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Can the DGT and Olsen P soil analyses predict phosphorus fertilisation requirements on Danish soils?

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1 Introduction

In order to optimise phosphorus (P) fertiliser management, farmers rely on soil tests to predict P fertilisation requirements. Currently in Denmark, the Olsen P method (Olsen et al., 1954) is used and the analysis is carried out according to descriptions in Plantedirektoratet (1994) and Rubæk and Kristensen (2017). The test result serves as guideline for recommendations for P fertilisation (Knudsen and Østergaard, 2004, Jordan-Meille et al., 2012). However, this method does not always identify soils responding to P fertilisation under Danish conditions (Rubaek and Sibbesen, 2000, Mundus et al., 2017) and it is therefore relevant to evaluate if other methods will have greater prediction value. In Australia, researchers have shown that the Diffusive Gradient in thin film Technique (DGT) is more precise than other common methods used in Australia (Speirs et al., 2013, Mason et al., 2010). Between 2013 and 2017 the DGT method has been tested under Danish conditions in Danish National Field Trials (Landsforsøgene®) in P response trials. In this report we present a preliminary analysis of data obtained from Danish field trials on P fertilisation carried out in 2013, 2014 and 2016 (Landsforsøgene®), where test results of the Olsen P and DGT methods are related to yield response to P fertilisation. It is a preliminary report for internal use. An international publication, jointly written by Søren Husted from University of Copenhagen and the authors of this report from Aarhus University is scheduled in 2018, where also new results from 2017 and possibly other soil test methods will be included.

The present report also includes brief reviews of the four papers based on field trials from the international peer reviewed literature, where the ability to predict response to P fertilisation of the DGT method and classical soil P tests are compared.

Please note that the results from 2013 included in this report are also reported in the publication by Mundus et al. (2017).

2 Predicting fertiliser response under field conditions by means of DGT and common soil P tests – a brief literature review

Phosphorus can be a limiting nutrient for crops and availability of P in soils is a complex matter. The amount of P present in soil solution directly available for the plant is insufficient to support plant growth. Therefore, the plant depends on release and diffusion of P associated with the soil solid phase to the root surface. This is initiated by the concentration gradient established when the root depletes soil solution for dissolved P (Johnston et al., 2014). These processes are highly dependent on soil properties such as pH, clay content, P sorption characteristics, soil organic matter and its turnover (Frossard et al., 2000).

There is a long tradition for using soil P tests to indicate whether soil P status is expected to limit crop production, but there no consensus about which soil P test to use. In Europe for example more than 10 different soil P test methods are used for routine soil testing (Jordan-Meille et al., 2012) and yet others are used in other continents (Speirs et al., 2013, Sibbesen and Sharpley, 1997). The lack of consensus is most probably related to the fact that each method only works on a narrow range of soil types, but also reluctance due to the considerable need for documentation of new methods may play an important role (Rubæk et al., 2015). More universal methods has been suggested previously e.g. Ion exchange resins on the bicarbonate form (Sibbesen, 1983) or iron oxide impregnated filter papers (Menon et al., 1990, Hosseinpur and Sinegani, 2009), but such methods has only to a limited extend been taken into use for routine purposes (Vanraij et al., 1986). The later years the DGT method has gained a lot of interest in the scientific community as an alternative to common soil P tests. The DGT method mimics the roots depletion of soil solution P and the initiation of P desorption and diffusion to the root. It is therefore reasonable to expect that the DGT method is more universal than the common soil P tests, which are based on chemical extraction of soil (Mundus et al., 2013, Zhang et al., 1998). The DGT method has recently been offered on commercial basis as soil analysis in Australia (Mason, 2017), but it is not available in Europe. In disfavour of recommending the DGT method as a replacement of well-established routine soil P tests are at the moment: (1) lack of documentation of how it performs under field conditions on a broad range of soils, climatic conditions and crops; (2) lack of a standardised description of the method and of possibilities for interlaboratory comparisons; (3) that each analysis require rather large amount of soil; and (4) that the method is time consuming and expensive compared to routine soil P tests. The superiority of the DGT method has been demonstrated under special conditions (Mundus et al., 2013, Degryse et al., 2009), but we have only identified four studies, which compare the suitability of DGT and Olsen P to predict yield response of phosphorus fertilizer under field conditions. One of these studies was conducted on Danish soils (Mundus et al., 2017), one was conducted in five different countries in Europe (Nawara et al., 2017) and two were carried out in Australia (Mason et al., 2010, Speirs et al., 2013). In the following sections, we highlight the findings in each of these four studies.

Mason et al. (2010): Australian soils

Mason et al. (2010) test the prediction value of DGT, Resin P (iron exchange resin membranes on the chloride form) and Colwell P (bicarbonate extractable P for 16 hours) to wheat response to P fertiliser in 35 field trials located in southern Australia in the years 2006 and 2008. In each field trial, they include a control without P fertiliser and at least two different levels of P fertiliser. Although the Olsen P is not used in this study Mason et al. (2010) points out that the Colwell P and Olsen P methods are expected to produce similar results because the two methods use the same extractant and differs mainly in having different extraction times. They calculate the relative yield response by dividing the yield in the no P treatments with the maximum yield obtained with P fertilization. For the relationship between relative yield and the soil P test values they fit a Mitscherlich curve. The intercept with the 90 % relative yield is used to find the critical soil P test value for expected yield response. They find that the DGT method had a greater prediction value than the two other methods. They divide their analysis into two parts: 1) including all trials and 2) including selected sites where maximum yield was reached. The DGT method has an R^2 = 0.74 for selected sites and R^2=0.42 for all sites. The resin method only has an R^2=0.35 for selected sites and R^2=0.17 for all sites (these relationships were statistically insignificant). They do not find any significant relationship between grain yield and Colwell P. Their conclusion is that the DGT method is a better and more robust method to determine P availability, than both the version of a resin extraction method they used and Colwell P methods on Australian soils.

