

Yield response of iceberg lettuce (*Lactuca sativa* Capitata group) to phosphorus fertilisation in a boreal soil

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Cold soils and a short boreal growing season are assumed to necessitate high soil phosphorus (P) status and ample P applications to vegetable crops. Yet, a previous Finnish study indicated lower than anticipated yield responses of onion and cabbage. Here we report 2-year P trials with iceberg lettuce (cv. Skindel) transplanted in an open field in spring and midsummer on a clay soil with moderately low P status. During the spring plantings, P concentration in soil solution was followed using Plant Root Simulator (PRS) probes in P0 (0 kg P ha⁻¹) and P60 (60 kg P ha⁻¹) treatments. The PRS probes indicated initially 5 to 7-fold higher soil solution P concentration in the P60 treatment compared to P0 due to fertilisation, but thereafter P concentrations equalised. For spring plantings, P applications did not explain yield variation, giving statistically non-significant, maximum 14% higher yields over P0. In summer plantings, about 30% of the yield variation was explained by P applications, and the P60 rate gave 20–35% higher yields over P0. Mitscherlich type model integrating all data predicted a maximum 20% yield, 10% of the variation being accounted for. The model suggested that 32 kg P ha⁻¹ brings 97% of the maximum yield, whilst the Finnish P fertilisation regulation allows 60 kg ha⁻¹ for the given soil. No correlation between P applications and P concentrations of lettuce leaves was found. The results stress the need for empirical evaluation of P requirements of vegetable crops to avoid unnecessary P applications.

Key words: yield model, planting time, open field experiment, Plant Root Simulator probe

Introduction

Iceberg lettuce (*Lactuca sativa* Capitata group) is a fast-growing vegetable species which is expected to require relatively high nutrient supply to produce high-quality yield. In earlier studies, lettuce has been found to respond to P fertilisation (e.g. Greenwood et al. 1980, Alt 1987). Both Greenwood et al. (1980) and Alt (1987) specifically noted that a special feature of lettuce among vegetable crops is the large P demand relative to the demand for K. The root system of lettuce is shallow thus the nutrient uptake is limited to a relatively small soil volume. Costigan (1986) further showed that a combination of cold soil conditions and scarce P supply increases the root-to-shoot ratio of lettuce which is undesirable for rapid yield production.

To determine sufficient P supply to lettuce, a number of P fertilisation studies in open field were conducted in 1980's and 1990's (e.g. Sanchez et al. 1990, Nagata et al. 1992, Sanchez and El-Hout 1995), with P fertilisation rates up to 300 kg ha⁻¹. In the five experiments of Sanchez et al. (1990) conducted on two organic soils, yield response curves turned flat at about 60–80 kg ha⁻¹ P rate when fertiliser was band-applied, but for broadcast application up to 200 kg P ha⁻¹ was required for the same yields. Similar yield curves were presented by Sanchez and El-Hout (1995) who also concluded that there are no marked differences in P response between different types of lettuce. Based on these results, University of Florida extension services, for example, recommended for lettuce grown on organic soils a maximum of about 100 kg ha⁻¹ (200 lb P₂O₅ ac⁻¹) band-placed fertiliser P, adjusted downwards as soil test P concentrations increases (Hochmuth et al. 1994).

During the last decades ensuring ample P supply to crops has no longer been the only thing to consider, but emphasis has also been laid on the risks of off-site P losses. In their field monitoring of subsurface drainage waters, Heckrath et al. (1995) showed that P leaching increases as soil test P (STP) concentration increases as a result of long-term abundant use of P fertilisers or manure. Among large number of studies that confirm the results of Heckrath et al. (1995), Hartz and Johnstone (2006) demonstrated a strong positive correlation between STP concentration and P losses in simulated irrigation tests of soils collected from Californian vegetable fields. Such relationships between STP and dissolved P losses have been found to hold for widely different agricultural regions and cropping systems (Withers et al. 2019).

At high soil test P concentrations, lettuce yields do not benefit from annual P applications as shown by Johnstone et al. (2005). Only in one of the 12 commercial field sites of their study, P fertilisation (29 kg ha⁻¹) increased the

lettuce yield statistically significantly (by 7%) compared to plots without applied P. In concert, Smith and Hartz (2008) recommended P fertilisation only in fields with low STP in winter or spring plantings of lettuce, and at rates similar to plant P uptake.

