

Critical Soil Phosphorus Values for Yield Reduction in Intensive Agricultural Systems

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Abstract: Phosphorus (P) is an essential element for agricultural production. Over-fertilization during decades caused an accumulation of P in soils leading to eutrophication in regions characterized by intensive agriculture. These environmental concerns together with the non-renewability of P resources have led to a more sustainable P use. Knowledge about the P need of crops is essential for a sustainable agriculture thereby minimizing P losses to the environment without lowering the yield substantially. Therefore, in this study, critical soil P values for yield reduction (P_{crit}) were determined based on fertilizer trials conducted between 1970 and 1988 and more recent fertilizer trials (2016-2017). At rotational level a common P_{crit} value of 109 mg P/kg dry soil (in an ammonium lactate and acetate extract) was determined. Crop specific P_{crit} values were also determined for seven crops (potato, winter wheat, barley, rye, maize, sugar beet and temporary grassland). These critical values ranged from 59 mg P/kg dry soil to 164 mg P/kg dry soil with winter wheat the least and maize the most sensitive towards P deficiency. The diversity in P_{crit} values among crops can mainly be explained by the root intensity but also rooting depth, exudation of organic acids and phosphatases may influence the P_{crit} value. The soil pH also influenced the P availability significantly. Soils with a favorable pH had a significantly higher availability (i.e., lower P_{crit} value) for all crops compared to soils with a suboptimal pH. Critical soil P values might help to set up new or to evaluate current soil P in target zones used for P fertilizer recommendations.

Key words: Phosphorus, critical levels for yield reduction, crop specific, target zone, soil phosphorus availability, intensive agriculture.

1. Introduction

Phosphorus (P) is an essential element for plant development and optimal yield production. To fulfill the P need of the plant and to maximize yield, farmers apply organic and/or inorganic P fertilizers. The intensive use of P fertilizers has led to two major problems. First, in Europe, soils have been over-fertilized during decades, i.e., the P added to the soil by fertilizers exceeded the amount of P taken up by plants. This caused an accumulation of soil P in several regions characterized by intensive agriculture such as for example Flanders (Belgium) [1]. Due to runoff, soil erosion and leaching, the excess of P ends up in

the surface and ground water [2]. This eutrophication negatively affects the biodiversity of surface water and decreases the quality of drinking water [3, 4]. Second, also economic problems may arise, for example during the global P crisis in 2007-2008, since P fertilizers are mainly derived from phosphate rocks which are a non-renewable resource. Depending on the forecast model, the P rock reserves will be exhausted in the next decades [5]. The higher manufacturing costs in combination with a P scarcity will lead to higher P fertilizer prices [5-7]. The environmental and economic concerns related to P fertilization have led to a reduced use of P in agriculture.

Sustainable P use in agriculture requires minimalizing P losses to the environment while maintaining an optimal yield. Critical soil P levels for

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yield reduction (P_{Crit}), are useful to determine sustainable P management measurements, e.g., P fertilization recommendations. A comparison of Jordan-Meille *et al.* [8] between European P fertilizer recommendation systems showed significant variations in P fertilizer recommendations across Europe. Differences in P_{Crit} values may possibly explain this diversity, but also differences in measuring methods. More than 10 different soil P tests are used across Europe to determine the soil available P, each of them measuring a different P amount of the soil. Consequently, critical soil P values are always related to a specific soil P test. A general comparison of P_{Crit} values between different soil P tests on European soils has already been made by Nawara *et al.* [9].

P_{Crit} values depend on plant properties such as the P need of crops, the length of the growing season and root morphology. Besides plant properties, the P_{Crit} also depends on the plant availability of P in soils which is rather complex and strongly relates to soil properties. P can be present in the soil solution, immobilized in organic compounds, precipitated in minerals or adsorbed on Fe/Al (hydro)oxides. The soil solution P is directly available for uptake by plants, whereas the other P forms replenish the soil solution P when it is depleted. The variety of interactions between P and soil particles results in a continuum of sorption and desorption kinetics. A parameter influencing these processes is the soil pH. This implies that the soil pH is a major factor controlling the soil P availability to plants [3, 10-12], and that it might also affect the P_{Crit} value. However, it is unknown to what extent the soil pH might affect P_{Crit} values.

The above highlights the importance of determining P_{Crit} values per region and per soil P test. However, P_{Crit} values specific for the soils in the Flanders region do not exist. This study was set up to determine P_{Crit} for Flanders for different crops. The study was based on historical and more recent P fertilizer trials in

Flanders. The soil P content was determined by an ammonium lactate extract [13, 14], which is the standard procedure used in Belgium to determine the soil P content. The objectives of this study were (i) to determine a common and seven crop specific P_{Crit} values (potato, winter wheat, barley, rye, temporary grassland, maize and sugar beet), and (ii) to evaluate the influence of the soil pH on the P_{Crit} values.

2. Materials and Methods

Data in this study were derived from two data sets: (i) from historical fertilization trials carried out by the Soil Service of Belgium during 1970-1988 and (ii) from new P fertilization field trials set up in 2016 and 2017 by the Soil Service of Belgium and the Institute for Agricultural and Fisheries Research.

2.1 Experimental Design of Historical P Fertilization Trials

The historical fertilization field trials (1970-1988), all long-term NPK-fertilizer trials, were selected from the archive of the Soil Service of Belgium. Only field trials with at least two different P treatments were selected. Further prerequisites for selection were a known soil P content per treatment and a known yield per treatment replicate. In total, 16 field trials met these conditions (Table 1). The soil types varied between sand, sandy loam and silt soils. Each field trial had a P0-treatment (no fertilization) and depending on the field trial there were in total two, three, four or five P treatments. The fertilization doses depend on the crop type and the number of P-treatments varying from 0 till 600 kg P_2O_5 /ha. The initial soil P content of the P0-treatments varied between 75 mg P/kg dry soil and 370 mg P/kg dry soil. Due to the long-term character of the field trials a large range of soil P level was obtained (50-430 mg P/kg dry soil). All field trials were constructed in a randomized block design of four blocks (treatment replicates) with exception of the field trials in Ath and Carlsbourg which had six blocks. Crops were

Table 1 Characteristics of the phosphorus (P) fertilizer trials conducted during 1970-1988.

