HOCHSCHULE OSNABRÜCK
UNIVERSITY OF APPLIED SCIENCES

Title:

Impact of reduced phosphorus fertilization on golf course putting greens

Master thesis

in the degree program Applied Livestock and Crop Sciences (M.Sc.)
at the Faculty of Agricultural Sciences and Landscape Architecture

Student author: Anne Friederike Borchert
297729

Submission date: October 20, 2021

1. Examiner: Professor Dr. Wolfgang Prämaßing
2. Examiner: Professor Dr. Hans-Werner Olfs

External Supervisor: M.Sc. Karin Juul Hesselsøe

Table of Contents

List of Abbreviations

Al	Aluminum
Appx.	Appendix
Ca	Calcium
CEC	Cation Exchange Capacity
Duete-DE	Experimental putting green at Golfclub Osnabrück-Dütetal e.V., Germany
DPS	Degree of Phosphorus Saturation (%)
Exper. site	Experimental site
Falken-SE	Experimental putting green at Falkenbergs Golfklubb, Sweden
Fe	Iron
Fr + Ac	*Festuca rubra* + *Agrostis capillaris*
Jingshan-CN	Experimental putting green at Jingshan Lake Golf Club, China
K	Potassium
L	Liter
Landvik-NO	Experimental putting green at the NIBIO turfgrass research center Landvik, Norway
M	Molar Mass (g mol^{-1})
Mg	Magnesium
mL	Milliliter
MLSN	Minimum Levels for Sustainable Nutrition
Mn	Manganese
N	Nitrogen
NIBIO	Norwegian Institute of Bioeconomy research
ns	Not significant
P	Phosphorus
PO_4-P	Orthophosphate forms of P, plant available P
Princen-NL	Experimental putting green at Golfclub Princenbosch, The Netherlands
PSC	Phosphorus Sorption Capacity (mmol kg^{-1} soil)
S	Sulfur
SLAN	Sufficiency Level of Available Nutrients
SPF	Scandinavian Precision Fertilization
Y	Year (y = Year, respectively)

List of Figures

List of Tables

1 Introduction

A high-quality putting green with a dense turfgrass sward and an even surface is the optimum condition for golf experiences. Even though, a golf player´s definition of playing quality varies, for many of them evenness or trueness combined with uniformity are the foremost criteria (DAHL JENSEN 2012). To meet the golfer´s needs, a high turfgrass quality, i.e. high tiller density and few areas with weeds, moss, disease and bare soil, is essential (MÜLLER-BECK 2019; TURGEON 2012). To assure this, course managers perform regular maintenance practices, such as a close-cut mowing, scarifying, aeration, topdressing, rolling, fertilization and irrigation (MC CARTY 2011). A sufficient application of nutrients, such as nitrogen (N), phosphorus (P) and potassium (K), is especially important for turfgrass resilience, plant health and divot recovery (MÜLLER-BECK 2019; PESSARAKLI 2008). In contrast to soils on many agricultural grasslands, the artificial sandy rootzone mixture on putting greens contains fewer nutrients, less organic matter and is very permeable to water (FLL 2008). For fertilization strategies, these circumstances need to be taken into account.

It is important to focus on P fertilization, as this nutrient stimulates root and shoot growth (CARROW et al. 2001). Thus, a situation of undersupply should be avoided not only in grow-in but also in long-established greens. An insufficient P supply is most likely to occur in situations when P levels in soil are low due to adverse soil and climate conditions, and during turfgrass establishment while roots are still developing (CARROW et al. 2001). An oversupply with P is disadvantageous, as some studies verified a stimulating effect on *Poa annua* (annual bluegrass) encroachment (RALEY et al. 2013; THIEME-HACK 2018; VARGAS and TURGEON 2004). In addition, P losses increase the risk of eutrophication of surface waters and algae formation explained by e.g. SCHINDLER (1971) and ULÉN et al. (2007), which must be avoided to protect the environment (BELL 2011; SCHOLZ et al. 2014). Thus, a sustainable fertilization management with adequate P rates is necessary to prevent P excess or deficiency to ensure environmental protection and the required turfgrass quality suitable for golfer's needs. Furthermore, course managers save non-renewable P primary resources, which are most limited in the world according to CORDELL et al. (2009), GILBERT (2009) and JASINSKI (2014), and avoid unnecessary fertilizer costs.