Improved farming techniques are one path ahead in decreasing surplus P applications. As an example, banding of fertiliser P has been found to allow lower P rates for the same yield response. Sanchez et al. (1990) suggested that P application to lettuce could be reduced to one-third, to 31–88 kg ha⁻¹ for 98% of maximum yield, when P fertiliser is banded instead of broadcasting. However, P applications that in long term exceed crop P off-take remain problematic when STP concentrations need to be lowered to comply with environmental targets (see Withers et al. 2019).

Under northern growing conditions, vegetables are assumed to need high rates of P fertilisers, because of the short growing season and cold soils in spring. Nonetheless, an earlier Finnish study (Uusitalo et al. 2018) suggested that P demand of vegetables such as onion and cabbage is smaller than previously thought also in Finland with our cryic soil temperature regime. In the study mentioned, statistically significant yield increases were found only on one of three sites, and P rates of 10–12 kg ha⁻¹ were sufficient to produce 97% of yield maxima. Hence, P applications that balanced P export in harvested products were enough to ensure near maximum yield production, whereas the Finnish Agri-environmental Programme would have allowed P applications of 30–60 kg ha⁻¹ that would have resulted in surplus P balance by tens of kilograms per hectare.

The objective of this study was to evaluate the yield responses to P fertilisation of iceberg lettuce transplants grown in the early and middle parts of the growing season, i.e., on cold and warm soils. This work continues our series of P fertilisation trials with vegetable crops, P demand of which has so far been based on expert view only, due to lack of Finnish P-fertiliser trial data. The effects of annual P fertilisation rate, type of P fertiliser and planting time were explored in 2017–2018 on a clay soil with relatively low STP concentration for vegetable fields.

Material and methods

Site of the study

Field experiments were conducted at the research site of the Natural Resources Institute Finland (Luke) in Piikkiö, SW Finland (60°23'15"N, 22°33'07"E). The experiments were established on a soil with 45–53% clay content determined by a pipette method of Elonen (1971), 2.2–2.7% total C (Leco CN analyzer), and 21–29 cmol(+) kg⁻¹ effective cation exchange capacity (summation method of Niskanen and Jaakkola 1986). Soil pH (in H₂O; 1:2.5 vol:vol) was 6.0–6.4. The soil had a relatively low soil test P concentration, 5–7 mg l⁻¹ determined with the (pH 4.65) ammonium acetate extraction of Vuorinen and Mäkitie (1955). P-Olsen (Olsen and Sommers 1982) and P-Mehlich 3 (Mehlich 1984) concentrations determined for the same parcel two years earlier were around 30–40 mg kg⁻¹. No large P applications to the used parcel have been made since then.

There were two separate experiments in both years: spring planting was done in early May (5 May 2017 and 8 May 2018) and summer planting in the end of June (30 June 2017 and 29 June 2018). All experiments were located on the same field, but the plots were rotated in parts of the field previously unused in P experiments. The lettuce cultivar Skindel F1 (Nunhems, the Netherlands) was used in the experiments, and it was grown on imported transplants which were planted at growth stage 13–14 on BBCH scale (Meier 2018).

Experiments

There were six fertilisation treatments, four of which involved granular P fertilisation at rates 0, 10, 20 and 60 kg ha⁻¹ (coding P0, P10, P20 and P60). In addition, two treatments involved liquid P fertiliser (P10liq and P20liq supplying P rates of 10 and 20 kg ha⁻¹, respectively) with trade name Flex NP7-8 (Flex Fertilizer System, Denmark). The liquid fertiliser contains 7% amide-N and 8% P. Undiluted liquid fertiliser was injected with a syringe at 3 cm distance from the plants and 3 cm under the base of the transplant.

Nitrogen (N) and potassium (K) were applied in similar amounts to all P treatments: N 100 kg ha⁻¹ prior to planting, complemented with additional 30 kg N and 70 kg K ha⁻¹ 4 weeks later, using fertilisers containing ammonium and potassium nitrate, and potassium sulphate. Other macro- and micronutrients were added as needed according to soil analyses. Granular fertilisers were added by hand on the soil surface and mixed with a rotary tiller in the top 10 cm of the field prior to planting.