No.	Location	Year	Crops	Soil type	P _{AL, initial, P0-treatment} (mg P/kg dry soil)	P _{AL-range} (mg P/kg dry soil)	pH-KCl _{average}	% C _{average}
1	Mol	1970-1971	Potato, temporary grassland	Sand	190	160-190	4.9	3.1
2	Weelde	1970-1972	Potato, temporary grassland, rye	Sand	160	140-210	4.6	2.7
3	Reppel	1970-1974	Potato, temporary grassland, rye, barley	Sand	130	90-190	5.0	1.4
4	Houthalen	1970-1974	Potato, temporary grassland, rye, barley	Sand	150	140-290	4.7	2.2
5	Kasterlee	1970-1973	Potato, temporary grassland, maize	Sand	260	210-300	4.6	3.3
6	Kaulille	1970-1974	Potato, temporary grassland, maize	Sand	120	70-150	4.2	2.4
7	Niel-bij-As	1970-1972	Potato, temporary grassland, barley	Sand	100	100-120	4.3	1.5
8	Olmen	1970-1973	Potato, temporary grassland, rye, maize	Sand	290	280-380	4.4	2.5
9	Retie	1970-1972	Potato, temporary grassland, rye,	Sand	300	270-330	4.7	3.4
10	Bocholt	1970-1974	Potato, temporary grassland, maize	Sand	280	190-350	4.7	2.1
11	Oostmalle	1970-1974	Potato, temporary grassland	Sand	370	370-430	4.9	2.5
12	Retie	1970-1974	Potato, temporary grassland, barley	Sand	330	260-330	5.6	3.8
13	Ath	1973-1987	Potato, winter wheat, barley, sugar beet	Silt	115	60-330	6.4	0.9
14	Carlsbourg	1972-1981	Temporary grassland, winter wheat, maize	Silt	75	50-390	5.3	2.9
15	Geetbets	1973-1980	Maize, winter wheat, barley, sugar beet	Sandy loam	175	130-220	6.0	1.3
16	Jezus-Eik	1983-1988	Sugar beet, winter wheat, barley	Silt	125	95-160	7.1	1.5

P_{AL} is the soil P content determined in an ammonium lactate and acetate extract; P_{AL, initial, P0 treatment} is the soil P content of the P0-treatment (zero fertilization) at the start of the field trial; P_{AL-range} is the range of the soil P content of all the P-treatments; pH-KCl_{average} is the average soil pH of all the treatment replicates determined in a KCl extract; % C_{average} is the average of total organic carbon (TOC) content of all the treatment replicates.

cultivated in a three- or four-year rotation. In total, seven crops were cultivated: potato (*Solanum tuberosum* L.), maize (*Zea mays* L.), rye (*Secale cereale* L.), winter wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), sugar beet (*Beta vulgaris* L.) and temporary grassland (Poaceae).

2.2 Experimental Design of Recent P Fertilization Trials

Data from the historical P fertilization trials were extended with more recent P fertilization trials. These soils were specifically chosen for their relatively low P content. Appropriate fields for the recent P fertilization trials were selected based on three criteria: a low soil P content, an optimal pH and an optimal carbon content (% C). The latter two factors are essential for optimal growth conditions [1]. Three crops were cultivated (winter wheat, maize and potato), each of them being cultivated at least once on sand, sandy loam and silt soils. In total, 13 P

fertilization trials were conducted in 2016 and 2017 (Table 2).

The majority of the field trials were arranged according to a randomized block design of three blocks. The field trials in Korbeek-Lo, Diest, Bekkevoort, Haasrode (2017) and Lille had four blocks. The area of the plots varied between 25 m² and 90 m² depending on the crop type, specific field trial properties and the equipment of the farmer. Four different P treatments were applied: zero fertilization (P0), equilibrium fertilization which corresponds to the annual P crop export [15] (P1), fertilization corresponding to twice the annual crop export (P2) and fertilization corresponding to thrice the annual crop export (P3). The crop specific fertilization doses correspond to these four fertilization levels given in Table 3. The P fertilizer was applied as triple superphosphate. All other nutrients were applied in sufficient amounts to ensure that the crop response depends only on the P supply.

Table 2 Characteristics of the P fertilizer trials conducted between 2016 and 2017.

No.	Location	Year	Crop	Soil type	P _{AL} (mg P/kg dry soil)	pH-KCl	% C
1	Parike	2016	Potato	Silt	90	6.4	1.0
2	Haasrode	2016	Potato	Silt	100	6.5	1.3
3	Assenede	2017	Potato	Sand	110	5.9	1.3
4	Kessel-Lo	2017	Potato	Sandy loam	178	6.7	1.1
5	Herfelingen	2016	Winter wheat	Silt	80	6.1	1.3
6	Korbeek-Lo ^a	2016	Winter wheat	Silt	74	6.4	0.9
7	Diest ^a	2017	Winter wheat	Sand	80	6.2	1.2
8	Bekkevoort ^a	2017	Winter wheat	Sandy loam	79	6.0	0.9
9	Haasrode ^a	2017	Winter wheat	Silt	85	5.2	1.4
10	Zarlardinghe	2016	Maize	Silt	60	6.8	1.4
11	Lille ^a	2016	Maize	Sand	78	5.2	2.5
12	Schoonaarde	2017	Maize	Sandy loam	91	5.1	1.5
13	Parike	2017	Maize	Silt	105	6.1	0.9

^a Field trial consisted of four treatment replicates instead of three.

P_{AL} is the initial soil P content determined in an ammonium lactate and acetate extract; pH-KCl is the soil pH determined in a KCl extract; the % C is the TOC.

Table 3 P fertilization doses (kg P₂O₅/ha) used in the recent fertilizer field trials (2016-2017) for winter wheat, maize and potato and the annual P crop export of the examined crops [15].

	P0	P1	P2	P3	Annual crop export	
		(kg P ₂ O ₅ /ha)			(kg P ₂ O ₅ /ha)	(kg P/ha)
Winter wheat	0	80	160	240	82	36
Maize ^a	0	80	160	240	83 79	36 34
Potato	0	60	120	180	58	25
Sugar beet	-	-	-	-	59	26
Grassland (mowing)	-	-	-	-	97	42
Barley/rye	-	-	-	-	74	32

^a Annual crop export for respectively forage and grain maize.

2.3 Data and Subdatasets Used in This Study

To calculate common and crop specific P_{Crit} values the data of the historical and more recent P fertilization trials are joined together. The total data set includes 1,538 observations originating from 29 field trials and seven crops (Table 4). To determine the effect of the soil pH on P_{Crit} values, the data set was subdivided into two data sets: one ($n = 1,104$) which consists of observations with a favorable pH-KCl and another ($n = 434$) which consists of observations with a suboptimal pH-KCl (Table 4).

The Soil Service of Belgium classifies several soil characteristics (such as % C, pH, N-, P-, K-content, etc.) in seven soil fertility classes. These are: very low, low, rather low, target zone, rather high, high and very

high. The pH is considered favorable in this study when it is classified in the soil fertility class “rather low”, “target zone” and “rather high” because the optimal pH depends on the crop, soil type, and % C. In this study, the data set with suboptimal pH consists solely of observations with a pH soil fertility class “low” and “very low”. In practice, favorable pH-KCl of soils with an optimal % C corresponds to a range of 4.6-6.2 for sand soils, a range of 5.6-6.9 for loam soils and 6.1-7.7 for silt soils.

