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Temperature effects on phosphorus requirements for creeping bentgrass establishment and spring growth

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Abstract

Phosphorus is an essential plant nutrient, but primary resources are limited and overfertilization may cause eutrophication of freshwater. Our objectives were to examine temperature effects on (a) optimal P rate for turfgrass establishment, and (b) increasing rates of foliar vs. granular P for early spring growth of established greens. Two trials, both on USGA root zones and replicated in April–May over 2 yr, were conducted in daylight phytotrons at 7, 12 and 17 °C. Experiment 1 compared 5 P rates from 0 to 0.48 g P m^{-2} wk^{-1} for creeping bentgrass establishment on a sand containing 13 mg P kg^{-1} (Mehlich-3). Results showed no temperature effect on the optimal P rate. Bentgrass coverage and clipping yield increased up to 0.12 and 0.24 g P m^{-2} wk^{-1}, corresponding to 6 and 12% of the N input, respectively. The concentration of P in clippings was higher at 7 than at 17 °C indicating that temperature was more limiting to shoot growth than to P uptake. A higher root/top ratio showed that plants invested more in roots under P deficiency. Experiment 2 was conducted using intact cores from a 4-yr-old creeping bentgrass (*Agrostis stolonifera* L.) green with a Mehlich-3 P level of 34 mg P kg^{-1}. Results showed increased clipping yields up to 0.18 g P m^{-2} wk^{-1} and higher P uptake with granular than with foliar application, but there was no effect on turfgrass color and no interaction with temperature. Low temperatures did not justify higher P applications.

1 | INTRODUCTION

Phosphorus is an essential nutrient for plants (Marschner, 2011), but also the nutrient for which the world's primary resources are most limited (Cordell, Drangert, & White, 2009; Jasinski, 2014). For this reason, and also due to the risk for eutrophication of lakes and rivers (e.g., Schindler, 1971; Soldat & Petrovic, 2008; Ulén et al., 2007), it is important to avoid excessive applications of P. Twenty years of monitoring water outlets from American golf courses revealed minimal levels of N but alarming levels of P with 86% of samples exceeding environmental thresholds (Baris, Cohen, Lam, & Ma, 2010). Rice and Horgan (2010) also found high levels of P in surface runoff from golf courses in Minnesota; and Guertal (2007) and Aamlid, Jensen, Kvalbein, and Rasmussen (2016) documented substantial leaching of P from sand-based greens in Alabama and Grimstad, Norway, respectively. During the last couple of decades, Norway and many other countries have reduced the recommendations for P inputs to agricultural crops, while there has been no similar reduction in the recommendations for turf.

Abbreviations: DPS, degree of soil phosphorus saturation.

Determining a sustainable level of P fertilization for turf requires a profound understanding of the conditions that can cause P deficiency. According to Carrow, Waddington, and Rieke (2001), P deficiency is most likely to in occur in three situations:

1. *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 (Kristoffersen & Riley, 2005; Pote et al., 1999). The soil's content of amorphous Al and Fe (hydr)oxides, organic matter, and pH are important factors that influence the soil's capacity to bind and release P (Bolland, Gilkes, Brennan, & Allen, 1996; Börling, Otabbong, & Barberis, 2001).

2. *During turfgrass establishment when grass roots have not yet penetrated the soil.* In this situation, P 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 (Carroll, Ngo, & Krouse, 2005; Hamel & Heckman, 2006; Liu & Landschoot, 2018).

3. *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 (Carrow et al., 2001). Kneebone and Johnson (1980) found that P uptake at low soil temperatures and tendency to develop purple color varied among creeping bentgrass (*Agrostis stolonifera* L.) cultivars, but there was no correlation between the two characters.

In the Nordic countries, there are often combinations of situations 2 and 3, for example, when reseeding turfgrass at low soil temperature in spring after winter damage. Again, the scientific evidence for applying extra P in this situation is limited or non-existent. Finnish studies in barley (*Hordeum vulgare* L.) indicated that slow establishment at low soil temperature in spring was only partly offset by extra applications of P, and that the extra P given at this time of the year represented a major risk for eutrophication of freshwater (Ylivainio & Peltovuori, 2012). Twenty-two Norwegian field trials with placed application of 1 g P m^{-2} into the row when seeding spring cereals resulted in improved seedling vigor and higher yields on silty soils that are usually cold and wet in spring, but not on well-drained moraine soils that usually warm up more rapidly (Kristoffersen, Bakkegard, & Hoel, 2005a).

Core Ideas

- Low temperatures did not justify higher P applications on sand-based greens.
- A fertilizer P/N ratio of 12% was sufficient for turfgrass establishment on sandy soils.
- Increased P application did not stimulate root growth.
- Foliar was not better than granular P inputs on soils with low P sorption capacity.

Currently, Scandinavian fertilizer recommendations for putting greens are applications of N and P in the ratio 100:12 both in the establishment situation and on established greens, and regardless of soil temperature (Ericsson, Blombäck, & Kvalbein, 2010). These guidelines have, however, been questioned by the fertilizer industry and many greenkeepers alike. Thus, the objectives of this research were to: (a) determine the P requirement for turfgrass (re)establishment on sand-based greens at various temperatures in spring and (b) determine the effect of foliar vs. granular P applications and increasing P rates on color, growth rate, and P uptake of surviving greens at various temperatures in spring.