The field experiments were set up according to randomised complete block design with four replicate blocks in 2017 and five blocks in 2018, treatments being randomised to each block. Size of the plot was 1.4 m × 5.0 m, including three plant rows (row distance 35 cm) with planting distance of 30 cm, yielding 50 plants per plot. The plants were irrigated after harvest and regularly during growth according to the soil moisture content measured by tensiometres (Nieuwkoop TM-93, Aalsmeer, NL) at 20 cm depth.

Head yield was harvested from 30 plants per plot (10 plants per row, leaving guard areas in both end of the rows) when the heads had reached marketable compactness, 45–60 days after planting. Six plants per plot were collected with the outer leaves attached for dry matter and nutrient content analyses. Dry matter content was analysed by drying chopped samples at 60 °C to constant weight. Plant N content was determined by the Kjeldahl method and other mineral elements with an ICP-OES (Thermo Fisher Scientific iCAP 6300 Duo MFC, Waltham, MA, USA) after microwave oven assisted digestion with concentrated nitric acid.

Soil sampling and soil P analyses

Soil samples, composed of 15 subsamples, were taken from the (0–20 cm) plough layer of each plot prior to the fertilisation. The samples were dried at about +35 °C, ground to pass a 2-mm sieve, and tested for P concentrations using the Finnish soil test protocol of Vuorinen and Mäkitie (1955) that involves 1-h ammonium acetate extraction at pH 4.65 in soil-to-solution ratio of 1:10 (vol:vol). The used extraction reflects the readily soluble P concentration in soil and extracts about the same amount of soil P as water at 1:50 w/vol ratio (Yli-Halla 1989).

Soil solution P concentration of the spring plantings were additionally followed using the Plant Root Simulator (PRS) probes (Western Ag, Canada) that equilibrate with nutrients present in soil solution. The probes were applied to P0 and P60 treatments. Four anion and four cation probes were placed in each plot for a one-week period and replaced weekly with new ones, the first ones being inserted right after planting. Used probes were washed under running water with a brush and stored refrigerated until they were sent for analysis to Western Ag laboratory in Canada. The four replicate probes of each plot were combined in the nutrient elution step. PRS probes were applied for subsequent 8 weeks, i.e. during the whole growth period of the first plantings in 2017 and 2018.

Weather data

Weather data were recorded on an automatic meteorological station of the Finnish Meteorological Institute, approximately 400 m distance from the site. Daily mean temperatures and precipitation sums were used to compare the growing conditions in different plantings in both years.

Yield model and statistical analysis

Yield response was calculated as the increase in yield over that of the P0 treatment. In the yield model P application rates were used as the explaining variable. The data of each planting were first separately fitted with a non-linear Mitscherlich type exponential equation (Eq. 1) and a linear regression equation (Eq. 2). Akaike's information criteria (AIC) and Pearson correlation coefficient were then used to select the more appropriate model for yield responses. In case of preference being a linear model, the extra sum-of-squares F-test was performed to find out if the slope estimate is different from zero (at *p*-value of 0.05). In case the slope did not differ from zero, no yield model was fitted.

Eq. 1.
$$Y = Y_0 + (\text{Plateau} - Y_0) \times (1 - \exp(-K \cdot X))$$

In Eq. 1, yield increase (*Y*) is modelled by fitting the P0 control yield (*Y*₀, Mg ha⁻¹), the maximum yield level (Plateau, Mg ha⁻¹), and a dimensionless fitting constant (*K*), using the rate of P application (*X*, kg ha⁻¹) as the explaining variable.

Eq. 2.
$$Y = B_0 + B_1 \cdot X$$

In Eq. 2, yield increase (*Y*) is fitted with the P0 control yield (*B*₀) and the slope (*B*₁) of the change in yield as P-rates (*X*) increase.

All data were finally combined to a common yield response model. For that, we normalised the actual yields of each planting (Mg ha⁻¹) to relative yields (percent increase due to P applications) by comparing them to the yield

of P0 control of the planting in question (yield in P0 set to 100). The preferred model (Eq. 1 or 2) was again tested with the AIC test and the more appropriate model selected for reporting.