2.4 Crop Sampling and Analysis

Only the center of the plots was harvested to avoid border effects. Maize and potato were harvested manually, winter wheat mechanically. A crop sample

Table 4 Number of observations per crop for the database with and without distinction between soil pH-KCl.

	Total number of observations	The number of observations per crop						
		Potato	Sugar beet	Maize	Temporary grassland	Rye	Barley	Winter wheat
Complete data set (all pH-KCl classes)	1,538	329	100	189	267	59	312	282
pH-KCl favorable ^a	1,104	253	100	112	132	29	214	264
pH-KCl suboptimal	434	76	0	77	135	30	98	18

^a pH-KCl is considered favorable when it is classified in the soil fertility class “rather low”, “target zone” and “rather high” defined by the Soil Service of Belgium.

Favorable pH-KCl of soils with an optimal % C: sandy soil = 4.6-6.2, sandy loam soil = 5.6-6.9, silt soil = 6.1-7.7.

Table 5 Critical soil P levels for yield reduction (P_{Crit}) (cut-off at 95% relative yield (RY)) (mg P/kg dry soil) for the different data sets.

Crop	Total data set		pH-KCl favorable		pH-KCl suboptimal	
	P_{Crit} (mg P/kg dry soil)	Std. dev. (mg P/kg dry soil)	P_{Crit} (mg P/kg dry soil)	Std. dev. (mg P/kg dry soil)	P_{Crit} (mg P/kg dry soil)	Std. dev. (mg P/kg dry soil)
Common	109		67		135	
Potato	111	9	61	15	126	14
Temporary grassland	86	9	37	24	80	11
Maize	164	10	144	54	257	21
Rye	159	28	/	/	/	/
Sugar beet	78	18	57	21	/	/
Barley	156	8	142	35	179	14
Winter wheat	59	10	26	9	83	28

pH-KCl is considered favorable when it is classified in the soil fertility class “rather low”, “target zone” and “rather high” defined by the Soil Service of Belgium.

Favorable pH-KCl of soils with an optimal % C: sandy soil = 4.6-6.2, sandy loam soil = 5.6-6.9, silt soil = 6.1-7.7.

was taken for every crop on every treatment replicate. The plant samples were dried at 105 °C for 16 h to determine the plant dry weight. The crop P content was determined after heating the dried samples at 550 °C until they were ashed. The ashed sample was dissolved in a solution of 1 N HNO₃ from which the P content was determined by inductively coupled plasma-optical emission spectrometry (ICP-OES).

2.5 Soil Sampling and Analysis

All soil samples were taken from the top soil (0-23 cm) and analyzed by the Soil Service of Belgium (BELAC accredited). The soil was dried at 70 °C and 2-mm sieved before analysis. The soil P content was determined in an ammonium lactate and acetate extract with a buffered pH of 3.75 abbreviated as P_{AL} . Under a soil:extract ratio of 1:20 a soil sample was

added to the extract which consists of 0.1 M ammonium lactate and 0.4 M acetate. The soil P content was determined by ICP-OES after an extraction time of 4 h [13, 14]. After analysis, the obtained soil P content (based on soil dried at 70 °C) was corrected for the moisture content (soil dried at 105 °C).

The soil pH is determined in a potassium chloride extract of 1 N (pH-KCl). The soil:extract volume ratio is 1:10. The pH-KCl is measured after an extraction time of 12 h [16]. The carbon content (% C) is determined as the total organic carbon (TOC) content. For this, inorganic carbon was removed by extracting the soil with phosphoric acid (85%) for at least 4 h. Hereafter the TOC analyzer burned the sample at 1,350 °C. The amount of CO₂ released during this process was measured by infrared spectrometry and is a direct measurement of the TOC content [17].

2.6 Critical Soil P Level

Because maximal yields vary between years due to climatological circumstances, a relative yield (RY) is used. This enables a comparison between yields from different years and different crops. RY is calculated as the yield relative to the maximum yield (Eq. (1)). The maximum yield is assumed to be the average yield of the treatment replicates which received the highest P fertilizer dose.

$$RY (\%) = \frac{\text{Yield}}{\text{Maximum yield}} \times 100 \quad (1)$$

The P_{Crit} value was defined in this study as the soil P level where the RY is 95%. A soil P content below this value is considered as a primary P-deficiency which results in a significant yield reduction. The Mitscherlich model (Eq. (2)) was used to determine this P_{Crit} value. This nonlinear model plots the RY against the P_{AL} :

$$RY (\%) = a + (100 - a) \times (1 - \exp(-b \times P_{\text{AL}})) \quad (2)$$

where a is the RY at $P_{\text{AL}} = 0$ and b is the slope of the model. The common P_{Crit} value (across all crops) is calculated by using the inverse of the Mitscherlich model (Eq. (3)).

$$P_{\text{Crit}} = \frac{\ln(1 - \frac{RY - a}{100 - a})}{-b} \quad (3)$$

Crop specific P_{Crit} values were determined besides a common P_{Crit} value to get more insight in the P needs of crops commonly cultivated in Flanders. The original Mitscherlich model was therefore expanded with dummy variables (0/1 coding) (Eq. (4)).

$$RY (\%) = a + (100 - a) \times (1 - \exp[-b_{\text{av}} \times P_{\text{AL}} \times (1 + b_{\text{po}} \times d_{\text{po}} + b_{\text{tg}} \times d_{\text{tg}} + b_{\text{ww}} \times d_{\text{ww}} + b_{\text{b}} \times d_{\text{b}} + b_{\text{r}} \times d_{\text{r}} + b_{\text{sb}} \times d_{\text{sb}} + b_{\text{m}} \times d_{\text{m}})]) \quad (4)$$

where a is the intercept and b_{av} is the average slope, b_x is the slope specific for crop x , d_x is the dummy variable specific for crop x (0/1). The studied crops are: potato (po), temporary grassland (tg), winter wheat (ww), barley (b), rye (r), sugar beet (sb) and maize (m).

A one-sided Z-test ($\alpha = 0.05$) was conducted to check whether the P_{Crit} values of the two data subsets (subdivided based on pH) were statistically significant different.

All data analysis was performed with the statistical program JMP Pro 14.

3. Results

3.1 Critical Soil P Level

The Mitscherlich model describing the RY against the soil P content (P_{AL}) is given in Fig. 1 for the three data sets: total data set ($R^2 = 0.14$), pH favorable soils ($R^2 = 0.05$) and pH suboptimal soil ($R^2 = 0.14$). The common P_{Crit} value, i.e., the soil P level which results in a RY of 95%, is 109 mg P/kg dry soil when no distinction is made between the soils depending on the pH. The crop specific P_{Crit} values (Table 5), range from 59 mg P/kg dry soil (winter wheat) to 164 mg P/kg dry soil (maize). The crop specific P_{Crit} values increase with their sensitivity to P deficiency in the following order: winter wheat < sugar beet < temporary grassland < potato < barley < rye < maize.