2 | MATERIAL AND METHODS

Cylinder experiments simulating U.S. Golf Association (USGA)-specifications root zones (U.S. Golf Association Green Section Staff, 2004) were conducted in spring 2017, 2018, and 2019 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.

2.1 | Experiment 1: Phosphorus requirements for turfgrass establishment

This experiment was conducted from 6 Apr. to 26 May 2017 and repeated from 5 Apr. to 25 May 2018 (both times 7 wk

TABLE 1 Chemical soil characteristics of the U.S. Golf Association-specifications root zones used in Exp. 1 and 2. DPS_{ox} = Degree of soil phosphorus saturation

Experiment	Depth		Total C	P–AL[a]	Mehlich-3 extracts				Oxalate extracts			DPS_{ox}[b]
					P	K	Ca	Mg	P	Al	Fe	
	cm	pH	%	mg kg^{-1}					mmol kg^{-1}			%
Exp. 1	0–30	5.3	0.2	29	13	9	66	14	1.4	9.6	6.1	18.6
Exp. 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

[a]Aluminum-extract (Egnér et al., 1960).
[b]DPS_{ox}: Molar ratio between P-oxalate and Al-oxalate + Fe-oxalate (Vadas et al., 2005).

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 root zone consisting of USGA-specifications 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 cultivar Independence at a rate of 7 g m^{-2} (0.055 g $cylinder^{-1}$). 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. Water with the same temperature as the room temperature was used. Three control cylinders were weighed at field capacity and before each irrigation to determine the evapotranspiration to be replenished, hence, there was virtually no leaching from the cylinders.

Starting 2 wk 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} wk^{-1}, giving 10 g N m^{-2} during the entire experiment (five applications).

The concentration of P in the fertilizer solutions varied among treatments. Phosphorus was applied at rates of 0, 0.12, 0.24, 0.36, or 0.48 g P m^{-2} wk^{-1} in the form of 85% monophosphoric acid (H_3PO_4). There were parallel cylinders per treatment and the 15 cylinders were randomized completely in racks within each of the three phytotron compartments.

The concentration of K, S, Ca, Mg, Fe, Mn, B, Zn, Cu, and Mo in all fertilizer solutions corresponded to 65, 9, 7, 6, 0.7, 0.4, 0.2, 0.06, 0.03, and 0.003% of the N concentration according to the Scandinavian guidelines for precision turfgrass fertilization (Ericsson et al., 2010). The fertilizer solutions were applied using 10 ml pipettes for an application volume of 1.27 L m^{-2}.

Weekly assessments after emergence included turfgrass coverage (percent 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 3 wk after seeding for cylinders at 12 and 17 °C and 4 wk 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 per cylinder including clippings from all sampling dates 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 wk^{-1}. 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.

2.2 | Experiment 2: Increasing rates of granular vs. foliar phosphorus applications to an established green in spring

The first time replicate of this experiment was conducted from 6 Apr. to 12 May 2017 (5 wk) using the same phytotron compartments and same type of cylinders as in Exp. 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 Exp. 1 and finally with a 10 cm diam. and 12-cm deep soil core taken with a cup cutter shortly after snow melt/soil thaw on a USGA-specifications green at the NIBIO Turfgrass Research Center Landvik, Southeast Norway. Care was taken to extract cores only from patches with 100% live coverage of creeping bentgrass, thus avoiding annual bluegrass (*Poa annua* L.) and pink snow mold (*Microdochium nivale*) The green had been seeded with creeping bentgrass cultivar Independence in 2013 after renovation using the same type of peat-amended sand as used in Exp. 1, but the soil pH and content of organic C and nutrients had increased during the 4 yr since establishment (Table 1).

The second time replicate of the experiment was scheduled to be conducted simultaneously with the second time replicate of Exp. 1 in 2018, but had to be postponed to 6 Apr. –4 May 2019 because of severe winter damage after ice encasement on the creeping bentgrass green in 2018.

Nitrogen was applied weekly at 1.0 g N m^{-2} wk^{-1} in 2017 and 2.0 g N m^{-2} wk^{-1} in 2019, both years with the first application at the start of the experiment. The N rate was doubled from 2017 to 2019 to increase growth and thus the chances for P deficiency to occur. The total N rate during the 5 wk duration of the experiment 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 Exp. 1 (Ericsson et al., 2010). 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^{-1}. Pots without P application were included as control, leaving a total of nine P treatments. In both replicates of the experiment, all treatments comprised three parallel cylinders, and the 27 cylinders were randomized completely in racks within each phytotron compartment.