Speirs et al. (2013): Australian soils

Speirs et al. (2013) study DGT and six different routine soil P-tests (Colwell P, Olsen P, $CaCl_2$-P, DGT-P, Mehlich 3-P and BSES-P) analysed according to Australian method descriptions (Rayment and Lyons, 2011). The performance of these methods for predicting wheat yield response to P fertilisation in 164 field trials carried out between 1968 and 2008 is analysed. Many of the soil analyses are carried out on achieved soil samples. Thirteen of the field trial already reported in Mason et al. (2010) were also included in this study. A Mitscherlich curve is fitted to each trial in order to calculate the maximum yield. To describe the relations between soil P tests and relative yield they fit a regression line across all field experiments of the following form: $= e^{\left(A\left(\arcsin\left(\sqrt{\%\frac{relative_{yield}}{100}}\right)\right)+B\right)}$. Speirs et al. (2013) analysed 1) all soils together and 2) calcareous soils and other soils separately. The division in two groups is done to test if certain methods had either problems or advantages on these soil groups. They also deduct the critical soil P test value where 90 % relative yield was obtained and calculate the confidence interval of this critical value.

When all soils are analysed together, the DGT method predicts yield response slightly better than the other methods as it obtains the highest R^2 (0.55), but lower than is observed in Mason (2010). The other soil P tests have R^2 between 0.37 and 0.49 (Olsen P was 0.43 and $CaCl_2$-P was 0.49), but the differences in R^2-values between the methods are relatively small. When dividing the soils into calcareous and other soils the DGT consistently come out with the best fits, while the Colwell P has problems on the calcareous soils. Comparing the relative confidence intervals of the critical soil P test value, the DGT method is not superior to the other methods, especially if soils are grouped in calcareous and other soils. Other methods come out with more narrow relative confidence intervals (Olsen P as the best on calcareous soils and Colwell P on the other soils). Speirs et al. (2013) conclude that DGT has a potential as a new soil P test and that this should be explored further. They also conclude that the use of Colwell-P for Australian soils still can be supported except for on calcareous Australian soils.

Nawara et al. (2017): European soils

Nawara et al. (2017) collect soil samples and yield data from long-term field trials across five different European countries. In total, they have collected 218 achieved or freshly sampled soil samples. These soils are analyzed for Olsen P, DGT, ammonium lactate (Pal), ammonium oxalate (Pox) and $CaCl_2$-P). In order to evaluate the performance of these methods in predicting crop response to P fertilization, they apply the Mitscherlich equation to fit the relationship between the soil P tests and the relative yield. They use R^2 of the fit between the expected relative yield of Mitscherlich equation and the actual relative yield as one way of comparing the methods. Methods are also compared by calculating the width of the confidence interval around the critical value relative to the critical value and estimate an index of the uncertainty of this relative width. They study the response to soil P tests in six different crops: wheat, barley, potato, sugar beet, maize and flax.

They find that Olsen P has the highest R^2 using the Mitscherlich equation (R^2=0.46), while the others are lower (0.21 for Pox, 0.31 for $CaCl_2$-P, 0.37 for DGT-P and 0.46 for Pal). By comparing the statistical uncertainty related to the widths of confidence intervals, DGT has the smallest uncertainty.

Nawara et al. (2017) calculate critical P values for the methods for different crops and find that these varied a lot between crops for all soil tests, and even when looking only at wheat and deriving the critical levels for each trial the values varied significantly. For Olsen P the range of critical values are between 8 and 46 mg P/ kg and for DGT it vary between 6 and 110 µg/l.

In their conclusion they find that the DGT does not perform markedly better than e.g. Olsen P and some of the other tests in contrast to what has been observed in the Australian studies (e.g. Mason et al. (2010)). They suggest that this difference is related to the fact that the Australian soils are mostly highly weathered and more P deficient soils compared to the studied European soils.

