Yield responses to P fertilisation of onion (*Allium cepa* L.) and cabbage (*Brassica oleracea* Capitata Group L.) in Finland

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Finnish data on vegetable crops' yield responses to phosphorus (P) applications are scarce, but P is usually applied in quantities that meet the crop demand with wide safety margins. We determined yield responses to P fertilisation of onion and cabbage at three sites in 3-year field trials. Only on a sandy loam with low P status did annual P applications give statistically significant yield increases, 7% and 20% over the P-unfertilised treatment for onion and cabbage, respectively. The maximum P rate allowed by national regulation for this soil is 80 kg ha^{-1}, but P rates of 10–12 kg ha^{-1} were sufficient to produce 97% of the yield maxima. The results strongly suggest that the P demand of the studied vegetables is smaller than previously thought also in a boreal climate. Critical soil test P concentrations for vegetables should be established to avoid unnecessary build-up of soil P that may be uneconomical and elevate the risk for P losses to waterways. However, too few data exist for this at present.

Key words: phosphorus, yield response, nutrients, vegetables, onion, cabbage

Introduction

There is no consensus on the total world reserves of phosphate rock suitable for P fertiliser production, or the date of 'peak phosphorus' (Cordell and White 2011). However, we know that phosphate rock that is sufficiently concentrated and have relatively low concentrations of harmful elements (such as cadmium or uranium) is becoming scarcer with time. In the supply-side, technological advances are needed to cope with raw material of lower quality, but we should also examine the possibilities to decrease fertiliser P demand where possible. One of the components in more efficient P use is fertiliser recommendations that do not encourage unnecessarily high P use on soils that during the past decades were liberally fertilised with P.

Comprehensive P response models for cereal and grass crops, summarizing Finnish field experiments conducted since 1950's, have been published recently by Valkama et al. (2011, 2015). Based on these models, critical soil test P (STP) concentrations – i.e., STP above which yield responses of cereals and grasses to annual P applications become unlikely – were derived for the four major soil types in Finland. This work showed that the effects of annual P applications on cereal and grass yields and quality are smaller than previously thought.

Because of an almost total lack of data on vegetable yield responses to P, critical STP levels for vegetable crops are unknown in Finland. Instead, a broad safety margin is often applied in fertilising vegetables with P to ensure sufficient nutrition. Vegetables grown in a boreal climate are assumed to need especially much P, because the growing season is short and soils are cold in spring. This affect plant P nutrition as P desorption from the soil's solid phase to soil solution slows down as temperatures get lower (Ylivainio and Peltovuori 2012). Root architecture of some vegetables, such as onions and leeks with their shallow root systems, is additionally expected to increase the need for good P availability in the plough layer (Föhse et al. 1988).

For vegetable crops that generate relatively high income per hectare, large safety margins in P applications make little difference in farm economy in the short term. However, such practices may result in high P balance surpluses in years when vegetable crops are present in a crop rotation. If large P surpluses are added each time a vegetable crop occurs in the rotation, accumulated P surpluses elevate the STP concentration of the soil (Yan et al. 2013). Increases in STP have repeatedly been shown to increase concentrations of dissolved P in surface runoff and drainage discharge waters (Heckrath et al. 1995, Vadas et al. 2005, Withers et al. 2017). Even though P losses of a few kilograms a year represent an insignificant economic loss to farmers, the response in primary production in surface waters may be dramatic (Schindler 1974). Toxic algal blooms are of special concern as substantial costs may follow as a result of impacts on water supplies, public health, commercial fisheries, recreation and tourism, as well as monitoring and management costs (Anderson et al. 2000).

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In their analysis of Scottish soil P statistics with pre-crop information, Edwards et al. (2016) found that soil samples with vegetables, berries, or potato, as the previous crop had generally higher STP levels than samples with other pre-crops. Arranging their data as cumulative frequencies according to pre-crops, they showed that for vegetables and berry production, STP associated to the 50th percentile was over twice the STP associated with arable cropping. In Norway, Bechmann and Øgaard (2010) reported that mean STP concentrations in the main vegetable growing areas were on average 2.5-fold and dissolved P concentrations in streams twice as high as those measured in cereal production areas. Due to higher precipitation and irrigation in vegetable growing areas, Bechmann and Øgaard (2010) concluded that a hectare of vegetable cropland produced 6-fold the P loss as a hectare under cereal production as the main cropping system. Subsequent studies by Riley et al. (2012) and Stubhaug et al. (2015), consisting of two large series of P trials, in which only small vegetable yield responses to added P were typically observed, the Norwegian recommendations for P fertilisation of some studied vegetable crops were lowered in 2012 by up to 50%.