Granular P was applied as triple superphosphate Opti-P 0–20–0 (Yara, Norway). Apart from P, this fertilizer also contains 17% Ca and 1.2% S which was considered acceptable and without any influence on yield, because Ca and S were already applied in sufficient amounts with the nutrient solution to all treatments. The superphosphate granules were crushed to less than 1 mm diam. 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. The spray bottle left small droplets on the leaf surfaces for a total application volume of 64 ml m^{-2} (0.5 ml $cylinder^{-1}$). Irrigation was conducted as after emergence in Exp. 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 Exp. 1, but root washing was considered too laborious and uncertain because of the thatch layer. Soil sampling by the end of the trial was restricted to the top 12 cm, that is, the depth of the original soil core taken from the green.

2.3 | Leaf and soil analyses common to both experiments

In both experiments, the clipping yields from all sampling dates were pooled to one sample per cylinder before analyzing N and P concentrations. The total N concentration was determined using a Leco TruSpec CHN analyzer. The total P concentration was determined by inductivey coupled plasma-optical emission spectroscopy (ICP-OES) after digestion with concentrated nitric acid in an ultraclave.

The soil samples were dried at 40 °C and passed through a 2-mm sieve before analyses. Soil pH, total C, and oxalate-extractable Al, Fe, and P were determined in the substrates at the start of each trial only (Table 1). Extractable P was determined by two methods, P–AL and Mehlich-3 P, both in the substrates at the start of the trial and as a response variable in all cylinders by the end of each trial. Soil pH was measured in deionized water with a soil/water ratio of 1:10 (v/v). Total C was analyzed on milled samples using the Leco TruSpec CHN analyzer. Mehlich-3 extractable P, K, Ca, and Mg were determined according to Mehlich (1984), P–AL according to Egnér, Riehm, and Domingo (1960) and oxalate-extractable Al, Fe, and P according to van Reeuwijk (1995). Ortho-P in the extracts was determined by colorimetric analysis using the Mo blue method according to Murphy and Riley (1962). Other elements in the extracts were measured by ICP-OES. The degree of soil phosphorus saturation (DPS) was calculated as the molar ratio between P-oxalate and Al-oxalate + Fe-oxalate:

$$DPS(\%) = 100\ x \left(\frac{P - ox}{\alpha(Al - ox + Fe - ox)} \right)$$

where the parameter α in the denominator is empirical and equals approximately 0.5 for non-calcareous soils (Maguire, Foy, Bailey, & Sims, 2001). The critical value of DPS, above which the release of P to the soil solution and thus the risk for P leaching increases rapidly, is usually considered to be 25% (Vadas, Kleinman, Sharpley, & Turner, 2005).

2.4 | Statistical analyses

Analyses of variance were performed to study the effect of temperature, P treatments, and their interaction on turfgrass coverage (Exp. 1 only), color, clipping yields, N and P concentration and P/N ratio in clippings, root dry weight (Exp. 1 only), P balance, and soil P values. The ANOVAs were conducted according to a split-plot model with years as blocks (time replicates; random variable), temperature (phytotron compartment) as main plots and P treatments (cylinders) as subplots. The Tukey honestly significant difference (HSD) multiple comparison test was used to separate means ($P \leq .05$). Treatment effects with P values in the range $.05 < P \leq .10$ were referred to as tendencies. In Exp. 2, the effects of P treatments (8 df) was split into orthogonal contrasts as follows: (a) (Contrast 1) No P vs. P (1 df); (b) Foliar vs. granular application (1 df); (c) P-rate (3 df); and (d) Interaction fertilizer type x P rate (3 df).

TABLE 2 Results from analyses of variance, Exp. 1

Character	Main effects: Temperature (df = 2)	Main effects: P rate (df = 4)	Interaction temperature × P rate (df = 8)
Turfgrass coverage, %			
2 wk after seeding[a]	***	ns[b]	ns
3 wk after seeding	***	ns	ns
4 wk after seeding	***	***	†
5 wk after seeding	***	***	ns
6 wk after seeding	***	***	ns
7 wk after seeding	***	**	ns
Turfgrass color, mean of four assessments) (1–9, 9 is darkest turf)	ns	***	ns
Accumulated clipping yield, g DM m^{-2}	***	***	***
Clipping yield P concentration, g P kg DM^{-1}	**	***	**
Clipping yield N concentration, g N kg DM^{-1}	*	*	***
Clipping yield P/N ratio	**	***	ns
Root weight, g DM m^{-2}	***	ns	ns
Roots/total clipping yield	ns	***	ns
Soil P–AL, 7 wk after seeding, mg kg^{-1}	ns	ns	ns
Soil Mehlich-3 P, 7 wk after seeding, mg kg^{-1}	*	***	†
P balance (P applied minus P removal in clippings)	***	***	***

[a]After 2 wk, only two temperatures were included, and, therefore, df = 1 for temperature and df = 4 for the interaction in this case.
[b]ns: $P > .10$.
†P value is indicated as follows $0.05 < P \leq .10$ ("tendency").
***: $P \leq .001$, **: $.001 < P \leq .01$, *: $.01 < P \leq .05$, (*): $.05 < P \leq .10$ ('tendency'), NS: $P > .10$.