Mundus et al. (2017): Scandinavian soils

The study conducted by Mundus et al. (2017) includes Scandinavian field trials (seven Danish and two Norwegian) on phosphorus fertilisation and spring barley is the test crop. They test whether the DGT method performs better than the Olsen P, ammonium lactate (Pal) and ammonium acetate (PAAC) when it comes to predicting plant responses to P fertilisation. In the field trials, they measure leaf P concentrations 30 and 56 days after sowing and final grain yield. They are able to establish relations between all the soil P tests and the leaf tissue P concentration after 30 days, but there is no such relations after 56 days and at harvest. In fact only one of the nine trial resulted in a positive response in grain yield to P fertilisation. In this soil plants already showed P deficiency symptoms at 30 days after sowing where they clearly had less than the required 2000 µg P/g DM at this growth stage. The Olsen P test value in this single trial is close to the 2 mg P/g, which is the limit commonly used between soils with mild P deficiency and soil with adequate P supply (Knudsen and Østergaard, 2004) while the DGT value was clearly below the limit of 65 µg P/l defined by Mason et al. (2010). This study reflects that Danish soils in general are rich in P and that yield responses to P fertilisation often are absent or small. It also demonstrates the importance of sufficient P supply in the early growth stages as deficiency at these early stages may compromise yield at a later stage. Mundus et al. (2017) also concludes that the DGT method was better than the three other soil P test methods in reflecting leaf P concentrations 30 days after sowing (R^2 were 0.83 for DGT, 0.75 for Pal, 0.68 for PAAC and 0.46 for Olsen P) and performed best with the relationship between leaf concentration and soil P test.

3 Methods

3.1 Field trials

The effect of P fertilization on grain yield of spring barley was studied in 33 field trials located in Denmark. The P response field trials were carried out in 2013, 2014 and 2016 in Danish National Field Trials (Landsforsøgene®). Nineteen of the 33 field trials were located on coarse sandy soils, since the suitability of the Olsen-P method on this soil type has been found to be questionable (personal communication, Leif Knudsen, SEGES).

Before sowing and fertilization, soil samples were taken randomly from each trial area (16 cores, 0-25 cm depth) and mixed to form a composite sample. The soil was sampled in November in 2014, and in March in 2013 and 2016. Soil texture, pH($CaCl_2$), soil organic carbon (SOC) and Olsen-P were analysed after Sørensen and Bülow-Olsen (1994) at Agrolab. DGT deployments were carried out after Mundus et al. (2017) at Copenhagen University. Soil characteristics for each trial are shown in Table 1, and the location of the field trials are given in Appendix 1.

In each trial, two treatments were embedded in a randomized block design with four replicates. An N-K fertilizer containing S and B (110 kg N/ha) was broadcasted on the whole field trial before sowing (300 seeds m^{-2}, cv. Quench (2013 & 2014) and cv. RGT Planet (2016)). The fertilized treatment received triple superphosphate placed below the seeds corresponding to an application rate of 30 kg P ha^{-1}, whereas the other treatment did not receive any P. The harvested area varied between the locations and ranged from 12 to 39 m^2.

Table 1: *Soil characteristics, DGT and Olsen-P for each field trial.*

ID	Year	JB no	Soil pH ($CaCl_2$)	SOM %	Coarse sand %	Fine sand %	Silt %	Clay %	DGT (µg P L^{-1})	Olsen P (mg P 100 g^{-1} soil)
1	2013	4	5.7	3.9	28	50	9	9	32	4.0
2	2013	7	6.6	3.1	29	38	13	18	33	4.0
3	2013	6	7.2	3.8	26	43	13	14	159	8.3
4	2013	7	7.4	5	6	41	30	17	22	2.4
5	2013	8	7.5	2.6	6	46	19	26	16	1.6
6	2013	6	6.0	2.5	29	42	12	14	49	2.2
7	2013	6	6.1	2.6	27	44	13	13	115	4.8
8	2013	1	5	5	65	21	5	4	102	7.4
9	2014	7	6.7	2.7	25	40	14	19	29	1.4
10	2014	7	6.5	2.5	26	43	15	15	39	1.2
11	2014	11	5	10.3	56	18	6	10	25	5.3
12	2014	*	4.8	32	*	*	*	*	43	2.2
13	2014	3	5.0	5.2	58	26	5.0	6.0	43	5.3
14	2014	3	5.3	5.5	54	30	5	5	42	4.1
15	2014	1	5.4	3	76	15	3	4	41	5.3
16	2014	1	5.3	2.2	82	10	2	4	74	2.6
17	2016	1	5.4	1.9	66	27	1	4	208	4.9
18	2016	1	5.2	1.8	65	28	2	3	141	7.9
19	2016	1	5.6	1.9	66	27	1	3	178	4.1
20	2016	1	5.6	2	74	21	1	2	141	7.4
21	2016	1	5.3	2.6	51	41	2	3	159	4.8
22	2016	1	5.6	3	53	38	3	4	158	5.4
23	2016	1	5.4	4.1	51	38	3	4	92	5.8
24	2016	1	5.8	3.5	71	21	1	3	32	5.2
25	2016	1	5.6	3.5	65	26	2	4	37	5.5
26	2016	1	5.4	2.8	62	28	3	4	324	6.9
27	2016	1	5.8	2.4	66	26	2	3	220	4.9
28	2016	1	5.1	2.2	66	27	2	3	272	6.0
29	2016	1	5.4	5.5	46	40	4	4	173	5.7
30	2016	1	5.4	5.6	40	47	2	5	20	1.4
31	2016	3	6.1	4.9	46	39	4	7	24	2.5
32	2016	1	5.2	2.5	57	36	1	3	199	5.9
33	2016	1	5.8	3	54	37	2	4	174	5.1

*Data not available

3.2 Data calculation and statistical analysis

In order to compare grain yield responses across the 33 field trials carried out at different locations and in different years, the relative yield was calculated for each trial in compliance with e.g. Mundus et al. (2017) and Mason et al. (2010) using equation 1:

$$\%relative\ yield = \frac{Yield\ (control)}{Yield\ (P\ fertilised)} * 100 \qquad (1)$$

where *Yield (control)* represents the grain yield in the treatment without P fertilization and *Yield (P fertilized)* represents the treatment applied with 30 kg P ha^{-1}.