P recommendations in Finland were in 1995 replaced by the maximum allowed P rates when the first national Agri-environmental Programme (AEP) was launched. Even though the maximum allowed P rates are generally lower than the P recommendations of the 1980's, the Finnish AEP allows higher P applications to many crops than those recommended in the other Nordic countries. For onion and cabbage, the Finnish AEP limit is 60 kg P ha^{-1} when STP level is regarded as ”satisfactory” (target STP class), and up to 110 kg P ha^{-1} for the lowest two STP classes. In Sweden and Denmark, soils with ”target” or ”optimal” STP, P recommendations are 40 kg ha^{-1} for onion, and 25 (S) or 40 (DK) kg ha^{-1} for cabbage (Marmolin and Björkholm 2014, Miljø- og Fødevareministeriet 2016). Norwegian recommendations for ”optimal” STP are 43–58 kg P ha^{-1} for onion (the lower rate when P is band-applied), and 30 kg P ha^{-1} for cabbage (Riley et al. 2012).

To find out whether the Finnish P application limits for vegetable crops are unnecessarily high or not, we conducted field studies with onion and cabbage on three soils at two research locations, Mikkeli in SE Finland and Piikkiö in SW Finland. The study extended over three years and included P applications from zero to above the maximum rate allowed for farmers committed to the national AEP. Onion and cabbage were selected as crops to study as they are among the most widely grown vegetables in Finland. They also have contrasting root architectures, onion being shallow rooted whereas cabbage has an extensive and deep root system, and we hypothesised that this might affect their yield responses to annual P fertilisation.

Material and methods

Field experiments were performed in 2014–2016. One experiment was established in Mikkeli (61°40’27”N 27°13’34”E) on a sandy loam soil with relatively low P status according to the Finnish soil test method and its interpretation (Peltovuori 1999). The two other study sites were located in Piikkiö (60°23’15”N, 22°33’07”E) on soils with clay and loamy sand textures, just 400 m apart from each other. The clay parcel had a relatively low soil P status, whereas the loamy sand parcel had a high STP concentration. Some chemical and physical characteristics of the soils are shown in Table 1. Different parts of the same parcels were used during all years and both of the studied crops were grown in the same fields.

Table 1. Selected soil properties of the parcels used in the study. Values are given as means, with ranges for individual samples taken in different years of the study in parentheses.

	P-Acetate (pH 4.65)	P-Olsen	P-M3[a]	Al-M3	Fe-M3	PSC[b]-M3	DPS[c]-M3	pH_w	Org. C	Clay <0.002 mm	Silt 0.002-0.06 mm	Sand >0.06 mm
	mg l^{-1}	mg kg^{-1}	mg l^{-1}	————mmol kg^{-1}	————		%		————————	%	———————	
Mikkeli sandy loam	7.6 (5.3-16)	47 (19-67)	110 (56-147)	77 (67-85)	5.0 (3.6-6.9)	82 (72-92)	4.4 (2.4-5.8)	6.1 (5.3-6.8)	3.4 (2.6-4.1)	5 (5)	19 (17-20)	76 (75-78)
Piikkiö clay	5.0 (2.7-7.6)	32 (22-38)	29 (19-37)	43 (41-46)	9.7 (9.3-10.4)	53 (50-55)	1.9 (1.2-2.4)	6.0 (5.6-6.5)	2.5 (2.2-2.7)	48 (45-53)	33 (32-35)	20 (14-23)
Piikkiö loamy sand	31 (20-43)	33 (27-40)	164 (146-185)	33 (30-35)	6.3 (5.7-7.2)	39 (37-42)	11.7 (10.3-12.8)	7.0 (6.7-7.5)	1.3 (1.1-1.6)	7 (6-9)	11 (7-12)	82 (81-86)

[a] Extractable in Mehlich-3 solution; [b] P Sorption Capacity (Al-M3 + Fe-M3); [c] Degree of P saturation [100×P-M3/(Al-M3 + Fe-M3)], mol mol^{-1}; P-M3 recalculated to mass basis using volume weight

On each parcel, P applications were replicated four times. Fertiliser P rates were set according to the soil P status so that the highest rates exceeded the AEP's maxima (Table 2); the maximum P rate allowed depends on crop to be grown, soil type and STP concentration. The P treatment 20+10 kg ha^{-1} was not included in the first year's experiment on Piikkiö clay soil, but was added in the 2015 and 2016 experiments. In Mikkeli and in the clay soil of Piikkiö, this treatment consisted of 20 kg ha^{-1} broadcast application of granular P fertiliser prior to soil preparation in May, complemented by 10 kg ha^{-1} P starter solution (Yara Ferticare, NPK 10-23-14) added in the plant rows in connection with planting. For the sand parcel in Piikkiö the 30 kg P ha^{-1} treatment was given similarly as the other P rates (as granular fertiliser before soil preparation). Other nutrients than P were given according to crop requirements, but in similar amounts to all P treatments (Table 2). Nutrient mixtures were composed of Yara's granular NPK, NK, NP, NH_4NO_3, K_2SO_4, and micronutrient fertilisers. Fertilisers were added by hand on the soil surface and mixed with a rotary tiller to 10 cm depth prior to planting. Additional in-season supplementary doses of nitrogen (N) and potassium (K) were given once for onions, whereas cabbage received 3–4 split applications.