3 | RESULTS

3.1 | Experiment 1: Phosphorus requirements for turfgrass establishment

3.1.1 | Turfgrass coverage

Turfgrass coverage was affected by temperature at all assessments and by P rate at assessments from 4 wk after seeding (Table 2). Interactions were not significant at $P \leq .05$. Turfgrass coverage developed more slowly at 7 °C than at 12 or 17 °C (Figure 1a) and on cylinders without P application than on cylinders with P application (Figure 1b). Between P rates in the range 0.12–0.48 g P m^{-2} wk^{-1}, there were no differences in coverage at any of the cuts.

3.1.2 | Color

Turfgrass color was darker on unfertilized cylinders than on cylinders receiving P, and darker also at 0.12 g P m^{-2} wk^{-1} than at higher P rates (Table 3).

3.1.3 | Clipping yields

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} wk^{-1} at all temperatures (Table 3). The temperature increase from 7 to 17 °C tripled clipping yields, and there was also a significant increase from 12 to 17 °C.

3.1.4 | Phosphorus and nitrogen concentrations in clipping dry matter

The concentration of P in clippings and the P/N ratio decreased with increasing temperature (Table 4). The highest N concentration was measured at the highest temperature.

On average for 2 yr, P concentration increased up to a P rate of 0.24 g P m^{-2} wk^{-1} at 7 °C and up to 0.48 g P m^{-2} wk^{-1} at 12 and 17 °C (Table 4). For N there was a decrease in concentration by increasing P rate at 17 °C. At 7 and 12 °C there was no effect of increasing P rate on N concentration. The mean P/N ratio increased up to the highest P rate of 0.48 g P m^{-2} wk^{-1}.

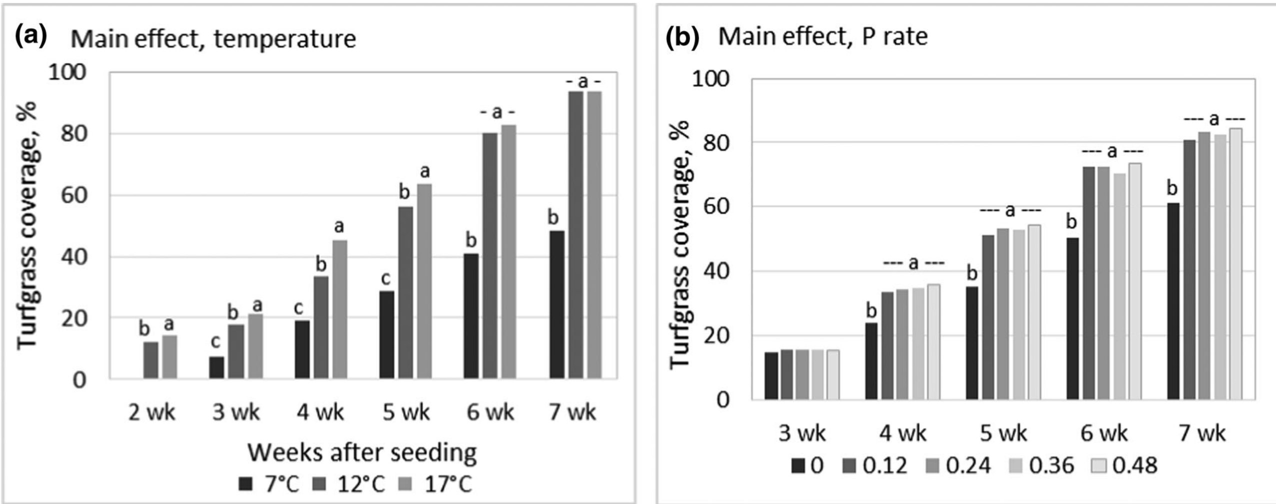

FIGURE 1 Main effects of (a) temperature and (b) P rate on development of turfgrass coverage (percent of cylinder surface area). Average of 2 yr, Exp. 1. Different lower case letters within week indicate significant differences according to Tukey's HSD, $P \leq .05$

TABLE 3 Turfgrass color (1–9, where 9 is the darkest turf) and dry matter yields (g DM m^{-2}) as affected by different P rates and temperatures in Exp. 1, sum of four or five cuts, average of 2 yr

		Dry matter yield			
P rate	Turfgrass color	7 °C Total for four cuts	12 °C Total for five cuts	17 °C Total for 5 cuts	Mean of 3 temperatures
g P m^{-2} wk^{-1}		g DM m^{-2}			
0	7.0a[a]	16b	40c	52c	36c
0.12	5.3b	27ab	78b	97b	67b
0.24	5.0c	36a	94a	107ab	79a
0.36	5.0c	40a	101a	106ab	82a
0.48	5.0c	41a	99a	116a	86a
Mean of 5 P rates		32C	83B	96A	70

[a]Different lower case letters within columns indicate significant differences between P rates, and different capital letters in the last row indicate significant differences between temperatures, both according to Tukey's HSD, $P \leq .05$.