The statistical analysis was carried out using the R Project software package Version 3.4.1 (R Development Core Team, 2015).

To evaluate the performance of each soil P test, the relative yield was plotted against each soil P test, and the Mitscherlich model was fitted using the *nls* function in R (equation 2):

$$y = y_0 + a(1 - e^{-bx}) \qquad (2)$$

where y is the relative yield and x is the soil P test value. The R^2 was found by the linear relationship between the predicted relative yield and the actual relative yield according to Nawara et al. (2017).

Threshold for plant P deficiency was defined as a soil P test value resulting in a relative yield below 90 % and 95 % after Menzies et al. (2005) and Nawara et al. (2017), respectively.

One-way analysis of variance (ANOVA) was used to study the effect of P fertilization on grain yield in each trial. Significance was declared at the $P \leq 0.05$ level of probability.

4 Results

4.1 Response to P fertilization

In seven of the 33 field trials, there was a significant positive effect of P fertilization on grain yield. In two field trials a significant higher grain yield was obtained in the treatment without P application compared to the treatment with P application (Table 2). In these particular trials, the germination rate was low in treatments with P application, which could explain the low grain yield at harvest in the treatment with P application. These trials have been included in the analysis of the dataset, but could be eliminated in a final analysis.

Table 2. *Average grain yield (n=4) for treatment without P fertilization and yield for treatment receiving 30 kg P ha^{-1} within each field trial (ID). Asterisks (*) indicate significant (P<0.05) difference between treatments within each trial.*

ID	**Grain yield (hkg ha^{-1})**	
	Without P	With P
1	74	78
2	60	63
3	88	87
4	72	74
5	72	73
6	82	89*
7	67	66
8	63	65
9	77	77
10	78	85*
11	63	63
12	71	69
13	38	44*
14	38	48*
15	73	74
16	31	33
17	58	57
18	61	62
19	49	48
20	53*	44
21	63	63
22	77	76
23	79	76
24	69	68
25	72	74
26	48	47
27	72	72
28	49	46
29	50	52
30	60	67*
31	44	48*
32	56*	52
33	45	49*

4.2 Relative grain yields related to the DGT response limit

Figure 1 shows the relationship between DGT and relative grain yield. The Mitscherlich equation does not have a very good fit to the data (R^2 = 0.24) and only the y_0 was a significant parameter, while a and b were not. If the critical DGT value of 65 µg L^{-1} suggested in Mason et al. (2010) is used to define the limit below which response to P fertilization is expected. The DGT method correctly identified yield response to P fertilization at six locations. Additional ten field trials had a P status below the DGT response limit of 65 µg P L^{-1}, but in these trials no yield response to P fertilization was observed. There was one trial with a significant grain yield response (92 % relative yield) to P fertilization (ID 33), which had a higher DGT value (174 µg P L^{-}) than the limit of 65 µg L^{-1}. In the remaining trials with DGT values above response limit, the DGT method performed well as there was no significant positive yield response to P fertilization in any of these trials.