Currently, there are different P fertilization recommendations common for putting greens, which are based either on P concentrations in soil or on a certain N : P ratio. The international research project "Sustainable phosphorus fertilization on golf courses 2017 – 2020 (SUSPHOS)" funded by the Scandinavian Turfgrass and Environment Research Foundation (STERF) studied which of these recommendations allow high turfgrass quality and environmental protection despite of reduced P rates. The project compared three P fertilization recommendations at selected golf courses in five countries, i.e. China, Germany, Norway, Sweden, and The Netherlands. The fertilization recommendations were "Minimum Levels for Sustainable Nutrition" (MLSN), "Scandinavian Precision Fertilization" (SPF), and "Sufficiency Level of Available Nutrients" (SLAN). MLSN recommendation by WOODS et al. (2014) recommends maintaining a P level in soil of above 18 mg kg^{-1} soil (Mehlich-3 extraction), which is three times lower than for the SLAN recommendation by CARROW et al. (2004b), which corresponds to a soil P level of above 54 mg kg^{-1} soil (Mehlich-3 extraction). The SPF recommendation does not take soil P analyses into account and recommends to apply P according to the expected P removal as 12 % of the annual N rate (ERICSSON et al. 2015).

The subject of this master thesis was to evaluate the impact of these selected P fertilization recommendations on soil PO_4-P concentration, soil pH, overall impression, *Poa annua* coverage, and rooting depth at the five golf course putting greens. The hypotheses were that a lower P rate due to MSLN and SPF fertilization recommendations in comparison to a higher P rate due to SLAN recommendation would

- decrease soil PO_4-P concentrations without negatively affecting turfgrass quality,
- suppress the undesirable turfgrass species *Poa annua* in the sward, but
- adversely decrease turfgrass rooting depth.

It was also expected that the SPF recommendation, which does not consider P concentrations in soil, would result in higher P rates and thus unnecessarily higher soil PO_4-P concentrations compared to MLSN recommendation, while turfgrass quality would remain the same.

2 Literature Review

According to KIRKBY (2012) the macronutrient phosphorus (P) is an essential nutrient for plant growth. Thus, turfgrass management on putting greens requires a sufficient and sustainable P application to ensure healthy turfgrass, golfer´s playing experience, and environmental protection. In this context, P processes in the soil and in the plant, its influence on turfgrass and playing quality, and common P fertilization recommendations are most important. For better comparability, the soil P concentrations are prepared in mg kg^{-1} soil. The terms of "soil" and "rootzone mixture" are used interchangeably in this text.

2.1 Phosphorus in soil

Phosphorus in soil is present in the three fractions: stable, labile, and soluble (Fig. 1). The stable P pool comprises e.g. calcium (Ca), iron (Fe), and aluminum (Al) phosphates. This pool releases P extremely slowly. The labile P fraction includes P ions that are attached to clay minerals, organic matter, and various P oxides. According to HOLSTEN et al. (2016), the P sorption capacity of sandy soils, such as sand-based rootzone mixtures used on putting greens, is lower than in other soil types. Thus, this soil types adsorbs less P. Soluble P is dissolved in the soil solution and is available for plant uptake (AMELUNG 2018). The stable P is the largest fraction, which according to MENGEL and KIRKBY (2001) often makes more than 90 % of the total P concentration in soil. In contrast, the P concentration in soil solution is very low according to CARROW et al. (2001) and usually less than 1 kg ha^{-1} referring to MENGEL and KIRKBY (2001).

