NIBIO final report from project

SUSPHOS: Sustainable phosphorus (P) fertilization on golf courses

Economic savings and lower environmental impact by reduced and more targeted fertilization with phosphorus (P) according to soil analyses.

Authors

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Phytotron compartments for WP 1 and 2 with temperatures: 7, 12 and 17 °C. Photo: Anne F. Øgaard

CONTENT

This report is a summary of previously published material.

1 Introduction

Phosphorus (P) can cause eutrophication of freshwater ponds and lakes by leakage or surface runoff, and it is the plant nutrient of which the world's mineral resources are most limited (1). This calls for less and more targeted use of P in turfgrass systems. A review (2) concluded that fertilization and irrigation management play the largest role in nutrient losses from turfgrass areas, though the magnitude from established, well managed turf seemed to be reasonably low. Despite of that substantial leaching of P was documented from sand-based greens in Norway (3). During the last couple of decades many countries have reduced the recommendations for P inputs to agricultural crops, while there has been no similar reduction in the recommendations for turf.

Determining a sustainable level of P fertilization for turf requires a profound understanding of the conditions that can cause P deficiency. P deficiency is most likely to occur in three situations (4):

- *When soil P values are very low*. The relationship between P values in soil tests and plant response to P is, however, not straightforward, but soil specific (5). The soil's content of amorphous aluminum (Al) and iron (Fe) (hydr)oxides, organic matter and pH are important factors that influence the soil's capacity to bind and release P (6).
- *During turfgrass establishment when grass roots have not yet penetrated the soil*. In this situation, phosphorus deficiency may occur even at relatively high soil P levels. Fertilizer companies often recommend the application of 'starter fertilizers' with similar concentrations of N and P, however, the benefits of such a high P:N ratio may vary with soil type, soil-P level, N-level, turfgrass species and several other factors (7).
- *On established turf during periods when root growth and nutrient uptake is restricted by low soil temperature*. In this situation, fertilizer companies sometimes recommend foliar applications of P, but there is little scientific evidence to support this practice. The purple color seen on golf greens in spring is often interpreted as P deficiency, but it may also be due to pigment changes as a protection against photoinhibition (4).

In the Nordic countries turfgrass is often reseeded at low soil temperature in spring after winter damage. The scientific evidence for applying extra P in this situation is limited or non-existent.

Thus, the objectives of the first part in the SUSPHOS project was to determine the need for extra P fertilizer for turfgrass (re)establishment on sand-based greens at various temperatures in spring (WP 1) and to determine the effect of foliar vs. granular applications of increasing rates of P on color, growth rate and P-uptake of surviving greens at various temperatures in spring (WP 2). Both are described in Chapter 2.

In a survey on US golf courses a 53 % reduction in P use was documented from 2006 to 2014 without apparent declines in turf quality and playability (8). The survey also revealed that higher P rates were applied on golf courses that take soil samples regularly, which could be due to conflicting standards for turfgrass fertilization as a function of the soil's content of plant available P.

Chapter 3 describes the results from WP 3 (the field experiments in the SUSPHOS project) where the objective was to investigate if P fertilization can be reduced on golf course putting greens without negative implications for turf quality. The research compared three P fertilization recommendations and comprised assessments of turf quality and coverage over a period of three or four years at five golf courses in Germany, Sweden, China, Norway and the Netherlands. The recommendations to be compared were: SLAN (Sufficiency Level of Available Nutrients), MLSN (Minimum Level of Sustainable Nutrition) and SPF (Scandinavian Precision Fertilization).

Figure 1. P fertilization on experimental green used for WP 3 at Landvik, Norway. Photo: Trygve S. Aamlid

The SLAN recommendation prescribes Mehlich-3 levels above 54 mg P/kg dry soil (9). Several studies have documented that this recommendation is higher than needed (10, 11). P fertilization and subsequently high soil P levels can promote annual bluegrass (12, 13).

Minimum Level of Sustainable Nutrition (MLSN) considers a Mehlich-3 P level of 18 mg P/kg dry soil as sufficient to maintain 'good looking turf' (14). The MLSN guideline was based on more than 17,000 individual soil samples, taken around the world from good performing turfgrass areas. Soil samples taken from 2013 to 2016 at 162 locations with good performing turf around the world (mainly putting greens) showed that the MLSN guideline was reasonable for turfgrass across a wide geographic region (15).

Up to present, Scandinavian fertilizer recommendation for putting greens (SPF) have recommended application of N and P in the ratio 100:12 both in the grow-in situation and on established greens, and regardless of soil temperature (16). The SPF guidelines have, however been questioned by the fertilizer industry and many greenkeepers alike, and although this is a safe method, it is likely to result in redundant P applications, and thus environmental and economic losses, on soils high in plant available P.

Both SLAN and MLSN recommendations are widely used on golf courses around the world, whereas SPF is common in the Nordic countries. The three recommendations have never been compared in systematic field experiments under different soil and climatic conditions.

2 WP 1 and 2 (Phytotron experiments)

- The need for extra P fertilizer for turfgrass establishment on sand-based golf greens at various temperatures (WP 1)
- Effect on time of green-up and turfgrass quality of foliar or granular applications of increasing amounts of P at various soil temperatures in spring (WP 2)

See original scientific publication (17).

2.1 Materials and methods

WP 1

Cylinder experiments simulating USGA-spec. rootzones were conducted in spring 2017 and 2018 in daylight compartments without supplemental light in the phytotron at the Norwegian University of Life Science, Ås, Norway. Three phytotron compartments had temperatures set to 7, 12 and 17 °C, respectively.