Statistical testing and curve fitting of yield data was done using GraphPad Prism (San Diego, CA, USA) 8.3 software.

Data on plant P concentrations in different fertilisation treatments and differences between granular and liquid fertilisers were analysed by SAS 9.4 statistical software, using a mixed model, with experiment, fertilisation and their interaction as fixed factors, and block as a random factor.

Results

Yield responses

In all plantings P fertilisation increased the average lettuce head yield somewhat in comparison to P0 treatment, but the effects were uncertain, as shown by the wide confidence intervals in Figure 1. In fitting the yield responses separately for each yield, the linear model (Eq. 2) was preferred over the non-linear Mitscherlich type model (Eq. 1). However, slopes of the linear equation were not significantly different from zero for the spring plantings, despite P60 treatment also then increased yield by up to 14% over the P0 treatment. For summer plantings, the slopes were significantly higher than zero, and the average yields measured in P60 treatment were 35 and 21% higher than in P0 in 2017 and 2018, respectively.

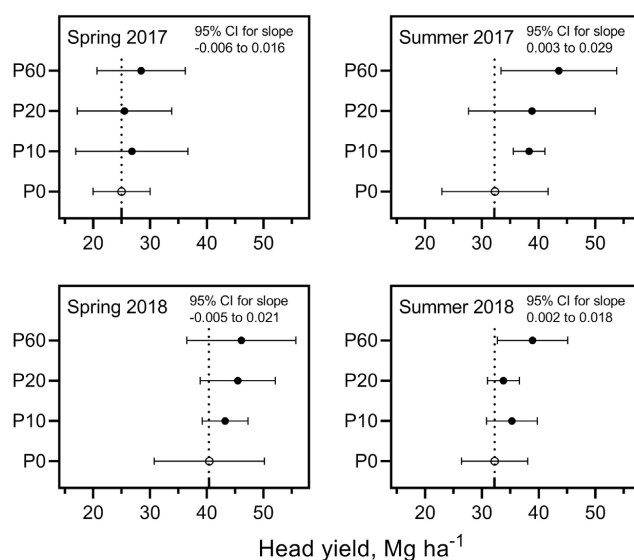


Fig. 1. Mean iceberg lettuce head yields of the four individual plantings with granular P fertiliser treatments. Bars indicate 95% confidence intervals and vertical dotted lines the mean value of the control treatment (P0); 95% CI for slope (B1 term of linear Eq. 2) are given inside the panels.

The overall yield response curve, with all data combined, was better fitted with the Mitscherlich type equation than linear one (Fig. 2). However, P fertilisation explained only 10% of the yield variation. The estimate for mean relative maximum yield increase was 20% over the P0 treatment. If 97% of the maximum yield level is targeted, the model suggests that it is obtained with a P application rate of 32 kg ha⁻¹. The Eq. 1 parameter estimate for the average yield of the P0 treatment in all plantings (Y0) was 32.5 Mg ha⁻¹ and the estimate for the maximum predicted yield (Plateau) was 39.0 Mg ha⁻¹, giving mean 6.5 Mg ha⁻¹ maximum yield increase due to P applications. For the fitting constant K (Eq. 1), value 0.05343 was estimated.

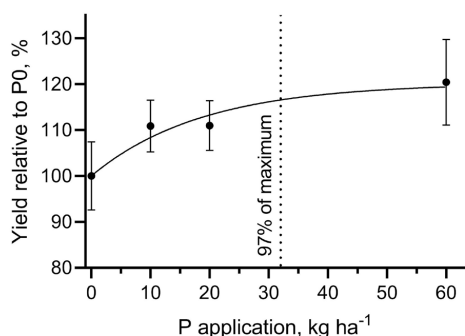


Fig. 2. Combined relative yields for P applications as granular P fertilisers over all four experiments. Vertical dotted line is drawn at the P application associated with 97% of the maximum yield. Error bars indicate 95% confidence intervals of the measured yield responses.