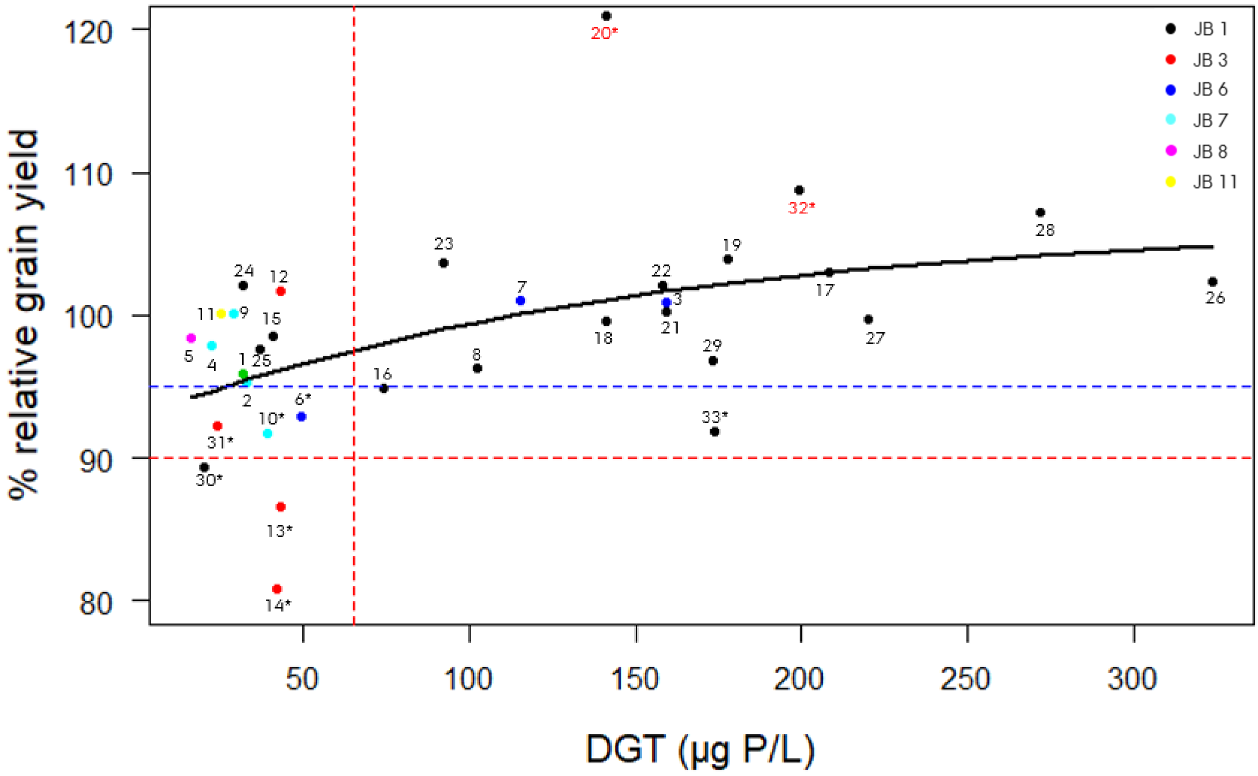

Figure 1: *Relative grain yield plotted against DGT (µg P/L) for each field trial (ID number shown). Horizontal red and blue dotted lines represent limits of plant P deficiency of 90 and 95 % relative yield, respectively. Vertical dotted red line represents the limit of expected grain yield response to P fertilization (DGT = 65 µg P/L). The solid line represents the fitted Mitscherlich equation. Asterisks (*) indicate significant (P<0.05) difference in grain yield between treatments with and without P fertilization within each field trials.*

4.3 Relative grain yield related to the critical Olsen-P limit

Figure 2 shows the relationship between Olsen P contents and relative grain yields of the 33 field trials. The limit for expected yield response is set at Olsen P = 2 mg P/ 100 g soil, which is used as the limit between low and adequate soil P status in Danish recommendation schemes (Knudsen and Østergaard, 2004, Jordan-Meille et al., 2012). In two field trials located on soils with a P status below the critical Olsen-P limit (ID 10 and 20) a significant yield response to P fertilization was obtained, but in another two field trials located on soils below the critical Olsen-P limit, no response to P fertilization was observed. However, five trials had significant positive yield responses to P fertilization (relative yields lower than 95%) in spite of Olsen-P values well above the limit of 2 mg P 100 g^{-1} soil. It was not possible to fit the Mitscherlich curve to these data.

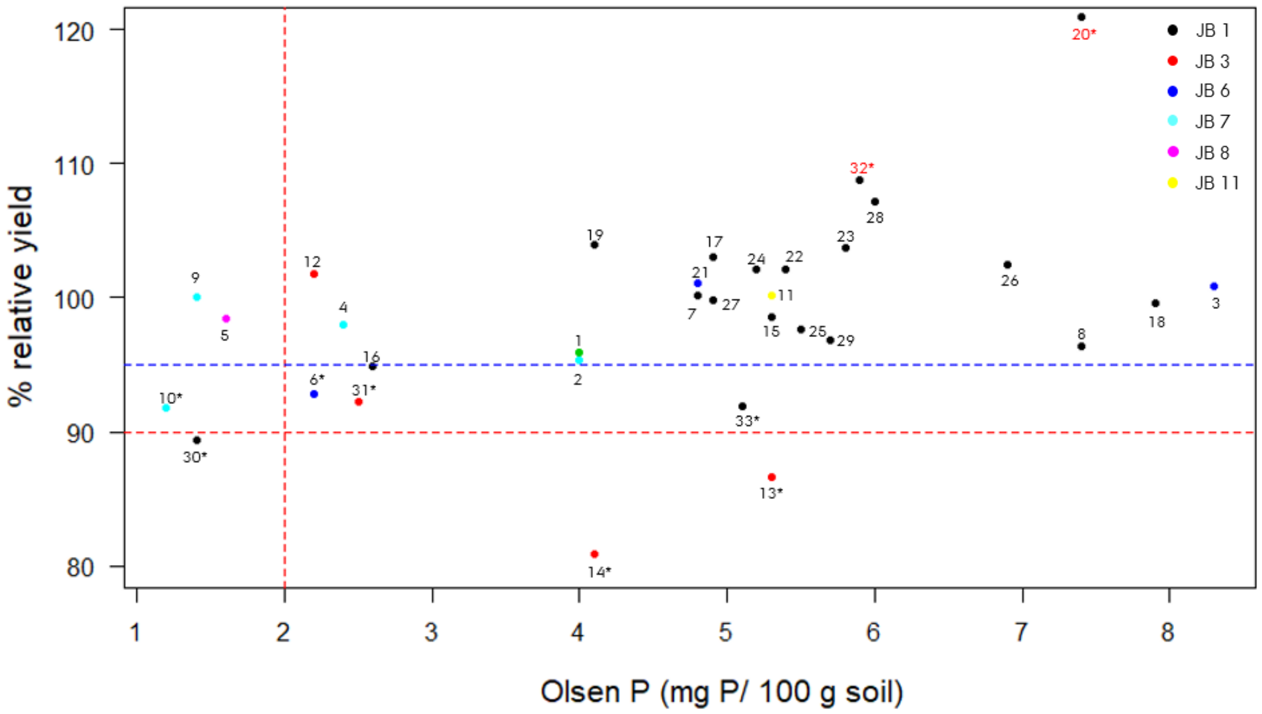

Figure 2: *Relative grain yield plotted against Olsen P (mg P/100 g soil) for each field trial (ID number shown). Horizontal red and blue dotted lines represent limits of plant P deficiency of 90 and 95 % relative yield, respectively. Vertical dotted red line represents the limit of expected grain yield response to P fertilization (Olsen P = 2 mg P / 100 g soil). We could not fit the Mitscherlich equation to this dataset. Asterisks (*) indicate significant (P<0.05) difference in grain yield between treatments with and without P fertilization within each field trials.*