3.2 Influence of pH on Critical Soil P Level

P_{Crit} values are the lowest for all crops when the soil pH is favorable (Table 5). The common P_{Crit} value decreases down to 67 mg P/kg dry soil when only taking the dataset with soils with a favorable pH into account, whereas an increase in P_{Crit} is observed up to 135 mg P/kg dry soil for soils with a suboptimal pH. Also, the crop specific P_{Crit} values decrease and increase, respectively. The crop order in sensitivity for P deficiency for the soils with a favorable pH is: winter wheat < temporary grassland < sugar beet < potato < barley < maize. This is similar to the analysis where no pH-distinction was made, except for sugar beet and temporary grassland. For the soils with a suboptimal pH, the crop specific P_{Crit} values range from 80 mg P/kg dry soil to 257 mg P/kg dry soil, whereas this varied between 26 mg P/kg dry soil and 144 mg P/kg dry soil for the soils with favorable pH.

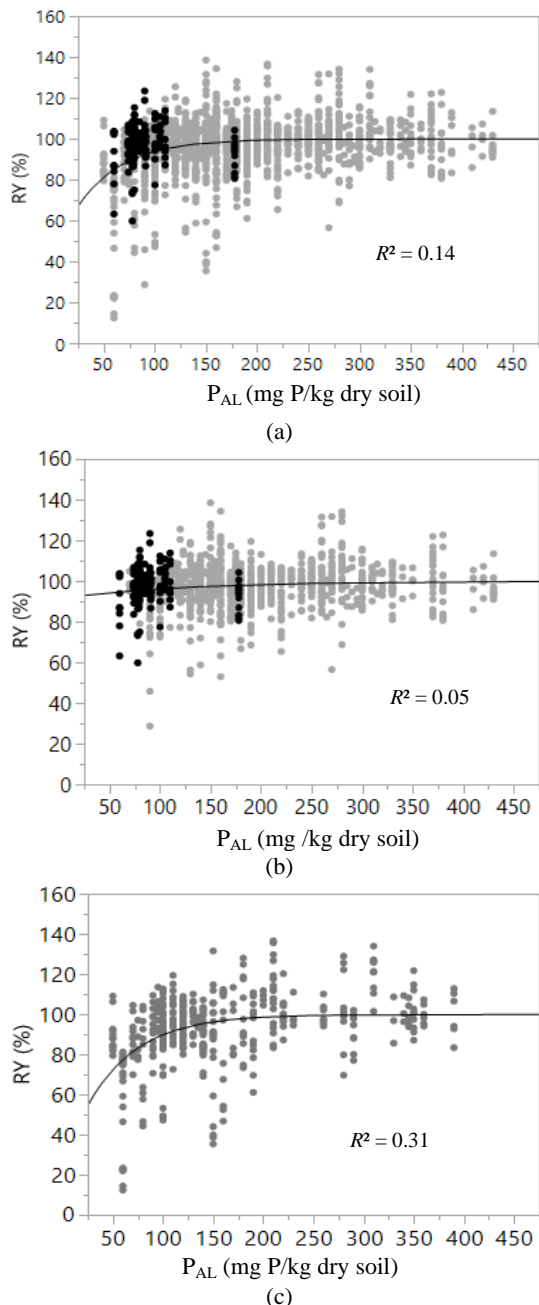


Fig. 1 Relative yield (RY) as a function of the soil phosphorus (P) content (determined in an ammonium lactate/acetate extract, P_{AL}) for: (a) all soils, (b) soils with a favorable pH-KCl and (c) soils with a suboptimal pH-KCl.

The pH-KCl is considered favorable when it is classified in the soil fertility class “rather low”, “target zone” and “rather high” defined by the Soil Service of Belgium. Favorable pH-KCl of soils with an optimal % C: sandy soil = 4.6-6.2, sandy loam soil = 5.6-6.9, silt soil = 6.1-7.7. Observations from the fertilization trials conducted between 1970 and 1988 are indicated in grey. Observations from the fertilization trials conducted in 2016 and 2017 are indicated in black. Lines represent the Mitscherlich model.

4. Discussion

4.1 Can Different Crop Specific P_{Crit} Be Explained by the P Need/Export?

From Table 5, it is clear that the P_{Crit} values differ widely between crops. A possible way to classify these P_{Crit} values is by the annual P crop export. However, the results in this study indicate that a classification based on P_{Crit} values does not relate to a classification based on the annual P crop export (Table 3). Winter wheat has the highest annual crop export of all cereals although it has the lowest P_{Crit} value (59 mg P/kg dry soil). Temporary grassland has a relatively low P_{Crit} value (86 mg P/kg dry soil) but has the highest annual P crop export of 110 kg P_2O_5 /ha [18]. Potato is considered to have a high soil P need [1, 19-22]. However, the annual P crop export is only 59 kg P_2O_5 /ha [18]. This indicates that solely the annual P crop export is not an adequate factor for classifying the crop specific P_{Crit} values.

Two plant properties which explain better the P_{Crit} values are the length of the growing season (which is correlated with the crop export [23]) and the root system. Crops with a long growing season have a relatively long period to complete their life cycle which results in lower P-uptake rate and lower sensitivity towards P deficiency. Such crops will most likely develop better in P deficient soils compared to crops with a short growing season. The length of the growing season is a reason why vegetables with a short growing season have high P_{Crit} values. For arable crops the effect of the growing season is less clear compared to vegetables although the length of the growing season may explain why the P_{Crit} value of winter wheat (59 mg P/kg dry soil) which has a longer growing season than barley is lower than the P_{Crit} of barley (156 mg P/kg dry soil). In this study barley consists of both winter and summer barley.

A second plant property important for explaining the variation of P_{Crit} values between crops is the root system. Since the P mobility in the soil is relatively limited due to several fixation processes, roots grow

towards the nutrition zone. This emphasizes the importance of an extended root system for P acquisition [4, 11, 24]. Plant roots form a complex system. They have several mechanisms for an enhanced nutrient acquisition such as secretion of phosphatases, exudation of organic acids, adaptation of root architecture, symbiosis with mycorrhiza, root hair formation, etc. [25-31]. These root mechanisms are more expressed under severe P deficiencies. However, also in P rich soils, which are often the case in Flanders, such root mechanisms are important for P acquisition.

4.2 Explaining Crop Specific P_{Crit} Based on Root Architecture

The rooting depth can also influence the P_{Crit} value of a crop. However, cereals like barley, rye and wheat have deep roots, yet their P_{Crit} values differ widely (respectively 156, 159 and 59 mg P/kg dry soil) [32, 33]. Crops with a deep rooting system have the biggest advantage in dry conditions or in soils low in P content and with P reserves in deeper soil layers [24, 28, 34]. Since these conditions are not often applied to most Flemish soils, the advantage of a deep root system for a better P acquisition is rather limited and plays only a minor role in explaining the differences in P_{Crit} values between the crops.