Onion (cv. Setton) was grown from sets and white cabbage (cv. Lennox) from transplants. The growing density was 381×10^3 plants ha^{-1} for onion and 27.8×10^3 plants ha^{-1} for white cabbage. The size of the plots was 1.5×6 m or 1.5×5 m for onion and 3.0–3.6×4.2–4.5 m for white cabbage, varying slightly between years and sites. White cabbage was grown under insect net to prevent damage by pests.

Planting time for both crops was May. The experiments were irrigated when necessary, according to soil moisture content that was followed with tensiometers at 20 cm depth. Onion yield was harvested in mid-August to early September and cabbage yield at the end of September or beginning of October. Onions were dried after harvest with their leaves attached, and the fresh yields were weighed both straight after harvest and after drying and grading.

Table 2. Macronutrient rates used in the study; for P, notation 20+10 refers to granular (20 kg P ha^{-1}) + starter solution P (10 kg P ha^{-1}), whereas N and K rates are given as spring + in-season applications.

Site	P rates, kg ha^{-1}					N rate, kg ha^{-1}	K rate, kg ha^{-1}
Onion experiments							
Mikkeli	0	20	20+10	50	100	80+27	120+84
Piikkiö clay	0	20	20+10[a]	50	100	80+27	120+84
Piikkiö sand	0	5	15	30		80+27	120+84
Cabbage experiments							
Mikkeli	0	20	20+10	50	100	80+131	120+140
Piikkiö clay	0	20	20+10	50	100	80+131	120+140
Piikkiö sand	0	5	15	30		80+131	120+140

[a] P-rate 20+10 was not applied at this site in 2014

Laboratory analyses

The soils were tested for P concentrations using the Finnish soil test protocol of Vuorinen and Mäkitie (1955), the method of Olsen and Sommers (1982), and for P, Al and Fe (P-M3, Al-M3 and Fe-M3) according to Mehlich (1984). The Finnish STP method (referred to as P_{Ac}) involves 1-h extraction with 0.5 M ammonium acetate and 0.5 M acetic acid, buffered to pH 4.65, at 1:10 soil-to-solution ratio. Olsen-P was extracted for 30 min with 0.5 $NaHCO_3$ adjusted to pH 8.5 at 1:20 soil-to-solution ratio. Mehlich 3 is an acidic (less than pH 3) solution, containing acetic and nitric acids, NH_4F, NH_4NO_3 and EDTA, used in 15-min extraction at 1:10 soil-to-solution ratio. In P_{Ac} and M3-P analyses extracts were passed through Munktell OOR paper filters (Munktell Filter AB, Grycksbo, Sweden) and in Olsen-P analysis through 0.2 µm Nuclepore (Whatman, Maidstone, UK) polycarbonate filters. The P_{Ac} and Olsen extracts were analysed for P using the molybdate blue colorimetry method of Murphy and Riley (1962), whereas Mehlich 3 extracts were analysed (for P, Al and Fe) with an inductively coupled plasma-optical emission (ICP-OES) spectrometer. Soil organic C was determined with LECO (St. Josephs, MI, USA) analyser and pH in 1:2.5 (v/v) water suspension.

For total mineral element concentrations in plants, 15 onions and 4 cabbages, with separate yield and outer leaf samples, were taken from each plot at harvest and dried at 60 °C. Samples were ground and digested under pressure with concentrated nitric acid in a microwave oven. Element concentrations were measured using an ICP-OES.

Statistical analyses and yield response model

The field experiments were set up according to a randomized complete block design. Because the P fertilization levels applied as treatments slightly varied from year to year and location to location (Table 2), data from each experiment were analysed separately. The data from individual experiments were analysed taking into account the experimental setting: P fertilisation was considered as the fixed treatment factor and replication was considered as a random blocking factor. In addition, the effect of soil P_{Ac} concentration in May was examined as a possible covariate; the results were compared with and without the covariate. In statistical analyses, REML was used as an estimation method and degrees of freedom were calculated using the Kenward-Roger method (Kenward and Roger 1997). The models were fitted using the MIXED procedure of SAS 9.4 (SAS Institute Inc., Cary, NC, USA). Model assumptions were checked using appropriate graphs and tests. Pairwise comparisons were performed by two-sided *t*-type tests.