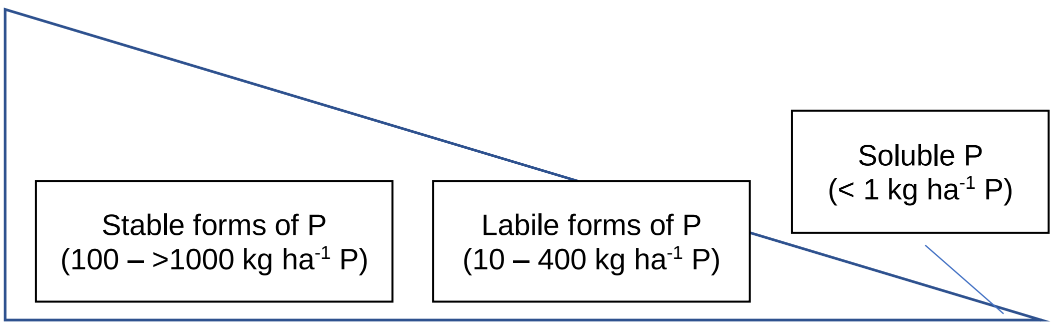


Fig. 1: Schematic illustration of the most important P fractions in soil and for the amount per hectare (0 – 30 cm) (MENGEL and KIRKBY 2001, modified).

Due to processes in soil, there is a steady exchange between the soil fractions (AMELUNG 2018). As plants take up P as phosphate ion from the soil solution, labile P is replaced due to equilibrium relationships between the pools (MENGEL and KIRKBY 2001). At the same time, the stable P is a slowly releasing P-source, which delivers P into the labile P pool. Additionally, organic P is released by microbial activity when soil temperature, moisture, and soil air content is suitable. According to FLL (2008) the organic matter content in rootzone mixtures for putting greens should not exceed a content of 1.5 to 2.5 % (by weight). Due to this low content, organically bound phosphates rarely exist in sand based rootzone mixtures.

An application with water-soluble P fertilizer increases the nutrients concentration in the soil solution. However, added P can be immediately fixed as labile P. P pool dynamics depend on:

- Soil pH (optimal 6.0 – 6.5; AMELUNG 2018),
- Redox potential and
- Ca, Fe and Al concentration in the soil (AMELUNG 2018).

Depending on soil pH, common practices such as liming (pH value too low) or in case of high soil pH an application of acidifying nitrogen (N) fertilizers, increase P availability. Under the conditions of a soil pH lower than 5.5, P is fixed as Fe, Al, and manganese (Mn) compounds, while in soils with high pH (> 7.5) Ca binds P (CARROW et al. 2001). In addition, plants themselves can decrease pH in soil at the root surface by excreting organic acids and H^+ ions, in order to dissolve labile P (SCHILLING 2000).

Fertilization and irrigation management play the largest role in nutrient losses from turfgrass areas as a review by BOCK and EASTON (2020) pointed out. However, the amount of nutrient losses from established, well-managed turf were evaluated to be low. In general, P in soil is immobile (HULL 1997). According to TURGEON (2012), P accumulates mainly in the upper soil layer. Literature about P losses from turfgrass are contradictory as SOLDAT and PETROVIC (2008) point out in their review. As stated by THIEME-HACK (2018), P leaching in turfgrass systems does not appear often, while soil erosion is considered to lead to distinct P losses. Studies by RICE and HORGAN (2010) documented high P concentrations of 0.71 mg soluble P L^{-1} ± 0.20 mg L^{-1} (water quality criteria to limit eutrophication within a stream: 0.1 mg L^{-1}) in surface run-off from golf courses in Minnesota. GUERTAL (2006) detected no excessive P leaching even with the highest P rate (≈ 29 g m^{-2}) in a two-year trial on sand-based bermudagrass greens in Alabama. Nevertheless, P losses from golf courses are of environmental concern according to a 20-years monitoring of water outlets from American golf courses, which revealed that 86 % of the samples surpassed environmental threshold values (BARIS et al. 2010). Especially, soils with a Degree of Phosphorous Saturation (DPS) of 30 % and higher increase the risk of P losses and therefore accelerated eutrophication according to (DESMET et al. 1996; LEINWEBER et al. 1997; LOOKMAN et al. 1996).

The P transport to the roots follows a concentration gradient (MARSCHNER and RENGEL 2012). This results in local P depletion in the area around the roots, the so-called rhizosphere, as the low P concentration in soil solution often does not supply enough P to the roots. This concentration gradient causes P to diffuse from areas with higher concentrations into the depletion zones. However, the area of depletion is only a few millimeters around the root, only a small portion of soil P is plant available. Furthermore, low soil moisture and low temperatures limit diffusion, which might lead to an insufficient P availability according to CARROW et al. (2001). However, low temperatures do not directly justify higher P applications on sand-based greens. This is the conclusion of ØGAARD and AAMLID (2020) in recent results of a pot trial with *Agrostis stolonifera*. In addition, CARROW et al. (2001) and WISSEMEIER (2019) point out that under P deficiency, root growth is less inhibited than shoot growth. Root growth does not decrease until the photosynthesis rate has declined.