The root intensity however is a more meaningful parameter in explaining the critical value for relatively immobile nutrients such as P [4, 24]. Since most soil P is concentrated in the upper soil layers an intensive root system in the upper soil layers is preferable [28, 30, 34, 35]. Plants grown in low P soils therefore increase their root surface in the upper soil layers by enhancing lateral root formation, shallower growth angles of lateral roots, increasing length and the number of root hairs, reducing root diameter, enhancing adventitious rooting etc. [28-30, 35, 36].

Grassland has a fibrous root system with a high root distribution in the upper soil [24]. Although there are differences in root distribution between grassland and

temporary grassland, the latter may have a higher root intensity in the upper layer than most arable crops which may explain why temporary grassland has a relatively low P_{Crit} value of 86 mg P/kg dry soil. Potatoes are considered to be P sensitive because of their shallow and not so intensive rooting system [1, 18, 20-22, 37, 38]. Although it must be stated that the measured P_{Crit} value of potato in this study (110 mg P/kg dry soil) was lower than what can be expected from the literature.

Maize has the highest P_{Crit} value (164 mg P/kg dry soil) of all the evaluated crops (Table 5). It may be hypothesized that this is due to the slow root growth of maize in early development stages. Early in the growth season the root intensity is too low and therefore the uptake capacity is insufficient to satisfy the crop P need. However, at the end of the growing seasons P deficiencies are often eliminated and no yield difference is observed. It is thus not sustainable for maize to increase the soil P level with high amounts of P fertilizers to fulfill the P need early in the growing season. A better and more efficient management strategy is placement of P fertilizers where relatively low amounts of P fertilizer are supplied nearby the roots [4, 23, 37].

Although root architecture (rooting depth and especially root intensity) is an important factor for P_{Crit} values, it cannot solely explain differences in P_{Crit} values. For example, sugar beet has, compared to wheat and grass, a smaller root system and a smaller root to shoot ratio [23, 39, 40]. Yet, it appears from the results in this study that sugar beet (78 mg P/kg dry soil) is relatively insensitive towards P deficiency. Föhse *et al.* [40] concluded already in 1988 that P uptake efficiency of plants is determined by the root to shoot ratio or the P influx. Wheat and temporary grassland are less sensitive towards P deficiency due to a high root to shoot ratio while sugar beet is less sensitive towards P deficiency because of its high absorption rate per unit of root (influx) [39]. This explains why this study achieved the lowest P_{Crit}

values for these three crops (59, 78 and 86 mg P/kg dry soil for respectively winter wheat, sugar beet and temporary grassland).

Root architecture and length of the growing season appears to be major factors in explaining the differences in P_{Crit} values between crops. However, not everything can be explained solely based on these characteristics; P acquisition also depends on several factors such as root hairs, excretions of organic acids and phosphatases, acidification of the rhizosphere, symbiosis with mycorrhizae, etc.

4.3 Influence of Soil pH on the P Availability

Previous paragraphs focused on the most important plant properties to explain the crop sensitivity toward P deficiency. However, soil characteristics (pH, moisture content, soil temperature, soil structure, etc.) are besides plant properties important factors which influence the P availability and hence the P_{Crit} values. This study focused on the soil property “soil pH” since it has a significant influence on soil P processes. Mineralization is impeded at a suboptimal pH, Ca-P minerals are formed at high soil pH, Fe/Al-P minerals are formed or P is adsorbed on Fe/Al (hydro)oxides when the pH is low [3, 4, 11, 12]. Based on these

studies it was expected that a suboptimal soil pH, both too low and too high, decreases the P availability resulting in a higher P_{Crit} value. Geypens *et al.* [41] reported in 1992 that the P availability is greatly affected by the soil pH. In that study winter barley showed a P fertilization effect at a P_{AL} of 350 mg P/kg dry soil (i.e., approximately twice the upper limit of the target zone currently used in Flanders (120-180 mg P/kg dry soil)) caused by the soils acidity (pH-KCl 5.3, silt soil). The results obtained in this study are in line with Kostic *et al.* [42]. The P_{Crit} value of soils with a suboptimal pH is statistically significant ($p < 0.001$) higher than the P_{Crit} value of soils with favorable pH for all crops (Fig. 2). These results imply that at a favorable pH the same yield can be obtained at a lower soil P level. This is beneficial from both economic and ecological point of view and highlights the importance of having an optimal soil pH on agricultural soils.

4.4 Uniform P_{Crit} Values across the World?

It is important to compare only P_{Crit} values determined by the same soil P test because a wide variety of soil P tests each have extracting different P quantities due to differences in chemical extract used,

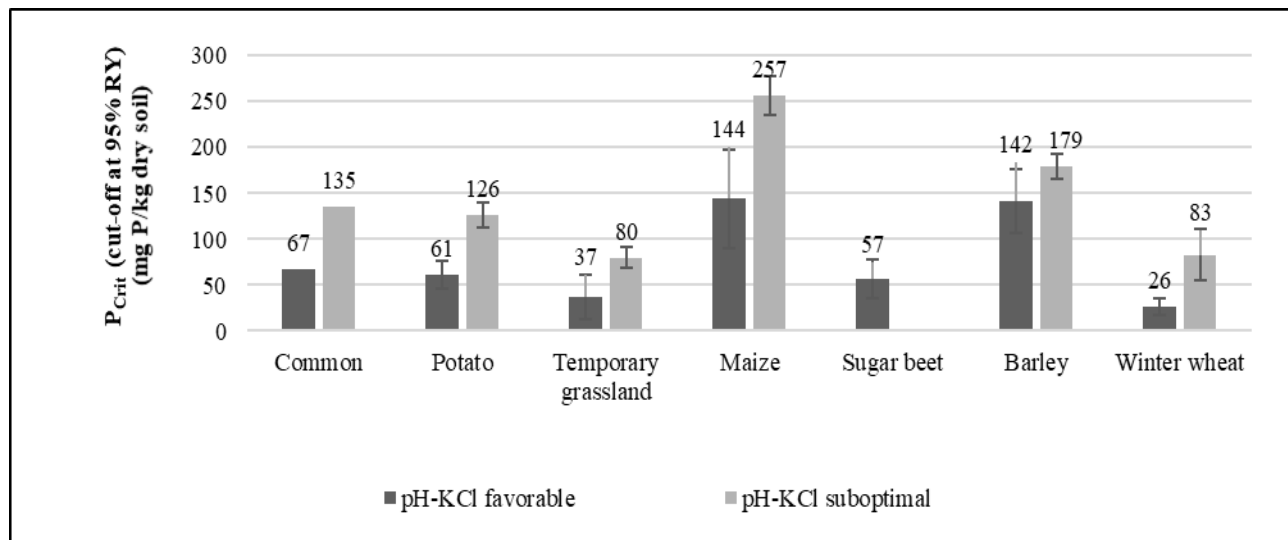


Fig. 2 Comparison of critical soil phosphorus levels for yield reduction (P_{Crit}) (cut-off at 95% RY) (mg P/kg dry soil) of soils with a favorable and soils with a suboptimal pH-KCl.