The experiment was conducted from 6 April to 26 May 2017 and repeated from 5 April to 25 May 2018 (both times 7 weeks duration). The cylinders, 10 cm in diameter, 40 cm deep and with a wire mesh at the bottom, were filled with a 10 cm gravel layer and then with a 30 cm rootzone consisting of USGA-spec. silica sand amended with 10 % (v/v) *Sphagnum* peat. Chemical soil characteristics of the substrate are presented in Table 1. No fertilizer was applied, but all cylinders were irrigated to field capacity on the day before seeding creeping bentgrass 'Independence' at a rate of 7 g/m^2. The cylinders were covered with a white permeable tarp and irrigated gently with a hand-held sprayer once a day until seedling emergence. After seedling emergence, cylinders were irrigated with tap water three times per week.

Table 1. Chemical soil characteristics of the USGA-spec. rootzones used in WP 1 and WP 2.

	Depth cm	pH (H_2O)	Total C, %	P-AL mg kg^{-1}	Mehlich-3 extracts, mg kg^{-1}				Oxalate extracts, mmol kg^{-1}			Degree of P-saturation, DPS$_{ox}$, %
					P	K	Ca	Mg	P	Al	Fe	
WP 1	0-30	5.3	0.2	29	13	9	66	14	1.4	9.6	6.1	18.6
WP 2	0-12	5.6	0.7	23	34	40	120	18	2.1	10.4	4.7	28.9
	12-30	5.1	0.2	28	13	8	66	14	1.4	9.6	6.1	18.6

Starting two weeks after seeding, premixed fertilizer solutions were applied weekly to all cylinders. All solutions contained N in the form of ammonium nitrate for a rate of 2 g N/m^2/week totaling 10 g N/m^2 during the entire experiment (five applications).

The concentration of P in the fertilizer solutions varied among treatments. P was applied at rates of 0, 0.12, 0.24, 0.36 or 0.48 g P/m^2/week in the form of 85 % monophosphoric acid (H_3PO_4). There were three replicates per treatment and the 15 cylinders were randomized completely in racks within each of the three phytotron compartments.

The concentration of potassium (K), sulfur (S), calcium (Ca), magnesium (Mg), iron (Fe), manganese (Mn), boron (B), zink (Zn), copper (Cu) and molybdenum (Mo) in all fertilizer solutions were applied according to SPF (Scandinavian Precision Fertilization) (16).

Weekly assessments after emergence included of turfgrass coverage (% of cylinder surface area) and color (1-9, where 9 is darkest turf). Soil temperatures inside cylinders (mean for 0-12 cm depth) were measured occasionally to account for radiant heat on sunny days. Starting three weeks after seeding for cylinders at 12 and 17°C and four weeks after seeding for cylinders at 7°C, the creeping bentgrass was cut weekly to 5 mm height using scissors and clippings collected. Clipping yields were dried at 40°C and weighed. One pooled sample including all clippings per cylinder was milled and subjected to analyses for total P and N. At the end of the experiment, soil samples were taken from the 0-30 cm root layer for the treatments 0, 0.24 and 0.48 g P/m^2/week. The soil samples were dried at 40°C and passed through a 2-mm sieve. Roots from each cylinder were then washed, dried at 40°C and weighed.

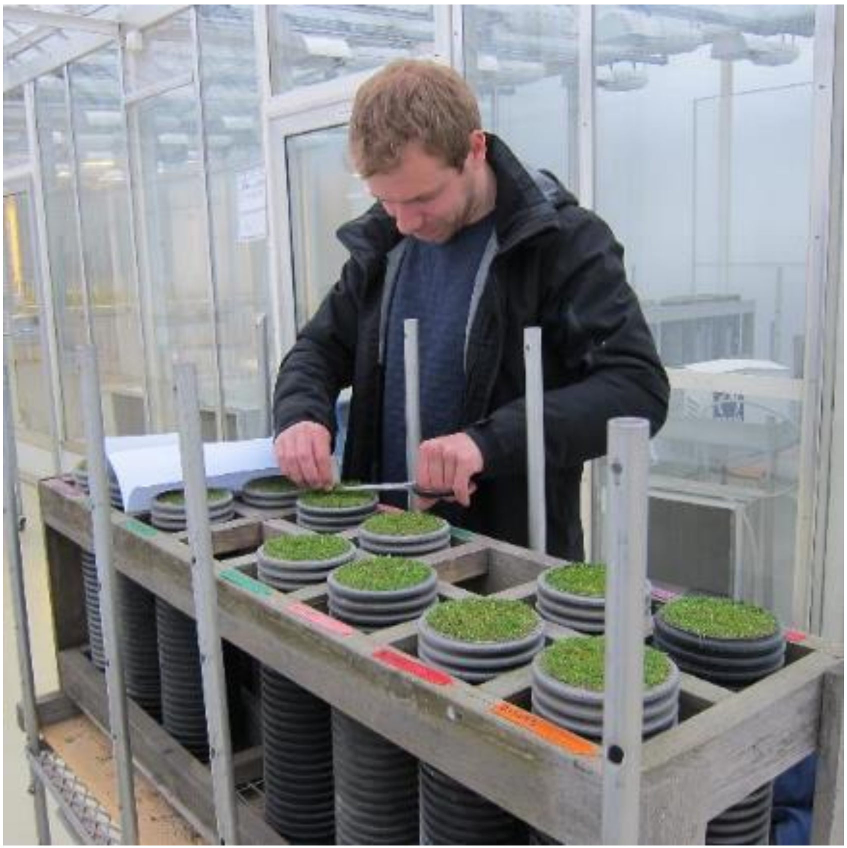

Figure 2. Manual mowing of the experiment at the phytotron compartment at Ås, Norway. Photo: Anne F. Øgaard.

WP 2

The first time-replicate of this experiment was conducted from 6 April to 12 May 2017 (5 weeks) using the same phytotron compartments and same type of cylinders as in WP 1. The cylinders were filled with 10 cm of gravel from the bottom, then with 18 cm of the same peat-amended substrate as used in WP 1 and finally with a 10 cm diameter and 12 cm deep soil core taken with a cup cutter shortly after snow melt/soil thaw on a USGA-spec. green at the NIBIO Turfgrass Research Center Landvik, SE Norway. The green had been seeded with creeping bentgrass ‘Independence’ in 2013 after renovation using the same type of peat-amended sand as used in WP 1, but the soil pH and content of organic C and nutrients had increased during the four years since establishment (Table 1).