A well-established turfgrass root system is necessary for sufficient P uptake from soil. Compared to overall plant size, turfgrass has an extensive root system. This root system allows the plants to exploit P in soil better compared to other plants referring to studies by CHRISTIANS (2007). However, CARROW et al. (2001) mentions an uptake efficiency by 10 – 40 % of the P added with fertilizers. P that is not taken up by turfgrass plants is either fixed into inorganic forms, taken up by microorganisms, or incorporated into organic forms. Experiments according to LYONS et al. (2008) have further shown that turfgrass roots grow into the direction of spots with higher P concentrations in soil. This may cause longer roots under low soil P levels. In addition, field trials conducted by LIU et al. (1995) revealed differences in P uptake efficiency between turfgrass cultivars *Poa pratensis L.* (Kentucky bluegrass), *Lolium perenne L.* (Perennial ryegrass) and *Festuca arundinacea* (Tall fescue) at P rates of 37 kg ha^{-1} $year^{-1}$.

2.2 Phosphorus in plants

Turfgrass contains nutrients as nitrogen (N), phosphorus (P), potassium (K) and Magnesium (Mg) in a ratio of 1 : 0.13 : 0.66 : 0.12 (DRG 2020). According to TURGEON (2012), the P concentration in dried turfgrass clippings is less than 0.5 %. CARROW et al. (2001) suggest for shoot tissues 0.1 – 1.0 % by dry weight. According to TURNER and HUMMEL (1992), sufficient P concentrations in shoot material range between 0.20 – 0.55 %. P concentrations below 0.20 % are considered to be deficient and above 1.00 % to be excessive.

According to BELL (2011), the highest P requirement occurs in situations of turfgrass development, fast shoot growth, and seed formation. In plants, P is necessary for the storage and transfer of energy as well as synthesis and decomposition processes. It is incorporated in enzymes for fat, protein, carbohydrate, and vitamin synthesis, and is an element of nucleic acids, the carrier of genetic information. This nutrient is also essential for the structure and function of the cell membrane (HAWKESFORD et al. 2012; TURGEON 2012).

After P uptake as $H_2PO_4^-$ or HPO_4^{2-} by the roots, the nutrient is transported to the young vegetative plant parts (HAWKESFORD et al. 2012; SHEN et al. 2011). In these sinks, the incorporation into organic P compounds takes place. According to TURGEON (2012), these P compounds are plant mobile and can quickly reach the place of greatest need. Young meristematic tissue, in which new cells grow, contains the highest P concentration. Turfgrass seeds store P as phytate (HAWKESFORD et al. 2012). According to CARROW et al. (2001) and VARGAS and TURGEON (2004), in a situation of P oversupply, more P is stored in the seeds, which is assumed to be one reason why *Poa annua* invasion increases.

A limited P uptake from soil leads to P deficiency. According to BELL (2011), P deficiency usually occurs because of insufficient P availability in soil, and not because of a low P level in soil. According to FRY and HUANG (2004), there is a risk of P deficiency in turfgrass especially in a sandy rootzone mixture according to FLL (2008) or USGA (2018) putting green construction. CARROW et al. (2001) also concludes that P deficiency is often greater on sandy, low in Cation Exchange Capacity (CEC) and irrigated soils due to low P in soil. In addition, there is almost no organic matter in the required rootzone mixtures for putting greens. Competition with constantly flowering plants, e.g. turfgrass species as *Poa annua* or dicot weeds, can also lead to P deficiency in the desired turfgrass species such as e.g. *Agrostis stolonifera* (creeping bentgrass) and *Festuca rubra* (Red fescue) on putting greens (Fig. 2).