4.4 Relationship between Olsen P and DGT

The relationship between Olsen P and DGT measurements is shown in figure 3. In general the plot is very scattered and there is a poor relation if any between the two tests. In the two field trials (ID 10 and 30), where the Olsen-P method was able to predict a P fertilization response (Olsen P below 2 mg /100 g soil), the DGT value was also below its critical limit of 65 µg L^{-1}.

Both the DGT and the Olsen P method fail when they predict a P fertilization response in two field trials (ID 5 and 9), since no response to P fertilisation was observed in these experiments. Twelve field trials were located on soils with a low P status according to the DGT response limit, but above the critical Olsen-P limit. In four of these 12 field trials a significant yield response to P fertilization was observed. Neither the Olsen-P method nor the DGT method were able to predict the P fertilization response in field trial 33.

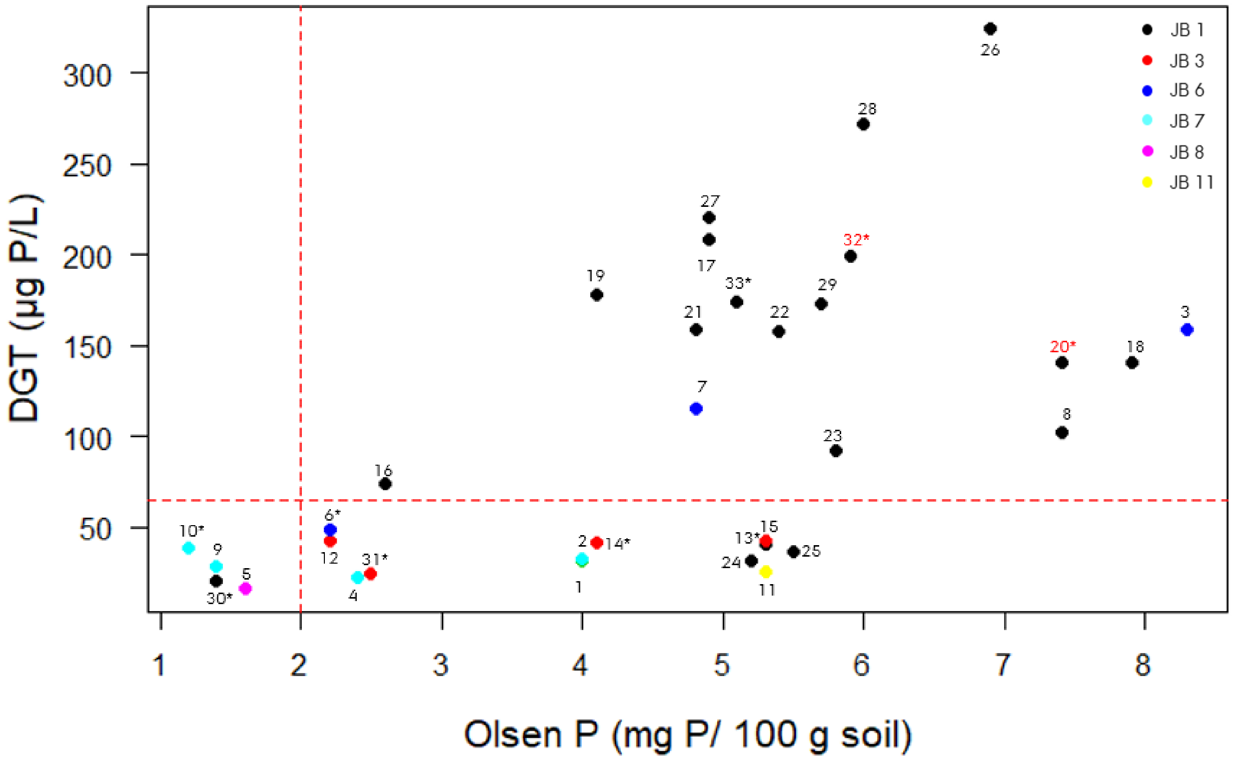

__Figure 3:__ Relationship between Olsen P and DGT values for the 33 field trials (ID number given). Limits for expected yield response to P fertilization are indicated at Olsen P = 2 mg P/100 g soil (vertical red dotted line) and DGT = 65 µg P/L (horizontal red dotted line). Asterisks (*) indicate significant difference (P<0.05) in grain yield between treatment with and without P fertilization.