Nitrogen was applied weekly at 1.0 g N/m^2/week in 2017 and 2.0 g N/m^2/week in 2019, both years with the first application at the start of the experiment. Hence, the total N rate during the 5 week experimental period was 5.0 g N/m^2 in 2017 and 10.0 g N/m^2 in 2019. Other nutrients except P were applied in the same solution and at the same rates relative to N as in WP 1. Phosphorus was applied either as one granular application at the start of the experiment or weekly as foliar feedings. By granular application, P was applied at rates of 0.30, 0.60, 0.90 or 1.20 g P/m^2 at the start of the experiment. By foliar feeding, P was applied weekly in rates of 0.06, 0.12, 0.18 or 0.24 g P/m^2/wk.

Granular P was applied as triple superphosphate Opti-P 0-20-0. The superphosphate granules were crushed to less than 1 mm diameter to ensure uniform application. Foliar P was applied in the form of diluted monophosphoric acid (H_3PO_4) using a hand-held spray bottle inside a circular shield with the same diameter as the cylinders. Irrigation was conducted as after emergence in WP 1, but always avoided for the first 24 h after foliar application of P.

The creeping bentgrass was cut weekly at 5 mm during the course of the experiment. Soil temperatures were measured, clipping yields collected and turfgrass color assessed as in WP 1. Results were analyzed by ANOVA including testing of the contrasts 1) No P vs. P, (2) P rate and (3) Granular vs. foliar application.

2.2 Results

Results of WP 1 (Phosphorus requirements for turfgrass grow-in)

Turfgrass coverage was significantly affected by temperature at all assessments and by P-rate at assessments from four weeks after seeding. Turfgrass coverage developed more slowly at 7 °C than at 12 or 17 °C (Fig. 1a) and on cylinders without P application than on cylinders with P application (Fig. 1b). Between P rates in the range 0.12 - 0.48 g P/m^2/week, there were no differences in coverage at any of the cuts.

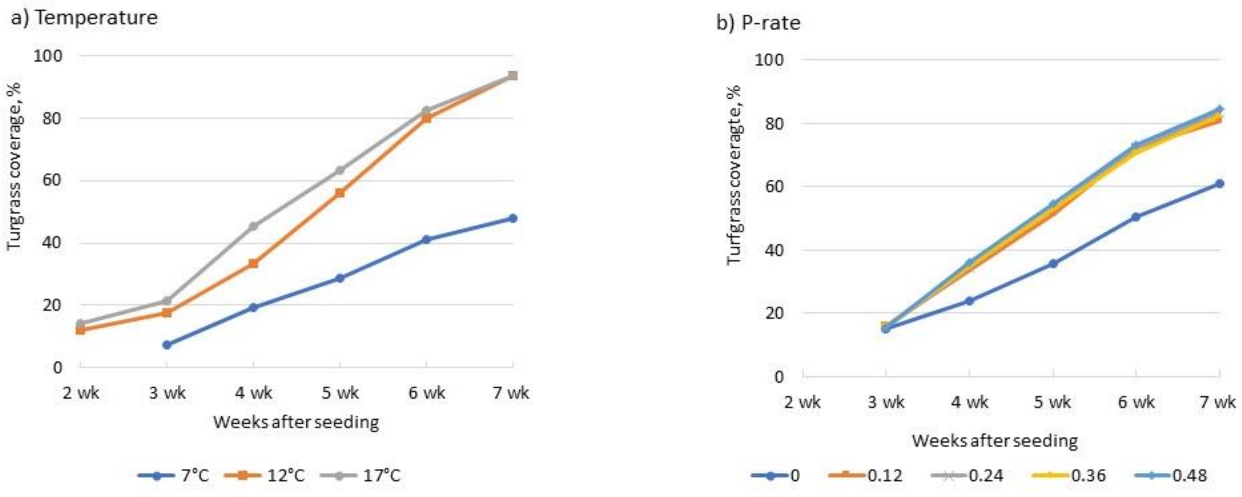

Figure 3. Main effects of (a) temperature and (b) P-rate on development of turfgrass coverage (% of cylinder surface area) in the turfgrass grow-in experiment (WP 1). Average of two years.

Turfgrass color was significantly darker on unfertilized cylinders than on cylinders receiving P and darker also at 0.12 g P/m^2/week than at higher P rates,

In total for four or five cuts, the dry matter yield of clippings increased with increasing P rate up to 0.24 g P/m^2/week at all temperatures. The rise in temperature from 7 to 17 °C tripled clipping yields, and there was also a significant increase from 12 to 17 °C. The concentration of P in clippings and the P/N ratio decreased with increasing temperature. The highest N-concentration was found at the highest temperature.

The initial Mehlich-3 P and P-AL values in the sand-based substrate used in WP 1 were 13 and 29 mg P/kg, respectively (Table 1). After seven weeks, the P-AL values were lower than the start value, but the treatments did not significantly affect the P-AL values at end of the experiment. For Mehlich-3 P, the final values were significantly higher at 7 °C than at 12 °C and 17 °C, and there tended to be an interaction as the final values were lower with no P application than with the highest P rate. All P applications resulted in a surplus in the P balance (applied P minus P in clipping yield), with increasing surplus by increasing P rate.

Results of WP 2 (Increasing rates of granular vs foliar P to established turf in spring)

There were no significant differences in color by different P applications at any of the temperatures. No tendency to anthocyan color was seen at any temperature in the first year. In the second year, there were some leaves with anthocyan color at the start of the experiment, but there were no significant differences in green-up between treatments.