2.3 Phosphorus and turfgrass quality for high playability

A high turfgrass quality on putting greens is related to a turf with high tiller density, fresh and uniform green color, homogeneous grass stands, few weeds and moss, no bare soil, healthy plants, and a well-established root system (MC CARTY 2011). These characteristics mainly influence the golfer´s playing quality in terms of ball behavior (smoothness of roll), green speed, and a firm surface suited to the golfer´s needs (BAKER 2004; MÜLLER-BECK 2019; NOLAN 2015). A survey among Nordic golf players revealed that green evenness/trueness and uniformity are more important than ball roll distance (green speed) for a high playing quality on greens (DAHL JENSEN 2012). Visual aspects, as bare soil and dry spots, fungal attack, and presence of weeds were also considerable criteria relating to the entire golf course. Visual rating values of 1 – 9 are usually used to evaluate turfgrass quality or so called overall impression (MORRIS 2004). All ratings ≥ 6 are considered acceptable, 9 is best. Other references as e.g. BELL et al. (2009) tested in parallel handheld optical sensor measurements (Greenseeker) to estimate turfgrass quality.

However, P availability has a considerable influence on turfgrass quality and playing quality (CHRISTIANS et al. 1979). In contrast to this, a survey by GELERNTER et al. (2016) on US golf courses documented that a P input reduction of 53 % did not considerably affect turfgrass quality and playability. A study by KREUSER et al. (2012) on a sand-based *Agrostis stolonifera* green indicated that P concentrations of 6 – 11 mg kg^{-1} soil (Mehlich-3 extraction) are the critical range for visual turfgrass quality. In the western United States of America (USA) P rates of 2.8 – 11.0 g m^{-2} y^{-1}led to better turfgrass quality compared to an application of 0.6 g m^{-2} y^{-1} on a calcareous sand-based *Agrostis stolonifera* putting green with an initial soil P concentration of 2.5 mg kg^{-1} soil (Olsen extraction; JOHNSON et al. 2003).

In terms of turfgrass color, P deficiency can lead to discoloration. WISSEMEIER (2019) describe a dark and dirty green color, as chlorophyll concentration increases per unit leaf areas explained by CARROW et al. (2001). This dark green color occurs before a reddish color from anthocyanin pigment accumulation will be visible on older leaves (CARROW et al. 2001; TURGEON 2012). An unpleasant appearance of the putting green can also occur when infectious diseases spread in the turfgrass. TURNER and HUMMEL (1992) and VARGAS (1994) described that under conditions of low P levels in soil, Pythium damping-off, take-all patch, and pink snow mold (*Microdochium nivale*) were promoted. Thus, in these cases P is necessary for resistance or divot recovery.

Fig. 2: ***Agrostis stolonifera*** **on a putting green (a), a flowering** ***Poa annua*** **plant in a sward (b), and a** ***Festuca rubra*** **semi-rough (c; Photo a and b: KVALBEIN).**

To keep the mowing height at 3 – 5 mm for dense grass stands, golf greens are mowed 5 – 7 times per week from March to November (DRG 2020). As P promotes turfgrass tillering according to FRANK and GUERTAL (2013), a sufficient supply is needed due to frequent mowing. Especially, under low temperatures in spring, P availability for regeneration is often low according to HÄHNDEL (2019). CARROW et al. (2001) stated that an insufficient P availability inhibits shoot growth resulting in reduced leaf expansion. In addition, narrow leaves are a visual symptom according to WISSEMEIER (2019). FRY and HUANG (2004) reports that turfgrass often shows limp leaves under P deficiency reducing turfgrass density. In such situations under P deficiency, ball roll can be negatively affected as e.g. shown in experiments by JOHNSON et al. (2003).

In grow-in putting greens, P supports turfgrass establishment after seeding. TURNER and WADDINGTON (1983) documented that P rates between 16 – 40 g m^{-2} responding to a soil P content of ≈ 110 – 180 kg ha^{-1} promoted rapid establishment and had the most important effect compared to K and limestone application. Such turfgrass growth leads to a dense turf sward with little space for invasive weeds, moss or bare soil. But, an excessive P supply supports flowering and seed formation (FRANK and GUERTAL 2013). In addition, a high P application is also known to promote *Poa annua* (Fig. 2) in *Agrostis stolonifera* greens (GROSS et al. 1975; GUERTAL and MC ELROY 2018; HULL 1997; JUSKA and HANSON 1969; TURNER and HUMMEL 1992; WADDINGTON et al. 1978). A study by RALEY et al. (2013) revealed an increase in *Poa annua* encroachment when P concentrations in soil (Mehlich-3-extraction) were > 12.9 mg kg^{-1} soil. VARCO and SARTAIN (1986) found out that *Poa annua* responded positively in establishment and average clipping yield to applied P rates of 40 – 120 kg ha^{-1}. According to NOLAN (2015), high contents of *Poa annua* provides a softer putting green surface, increased ball bounce stated by TOLER (2007) and a shorter ball rolling distance. Conversely, other studies did not find a relationship between high P supply and the relative composition of *Agrostis stolonifera* + *Poa annua* swards according to e.g. DEST and GUILLARD (1987).