TABLE 4 Phosphorus and N concentrations and P/N ratio in clippings from Exp. 1 as affected by temperature and P rate. Average of two experimental runs except for N concentration and P/N ratio at 7 °C, where there was not enough plant material for analyses of N concentrations in 2018

	P concentration				N concentration				P/N ratio,			
P rate	7 °C	12 °C	17 °C	Mean	7 °C	12 °C	17 °C	Mean	7 °C	12 °C	17 °C	Mean
g P m^{-2} wk^{-1}	g P (kg $DM)^{-1}$				g N (kg $DM)^{-1}$				%			
0	1.7c[a]	1.8e	2.2d	1.9e	37.3	47.0	55.8a	46.7b	5.9	4.4e	4.0 d	4.8e
0.12	4.3b	3.3d	3.2c	3.6d	48.7	47.9	52.5ab	49.7ab	8.3	7.0d	6.1c	7.1d
0.24	5.3ab	4.6c	4.4b	4.8c	52.0	50.6	49.7bc	50.8ab	9.6	9.1c	8.9b	9.2c
0.36	5.6a	5.5b	5.0b	5.4b	55.0	51.2	51.1bc	52.4a	11.0	10.7b	9.9b	10.5b
0.48	6.0a	6.3a	5.8a	6.0a	56.4	49.8	48.6c	51.6ab	11.0	12.6a	12.0a	11.9a
Mean	4.6A	4.3AB	4.1B	4.3	49.9B	49.3B	51.5A	50.2	9.2A	8.8AB	8.2B	8.7

[a]Different lower case letters within columns indicate significant differences between P rates, and different capital letters in the last row indicate significant differences between temperatures, both according to Tukey's HSD, $P \leq .05$.

TABLE 5 Phosphorus balance (P applied minus P in clipping yield) as affected by different P rates and temperatures in Exp. 1

		P balance			
P rate	Total P rate	7 °C	12 °C	17 °C	Mean of 3 temperatures
$g\ P\ m^{-2}\ wk^{-1}$	—g P m^{-2}—				
0	0	−0.03e[a]	−0.08e	−0.12e	−0.08e
0.12	0.60	0.49d	0.34 d	0.29d	0.37d
0.24	1.20	1.02c	0.77c	0.74c	0.84c
0.36	1.80	1.57b	1.24b	1.27b	1.36b
0.48	2.40	2.15a	1.78a	1.73a	1.89a
Mean of 5 P rates		1.04A	0.81B	0.78B	0.88

[a]Different lower case letters within columns indicate significant differences between P rates, and different capital letters in the last row indicate significant differences between temperatures, both according to Tukey's HSD, $P \leq .05$.

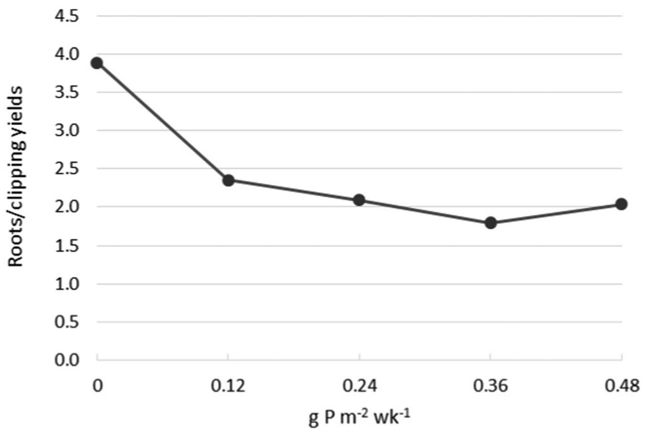

FIGURE 2 Ratio between dry weight of roots 7 wk after seeding and total dry weight of clippings during the same period in Exp. 1. Average of three temperatures and 2 yr. Different lower case letters indicate significant differences according to Tukey's HSD, $P \leq .05$

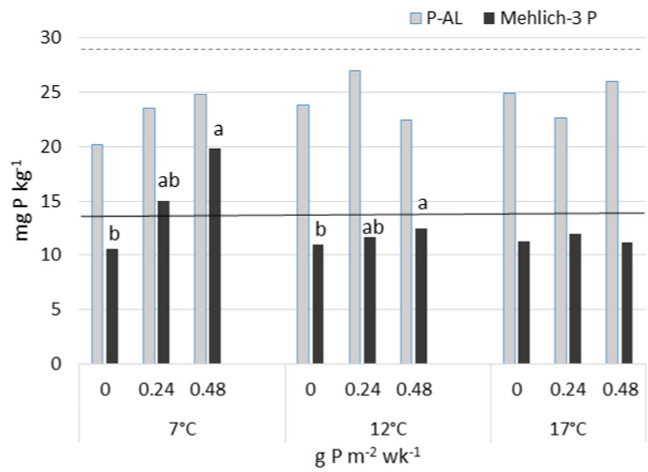

FIGURE 3 Average P-Mehlich-3 P and P–AL values in soil by end of the experimental period of Exp.1 for different temperatures and P rates. ——— start value for P-Mehlich-3 P, ——— start value for P–AL. Different lower case letters within temperatures indicate significant differences according to Tukey's HSD, $P \leq .05$

3.1.5 | Roots and ratio between roots and clipping yields

Root dry weight 7 wk after seeding increased from 53 g m^{-2} at 7 °C to 174 g m^{-2} at 12 °C, with no further increase at 17 °C (data not shown). Root dry weight was not affected by P rate. Because of greater clipping yields, the ratio between root dry weight and total clipping dry weight was greater in treatments not receiving P than in treatments receiving P, whereas there was no difference between P rates in the range 0.12–0.48 g P m^{-2} wk^{-1} (Figure 2).