There was a tendency for increasing temperature to increase clipping yield one week after the start of the trial. In total for five cuts, clipping yields were higher at 17 °C. than at 7 °C. Both for the first week and for the entire trial period, clipping yields were also higher for cylinders receiving P than for cylinders not receiving P. In total for the five cuts, there was an increase in clipping yields up to a P-rate of 0.18 g/m^2/wk. Clipping yields did not differ depending on foliar vs. granular application.

As in WP 1, soil P-AL values decreased while soil Mehlich-3 P values remained stable during the trial period in WP 2. Neither of the extraction methods showed any temperature effect on soil P by the end of the trial, but P-AL values were significantly higher after granular than after foliar application and Mehlich-3 P values were significantly higher in cylinders that had received P than had not received P.

2.3 Discussion of WP 1 and 2

Seedling growth is a critical stage for turfgrass establishment from seed. Compared with established turf, seedlings are usually considered more sensitive to low soil P values because of less roots and thus less soil volume to explore for P uptake. In the present material this was evident from the fact that the relative increase in the total clipping yields after application of 0.24 g P/m^2/week was 119 % in WP 1 as opposed to only 9 % in WP 2.

Effect of soil P status

The profound difference between the two experiments may also be influenced by the fact that soil Mehlich-3 P values were, on average for two years, 29 mg P/kg in the old substrate underlying the established green in WP 2 vs. only 13 mg P/kg in the new substrate used for grow-in in WP 1. These values explain why we did not see any P deficiency symptoms without P application in WP 2.

Phosphorus effects on various turfgrass characters

The response to soil P values and P fertilizer rate will also depend on which turfgrass character is considered. In the grow-in trial (WP 1), turfgrass coverage was significantly less in the P treatment not receiving P, but there was no difference between P rates in the range 0.12 to 0.48 g P/m^2/week. Turfgrass color and clipping yields showed, in contrast, a significant increase up to 0.24 g P/m^2/week. It is often claimed that extra P is needed to stimulate root growth. However, WP 1 showed that root dry weight was not significantly affected by P-rate and that the ratio between root dry weight and total clipping dry weight was significantly higher in the treatment not receiving P than in treatments receiving P, while there was no difference between P-rates in the range 0.12 - 0.48 g P/m^2/week. Producing roots have a carbon cost and may explain lower root/top ratio at sufficient P supply. When the supply is limited, it is reasonable to assume that turfgrass plants will invest more in roots to acquire P.

Response to phosphorus applications as influenced by temperature

One of the central questions in this research was to evaluate turfgrass P requirements in relation to temperature. Apart from restricted root growth during establishment, low temperatures are likely to have a direct effect on P movement by restricting the diffusion of P in the soil solution. However, the present study could not confirm that the need for applied P is higher during establishment at low temperature (7 °C) than at higher temperatures (12 °C and 17 °C). In WP 1 the situation was opposite, as there was a significant increase in clipping yields up to 0.12 g P/m^2/week at 7 °C, whereas at 12 °C and 17 °C there was a significant increase in clipping yields up to 0.24 g P/m^2/week. The lower requirement for P at 7 °C than at 12 and 17 °C can be explained by low temperature being more limiting to shoot growth than to P uptake. This is further confirmed by the P concentration and P/N ratio in clipping yields, which were both significantly higher at 7 °C than at 17 °C. The lower P concentration by high temperature in WP 1 may, in other words, be explained as a dilution effect, although this result is in contrast to WP 2 and to studies where higher P concentration was found in plants grown at 13-19 °C than at 7-9 °C.

Granular versus foliar P application

In WP 2, five foliar applications of phosphoric acid at rates up to 0.24 g P/m^2 for a total of up to 1.20 g P/m^2 had no visual effects but increased clipping yields compared with the unfertilized control treatment. The fact that the P concentration and P/N ratio in clippings were higher after one application of the same amount of P in granular form nonetheless suggests that granular application and root uptake of P was more efficient. The apparently higher P use efficiency by granular P application compared to foliar P application could, however, also be caused by uncertainties in the methodology used for the foliar P application. Consequently, we cannot conclude that granular P application is more efficient than foliar P application. However, the opposite claim, that foliar P application is more efficient than granular application is less likely, at least on soils with a low sorption capacity for P.

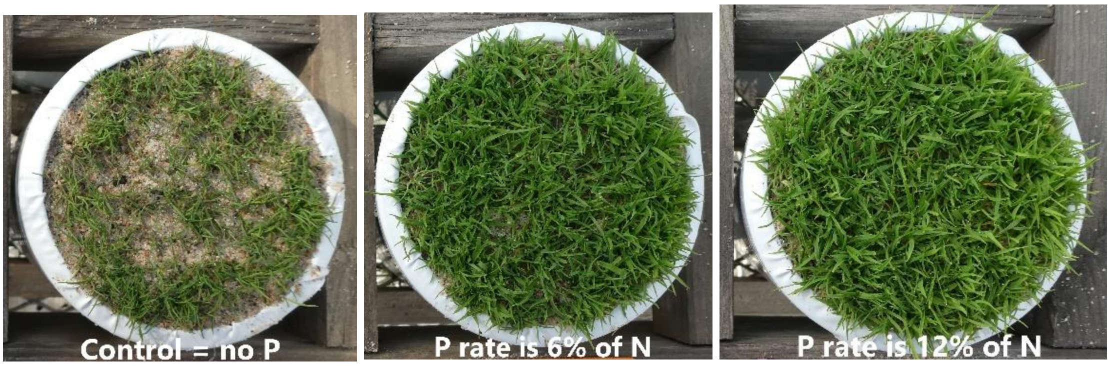

Figure 4. Effect of P application on coverage and colour on creeping bentgrass in soil very low in P (Mehlich-3 P: 13 mg P/kg soil) eight weeks after sowing at 12 ˚C. (P rates relative to N rate from left to right: 0, 6 and 12 %). Photos: Anne F. Øgaard.