The pH-KCl is considered favorable when it is classified in the soil fertility class “rather low”, “target zone” and “rather high” defined by the Soil Service of Belgium. Favorable pH-KCl: sandy soil = 4.6-6.2, sandy loam soil = 5.6-6.9, silt soil = 6.1-7.7.

extract pH, extraction time, etc. [9, 43]. Currently, more than 10 different soil P tests are used in Europe [8]. Correlation and conversions between different soil P tests are confounded by strong interactions between soil and extractants and are often tested on only a few soil types. Using such generalized correlations to recalculate soil P values for all soils is not recommended [8].

P_{Crit} values are mostly defined based on a P_{Olsen} soil test (alkaline P extraction with NaHCO_3). Due to the above mentioned reason these P_{Crit} values cannot be compared in absolute values with the Flemish P_{Crit} values based on the P_{AL} soil test. However, a relative ranking of the crop specific P_{Crit} values can be used for comparing P_{Crit} values determined by different soil tests. Johnston *et al.* [44] determined the following order of P_{Crit} values: grass (pot experiment) < sugar beet < spring barley < potato. The results in this study are in line with these conclusions except for potato. Poulton *et al.* [45] determined a similar P_{Crit} value for winter wheat and spring barley which is contradictive with this study. Zicker *et al.* [35] obtained the following order in P sensitivity: winter cereals < spring cereals < maize < sugar beet. These results correspond with this study except for the high P sensitivity of sugar beet. Colomb *et al.* [46], Cox [47], Sucunza *et al.* [48], Tang *et al.* [49] and Wu *et al.* [50] concluded all that wheat is more sensitive towards P-deficiency than maize which is the opposite of the results in this study. In the work of Cox [47] and Tang *et al.* [49] this was due to the lower temperature in which winter wheat was grown which impeded P uptake.

P_{Crit} values are often only determined for a limited number of crops and they are rarely based on a P_{AL} soil test. However, a study of Nawara *et al.* [9] determined a common and six crop specific P_{Crit} (potato, wheat, flax, sugar beet, barley and maize) for European soils for five different P soil tests (extraction with ammonium lactate (P_{Ox}), alkaline extraction with NaHCO_3 (P_{Olsen}), extraction with ammonium lactate/acetate (P_{AL}), extraction with

CaCl_2 (P_{CaCl_2}) and the diffusive gradient in thin film technique (P_{DGT}). Despite a similar methodology as in Nawara *et al.* [9] the Flemish P_{Crit} values of this study differed greatly for some crops from the European P_{Crit} values of Nawara *et al.* [9]. The latter determined a potato P_{Crit} value of 200 mg P/kg dry soil compared with 111 mg P/kg dry soil in this study. The Flemish P_{Crit} value of 164 mg P/kg dry soil and 156 mg P/kg dry soil for respectively maize and barley are more than the three- and two-fold of the P_{Crit} values determined by Nawara *et al.* [9]. The common P_{Crit} value in this study is 36 units higher than this of Nawara *et al.* [9] (109 mg P/kg dry soil compared to 73 mg P/kg dry soil).

A first major reason for discrepancies between studies can be the mathematical model that is used. Cox [47] and Tang *et al.* [49] stated that critical levels depend on the mathematical function used. A different definition of the RY or P_{Crit} value also influences the determination of the P_{Crit} value. Johnston *et al.* [44] and Poulton *et al.* [45] defined the P_{Crit} value as: “The Olsen P associated with 98% of the asymptotic yield”. Sucunza *et al.* [48] determined the critical level at 90% RY while this study uses 95% RY as an operational cut-off for P deficiency.

Two other factors that may explain differences between studies are the agricultural system and the history of the soil P content. Colomb *et al.* [46] calculated P_{Crit} values for a low input cropping system in South-West France. Such a system is different compared to an intensive agricultural system which is the case in this study. Nawara [51] stated that the P availability is lower in a P depletion scenario than in a P build-up scenario due to hysteresis. P_{Crit} values may therefore be higher in a P depletion scenario than in built-up scenario.

Soil properties such as soil type, soil structure, pH, the amount of Fe/Al oxyhydroxides, amount of Ca, organic matter and soil moisture content also influence the P availability in soil, the crop P uptake and hence the P_{Crit} value [6, 44-46, 49].

4.5 Practical Use of P_{Crit} Values: Evaluation of P in Target Zone

The general fertilizer strategy across Europe is bringing the soil P content to a target zone, thereafter maintaining the soil P content in this zone. Within this target zone optimal yields can be obtained if only the pH and the supply of other nutrients are optimal. P_{Crit} values can be used to set up new target zones or to evaluate current target zones. When doing so it is important to look on rotational level rather than on crop level. The wide range in P_{Crit} values (59-164 mg P/kg dry soil) and the slow differences in soil P content namely imply that it is impossible for the soil P level to meet the crop specific P_{Crit} value every year.

Sucunza *et al.* [48] and Colomb *et al.* [46] advise that the soil P level should approach the crop specific P_{Crit} value of the highest crop specific P_{Crit} value grown in rotation to prevent yield losses due to P deficiency and to minimize the environmental impact. Following this approach, the current Flemish P target zone (120-180 mg P/kg dry soil), which is determined based on 100% RY, is evaluated.

From this study it can be concluded that the lower limit of the target zone is confirmed by the common P_{Crit} value, 109 mg P/kg dry soil determined at 95% RY. Note that the common P_{Crit} value was used and not the crop specific P_{Crit} levels (59-164 mg P/kg dry soil) to evaluate the target zone because it is more meaningful when crop rotation is considered. The upper limit of the target zone cannot be evaluated because it depends on the P_{Crit} for leaching which was not part of this study.

5. Conclusions

This study defined for the first time P_{Crit} for different crops in Flanders (Belgium). Critical P values, calculated from previous long-term and recent P fertilizer trials, varied between crops. Winter wheat was the least and maize the most sensitive towards P deficiency with a P_{Crit} value of respectively 59 mg P/kg dry soil and 164 mg P/kg dry soil. Differences in

P_{Crit} might be explained by differences in growth season length, by differences in root architecture, and by mechanisms and adaptation of strategies to acquire P. The results of this study also show that the P_{Crit} value of a soil depends on the soil pH. Farmers should thus be encouraged to obtain/maintain a favorable soil pH because the same crop yield can be obtained at a lower soil P content when the soil pH is favorable compared to a suboptimal soil pH.