In cases where statistically significant yield responses to P-fertilisation were observed, the yield responses were modelled using nonlinear curve fitting. Based on data from all three years of the study, a Mitscherlich-type equation in its simple form was used:

$$Y = a \times (1\text{-}\exp(-k \times X))$$

In the equation, the terms *a* (the maximum yield increase) and *k* (the coefficient that dictates the pace of the rise of the yield curve to the maximum) are site- and crop-specific constants to be fitted. The term X is the amount of P applied (kg P ha^{-1}) annually. In modelling yield responses, the data were calculated as the relative change over the P-unfertilised yield, with Y expressed as percentage yield increase.

Results

Soil P status

Mikkeli sandy loam tested relatively low in soil P_{Ac} (P_{Ac} is a P-intensity test, i.e. an index for readily soluble P), but in contrast P-Olsen and M3-P extractions (as P-quantity tests, i.e. indices of adsorbed P stock in soil) showed relatively abundant P reserves. This discrepancy between the intensity and quantity-responsive P tests stemmed from the high concentrations of M3-extractable Al and thus a high P sorption capacity (PSC-M3; Table 1) of the Mikkeli soil. The two soils at Piikkiö had similar Olsen-P concentrations, but the clay soil tested relatively low in P_{Ac} and M3-P and had a clearly lower DPS-M3 than the loamy sand of the same site (Table 1).

Onion experiments

The only statistically significant (p<0.05) yield responses in onion were obtained on the Mikkeli sandy loam soil, where P-unfertilised plots produced 35-38 Mg ha^{-1} bulbs during all years of the study (Fig. 1). In 2014 yield responses to P applications were variable, from –6% to +5% and statistically non-significant (p=0.688–1.000); the highest yield was obtained with 20 kg P ha^{-1}. In 2015, statistically significant yield increases of 16% (p=0.001) and 11% (p=0.016) were obtained with P rates of 30 and 50 kg ha^{-1}, respectively. In 2016, a statistically significant (p=0.021) yield increase of 15% was obtained with P application of 20 kg ha^{-1}. The yield difference between the highest P application of 100 kg P ha^{-1} and the P-unfertilised plots were in all years statistically non-significant (p=0.097 and 1.000 in 2014 and 2015, and p=0.054 in 2016).

The clay parcel in Piikkiö produced P-unfertilised yields between 33 and 45 Mg ha^{-1}, the lowest yield being obtained in 2014 (Fig. 1). Due to a relatively high within-treatment variation in yields on this soil, responses to applied P were in all years non-significant (p=0.105–1.000). The highest measured yields were in 2014 and 2016 obtained with P application of 20 kg ha^{-1} (with 14–15% over the P-unfertilised yield, but with p=0.544 and 0.105), and in 2015 with the 50 kg ha^{-1} P rate (a 20-% increase, p=0.240).

The loamy sand soil in Piikkiö with the high P_{Ac} status was the site with the highest year-to-year yield variation, with a P-unfertilised yield range from 38 Mg ha^{-1} in 2014 to about 70 Mg ha^{-1} during the two following two years (Fig. 1). In 2014, mid-summer was relatively dry, followed by a wet August, and harvested onions were to a greater extent than in other years infected by *Fusarium*, which may have contributed to the lower overall yields. Yield responses to applied P were non-significant, albeit in 2014 and 2015 the highest P rate of 30 kg ha^{-1} gave 15% (p=0.076) and 6% (p=0.538) higher measured yields than the P-unfertilised treatment. In 2016 highest yield (6–7% increase from P-unfertilised yield, p=0.127) was obtained with the 15 kg P ha^{-1} application rate.

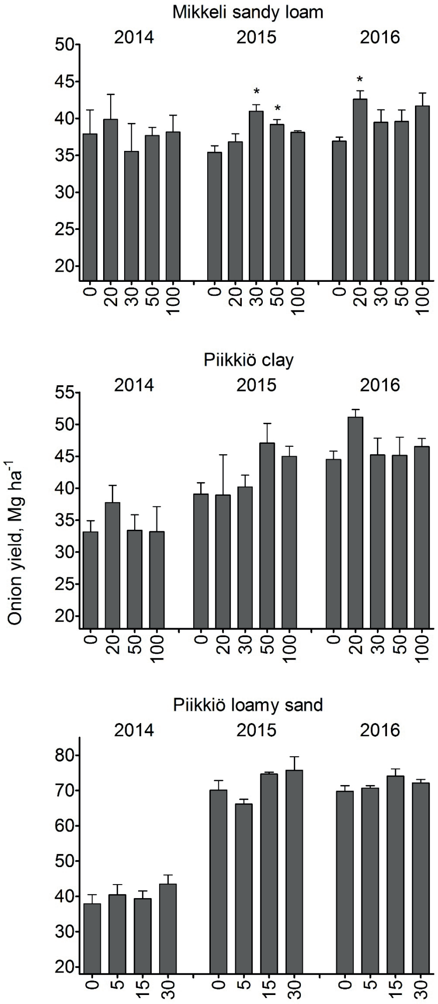

Fig. 1. Onion yields during 2014–2016 at the three study locations. Error bars indicate standard errors of mean (n=4). Statistically significantly (p<0.05) higher yields over the P-unfertilised treatments are marked with asterisks. Note, the presented means and standard errors are descriptive statistics calculated from the data, but the statistical significances are obtained from the fitted statistical models.