3 WP 3 (Field experiments)

Effects on turfgrass quality by reducing P inputs on golf courses representing a range of climatic zones, soil types and turfgrass species

See original scientific publications (18) and (19).

3.1 Materials and methods

Field experiments were conducted on putting greens at the five golf courses: Dütetal in Germany (Duete-DE), Falkenberg in Sweden (Falken-SE), Jingshan Lake, Beijing in China (Jingshan-CN), NIBIO turfgrass research center Landvik in Norway (Landvik-NO) and Princenbosch in the Netherlands (Princen-NL). The five locations, their GPS-coordinates, elevation and the long-term average air temperature and precipitation are shown in Table 2. The trials were laid out in June 2017 (Duete-DE: December 2017) on greens with a soil pH between 5.9 and 6.7, except for the calcareous sand at Jingshan-CN which had an initial soil pH of 8.3. The putting greens were constructed according to FLL and USGA-specifications except for a 'push-up green' at Falken-SE. Soil bulk density, loss on ignition, total carbon (C) and soil pH values are shown in Table 3. Data on soil P sorption and Cation Exchange Capacity (CEC) from the initial soil samples are shown in Table 4.

Table 2. The five trial sites, GPS-coordinates, elevations and the long-term average air temperature and precipitation.

Experimental sites	Location	Coordinates N	E	Elevation m.a.s.l.	Long-term average annual air temperature °C	precipitation mm
Duete-DE	Dütetal, Germany	52°18'	7°55'	60	9.1	830
Falken-SE	Falkenberg, Sweden	56°89'	12°57'	48	9.0	872
Jingshan-CN	Jingshan Lake, China	40°19'	116°43	68	12.0	507
Landvik-NO	Landvik, Norway	58°20'	8°31'	12	7.8	1416
Princen-NL	Princenbosch, The Netherlands	51°32'	4°87'	10	10.9	834

a.s.l. = metres above sea level

Table 3. Putting green construction, soil bulk density, loss on ignition, total C and soil pH of initial soil samples.

Experimental sites	Putting green construction	Soil bulk density g/cm^3	Loss on ignition %	Total C %	pH -
Duete-DE	FLL K3 profile	1.56	1.5	0.80	6.7
Falken-SE	Push-up / modified USGA	1.39	1.6	0.62	6.0
Jingshan-CN	USGA profile	1.37	1.1	0.31	8.3
Landvik-NO	USGA profile	1.40	1.4	0.63	5.9
Princen-NL	USGA profile	1.42	1.3	0.53	6.3

Table 4. Soil phosphorus sorption and CEC of the initial soil samples.

Experimental sites	Soil phosphorus sorption					Soil Cation Exchange Capacity (CEC)					
	Al_{ox}	Fe_{ox}	P_{ox}	$Al_{ox} + Fe_{ox}$	DPS	Ca	K	Mg	Na	H	CEC
	g (kg soil)$^{-1}$			mmol (kg soil)$^{-1}$	%	cmol c^{+} (kg soil)$^{-1}$					
Duete-DE	0.08	0.36	0.05	**9.2**	**36**	2.30	0.09	0.46	< LD	0.00	**2.85**
Falken-SE	0.17	0.40	0.08	**13.5**	**37**	0.93	< 0.22	0.22	< 0.03	2.58	**< 3.73**
Jingshan-CN	0.14	0.61	0.04	**16.1**	**15**	4.60	< 0.22	0.98	0.10	0.42	**< 6.10**
Landvik-NO	0.24	0.22	0.05	**12.8**	**24**	0.50	< 0.22	0.10	0.04	2.67	**< 3.31**
Princen-NL	0.10	0.27	0.02	**8.5**	**17**	1.00	< LD	0.48	< 0.03	1.08	**< 2.56**

Grass species and management 2017-20

The experimental greens differed in species composition and management (Table 5). The greens at Duete-DE, Falken-SE, Jingshan-CN and Landvik-NO were creeping bentgrass-greens with varying ingression of annual bluegrass, and N fertilizer rates varying between 9.9 and 27 g N/m^2/yr. The green at Princen-NL was a mixed red fescue (*Festuca rubra*)/colonial bentgrass (*Agrostis capillaris*) green with a low N-fertilizer rate. Fertilization with N and all nutrients except P as well as other management operations including mowing, irrigation, verticutting, aeration, topdressing, pest management, use of wetting agents and overseeding were done according to the individual course manager's schedule. At Landvik-NO a severe damage of the experimental green happened during the winter 2017-18. The following two seasons the yearly N rates increased from 12 to 25 g N/m^2 due to reestablishment. At Falken-SE a breakdown of the irrigation system in late July caused dry spots/patches of 10-60 % in some of the experimental plots in August and September 2020. Reestablishment of the green after this event caused a higher N rate than planned in the last season. At Duete-DE a new course manager who started in early summer 2020 also increased the N rate above the actually planned level from July.

Experimental design and treatments

Figure 5. The experimental green at Dütetal GC in Germany. Plots were 2 m x 2 m.

The experimental design was a 4 x 4 Latin square with four treatments and four replicates (Figure 5). Thus, the experiment consisted of 16 plots, each with an area of 2.0 m x 1.5 m or 2.0 m x 2.0 m, of which the central 1.0 m x 1.5 m was used for observations. The treatments were: (1) no P fertilization (Zero P), (2) P fertilization according to the MLSN guideline aiming to establish or maintain Mehlich-3 soil P values above 18 mg P/kg dry soil, (3) P fertilization corresponding to 12 % of the N rate according to ‘Scandinavian Precision Fertilization’ (SPF) and (4) P fertilization according to the SLAN guideline aiming to establish or maintain Mehlich-3 soil P values above 54 mg P/kg dry soil. For July-October 2017 the P rates in the MLSN and SLAN treatments at Falken-SE, Jingshan-CN, Landvik-NO and Princen-NL were calculated from the soil analyses taken in June 2017, while in 2018-2020, the P rates were calculated from the soil samples taken in November at the end of the previous growing season, and it was assumed that Mehlich-3 P values corresponded to the absolute amount of plant-available P in soil. The calculated annual P rates in the different treatments were split into six or seven applications at approximately monthly intervals of a liquid solution of triple phosphate ($Ca(H_2PO_4)_2$, 20 % elemental P). Yearly added P rates for MLSN, SPF and SLAN treatments are shown in Table 6. For N, K and other nutrients, the course managers mostly followed their initial plans set up in spring.