3.1.6 | Extractable phosphorus in soil and phosphorus balance

The initial Mehlich-3 P and P—AL values in the sand-based substrate used in Exp. 1 were 13 and 29 mg P kg^{-1}, respectively (Table 1). After 7 wk, the P—AL values were lower than the start value, but the treatments did not affect the P—AL values at the end of the experiment (Figure 3). For Mehlich-3 P, the final values were higher at 7 °C than at 12 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 (0.48 mg P m^2 wk^{-1}) at 7 and 12 °C, but not at 17 °C.

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 (Table 5). The surplus was larger at 7 °C than at 12 and 17 °C.

3.2 | Experiment 2: Increasing rates of granular vs. foliar phosphorus applications to an established green in spring

3.2.1 | Color

There were no differences in color by different P application at any of the temperatures (data not shown). No

TABLE 6 Results from analyses of variance, Exp. 2

Character	Main effects: Temperature (df = 2)	Main effects: P treatment (df = 4)	Interaction: Temperature × P treatment (df = 8)	P treatment contrasts: No P vs. P (df = 1)	P treatment contrasts: Granular vs. foliar (df = 1)	P treatment contrasts: P rate (df = 3)	P treatment contrasts: Interaction fertilizer type × P rate (df = 3)
Turfgrass color (mean of five assessments)	ns[a]	ns	ns	ns	ns	ns	ns
Clipping yield, Week 1	†	*	ns	*	ns	†	ns
Accumulated clipping yield, Week 1–5	*	†	ns	*	ns	**	ns
Accumulated clipping yield P concentration	ns	***	ns	***	***	***	ns
Accumulated clipping yield N concentration	ns	*	ns	*	ns	ns	ns
Accumulated clipping yield P/N ratio	ns	***	ns	***	***	***	ns
Soil P–AL, 7 wk after seeding, mg kg^{-1}	ns	†	ns	ns	*	ns	ns
Soil Mehlich-3 P, 7 wk after seeding, mg kg^{-1}		†	ns	*	ns	ns	ns
P balance (P applied minus P removal in clippings)	ns	***	ns	***	ns	***	ns

[a]ns: $P > .10$.
†P value is indicated as follows.05 < $P \le .10$ ("tendency").
***: P ≤ .001, **: .001 < P ≤ .01, *: .01 < P ≤ .05, (*): .05 < P ≤ .10 (‘tendency’), NS: P > .10.

anthocyanin color was seen at any temperature in the first year. In the second year, there were some leaves with anthocyanin color at the start of the experiment, but there were no differences in green-up between treatments.

3.2.2 | Clipping yields

There was a tendency (Table 6) for increasing temperature to increase clipping yield 1 wk after the start of the trial (Table 7). 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, they did not differ between P rates in the range 0.12–0.24 g P m^{-2} wk^{-1} but were higher at 0.18 and 0.24 than at 0.06 and g P m^{-2} wk^{-1}. Clipping yields did not differ depending on foliar vs. granular application.

3.2.3 | Phosphorus and nitrogen concentrations and phosphorus/nitrogen ratio in leaves

Neither P concentration, N concentration nor the ratio between them was affected by temperature (Table 7). The P concentration was higher in clippings from plants receiving P than from plants not receiving P and in clippings

TABLE 7 Clipping yields, concentrations of P and N and P/N ratio in clippings, soil P levels by the end of the experiment and P balance as affected by temperature and different P treatments. Data are means of the 2017 and 2019 runs of Exp. 2. For each factor or contrast, different letters within columns indicate significant differences according to Tukey's HSD, $P \leq .05$

Experimental factor/contrast	Clipping yield Wk 1	Clipping yield Wk 1–5	Concentration in clippings P	Concentration in clippings N	P/N ratio	Soil P by end of trial P–AL	Soil P by end of trial Mehlich-3	P balance
Temperature, °C	g DM m^{-2}		g kg^{-1}		%	mg kg^{-1}		g P m^{-2}
7	29	131b	4.3	40.6	11.1	17	23	0.15
12	42	159ab	5.3	44.4	12.5	17	23	−0.11
17	59	196a	5.7	46.1	13.0	16	21	−0.36
P-Contrast 1:								
No P vs. P	38b	150b	4.3b	42.6b	10.5b	15	20b	−0.62b
No P	44a	163a	5.2a	43.9a	12.4a	17	23a	−0.04a
P-Contrast 2: Repeated foliar vs. one granular application								
Foliar	44	163	5.0b	43.9	12.0b	16b	24	−0.05
Granular	43	164	5.4a	43.9	12.8a	18a	22	−0.03
P-Contrast 3: P rate, g P m^{-2}								
0.06	41	155b	4.5d	42.9	11.1c	–	–	−0.37d
0.12	43	161ab	5.0c	44.3	11.7c	16	23	−0.15c
0.18	45	168a	5.5b	44.7	12.8b	–	–	0.05b
0.24	46	169a	5.9a	43.7	14.0a	18	24	0.29a

from plants receiving granular vs. foliar fertilization. The P concentration showed an almost linear increase with increasing P inputs in the range 0.06–0.24 g P m^{-2} wk^{-1}. The N concentration in clippings was higher with than without application of P, but unaffected by P rate or foliar vs. granular application. The contrasts for P/N ratio mirrored those for P concentrations.