Putting greens with a well-established root system provides not only the required shear strength for the golfer, but also a better tolerance to drought stress (DACOSTA and HUANG 2006; LYONS et al. 2008). As a result, such turfgrass plants were more efficient in nutrient and water uptake from the soil and were more resistant to physiological stress factors. In a P response trial on a bluegrass-red fescue turfgrass establishment by KING and SKOGLEY (1969) P rates between 5.0 – 39.0 g m^{-2} y^{-1} did not influence root weight significantly. According to TURGEON (2012), roots generally only grow a little and mostly flat in summer. As root growth of cool-season turfgrass species, e.g. *Agrostis stolonifera*, increases especially in early spring and late autumn (Fig. 3), optimal P availability at these times is particularly necessary (CARROW et al. 2001). Nevertheless, an insufficient P supply affects root growth less than shoot growth as CARROW et al. (2001) concludes.

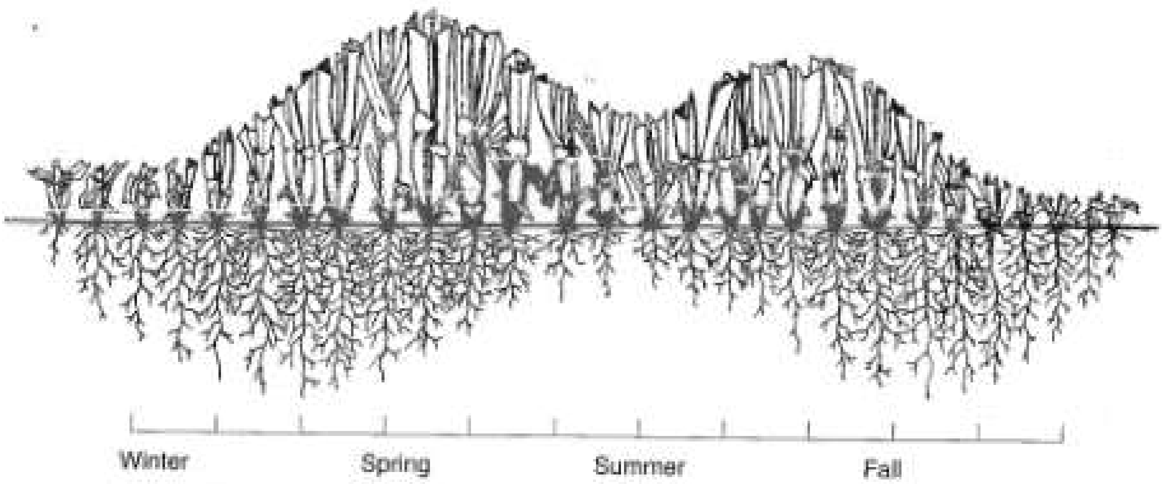


Fig. 3: Seasonal root growth of cool-season grass (TURGEON 2012).