Fitting data from the Mikkeli experiments (i.e. the only site with statistically significant yield responses) in a Mitscherlich model suggests a 7.1-% average maximum increase in dried onion yield (Fig. 2). The model further suggests that P applications that would correspond to 95 and 97% of the maximum yield would be as low as 4 and 10 kg P ha^{-1}, respectively. Averaged over the three years, the Mikkeli experiments gave the highest observed bulb yields with 20 kg P ha^{-1} fertilisation that was the lowest P application rate studied in this soil. As compared to the maximum allowed P dressing of 80 kg P ha^{-1} for a soil within the STP class of the Mikkeli soil, all the preceding numbers are a fraction of that allowed in the AEP ordinance.

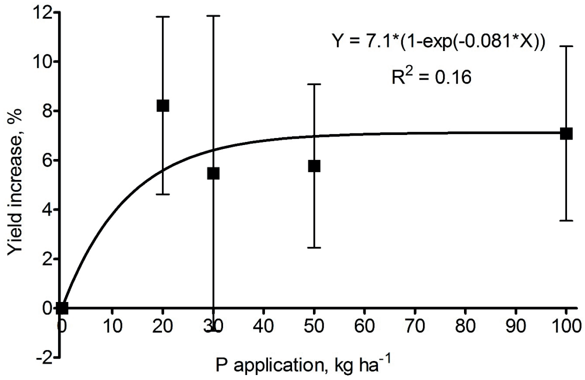

Fig. 2. Yield response of onion to increasing P applications on the Mikkeli sandy loam soil. Error bars indicate standard errors of yearly mean responses (n=3).

Onion P concentration was unaffected by the P applications (Table 3). For the two soils with the relatively low STP class, the Mikkeli sandy loam and Piikkiö clay soil, P offtake by onion during the study was on average 16 and 18 kg P ha^{-1}, respectively. Using the maximum 80 kg ha^{-1} allowed P rates for these soils would thus have meant P balance surpluses in excess of 60 kg ha^{-1}. For the Piikkiö sand soil with the high STP, P offtake by onion was a few kilograms more than the maximum (by AEP) allowed P application of 25 kg ha^{-1} and only the highest P rate used (30 kg ha^{-1}) was associated with a slight P balance surplus.

Table 3. Phosphorus concentration of onion bulbs and tops at harvest in different P application treatments during the study. The values marked with an asterisk differ statistically significantly ($p \le 0.05$) from the 0 kg P ha^{-1} treatment. The *p*-values denote the overall statistical significances of the P treatments based on the F-tests.

P-rate, kg ha^{-1}	P-conc. of onion bulbs, g kg^{-1} DW			P-conc. of tops, g kg^{-1} DW		
	2014	2015	2016	2014	2015	2016
Mikkeli sandy loam						
0	2.40	2.00	2.54	1.88	2.12	2.76
20	2.28	2.06	2.36	1.98	2.08	2.54
30	2.33	1.97	2.43	2.18	2.04	2.70
50	2.43	1.97	2.42	2.08	1.93	2.53
100	2.25	2.11	2.43	2.00	2.08	2.72
p-value	0.470	0.714	0.882	0.696	0.292	0.500
Piikkiö clay						
0	3.41	2.03	2.72	2.36	2.35	2.71
20	3.62	2.19	2.46	2.52	2.52	2.58
30	N.A.	2.18	2.60	N.A.	2.25	2.55
50	3.44	2.35	2.73	2.47	2.50	2.84
100	3.58	2.26	2.64	2.36	2.28	2.51
p-value	0.554	0.176	0.753	0.314	0.273	0.164
Piikkiö loamy sand						
0	3.80	2.58	2.73	2.96	2.36	3.35
5	3.99	2.42	2.67	3.06	2.24	2.98
15	4.01	2.62	2.70	2.68*	2.43	2.87
30	4.12	2.65	2.54	2.81	2.40	3.09
p-value	0.173	0.573	0.162	0.004	0.817	0.200

Cabbage experiments

Yield responses of cabbage to added P agreed with those of onion in that the only soil on which statistically significant responses were found was the Mikkeli sandy loam (Fig. 3). There, P-unfertilised cabbage yields during the study ranged between 49 and 58 Mg ha^{-1}. Application of 30 kg P ha^{-1} gave in 2014 a significant 13% yield increase (p=0.024), whereas yields associated with the other P rates did not differ statistically from the P-unfertilised yield (p=0.268-0.996). In 2015, all P rates produced significant yield responses with 17–26% increase over the P-unfertilised treatment (p=0.002–0.027), the highest yield being obtained with 50 kg P ha^{-1}. In 2016, yield responses to added P were seemingly clear (Fig. 3), and about equal (28–31%) for all P treatments. However, because of insect and weed problems in the P-unfertilised plots, the differences were statistically non-significant (p=0.068–0.117).

