectare basis placement required only limited amounts of P (from 1.7 to 10.8 kg P ha^{-1}).

After 30 days of growth realized uptake of P was compared with the P-uptake, necessary for unconstrained growth (P-demand).

If the required P-uptake could not be met (due to insufficient root length and/or low P-concentration), there was no negative feedback on growth in the model, so no yield predictions were made. The difference between required and actual P-uptake only indicates that the P demand for optimal growth could not be realized. How much this will have retarded growth is not calculated in the current model. Nitrogen was kept non-limiting under any condition.

Climate Chamber Experiment

An experiment in a climate chamber was performed with spinach, carrots and onion to verify the results of the simulation study. 3-L containers were used with a diameter of 15 cm and a height of 20.5 cm. A sandy soil low on P (Pw = 24) was selected from an experimental site in Achterberg (near Wageningen). The containers were either filled with unfertilized soil or soil which was homogeneously fertilized with P corresponding to 87 kg P ha^{-1}. The P fertilization resulted in an increase in water extractable phosphorus (Pw) from 24 to 31 (average during the time of the experiment, see Table 2). From the containers filled with unfertilized soil a small cylinder of soil (Ø 6 cm, 3 cm thick, corresponding to 3% of the pot volume) was removed in the center of the pot and was replaced by the same soil amended with different P rates (corresponding to either 4.4 or 13.1 kg P ha^{-1}). The same procedure, but without adding P-amended soil was done with the control treatment and the homogeneously fertilized soil.

This resulted in the four treatments:

P1: Control (Pw 24), not fertilized;
P2: Pw 24, + placement of 4.4 kg P ha^{-1};
P3: Pw 24, + placement of 13.1 kg P ha^{-1};
P4: homogeneously mixed with 87 kg P ha^{-1}, resulting in a Pw of 31.

The experiment was done in 4 replicates. After a germination period at 15ºC, temperature was lowered to 10ºC in order to mimic a field situation in early spring. Crops were harvested at 35, 54 and 55 days after sowing for spinach, carrots and onions resp.

Leaf area, dry matter yield and P-content were assessed.

RESULTS AND DISCUSSION

Model Study

In Table 1 the simulated P-uptake is shown for crops coded as C10, C20 and C30 with a total P-uptake of 10, 20 and 30 kg P respectively. Simulated P-uptake at Pw 25 was much lower than the demand for P. As could be expected less rooting and a higher demand lowers the percentage (% of required) indicated in the last column of the table. A higher Pw status of the soil increases this percentage but not more than 10%. However, this does not contradict the P-recommendations in the Netherlands: at soils with a Pw of 35 the most P-sensitive crops are advised to be fertilized with 68 kg P ha^{-1} (155 kg P_2O_5 ha^{-1}).

The ratio realized/demanded P-uptake was maximal (76%) for crop C20 with strong rooting characteristics. In contrast to the moderate effect of a higher P-status of the soil, a relative small application of placed P (6 kg P/ha) was very effective to realize the demanded P-uptake for all the conditions simulated. The simulation showed that in the early stages of growth P-uptake is strongly limited by the length of the root system, although relatively small amounts of P are concerned. On a hectare basis daily P-uptake, expressed as kg P/ha/day, will be very low in the juvenile stage and will increase with the development of the crop. However, we could confirm with the simulation model that if uptake of P is expressed as kg P/cm root length/day then quite an opposite picture appears: a with time decreasing uptake rate. This emphasizes the role of the root system in the early stages of growth, especially for sown vegetable crops with a short growing period.

Climate Chamber Experiment

The results of the climate chamber experiment are summarized in Table 3.