Table 6. Annual added P in the treatments with P application according to MLSN, SPF and SLAN. The trial at Duete-DE started in spring 2018.

Experimental sites	Annual added P g m^{-2}											
	MLSN				SPF				SLAN			
	2017	2018	2019	2020	2017	2018	2019	2020	2017	2018	2019	2020
Duete-DE		4.0	1.0	1.5		2.7	2.5	2.3		14.8	7.8	8.0
Falken-SE	0.0	0.0	0.0	0.0	2.3	2.5	2.9	2.9	8.2	7.0	2.8	3.9
Jingshan-CN	3.8	2.1	2.4	1.9	1.2	1.4	1.4	1.4	13.7	7.7	5.7	5.1
Landvik-NO	0.0	2.6	0.2	0.0	1.5	3.0	3.1	2.2	9.7	7.2	4.7	2.0
Princen-NL	3.6	3.1	3.8	2.4	0.3	0.8	0.7	0.7	13.9	11.1	11.3	8.7

Soil sampling and analyses

Soil samples were always taken to a depth of 20 cm. The air-dried soil samples were shipped to the soil laboratory at the Norwegian University of Life Sciences (NMBU) in Ås (Norway) for analyses. Before the trial started, soil bulk density, loss on ignition, total C and the CEC were determined in a representative pooled soil sample for each experimental site (Tables 3 and 4).

Assessments of turf cover

Visual assessments were performed monthly by the local project managers just before the P applications from April/May to October/November (depending on the length of the growing season). Turf quality was rated on a scale from 1 to 9 with 5 as the lowest acceptable value. Coverage was assessed as percent (%) of plot area covered by healthy turf of sown species, broadleaved weeds, annual bluegrass, diseased turf and bare soil.

3.2 Results

Development of soil P at the five trial sites

The changes in soil P concentrations at the five experimental greens are shown in Figure 6 and 7. At all sites the SLAN treatment increased the soil P level significantly compared with the other treatments. However, in the third and especially in the fourth year of the project, the soil P level in the SLAN treatment at Falken-SE declined after reaching the SLAN threshold in the second year. The same thing happened at Landvik-NO in the fourth project year after reaching the SLAN threshold after three years, thus reflecting the lower application of P at Landvik-NO in the fourth year (Table 6). Despite high applications of P at Princen-NL, the SLAN-treatment only resulted in a small and slow increase of the P-level with no increase at all in the second year of the experiment (Figure 7).