P_{Crit} values can be used to evaluate current soil P in target zones used for fertilizer recommendations. The common P_{Crit} (109 mg P/kg dry soil) determined in this study confirms the lower limit of the soil P in target zone (120-180 mg P/kg dry soil) currently used in Flanders (Belgium).

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References

- [1] Vandendriessche, H., Tits, M., Boon, W., Vogels, N., Bries, J., and Elsen, A. 2016. "Soil Service of Belgium: Seven Decades of Soil Fertility in Belgium 1945-2015." In *Soil Service of Belgium*, 156. (in Dutch)
- [2] Johnston, A. E., and Dawson, C. J. 2005. *Phosphorus in Agriculture and in Relation to Water Quality*. Peterborough: Agricultural Industries Confederation, 71.
- [3] De Bolle, S. 2013. "Phosphate Saturation and Phosphate Leaching of Acidic Sandy Soils in Flanders: Analysis and Mitigation Options." Ph.D. thesis, Ghent University.
- [4] Dekker, P. H. M., and Postma, D. 2008. *Increasing Phosphorus Fertilization Efficiency*. Lelystad: PPO-AGV. (in Dutch)
- [5] Cordell, D., and White, S. 2014. "Life's Bottleneck: Sustaining the World's Phosphorus for a Food Secure Future." *Annual Review of Environment and Resources* 39: 161-88.
- [6] Bai, Z., Li, H., Yang, X., Zhou, B., Shi, X., Wang, B. R.,

- Li, D. C., Shen, J. B., Chen, Q., Qin, W., Oenema, O., and Zhang, F. S. 2013. "The Critical Soil P Levels for Crop Yield, Soil Fertility and Environmental Safety in Different Soil Types." *Plant and Soil* 372 (1-2): 27-37.
- [7] Cordell, D., Drangert, J.-O., and White, S. 2009. "The Story of Phosphorus: Global Food Security and Food for Thought." *Global Environmental Change* 19 (2): 292-305.
- [8] Jordan-Meille, L., Rubæk, G. H., Ehlert, P. A. I., Genot, V., Hofman, G., Goulding, K., Recknagel, K. J., Provolò, G., and Barraclough, P. 2012. "An Overview of Fertilizer-P Recommendations in Europe: Soil Testing, Calibration and Fertilizer Recommendations." *Soil Use and Management* 28 (4): 419-35.
- [9] Nawara, S., Van Dael, T., Merckx, R., Amery, F., Elsen, A., Odeurs, W., Vandendriessche, H., Mcgrath, S., Roisin, C., Jouany, C., Pellerin, S., Denoroy, P., Eichler-Löbermann, B., Börjesson, G., Goos, P., Akkermans, W., and Smolders, E. 2017. "A Comparison of Soil Tests for Available Phosphorus in Long-Term Field Experiments in Europe." *European Journal of Soil Science* 68 (6): 873-85.
- [10] Amery, F., and Vandecasteele, B. 2015. *What Do We Know about Phosphorus and Agriculture? Part 1: Soil Phosphorus Availability and Fertilization*. Merelbeke Institute for Agricultural and Fisheries Research (ILVO). (in Dutch)
- [11] Havlin, J. L., Tisdale, S. L., and Nelson, W. L. 2014. *Soil Fertility and Fertilizers: An Introduction to Nutrient Management*. Pearson: Upper Saddle River, 519.
- [12] Hinsinger, P. 2001. "Bioavailability of Soil Inorganic P in the Rhizosphere as Affected by Root-Induced Chemical Changes: A Review." *Plant and Soil* 237 (2): 173-95.
- [13] Egnér, H., Riehm, H., and Domingo, W. R. 1960. "Studies on Chemical Soil Analysis as the Basis for Assessing the Nutrient Status of the Soil. II. Chemical Extraction Methods for the Determination of Phosphorus and Potassium." *Annals of the Agricultural College of Sweden* 26: 199-215.
- [14] Anon. 2010. "Determination of Soil Phosphorus Content Extractable with an Ammonium Lactate and Acetate Buffer." In *BAT—Best Available Techniques*, Version 2010. (in Dutch)
- [15] Flemish Land Agency. 2015. "Action Program for the Execution of the Nitrate Directive, 2015-2018." Flemish Land Agency. Assessed March 27, 2020. <https://docplayer.nl/26385916-Actieprogramma-ter-uitvoering-van-de-nitraatrichtlijn.html>. (in Dutch)
- [16] ISO 10390. 2005. *Soil Quality—Determination of pH*. Geneva: International Organization for Standardization.
- [17] NBN EN 15936. 2012. *Sludge, Treated Biowaste, Soil and Waste—Determination of Total Organic Carbon (TOC) by Dry Combustion*. Stockholm: Swedish Institute for Standards.
- [18] D'Haene, K., and Hofman, G. 2015. "Phosphorus Offtake and Optimal Phosphorus Fertilization Rate of Some Fodder Crops and Potatoes in Temperate Regions." *Agrochemistry and Soil Science* 64 (2): 403-20.
- [19] Haan, D. J. J., and Geel, V. W. C. A. 2013. *Advice Basis for Fertilization of Arable and Full Ground Vegetable Crops*. Wageningen: Wageningen University & Research Centre.
- [20] Van Geel, W. 2015. "Advising Row Fertilization for Potato and Sow Onion." In *Soil and Fertilization*. Wageningen: Research Institute Plant Research International. (in Dutch)
- [21] Wishart, J., George, T., Brown, L., Ramsay, G., Bradshaw, J., White, P., and Gregory, P. 2013. "Measuring Variation in Potato Roots in Both Field and Glasshouse: The Search for Useful Yield Predictors and a Simple Screen for Root Traits." *Plant and Soil* 368 (1): 231-49.
- [22] Zarzynska, K., Boguszewska-Mankowska, D., and Nosalewicz, A. 2017. "Differences in Size and Architecture of the Potato Cultivars Root System and Their Tolerance to Drought Stress." *Plant, Soil and Environment* 64 (4): 159-64.
- [23] Smit, A. L., De Willigen, P., and Pronk, A. A. 2009. "Part 1 Literature and Model Research." In *Fertilizer Placement as a Strategy for a More Efficient Phosphorus Fertilization*. Wageningen: Plant Research International.
- [24] Deru, J., Eekeren, N. V., and Boer, H. D. 2010. *Rooting of Grassland a Literature Study: Nutrient Uptake in Relation to Rooting Depth and Intensity: Factors and Potential Measurements Which Influences Rooting*. Wageningen: Louis Bolk Instituut. (in Dutch)
- [25] Clark, R., Parentoni, S., and Kochian, L. 2012. "A Role for Root Morphology and Related Candidate Genes in P Acquisition Efficiency in Maize." *Functional Plant Biology* 39 (11): 925-35.
- [26] Haling, R., Brown, L., Bengough, A. G., Young, I., Hallett, P. D., White, P., and George, T. 2013. "Root Hairs Improve Root Penetration, Rootsoil Contact, and Phosphorus Acquisition in Soils of Different Strength." *J. Exp. Bot.* 64 (12): 3711-21.
- [27] Hill, J., Simpson, R., Moore, A., and Chapman, D. 2006. "Morphology and Response of Roots of Pasture Species to Phosphorus and Nitrogen Nutrition." *Plant and Soil* 286 (1): 7-19.
- [28] Parra-Londono, S., Kavka, M., Samans, B., Snowdon, R., Wieckhorst, S., and Uptmoor, R. 2018. "Sorghum Root-System Classification in Contrasting P Environments Reveals Three Main Rooting Types and Root-Architecture-Related Marker-Trait Associations."