The clay soil in Piikkiö produced P-unfertilised cabbage yields of 60–79 Mg ha^{-1} (Fig. 3), but no statistically significant yield increases to added P could be established in any of the three years (p=0.404–1.000). In 2014, all P treatments produced slightly (1 to 5%) lower yields than the P-unfertilised treatment, but the differences were not significant. In 2015, P rates 20–50 kg ha^{-1} increased cabbage yield by 5–9%, but with *p*-values of 0.728 or higher. In 2016, maximum yield was obtained with 30 kg P ha^{-1} application, but with a statistically non-significant (p=0.404) increase of 5% over the P-unfertilised treatment. It may be noted that the highest P rate of 100 kg ha^{-1} produced in all years the lowest yields of all treatments, including the P-unfertilised one.

When P fertiliser was added, also the loamy sand soil in Piikkiö produced in 2014 less cabbage yield (2–5%, p=0.092–0.598) than the P-unfertilised soil (Fig. 3). During 2015 and 2016 yield responses to added P were also around zero (–4% to +3%), with p-values of 0.236 or higher. In none of the study years did the highest P rate (30 kg P ha^{-1}) produce the highest yields on the Piikkiö loamy sand.

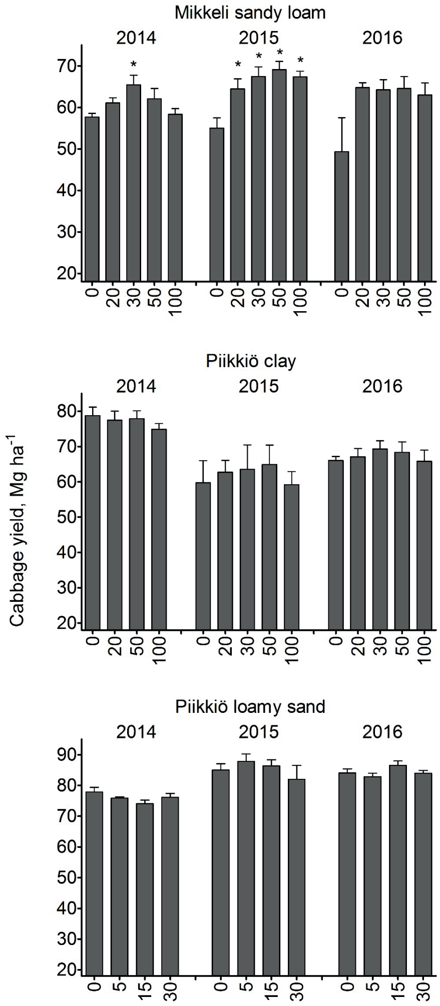

Fig. 3. Cabbage yields during 2014–2016 at the three study locations. Error bars indicate standard errors of mean (n=4). Statistically significantly (p<0.05) higher yields over the P-unfertilised treatments are marked with asterisks. Note, the presented means and standard errors are descriptive statistics calculated from the data, but the statistical significances are obtained from the fitted statistical models.

Yield response data for cabbage from the Mikkeli sandy loam (the only soil with statistically significant yield responses) was fitted to the Mitscherlich model, suggesting a maximum yield response to added P of 20% (Fig. 4). The model further suggested that if farmers would be satisfied with 95–97% of the maximum yield, P rates of 8–12 kg ha^{-1} would be sufficient. The highest measured average yield was obtained with the 30 kg P ha^{-1} treatment. Also for cabbage, the maximum allowed P application to a soil within the STP class of the Mikkeli soil is 80 kg ha^{-1}, thus widely exceeding the rates required for ensuring a good yield.

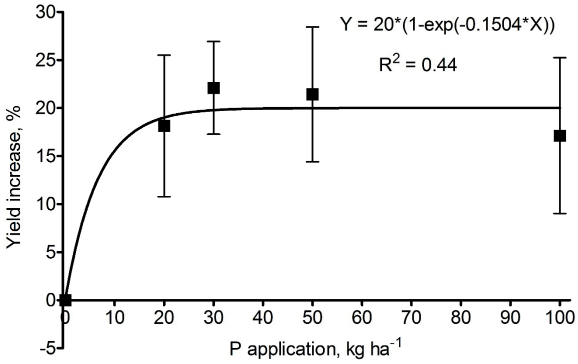

Fig. 4. Yield response of cabbage to increasing P applications on the Mikkeli sandy loam soil. Error bars indicate standard errors of yearly mean responses (n=3).