When comparing the granular and liquid P fertilisers (Fig. 3), the mean yield over all plantings and both P rates (10 and 20 kg ha⁻¹) was marginally higher for the liquid than the granular fertiliser type, 36.7 vs. 35.9 Mg ha⁻¹ but the difference was not statistically significant at either P10 ($p=0.69$) or P20 rates ($p=0.48$).

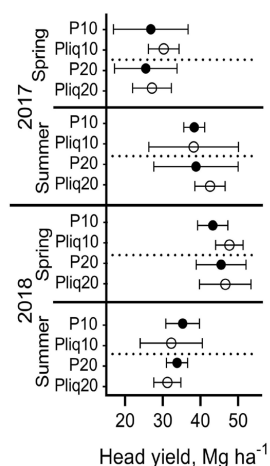


Fig. 3. Comparison of mean lettuce yields (with 95% confidence intervals) fertilised with granular or liquid P fertilisers.

The proportion of marketable yield was usually high, 80–95% of the total yield, and generally not affected by the formulation of P fertiliser or P rates. An exception was the summer planting of 2018 when the growing conditions were stressful, with high temperature and high humidity prior to harvest that resulted in poor yield quality. For that planting, the P10liq and P20liq treatments had the highest percentages of marketable yield of all treatments, 32 and 38%, respectively. At the same time, P20 and P60 were associated with the lowest shares of marketable yields, 15 and 12%, respectively.

Water availability was not likely to hinder the growth, as the precipitation sums over the growing periods varied between 62 and 111 mm in different plantings and the plants were also irrigated during the dry periods, occurring especially in early June and July 2018.

Soil solution P intensity

Soil solution P intensity monitored with the PRS anion exchange membranes showed that fertiliser P added to P60 treatment one day before planting was clearly visible in PRS analysis about 2 weeks after applications, after which the concentrations in the P60 plots declined (Fig. 4). In 2017, mean concentrations during the first two weeks after fertilisation were (for deployment time of 7 d) 0.8 and 4.0 $\mu\text{g (10 cm}^2\text{)}^{-1}$ in P0 and P60, respectively. In weeks 3–8 from fertilisation the means were 1.2 and 1.7 $\mu\text{g (10 cm}^2\text{)}^{-1}$. In the same periods in 2018, higher concentrations were measured for both treatments, 2.1 and 14.7 $\mu\text{g (10 cm}^2\text{)}^{-1}$ for the two first weeks and later 1.8 and 2.6 $\mu\text{g (10 cm}^2\text{)}^{-1}$ (P0 and P60, respectively). The reason for the clearly higher P intensities in spring 2018 was possibly associated with higher soil temperatures around the time when P fertiliser was applied.

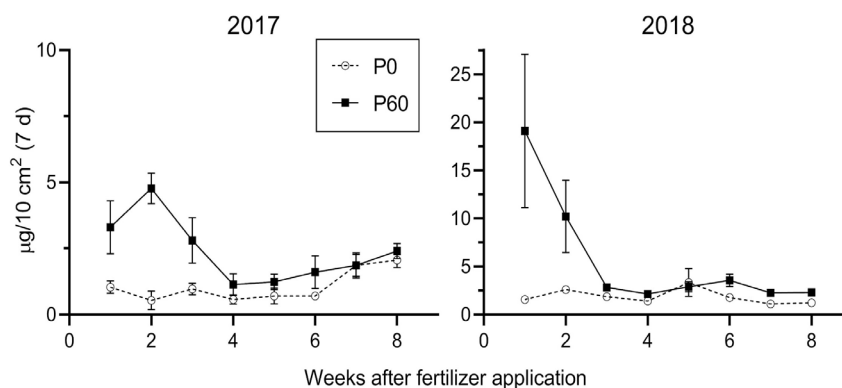


Fig. 4. Soil solution P intensity monitored by PRS probes starting from spring planting; probes were replaced weekly. Error bars show standard error. Note the different y-axis scales.