Annals of Botany 121 (2): 267-80.

- [29] Richardson, A., Lynch, J., Ryan, P., Delhaize, E., Smith, F., Smith, S., Harvey, P. R., Ryan, M. H., Veneklaas, E. J., Lambers, H., Oberson, A., Culvenor, R. A., and Simpson, R. J. 2011. "Plant and Microbial Strategies to Improve the Phosphorus Efficiency of Agriculture." *An International Journal on Plant-Soil Relationships* 349 (1): 121-56.
- [30] Vance, C. P., Uhde-Stone, C., and Allan, D. L. 2003. "Phosphorus Acquisition and Use: Critical Adaptations by Plants for Securing a Nonrenewable Resource." *New Phytologist* 157 (3): 423-47.
- [31] Tucher, S., Hörndl, D., and Schmidhalter, U. 2018. "Interaction of Soil pH and Phosphorus Efficacy: Long-Term Effects of P Fertilizer and Lime Applications on Wheat, Barley, and Sugar Beet." *Ambio* 47 (1): 41-9.
- [32] Fan, J., McConkey, B., Wang, H., and Janzen, H. 2016. "Root Distribution by Depth for Temperate Agricultural Crops." *Field Crops Research* 189: 68-74.
- [33] Weaver, J. E., and Bruner, W. E. 1926. *Root Development of Field Crops*. New York, NY: McGraw-Hill.
- [34] Lucas, M. E., Hoad, S. P., Russell, G., and Bingham, I. J. 2000. *Management of Cereal Root Systems*. London: Home Grown Cereals Authority, 43.
- [35] Zicker, T., Von Tucher, S., Kavka, M., and Eichler-Löbermann, B. 2018. "Soil Test Phosphorus as Affected by Phosphorus Budgets in Two Long-Term Field Experiments in Germany." *Field Crops Research* 218: 158-70.
- [36] Lynch, J. P. 2011. "Root Phenotypes for Enhanced Soil Exploration and Phosphorus Acquisition: Tools for Future Crops." *Plant Physiology* 156 (3): 1041-9.
- [37] de Ruijter, F. J., Smit, A. L., and Meurs, E. J. J. "Part 2 Field Trials." In *Fertilizer Placement as a Strategy for a More Efficient Phosphorus Fertilization*. Wageningen: Plant Research International, 314.
- [38] Stalham, M. A., and Allen, E. J. 2001. "Effect of Variety, Irrigation Regime and Planting Date on Depth, Rate, Duration and Density of Root Growth in the Potato (*Solanum tuberosum*) Crop." *The Journal of Agricultural Science* 137 (3): 251-70.
- [39] Bhadoria, P., Steingrobe, B., Claassen, N., and Liebersbach, H. 2002. "Phosphorus Efficiency of Wheat and Sugar Beet Seedlings Grown in Soils with Mainly Calcium, or Iron and Aluminium Phosphate." *Plant and Soil* 246 (1): 41-52.
- [40] Föhse, D., Claassen, N., and Jungk, A. 1988. "Phosphorus Efficiency of Plants: I. External and Internal P Requirement and P Uptake Efficiency of Different Plant Species." *Plant and Soil* 110: 101-9.
- [41] Geypens, M., Vandendriessche, H., Bries, J., Carlier, L., and Baert, J. 1992. "Judicious Use of Animal Manures." *Agricultural Review* 45 (2): 303-15.
- [42] Kostic, L., Nikolic, N., Samardzic, J., Milisavljevic, M., Maksimović, V., Cakmak, D., and Nikolic, M. 2015. "Liming of Anthropogenically Acidified Soil Promotes Phosphorus Acquisition in the Rhizosphere of Wheat." *Biology and Fertility of Soils* 51 (3): 289-98.
- [43] Neyroud, J. A., and Lischer, P. 2003. "Do Different Methods Used to Estimate Soil Phosphorus Availability across Europe Give Comparable Results?" *Journal of Plant Nutrition and Soil Science* 166 (4): 422-31.
- [44] Johnston, A. E., Poulton, P. R., and White, R. P. 2013. "Plant-Available Soil Phosphorus. Part II: The Response of Arable Crops to Olsen P on a Sandy Clay Loam and a Silty Clay Loam." *Soil Use and Management* 29 (1): 12-21.
- [45] Poulton, P. R., Johnston, A. E., and White, R. P. 2013. "Plant-Available Soil Phosphorus. Part I: The Response of Winter Wheat and Spring Barley to Olsen P on a Silty Clay Loam." *Soil Use and Management* 29 (1): 4-11.
- [46] Colomb, B., Debaeke, P., Jouany, C., and Nolot, J. M. 2007. "Phosphorus Management in Low Input Stockless Cropping Systems: Crop and Soil Responses to Contrasting P Regimes in a 36-Year Experiment in Southern France." *European Journal of Agronomy* 26 (2): 154-65.
- [47] Cox, F. R. 1992. "Range in Soil Phosphorus Critical Levels with Time." *Soil Science Society of America Journal* 56 (5): 1504-9.
- [48] Sucunza, F. A., Gutierrez Boem, F. H., Garcia, F. O., Boxler, M., and Rubio, G. 2018. "Long-Term Phosphorus Fertilization of Wheat, Soybean and Maize on Mollisols: Soil Test Trends, Critical Levels and Balances." *European Journal of Agronomy* 97: 87-95.
- [49] Tang, X., Ma, Y., Hao, X., Li, X., Li, J., Huang, S., and Yang, X. 2009. "Determining Critical Values of Soil Olsen-P for Maize and Winter Wheat from Long-Term Experiments in China." *Plant and Soil* 323 (1): 143-51.
- [50] Wu, Q., Zhang, S., Ren, Y., Zhan, X., Xu, M., and Feng, G. 2018. "Soil Phosphorus Management Based on the Agronomic Critical Value of Olsen P." *Communications in Soil Science and Plant Analysis* 49 (8): 934-44.
- [51] Nawara, S. 2018. "The Availability of Phosphorus in a Soil Phosphorus Depleting Scenario." Ph.D. thesis, KU Leuven.