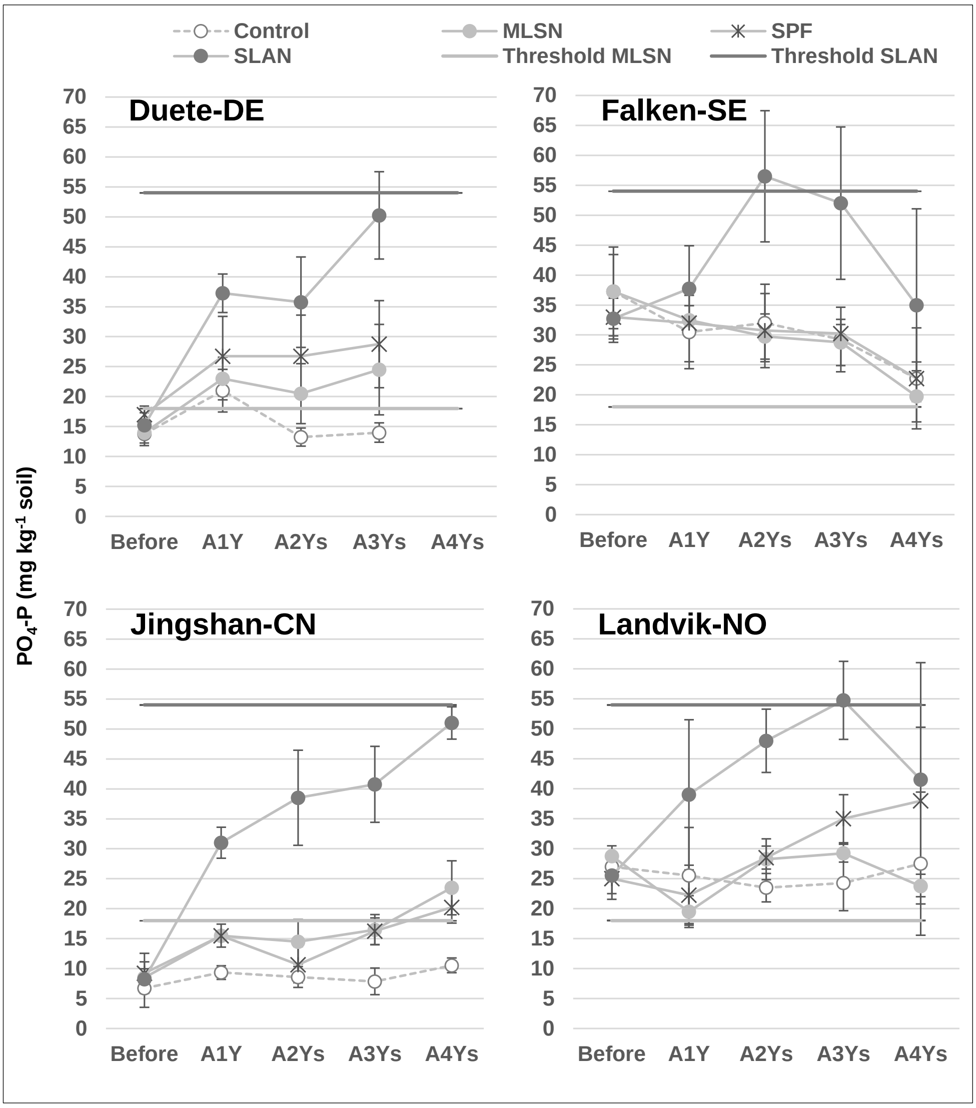

Figure 6. Changes in PO_4-P concentration in soil (mg kg^{-1} soil) during the trial in response to different P fertilization recommendations on the four creeping bentgrass experimental greens. Five sampling dates: before the trial started (Before), after 1 year of trial (A1Y), after 2 years (A2Ys), after 3 years (A3Ys), and after 4 years (A4Ys, no data for Duete-DE). Light gray line = threshold MLSN (18 mg/kg soil); dark gray line = threshold SLAN (54 mg/kg soil).

The applications of P in the SPF treatment differed corresponding to the N applications at the five sites. At Duete-DE and Falken-SE the applications were very similar in all years (between 2.3 and 2.9 g P/m^2, Table 6) resulting in small or no increases in the soil P levels at Duete-DE, but a decline at Falken-SE. At Landvik-NO the applications of P in the SPF treatments differed from year to year reflecting changes in the yearly N rates. From 2017 to 2018 the yearly N rate increased from 12 to 25 g N/m^2 due to reestablishment of the green after severe damage during the winter 2017-18. The following increase in the annual P rate (from 1.5 to 3.0 g P/m^2) was also reflected in the soil P level. At Jingshan-CN the uniform applications in the SPF treatment (1.2-1.4 g P/m^2) resulted in a small increase of the soil P level, while at Princen-NL the very low applications (0.3-0.8 g P/ m^2) did not affect the P level in the soil.

The amounts of P given in the MLSN treatment through the years were reflected in the P levels at all sites except Princen-NL, where there was almost no increase despite high applications of P.

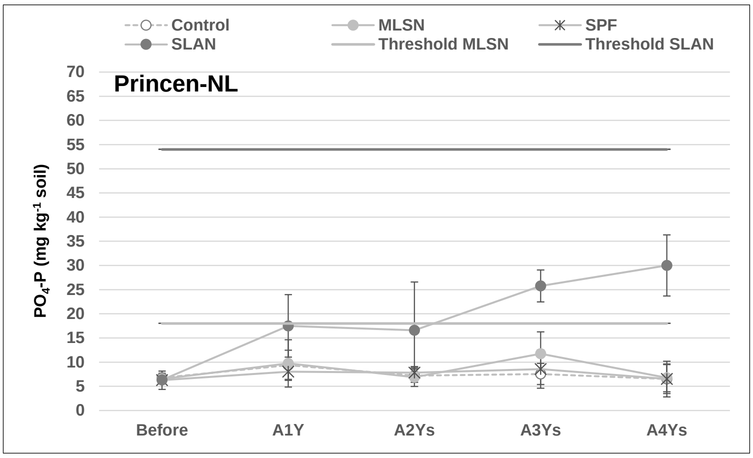

Figure 7. Changes in PO_4-P concentration in soil (mg/kg soil) during the trial in response to different P fertilization recommendations on the fescue/bentgrass experimental green at Princen-NL. Five sampling dates: before the trial started (Before), after 1 year of trial (A1Y), after 2 years (A2Ys), after 3 years (A3Ys), and after 4 years (A4Ys). Light grey line = threshold MLSN (18 mg/kg soil); dark grey line = threshold SLAN (54 mg/kg soil).

Turf quality from 2017 to 2020 at the five trial sites

Boxplots of mean turf quality (2017-20) in the various treatments are shown in Figure 8. A boxplot from Princen-NL is not shown as the median and upper and lower quartiles were exactly the same.

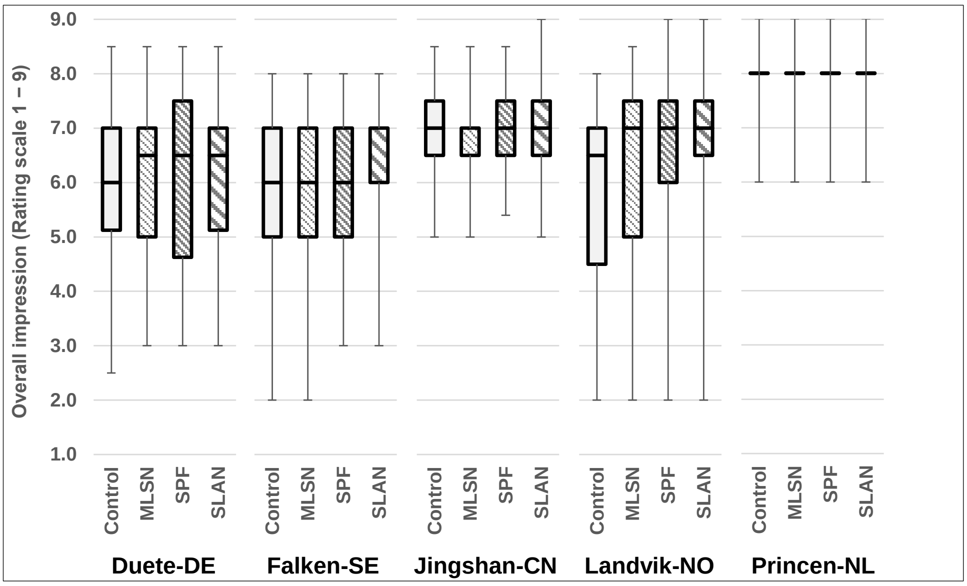

Figure 8. Impact of different P fertilization recommendations on turfgrass quality (Rating scale 1 – 9) across all dates for each experimental site. Boxplot with median as vertical bold line inside the box, the ends of the box represent the upper and lower quartiles (Q3 - Q1 = interquartile range) and the two lines outside the box (whiskers) show highest and lowest rating values.