3.2.4 | Extractable phosphorus in soil and phosphorus balance

As in Exp. 1, soil P–AL values decreased whereas soil Mehlich-3 P values remained stable during the 5-wk trial period in Exp. 2. Neither of the extraction methods showed any temperature effect on soil P by the end of the trial, but P–AL values were higher after granular than after foliar application and Mehlich-3 P values were higher in cylinders that had received P than had not received P (Table 7).

The P balance (applied P minus P in yield) was not affected by temperature or granular vs. foliar fertilization but increasing P rate shifted the balance from negative at 0.06 and 0.12 g P m^{-2} wk^{-1} to positive at 0.18 and 0.24 g P m^{-2} (Table 7).

4 | DISCUSSION

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 (e.g., Carroll et al., 2005; Liu & Landschoot, 2018). In the present material, this is evident from the fact that the relative increase in the total clipping yields after application of 0.24 g P m^{-2} wk^{-1} was 119% in Exp. 1 (establishment, Table 4) as opposed to only 9% in Exp. 2 (established turf, Table 7).

4.1 | Effect of soil phosphorus status for establishing vs. established turf

The profound difference between the two experiments may also be influenced by the fact that soil Mehlich-3 P values were, on average for 2 yr, 29 mg P kg^{-1} in the old substrate underlying the established green in Exp. 2 vs. only 13 mg P kg^{-1} in the new substrate used for establishment in Exp. 1. Kreuser, Pagliari, and Soldat (2012) found the critical soil Mehlich-3 P value (i.e., value above which there was not response to P fertilizer) to be as low as 6–11 mg P kg^{-1}

for turf quality on established creeping bentgrass greens, and Woods, Stowell, and Gelernter (2014) determined a critical value (Minimum level of Sustainable Nutrition) to be 18 mg P kg^{-1} based on a large dataset of soil-test values from good-looking turf. These values may explain why P deficiency symptoms were not observed on established turf not receiving P in Exp. 2. In contrast, Carroll et al. (2005) found clipping yield responses for P fertilizer to establishing tall fescue (*Festuca arundinacea* Schreb.) turf on soils with Mehlich-3 P levels up to 97 mg P kg^{-1} at day/night temperature 25/15 °C and up to 163 mg P kg^{-1} at 15/5 °C, while Hamel and Heckman (2006) determined critical Mehlich-3 P level as high as 280 mg P kg^{-1} during establishment of tall fescue and perennial ryegrass (*Lolium perenne* L.) in greenhouse studies.

Apart from establishing vs. established turf, the wide variation in critical Mehlich-3 P levels reported in the literature is probably due to different P sorption to soil particles. Carroll et al. (2005) and Hamel and Heckman (2006) worked with silt loam soils, but the present experiments and those of Kreuser et al. (2012) were conducted on USGA-sands with low P sorption capacities. In the present research, oxalate-extractable Fe and Al [amorphous Fe and Al (hydr)oxides], which is a measure of the soil P sorption capacity in acid soils, was low compared to agricultural soils (Øgaard, 1994). Soil pH in the present study was between 5.0 and 5.5, and thereby, in the pH range where the P sorption is controlled by the soil's content of Fe and Al (hydr)oxides. Hamel and Heckman (2006) found the ratio of P to Al was a better predictor than the Mehlich-3 P value alone for tall fescue and perennial ryegrass establishment response to P fertilization. On Norwegian agricultural soils, there was no yield response to P application for barley when the degree of P saturation (DPS-ox) was above 25–28% (Øgaard, unpublished data, 2019), a value that coincides with the value above which the release of P to the soil solution and thus the risk for P leaching increases rapidly (Vadas et al., 2005). A DPS-ox of almost 29% explains why no typical P deficiency was seen, and also the mostly low P responses of established turf in Exp. 2. This criterion may also explain why the response in clipping yield to increasing P was greater in Exp. 1 where the initial DPS-ox value was only 19%.

4.2 | 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 establishment trial (Exp. 1), turfgrass coverage was less in the treatment not receiving P, but there was no difference between P rates in the range 0.12–0.48 g P m^{-2} wk^{-1}. Turfgrass color and clipping yields showed, in contrast, an increase up to 0.24 P m^{-2} wk^{-1}. By comparison, Liu and Landschoot (2018) also found P supply to be more influential on clipping yield than on coverage during establishment of tall fescue in one out of four field experiments. Kreuser et al. (2012) found that critical Mehlich-3 P thresholds for response to P fertilization ranged from 6 to 28 mg P kg^{-1} for clipping yields vs. 6–11 mg P kg^{-1} for turfgrass quality and posited the greater variability for clipping yields as due to difficulties with the collection and cleaning of clippings in pot trials.