P uptake

Fertilisation treatments had statistically significant effects on the plant P concentrations (Table 1), but there was no regularly increasing trend in lettuce P contents according to P rates. However, the use of liquid fertilisers resulted in a lower P concentration than granular fertilisers, especially in heads. The effect was consistent over separate experiments, as the interaction between experiment and fertilisation treatment was statistically non-significant ($p= 0.504$). As averaged over treatments in 2017, the head P concentration was higher in spring planting than in summer planting (6.15 vs. 5.09 g kg⁻¹). On the contrary in 2018, the head P concentration was lower in spring planting than in summer (5.44 vs. 6.35 g kg⁻¹). This may be a result of nutrient dilution as the yields showed the opposite trends.

Table 1. P concentrations in lettuce heads and outer leaves, averaged over four separate experiments in 2017–2018

Treatment	P concentration (g kg ⁻¹ DM)	
	Heads	Outer leaves
P0	5.94	2.64
P10	5.90	2.66
P10liq	5.55	2.43
P20	5.81	2.64
P20liq	5.52	2.56
P60	5.85	2.66
SEM	0.11	0.06
<i>p</i> -value	<0.0001	0.0015

The total P uptake in above-ground biomass was 6–12 kg ha⁻¹, most of which was located in heads and removed from the field. Hence, field P balance was mostly positive already with the lowest studied P rate of 10 kg ha⁻¹.

Discussion

For vegetable crops, no Finnish experimental data on P responses has existed until recently but P recommendations have been based on expert judgement. These recommendations are quite similar compared to the old Norwegian ones that were later revised downwards after data from large number of P trials with vegetables were analysed (Riley et al. 2012, Stubhaug et al. 2015). We foresee a similar revision also in Finland after sufficient data are collected.

Even though similarities between different countries may be found in soil characteristics, length of the growing season and crop varieties grown, there are usually differences in conducting and interpretation of soil P analysis. There is a vast number of soil P extractants in use in different countries, and the amount of P they extract do not necessarily correlate very closely with each other (see Neyroud and Lisher 2003). Also, climate likely plays a major role in interpretation of sufficiency of soil P stock. Since P-Olsen concentrations on our study site has been within a range 30–40 mg kg⁻¹, in many countries considered sufficient for several crops, our claim that this study conducted on a soil with relatively low STP for vegetable growing may seem ambiguous. However, the field site of the experiment had ammonium acetate P (P-Ac) concentration of 5–7 mg l⁻¹, which according to earlier Finnish meta-analyses (Valkama et al. 2011, 2015) corresponds to the point at which yield responses to P of cereals and grasses grown on clay soils turn unlikely. We expected that a crop with a small root system, such as iceberg lettuce, would show clear responses to P fertilisation.

Indeed, the maximum overall response of 20% more lettuce yield was much higher than typically documented, about 5% increase, for cereal and grass crops on clay soils (Valkama et al. 2011, 2015). Combined with a much higher yield value of lettuce as compared to cereals, targeting near the potential maximum yield would be paying back the price of the P fertilisers used. However, this would result in a P surplus that gradually builds up STP if not accounted for in fertilisation of successive crops.

In cases when STP can be assumed to restrict yield production, P fertilisation is recommended especially in cooler periods (e.g. Prasad et al. 1998, Smith and Hartz 2008) when dissolution and diffusion of P slows down (Lewis and Quirck 1965, Grant et al. 2001, Ylivainio and Peltovuori 2012). We thus presumed that P added for the spring plantings in cooler soil would result in more clear yield responses than in summer plantings. In contrast, statistically significant yield responses to added P were observed only for the summer plantings in warm soils. As discussed by Ylivainio and Peltovuori (2012), low P acquisition in cold soils is likely a combined effect of lower P mobility and slower plant physiological activity. Lower P uptake would thus partly be because of slow transport through the P ports over the root membrane and low transpiration rates, regardless availability in soil. Then, increasing P supply would not necessarily push up yield production.

Nonetheless, yield variation of the spring plantings was substantial. The lowest total yield of all plantings in P0 treatment (25 Mg ha⁻¹) was measured in spring of 2017 when the mean air temperature over the two-week period after planting was just 5.6 °C, as compared to the highest yield (about 40 Mg ha⁻¹) in spring 2018 when mean air temperature was 15.3 °C. Summer plantings yielded constantly about 30 Mg ha⁻¹ in the P0 treatment, but high summer temperature combined with high humidity before harvest resulted in substantial quality loss for the summer 2018 planting. The loss in yield quality actualised some days before harvest, and it did not affect total yield used in reporting our results.