2.4 Phosphorus fertilization

For golf course putting greens, varying literature on P requirements can be found. According to THIEME-HACK (2018) a P rate of ≈ 2.6 g m^{-2} per year ensures normal turfgrass growth, while BÜRING (1989) state that up to 10.0 g m^{-2} per year is adequate. In addition to these more general annual P rates, country-specific P fertilization recommendations, either based on soil P analysis or on a defined N : P ratio, are currently used in practical putting green management. For an overview of current P recommendations and present research results see Tab. 1. In the United States of America (USA) and in China, P fertilization recommendations according to the "Sufficiency Level of Available Nutrients" (SLAN) guidelines have been common practice on putting greens for many years. However, this guideline has been evaluated in agricultural field trials according to AAMLID and SANDELL (2018). For SLAN recommendation, Mehlich-3-extraction according to MEHLICH (1984) is used for soil P extraction. In this extraction, an acetic acid buffers the solution below pH 2.5. Thus, the method allows estimating plant available P in soil by increasing the solubility of Fe and Al phosphates and by complexing Al^{3+} that potentially binds with P. If the measured soil P concentration is > 54 mg kg^{-1} soil, a sufficient P level in soil with no turfgrass response to any P application is present (CARROW et al. 2004a, b). For P concentrations between 26 and 54 mg kg^{-1} soil (medium sufficiency level) there is a 50 % chance to get a turfgrass response to P fertilization. Besides the SLAN recommendation, a new procedure according to "Minimum Levels for Sustainable Nutrition" (MLSN) has become of practical interest. This recommendation is based on the evaluation of more than 17,000 soil samples beneath well-established turfgrass and its threshold value was determined by a mathematical model, which considered optimal turfgrass quality (WOODS et al. 2014). P in soil is also extracted using the Mehlich-3 method, but the P concentration in soil to allow unaffected turfgrass development of about 18 mg kg^{-1} soil is lower than for SLAN recommendation (AAMLID and SANDELL 2018; WOODS et al. 2014; WOODS et al. 2016). According to a soil P status study from 2013 until 2016 by WOODS et al. (2020), the MLSN recommendation is appropriate for putting greens across a wide geographic region.

In Germany, CAL-extraction according to SCHÜLLER (1969) is the standard method used by the laboratories of the Association of German Agricultural Research Institutes (VDLUFA). This method can be used for all soil types and extracts with an acidic buffer solution (pH 4.1) of Ca acetate lactate and acetic acid (ratio 1 : 20). It simulates the acidification of the rhizosphere by plants and is intended to extract plant available P (VDLUFA 2012). For fertilization recommendation, the determined P concentrations in soil are categorized into five levels (A to E), which have been derived from agricultural field trials. To maintain the soil P in level C is preferred, in which the P rate applied corresponds to the amount of plant P removal from soil. In A and B, P fertilization needs to be increased, while in D and E it needs to be reduced or even paused. According to WIESLER et al. (2018) for level C the soil P concentration on arable and grassland has to be between 31 – 60 mg kg^{-1} soil. In turfgrass rootzone mixtures, a range between 31 – 66 mg kg^{-1} soil is reported by THIEME-HACK (2018) for level C.

In Scandinavia and in the Netherlands, the ammonium lactate method (AL method) according to EGNÉR et al. (1960) is the standard extraction method for soil P analysis and P fertilization recommendations. Plant available P is extracted in a mixture of ammonium lactate and acetic acid adjusted to pH 3.75. For the associated fertilization recommendation in e.g. Norway the determined P-AL values are classified in four P levels A – D, in which level B is the optimum to be maintained (EUROFINS 2021). The classification is related to crop yield response, but also used for turfgrass management. The Olsen method according to OLSEN et al. (1954) is mainly used in Denmark, extracting P in a sodium bicarbonate solution adjusted to pH 8.5. Thus, it is often used for calcareous soils (JORDAN-MEILLE et al. 2012). Soil P concentrations are classified in five levels (I – V) based on agricultural soils and crops according to SEGES (2017). The aim is to maintain soil P concentrations in level III (medium: 21 – 40 mg kg^{-1} soil) by P application according to the nutrient removal during the vegetation period. At concentrations below level III, additional P must be applied. JOHNSON et al. (2003) found that on calcareous *Agrostis stolonifera* USGA putting greens a soil P concentration of 3 mg kg^{-1} soil (Olsen-P) corresponding to level I (very low) led to maximum turfgrass quality.

Tab. 1: Selected P fertilization recommendations and present research results for turfgrass maintenance. Sufficient supply level for P in soil written in bold letters.