5 Discussion

5.1 Response to P fertilization in the field trials

There was a significant effect of P fertilization on grain yield in only seven of the 33 field trials, indicating that the soils generally had adequate P status. This is in accordance with the fact that Danish soils for decades have been enriched in P (Andersen et al., 2016). This underlines the importance of identifying the relatively few soils that respond to P fertilization in order to optimise P fertilizer management and reduce the risk of both over-fertilization and sub-optimal P fertilization.

5.2 Prediction of P fertilization response

The Olsen P method predicted a significant yield response to P fertilization only in two out the seven field trials where positive P responses were observed based on the critical limit of 2 mg P/ 100 g soil. For the five soils where yield response to P fertilization was observed in spite of Olsen P levels above the critical limit there could be a risk of sub-optimal P fertilization and reduced yields, if P fertilization requirements were solely based on the Olsen-P method.

The DGT method predicted yield response to P fertilization correctly in six out of seven field trials based on the critical limit of 65 µg P/L. However, the DGT method also predicted response to P fertilization in additional ten field trials, where no response to P fertilization was observed. In conclusion, the DGT method performed better than the Olsen P method, when predicting the field trials with P fertilization responses, but there was also a risk of over-fertilization on 10 soils if P fertilization requirements were based on the DGT method.

It was not possible to fit the Mitscherlich equation to the relationship between the Olsen P and the relative yield, and therefore we could not determine the critical value for Olsen P based on data from the Danish trials. Instead the critical limit on 2 mg P/ 100 g soil was applied, which is the current limit for low P status in Denmark (Knudsen and Østergaard, 2004; Jordan-Meille et al. (2012)). Nawara et al. (2017) determined a critical value of Olsen P of 2.2 mg P/ 100 g soil for barley, which reaffirms, that the limit of 2 mg P/ 100 g soil used in Denmark is reasonable for the Olsen P method.

The Mitscherlich equation could be fitted to the relation between DGT and relative yield, but only one model parameter, $y_{0,}$ was significant while the parameters controlling steepness and curvature turned out insignificant. The Mitscherlich equation is therefore an over-parameterized model for the present data set.

We chose to show the Mischterlich curve and the R^2 of the fit, mainly to be able to compare to other studies. However, we refrained from using the model to determine a critical DGT value for expected yield response because it would be associated with considerable uncertainty. Therefore we chose to work with the critical limit of 65 µg P/L suggested by Mason et al. (2010), but is should be noticed that Navarra et al. (2017) estimated a critical limit for barley of 38 µg P/L. If this limit had been used on the Danish data set it would have influenced our interpretation to some extent.

As an alternative to the Mitscherlich it could be relevant to try to fit a "brocken stick" model to this data set, which is implemented in the *segmented* package in R. If additional information on soil properties for each trial can be obtained it would be relevant to check if any of these could help identifying soils where DGT and Olsen-P method fail to predict fertilizer response correctly. It would also be relevant to check how other soil test methods performs on these Danish field trials.

5. 3 Assumption and limitations of the dataset

The relative yield ranged from around 100% to 80% in the present study. Contrastingly, the relative yield ranged from 100 % to below 20 % in Speirs et al. (2013) and from 100 % to 40 % in Mason et al. (2010). In the other studies, several more and also high rates of P fertilization were applied, and therefore it was possible to determine the maximum yield potential of each experimental site by fitting the P response curve to the Mitscherlich equation (Nawara et al., 2017, Speirs et al., 2013, Mason et al., 2010). In the Danish field trials, only one rate of P was used, and it is therefore unknown if the maximal P yield response was reached with the P dose given on each location. The relative yields in this study may therefore be underestimated. However, the modest range in relative yield response on the Danish soils is most probably also related to the general high P status of Danish soils.

In the present study, the soil P tests were only related to the final grain yield of spring barley. If it had been possible also to relate the soil P tests to measurements of leaf P concentrations, we might have observed better relations between plant responses and soil P tests, in line with the results reported in Mundus et al. (2017). It is also important to note that only spring barley was used as a test crop in the present study. Other crops may have lead to other results as Nawara et al. (2017) also find.

6 Conclusion

- Only seven trials out of 33 showed positive yield response to P fertilisation, indicating that most soils had sufficient amounts of P to support barley growth in the year of the experiment.
- The observed significant yield responses were modest (between 81 and 93 % relative yield)
- Based on critical limits for Olsen P and DGT derived from literature and the Danish yield response experiments to P fertilisation presented in this report, we conclude that:
    - The DGT method was superior to Olsen P in detecting soils responding to P fertilisation. It detected six out of seven experiments with positive response to P fertilisation, while the Olsen P only detected two out of seven.
    - The DGT method identified more soils (10 soils) as P responsive and in need for P fertilisation where no response was observed, than did the Olsen P method (two soils).
- Based on the Danish data set presented here it was not possible to identify certain soil types as more in danger of being wrongly classified by any of the two soil P test methods than other soil types.
- Further characterisation of the soils may reveal key properties of those soils where one or more of the soil P test methods fail.
- The comparison is limited to two soil P methods only, it would be relevant also to test methods like water extraction, dilute CaCl2 extractions and PAL for a more comprehensive comparison like in the international studies briefly reviewed in this report.