Compared to spring 2018, soil solution P intensity measured with the PRS probes also showed much smaller elevation after fertilisation of the P60 treatment when the spring temperatures remained low in 2017. But these cold spring temperatures appeared not to affect plant P concentrations that were equal or higher than in other plantings, and thereby we cannot draw the conclusion that the spring 2017 planting would have been suffering from low plant-availability of P. Also, the P concentrations measured in the head tissues were similar or even slightly higher than the values reported by Greenwood et al. (1980), Johnstone et al. (2005), and Hoque et al. (2010).

For barley grown in different soil temperatures, Ylivainio and Peltovuori (2012) recorded lower P content in shoots grown in +8 °C than those grown in ambient (mean +15 °C) early summer temperatures, suggesting that P acquisition of barley was affected by cold soil. Generally, in soils with low P supply, sufficient P during the first weeks after sowing is considered the most critical period for yield, and later P applications may not allow recovery of plant yields (Grant et al. 2001). In our study, with seedlings developed on a growth medium that likely had an ample P supply and transplanted for maturation on a relatively low-P soil, yields and P content of lettuce heads at harvest did not suggest any substantial P shortages. Supply of P during lettuce head maturation was satisfied (to 97% of the yield maximum) with 32 kg ha⁻¹ P applications, thus about half of that allowed in the national Agri-environmental scheme for the given soil type and P status. Our results suggest that the past expert judgement is an overestimation of P needs of lettuce grown from transplants used in the Finnish production system. It is also possible that gradual warming of climate has affected plant P requirements in general.

Liquid starter fertiliser did not increase the yield statistically significantly compared to the granular fertiliser with the same P rate, although the starter fertiliser was placed near to the transplants while granular fertiliser was broadcasted. In their study made with lettuce seedlings which are probably more responsive to fertiliser effects

than the transplants used in the Finnish production system, Costigan (1986) reported that starter fertilisers containing P and N increased nutrient uptake both in 10 and 20 °C, but with a positive effect on the final yield only in 10 °C. There are thus contrasting observations on how temperature affects P responses in general, and if such effects are rectified by selection of fertiliser type or its placing. Our conclusion is that lettuce grown on transplants does not appear to be highly sensitive to the soil P sorption/desorption behaviour associated with low temperatures, but as noted above the situation may be different when grown from seeds. Further, fertiliser type or placing did not have a clear effect on head yield.

The total lettuce P uptake in the above-ground biomass was 6–12 kg ha⁻¹ which was lower than the average uptake of 14 kg ha⁻¹ in the experiments by Johnstone et al. (2005) performed in high STP soils. Offtake in our harvested head yield varied between 5 and 8 kg P ha⁻¹ in different plantings, meaning that the field balance was positive already with the P application rate of 10 kg ha⁻¹. Using the maximum allowed 60 kg P ha⁻¹ rate of the Finnish Agri-environmental Programme (FAEP) would mean about 50 kg ha⁻¹ P surplus which cannot be considered irrelevant from an environmental point of view, especially when vegetable growing does not usually rotate over large land areas with other crops in sequence for most of the time.

Like our earlier study with onion and cabbage (Uusitalo et al. 2018), also lettuce grown from transplants appears to have lower P demand than the limits of P use set by the FAEP. For onion and cabbage, field trials suggested that about half of the maximum P use limit of FAEP suffices to produce nearly maximum yield. The results of the present study agree with that. The FAEP limits aim to reduce risks for P losses to watercourses, but for vegetables the limits are set according to expert view instead of experimental data because of almost total lack of local experimental data regarding vegetables and their P utilisation. The studies conducted in recent years with vegetable crops suggest that expert view has failed in estimating the actual P demand of the crops that have been grown in field P-experiments. Based on these experiences, we see little risk for marked yield losses upon adoption of recommendations that would halve the P fertiliser rates from the present FAEP limits. Even when such recommendations would still mean P surpluses in the years when vegetable crops are grown, they would help to reduce STP build-up and the risks for off-site environmental damage due to P losses.

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