Generally higher cabbage head P concentrations were measured for P treatments than for P-unfertilised plants in 2014 and 2015 for the two soils with relatively low P_{Ac} and in 2015 also for the sand soil with high P_{Ac} (Table 4). Concentrations in the outer leaves were significantly increased by P applications in all years in Mikkeli, but the increase was non-significant for the Piikkiö clay soil. The loamy sand soil in Piikkiö had significantly increased P concentration of outer leaves in 2015.

Table 4. Phosphorus concentrations of cabbage heads and outer leaves at harvest in different P application treatments during the study. The values marked with an asterisk differ statistically significantly ($p \leq 0.05$) from the 0 kg P ha^{-1} treatment. The *p*-values denote the overall statistical significances of the P treatments based on the F-tests.

P-rate, kg ha^{-1}	P-conc. of cabbage head, g kg^{-1} DW			P-conc. of outer leaves, g kg^{-1} DW		
	2014	2015	2016	2014	2015	2016
Mikkeli sandy loam						
0	2.25	2.27	2.37	2.05	1.72	2.04
20	2.38	2.49*	2.23	1.90	2.01*	2.17
30	2.93*	2.54*	2.57	2.30	2.03*	2.52*
50	3.23*	2.87*	2.37	2.78*	2.37*	2.31*
100	3.10*	2.98*	2.64	2.58*	2.72*	2.65*
p-value	<0.001	<0.001	0.249	0.002	<0.001	0.007
Piikkiö clay						
0	3.64	3.01	4.09	2.49	1.66	3.05
20	3.22*	3.27	4.26	2.29	1.88	2.88
30	N.A.	3.11	4.21	N.A.	1.78	2.87
50	3.46*	3.31	4.41	2.42	1.96	3.16
100	3.53	3.37	4.91	2.42	2.10	3.16
p-value	0.001	0.006	0.078	0.785	0.174	0.682
Piikkiö loamy sand						
0	3.13	3.07	4.22	2.08	1.80	3.01
5	3.19	3.29*	4.33	2.07	2.01*	3.25
15	3.10	3.46*	4.25	2.12	2.04*	3.48*
30	3.16	3.19	4.69	2.24	2.05*	3.22
p-value	0.913	0.012	0.458	0.625	0.036	0.066

Total uptake (including head and outer leaves) averaged 28, 38, and 44 kg P ha^{-1} for the Mikkeli sandy loam, Piikkiö clay, and Piikkiö loamy sand, respectively. However, of the total P uptake, 38–45% was returned to the soil as outer leaves. Offtake from soil as marketable heads was on average 16 kg P ha^{-1} in the Mikkeli experiment and 24 kg P ha^{-1} in the both Piikkiö experiments. If the soils had been fertilised according to the AEP limits, these offtakes would have resulted in P surpluses of 56–64 kg ha^{-1} for the soils with low P_{Ac} status, but close to zero P balance for the loamy sand in Piikkiö.

Discussion

In most cases applying P increased onion and cabbage yields by only a few percent, and the increase brought about by P applications was modest if compared to the effects of N fertilisation. In an accompanying N experiment with cabbage in Piikkiö, an increase in N application from 100 to 230 kg N ha^{-1} increased yield by 30–40 Mg ha^{-1} which is tenfold the average increase obtained by P applications in the present study. Only one of our study sites, the Mikkeli sandy loam with low P_{Ac} status, was clearly responsive to added P, and both of the studied crops behaved alike in this respect. On the two other soils, including the clay soil with low P_{Ac}, yield responses were irregular and never statistically significant at the 5% probability level. Our results are from only three sites, but they do not differ from the earlier findings of Valkama et al. (2011, 2015) regarding cereals and grasses, i.e. that yield increases to annual P applications are unlikely on soils with high P_{Ac} status, and that clay soils have a clearly lower critical P_{Ac} concentration than coarse-textured soils.

In Mikkeli, where the 3-yr yield response was found to be statistically significant, the highest average yield of onion was obtained with 20 kg P ha^{-1} and the highest cabbage yield with 30 kg P ha^{-1} (Figs. 2 and 4). According to the yield response model, 10–12 kg P ha^{-1} would be enough to attain 97% of the maximum yields. All of these P rates are far lower than the AEP maximum of 80 kg P ha^{-1} for the P_{Ac} class of the Mikkeli sandy loam soil. This suggests that the Finnish P limits are unnecessarily high, resulting in substantial P balance surpluses and consequent soil P build-up with time.