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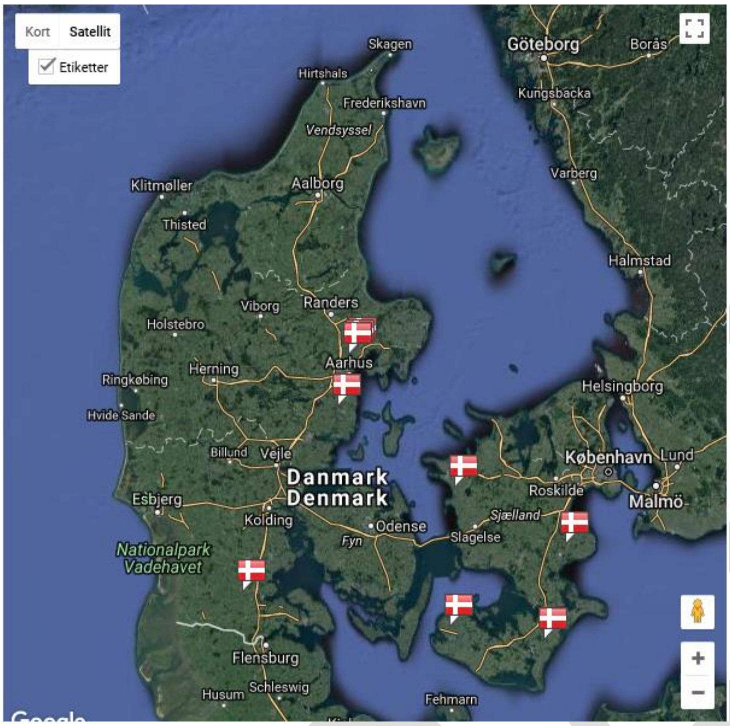
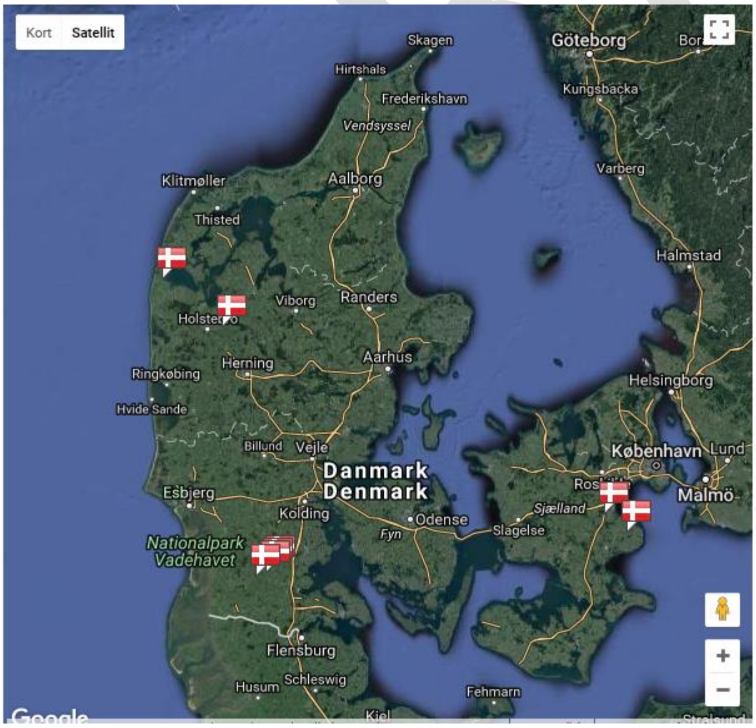
Appendix 1 - the location of the field trials

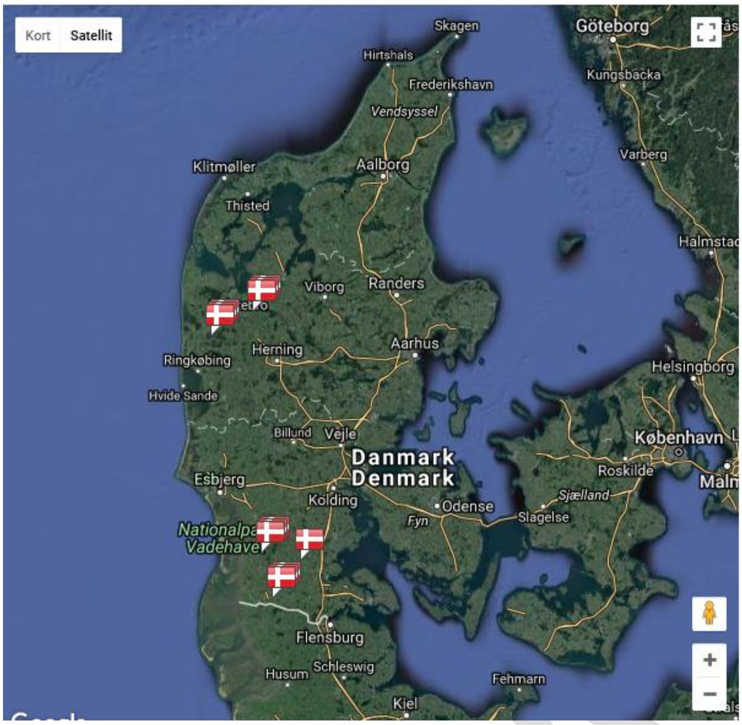
2013



2014



2016



Source: *https://nfts.dlbr.dk/Forms/GoogleMapSearchParams.aspx*