Placement of 4 and 13 kg P/ha (P2 and P3) had a strong and significant effect on growth (as illustrated by leaf area development and dry matter production) as well as on P-content of aboveground biomass. Strongest effects were measured in spinach and carrots. But also in onions leaf area increased more than 50% compared to the P1 treatment. In most cases a placement of only 4 kg P was as effective as the 87 kg P broadcasted (P4). Broadcasting 87 kg P/ha (in line with the recommendation for this P-fertility level) had increased the soil P-status from Pw 24 to 31. The results are comparable with the simulation study, in which we compared a Pw of 25 with 35, a similar range. Also there the conclusion was drawn that placement of small amounts of P had more effect than raising the P-fertility of the soil from Pw 25 to Pw 35. So the results of both studies are quite in line with each other, but will be tested under field conditions. In general we think that in the early growth stages the balance between root length and actual P-uptake is very fragile and may be easily influenced by environmental conditions (e.g., soil temperature, air temperature, soil moisture and radiation). This may explain why placement studies in the field often have conflicting and variable results.

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Tables

Table 1. Simulated P-uptake after 30 days for various crops, differing in total P-uptake at harvest (10, 20 and 30 kg P/ha; coded C10, C20 and C30 resp.) and in rooting characteristics (weak (R+), moderate (R++) or strong (R+++) as influenced by P-placement and soil P-status.

Crop code	Total P-uptake[1]	Rooting[2]	Soil P-status[3]	Place-ment[4]	P uptake after 30 days		
					Demand	Realized	% of demand
C10R+	10	+	25	0	1.5	0.8	53%
C10R+	10	+	25	6.3	1.5	1.6	101%
C10R+	10	+	35	0	1.5	1.0	62%
C10R+	10	+	35	6.3	1.5	1.6	101%
C20R+++	20	+++	25	0	3.1	2.1	67%
C20R+++	20	+++	25	6.3	3.1	3.2	101%
C20R+++	20	+++	35	0	3.1	2.4	76%
C20R+++	20	+++	35	6.3	3.1	3.2	101%
C20R++	20	++	25	0	3.1	1.6	51%
C20R++	20	++	25	6.3	3.1	3.2	102%
C20R++	20	++	35	0	3.1	1.9	61%
C20R++	20	++	35	6.3	3.1	3.2	102%
C20R+	20	+	25	0	3.1	1.1	33%
C20R+	20	+	25	6.3	3.1	3.2	102%
C20R+	20	+	35	0	3.1	1.4	44%
C20R+	20	+	35	6.3	3.1	3.2	102%
C30R++	30	++	25	0	4.7	1.9	40%
C30R++	30	++	25	6.3	4.7	4.8	101%
C30R++	30	++	35	0	4.7	2.3	49%
C30R++	30	++	35	6.3	4.7	4.7	99%

[1] Total P-uptake at harvest after 75 days of growth
[2] Root length density after 30 days of growth was 0.43, 0.84 and 1.72 respectively for +, ++ and +++
[3] P-status (Pw) is expressed in mg P_2O_5 L^{-1} after extraction in a 1:60 v/v ratio soil: water solution
[4] Placement of P is done in 1% of the soil volume

Table 2. Treatments of the P-placement experiment.

Treatment	P-fertilization in kg P/ha	P added as mg P/kg soil	Average P-status (Pw) during the experiment
P1	0	0	24
P2	4.4	58 in 3% of the soil volume	-
P3	13.4	175 in 3% of the soil volume	-
P4	84	35 homogeneously	31

Table 3. The effect of P-fertilization (by placement and broadcasted) on some plant characteristics in spinach, onions and carrots in a climate chamber pot experiment.

Variable	Crop	P fertilization in kg P/ha[1]			
		Placement			Broadcast
		0	4.4	13.1	87
Leaf area (cm^2)	spinach	90	123	196	113
	onion	6	5	9	7
	carrots	5	7	17	7
Dry matter (mg per pot)	spinach	603	828	1070	715
	onion	115	123	160	135
	carrots	48	70	123	62
P-content (mg/kg)	spinach	1.6	2.0	3.2	2.0
	onion	1.1	1.1	1.5	1.1
	carrots	2.1	2.3	2.8	2.5

[1] The P-rates in the table are scaled up to kg P/ha assuming a topsoil of 20 cm (the height of the pots). The effects of P-fertilization were significant (ANOVA) for all crops and all variables.