The turf quality was acceptable at all sites with a median between 6 and 8 (8.0 at Princen-NL). Significant differences between the treatments were observed only occasionally at some of the experimental sites. At Jingshan-CN the MLSN and the unfertilized control treatment had significantly lower ratings than the SLAN treatment in June, August, and September in the fourth year of trial (2020), but the SPF and SLAN treatment were not significantly different. treatment.

Coverage

Annual bluegrass in differing proportions were found at Duete-DE, Falken-SE, Landvik-NO and Princen-NL. At Jingshan-CN no annual bluegrass was found. At Falken-SE the evaluations of coverage in 2018 and 2019 showed a 2-4 % increase in annual bluegrass and a corresponding decrease in creeping bentgrass with SLAN fertilization relative to the treatments that did not receive P. However, this difference could not be verified in 2017 and 2020.

3.3 Discussion on WP 3

Development of soil P values

All locations had low P sorption capacity (PSC), as indicated by the low concentrations of Al_{ox} and Fe_{ox}. The low sorption capacity was mainly due to the sandy soil with low specific surface area and thereby relatively few binding sites for phosphate ions resulting in a fast increase in the degree of P saturation (DPS) when adding P in surplus. Not surprisingly, the SLAN treatment increased P in soil compared with the Zero P, MLSN and SPF treatments at all sites. However, the SLAN threshold of 54 mg P/kg dry soil was reached only at Falken-SE and Landvik-NO, which were the sites with the highest start values for soil P and also among the sites with highest P sorption capacity. Even at those sites, the P rates given according to SLAN recommendations were not able to keep up the high soil P level in the last experimental year. The maintenance of 54 mg P/kg dry soil required more P than was removed in the clippings, and such high applications of P will inevitably increase the risk for leaching of P from sandy rootzones low in Fe and Al oxides. Even in the SPF treatment, it is likely to assume that a certain leaching of P occurred at some of the experimental sites since soil P levels were not taken into account when deciding P-rates.

Turf quality from 2017 to 2020 on the five courses

As for the MLSN guideline, a response was expected at Princen-NL, Jingshan-CN and Duete-DE, but not at Falken-SE and Landvik-NO. However the turf quality showed no significant response to soil P at any site except at Jingshan-CN in the last experimental year. At Princen-NL the initially very low Mehlich-3 P of 6 mg/kg soil increased to a maximum of 12 mg/kg soil in the MLSN and SPF treatments, and in the SLAN treatment to 30 mg/kg soil. Nevertheless, these changes in Mehlich-3 P had no impact on the turfgrass quality, which was very high during the whole experimental period, only varying between 7.6 and 8.2 as yearly averages. While no response to P application in this trial is hard to explain based on the MLSN or SLAN recommendations, a low growth rate of the red fescue due to low N input and minimal use of irrigation water may have contributed to the extremely low requirement for P at Princen-NL.

Encroachment of annual bluegrass

At Falken-SE the evaluations of coverage in 2018 and 2019 showed slightly more annual bluegrass with P fertilization (SLAN) compared to no P fertilization. This is in agreement with earlier experiments on mixed annual bluegrass / creeping bentgrass greens in North America (12,13).

At Duete-DE the ratio between creeping bentgrass and annual bluegrass showed no significant differences among P treatments in any of the years. However, on average for the P treatments the ratio increased significantly from 2018 to 2020 with a 10 - 12 per cent unit increase in the coverage of creeping bentgrass and a corresponding decrease in annual bluegrass. This decrease in the competitive ability of annual bluegrass can mostly be explained by the hot and dry weather in 2018 and 2019 combined with a change in management with less irrigation and repeated overseeding with creeping bentgrass.

All taken together, the results from Falken-SE show that P fertilization can have a small influence on annual bluegrass encroachment on creeping bentgrass greens, but at the same time the results from the other sites showed that other management practices such as controlled irrigation and overseeding with creeping bentgrass are more efficient in reducing ingression of annual bluegrass.

Figure 10. The experimental fescue/bentgrass green at Princen-NL showed high turf quality in all P fertilization treatments throughout the project period despite low soil P values.

4 Conclusions and advice for the golf turfgrass sector

WP 1 and 2

- A central objective of this research was to validate under adverse conditions in spring the Scandinavian Precision Fertilization recommendation of never applying fertilizers with a higher P/N ratio than 12 %. Given the low sorption capacity for P of the sand-based rootzones, our research confirmed this principle. Applications of P beyond 12 % of the N input because of low spring temperature cannot be justified, either when growing-in new playing surfaces or on established greens.

WP 3

- The field experiments showed no improvement of turf quality by the SLAN-treatment compared to the lower input recommendations MLSN and SPF.
- A lower P surplus in the soil suggests that the MLSN and SPF fertilizer recommendations can reduce P use and P losses on putting greens with a low sorption capacity for P. This reduction can be implemented without negative implications for turf quality despite low Mehlich-3 P levels in the range 6 -15 mg P/kg soil.
- Phosphorus applications aiming at increasing Mehlich-3 P values in soil imply a high risk of P leaching from sand-based greens.
- The results also show that the MLSN recommendation of > 18 mg P/kg soil can be recommended on established putting greens with low P sorption capacity under a wide range of climatic and management conditions.
- The SPF (12 % P relative to N rate) may result in too high P application on soils with high Mehlich-3 values as soil analyses are not considered.

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