If getting such yield responses as shown in Figures 2 and 4, we can envisage that farmers would want to increase P applications up to the point when the successive yield increases from P applications would just cover the cost of the last kilogram of extra P fertiliser, which is about 2 EUR kg^{-1} P. If farmers can sell a ton of onions or cabbage for 300 or 500 EUR, the last additional kilogram of P fertiliser should return an extra yield increase of 7 or 4 kg, respectively. Calculated according to the equation embedded in Figure 2, and with 35 Mg ha^{-1} P-unfertilised yield, these conditions are met up to P applications of 42 or 48 kg ha^{-1} for yield values of 300 or 500 EUR Mg^{-1}, respectively. For a cabbage crop giving 55 Mg ha^{-1} P-unfertilised yield, maximum P application that would totally cover the cost of fertiliser P at crop prices of 300 and 500 EUR Mg^{-1} would be 36 and 40 kg P ha^{-1}, respectively. Thus, even when yield responses would be as high as in the Mikkeli experiments, a farmer who applies the maximum allowed 80 kg P ha^{-1} to this soil will be well past the point when P fertiliser is used in the most economical manner.

As for the effect of root architecture on P responses, we found that for the Mikkeli experiment, where a statistically significant response was established, the rise of the yield response curve of onion was less steep than that of cabbage. For onion, 50% and 95% of the maximum yield increase due to P application were according to the model obtained with 9 and 38 kg kg^{-1} P rates, respectively, whilst the corresponding values for cabbage were 5 and 20 kg P ha^{-1}. This accords with the good P uptake efficiency of cabbage (Dechassa et al. 2003), whereas onion has been shown to benefit from richer P supply (Föhse et al. 1988, Alt et al. 1999). However, statistically significant yield responses were observed at only one site, and even there responses were absent in one of the three years of our study. Further, only for cabbage responses in 2015 was a statistically significant rise in yields obtained with all P application rates. Especially for onion, only a small part (16%) of the variation in yield response was explained by P applications (Fig. 2).

When comparing with studies conducted in our neighbouring Norway, our results are in line with those reported by Riley et al. (2012). In their 10 experiments with onion at different locations Riley et al. (2012) did not find statistically significant overall yield increases due to P applications, even though P rates exceeding 30 kg ha^{-1} were associated with slightly (5%) higher yields, accompanied by an about 10-% increase in large-sized bulbs. Nor did Riley et al. (2012) find any correlation between STP and yield responses, perhaps because of a lack of truly low STP soils in their study. Further, these authors reported that banding P increased the P use efficiency and increase yields by 7–12%. This application method would make it possible to lower P applications by 10–15 kg ha^{-1}. In their revision of P recommendation for a soil at "optimal" (i.e. medium) P status they lowered recommended P rates for onion from 60 to 43 kg P ha^{-1} when P is band-applied, but only marginally, to 58 kg ha^{-1}, when P is broadcast. On soils with the highest P status, often found on vegetable-growing farms, the corresponding recommendations were reduced to 30 and 20 kg P ha^{-1}, respectively.

In their 11 experiments with late harvested cabbage Riley et al. (2012) measured mean 5–7% statistically significant yield response to added P at P rates 30 and 60 kg ha^{-1}. Cabbage harvested earlier in summer and grown under plastic in two experiments gave a non-significant maximum yield increase of 5% already at 15 kg P ha^{-1} rate. They revised the earlier recommendation for cabbage in "optimal" STP soils from 40 kg ha^{-1} to 30 kg P ha^{-1}, and to 15 kg ha^{-1} or less on soils with the highest P status.

Comparisons between recommendations in different countries, even with similar climate and soil settings, are not straightforward when the methods for soil P testing are different. Different STP methods may give very dissimilar results and correlate poorly with each other (Neyroud & Lischer 2003), especially when comparing a method that extracts a small fraction of soil P (P intensity-responsive methods, such as water-extractable P or the Finnish P_{Ac} method) to one that uses more aggressive extractants (e.g. P quantity-responsive ammonium lactate used in Norway and Sweden). However, if we look at recommendations given for "target" STP class, it is obvious that the Finnish limits are clearly higher than the recommendations in Sweden and Denmark, and also higher than the present Norwegian recommendations.

Conclusions

Our results strongly suggest that P requirements of onion and cabbage are lower than the Finnish AEP limits. When yield responses were measured, 97% of maximum yield was obtained with less than 15 kg P ha^{-1} and the price of an additional P application cost more than the value of additional yield at about 40–50 kg ha^{-1} P rates. If yield responses remain lower than in our Mikkeli experiments, even these P application levels would be too high, and replacement fertilisation would suffice if farmers wish to maintain their current STP concentrations. Increasing P applications had only minor effects on yield quality and high application rates are not needed for that reason either. We could not make any statement on critical P_{Ac} concentration because of too few study sites, but it would be necessary to clarify the critical STP levels for the most widely grown vegetables. Only then can P recommendations or limits be set correctly.

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