It is often claimed that extra P is needed to stimulate root growth (e.g., Christians, 2004). However, results of the establishment trial (Exp. 1) indicated that root dry weight was not affected by P rate and that the ratio between root dry weight and total clipping dry weight was higher on turf not receiving P than on turf receiving P, whereas there was no difference between P rates in the range 0.12–0.48 g P m^{-2} wk^{-1}. Higher root/shoot DM ratio with restricted P supply was also reported by Wang et al. (2015); Wang et al. (2016); and Cong, Christensen, and Eriksen (2019). Producing roots have a C cost (Marschner, 2011), and may explain lower root/shoot ratio at sufficient P supply.

4.3 | 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 as Power (1963) found that poor growth of spring barley at suboptimal temperatures could, to some extent, be alleviated by increased P inputs. 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 (Lewis & Quirk, 1965). Further, low temperature are found to retard the release of P from organic matter (Eid, Black, & Kempthorne, 1951) and from Fe and Al (hydr)oxides at low pH and Ca phosphate at high pH (Frossard, Brossard, Hedley, & Metherell, 1995). 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 and 17 °C). In the establishment trial (Exp. 1) the situation was opposite, as there was an increase in clipping yields up to 0.12 g P m^{-2} wk^{-1} at 7 °C, whereas at 12 and 17 °C there was an increase in clipping yields up to 0.24 g P m^{-2} wk^{-1}. 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 higher at 7 °C than at 17 °C. The lower P concentration by high temperature in Exp. 1 may be explained as a dilution effect, although this result is in contrast to the results from established turf (Exp. 2) and to studies where higher P concentration was found in plants grown at 13–19 °C than at 7–9 °C (Kristoffersen, Riley, & Sogn, 2005b; Singh & Subramanian, 1997).

4.4 | Phosphorus balance and soil phosphorus values

When calculated as the difference between applied P and P in clipping yields, there was a large surplus of P in Exp. 1 However, during turfgrass establishment, P was also used for root growth and incorporated in stolons and verdure which were not removed by the clippings. Given a root/clipping yield dry matter (DM) ratio close to 2 for treatments receiving P, as shown in the present experiment, and the same P concentration in root DM as in clipping yields (Wang et al., 2016), the risk for P leaching at 12 and 17 °C was probably limited to treatments receiving 0.36 or 0.48 g P m^{-2} wk^{-1}. In contrast, at 7 °C there was a calculated surplus after accounting for roots, stolons, and verdure of approximately 0.60 g P m^{-2} at the intermediate P rate of 0.24 g P m^{-2} wk^{-1}, and this was reflected also in a small increase in the Mehlich-3 P value in the soil core comprising the top 12 cm of each cylinder. When the P rate at this low temperature was doubled to 0.48 g P m^{-2} wk^{-1} or 2.4 g P m^{-2} during the entire duration of the trial, P in plant material and soil accounted for approximately 0.7 and 1.1 g P m^{-2}, giving a surplus of 0.6 g P m^{-2} which was not accounted for. Field trials with small grain crops have documented the risk for P surpluses during establishment to result in P leaching at low temperatures and on soils with low sorption capacity for P (Ylivaino & Peltovuori, 2012), and this is an aspect that requires further research when it comes to turfgrass (re)establishment on sand-based greens.

4.5 | Granular vs. foliar phosphorus application

Kruse, Christians, and Chaplin (2005) reported that one single foliar application of 0.5 g P m^{-2} in phosphoric acid was insufficient to correct purple discoloration, a typical P deficiency, on a sand-based creeping bentgrass green, but that turf quality was improved and that no leaf scorching occurred if the application rates was tripled to 1.5 g P m^{-2}. Using radiolabeled ^{32}P, Okuda, Kawasaki, and Yamada (1960) also reported efficient translocation of P after foliar application of phosphoric acid, with maximum absorption at a pH of 2.6 or in the range 5.6–6.2. In our trial on established turf (Exp. 2), five consecutive applications of phosphoric acid at rates up to 0.24 g P m^{-2} for a total of 1.20 g P m^{-2} had no visual effects but increased clipping yields compared with the control treatment not receiving P. The fact that the P concentration and P/N ratio in clippings were higher after 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, be also be caused by the methodology used for the foliar P application. A hand-held spray bottle was used inside a circular shield, and it was difficult to avoid that some of the liquid hit the wall of the shield. Thereby, the total P application may have been somewhat lower with foliar application than with granular application. Regardless of this, the opposite claim, that foliar P application is more efficient than granular application at low temperature, could not be verified by this experiment.

5 | CONCLUSION

A central objective of this research was to validate under adverse conditions in spring the Scandinavian Precision Fertilization recommendation of not using fertilizers with a greater P/N ratio than 12%. Given the low sorption capacity for P of the sand-based root zones, our research confirmed this recommendation: Under the conditions of these studies, and regardless of temperature, applications of P beyond 12% of applied N was unnecessary both during turfgrass establishment and on established greens.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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