Fertilization recommendation	Extraction method	Supply level for P in soil	References
SLAN	Mehlich-3	**Medium: 26 – 54 mg kg^{-1} soil** High: > 54 mg kg^{-1} soil	(CARROW et al. 2004a, b)
MLSN	Mehlich-3	> 18 mg kg^{-1} soil	(WOODS et al. 2014; WOODS et al. 2016)
	Mehlich-3	Very low: 0 – 12 mg kg^{-1} soil Low: 13 – 26 mg kg^{-1} soil **Medium: 27 – 54 mg kg^{-1} soil** High: > 55 mg kg^{-1} soil	(CARROW et al. 2001)
	Mehlich-3	Critical range for acceptable turfgrass quality on calcareous *Agrostis stolonifera* putting greens: 6 – 11 mg kg^{-1} soil (8 cm depth)	(KREUSER et al. 2012)
VDLUFA-Standard	CAL	**C (medium): 31 – 60 mg kg^{-1} soil (arable land and grassland)** **Medium supply: 31 – 66 mg kg^{-1} soil (sandy rootzone mixture)**	(WIESLER et al. 2018) (THIEME-HACK 2018)
P-AL	AL	A (low): 0 – 40 mg kg^{-1} soil **B (medium): 50 – 70 mg kg^{-1} soil** C1 (high): 80 – 100 mg kg^{-1} soil C2 (high): 110 – 140 mg kg^{-1} soil D (very high): > 140 mg kg^{-1} soil	(EGNÉR et al. 1960; EUROFINS 2021)
Olsen-P	Olsen	I (very low): < 10 mg kg^{-1} soil II (low): 10 – 20 mg kg^{-1} soil **III (medium): 21 – 40 mg kg^{-1} soil** IV (high):41 – 60 mg kg^{-1} soil V (very high): > 60 mg kg^{-1} soil	(OLSEN et al. 1954; SEGES 2017)
	Olsen	Very low: 0 – 6 mg kg^{-1} soil Low: 7 – 12 mg kg^{-1} soil **Medium: 13 – 28 mg kg^{-1} soil** High: > 29 mg kg^{-1} soil	(CARROW et al. 2001)
	Olsen	Calcareous *Agrostis stolonifera* USGA putting green: 3.0 mg kg^{-1} soil enough for maximum turfgrass quality	(JOHNSON et al. 2003)
SPF	-	12 % of nitrogen input	(ERICSSON et al. 2015; KVALBEIN and AAMLID 2016)
	-	*Agrostis stolonifera* turf on sand-based soil: 10 % of nitrogen input (clippings removed); 7 % of nitrogen input (clippings remain)	(KUSSOW et al. 2012)

In another approach, the Scandinavian Turfgrass and Environment Research Foundation (STERF) propose in its Precision Fertilization Recommendation (SPF) a P application rate in a certain ratio to the given N rate (ERICSSON et al. 2015). This recommendation has been adapted for putting greens due to KVALBEIN and AAMLID (2016), who recommend to add a P rate of 12 % of the N input. This recommendation is based on the principle that all nutrients, including P, are present in turfgrass in a certain relationship to each other (Chapter 2.2). The P concentration in soil is not taken into account (NIBIO 2017).

Generally, in Europe there are more than ten different extraction methods for soil P testing used for fertilization recommendations performed with subsequent spectrophotometric measurement or Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) according to an overview by JORDAN-MEILLE (2012). Studies of agricultural soils by NEYROUD and LISCHER (2003) and WUENSCHER et al. (2016) have shown that the determined soil P concentrations varied significantly due to the soil extraction method. A fertilization recommendation based on soil samples is therefore always associated with the corresponding extraction method. This was also confirmed by MÜLLER-BECK and LAWSON (2017) for turfgrass fertilization. Additionally, none of the currently in Europe used P fertilization recommendations based on soil samples were intend for turfgrass fertilization.

As P fertilizers, rock phosphates are commonly used on putting greens. However, organic fertilizers are getting more popular as they are expected to reduce P losses from runoff or erosion. But, previous studies have shown that this is not always the case (SOLDAT and PETROVIC 2007; STAHNKE et al. 2013). In rock phosphates, P is not plant available and needs to be solubilized with acids (e.g. sulfuric acid). This procedure leads to different granular fertilizers with varying P solubility. To irrigate small amount of water after application granular fertilizer is common practice and is supposed to limit P runoff (SHUMAN 2004). An often used fertilizer on turfgrass is superphosphate with 8.0 % total P or 7.4 % water-soluble P, respectively. Besides granulated P fertilizers, liquid fertilizers are of interest (CARROW et al. 2001).

3 Material and Methods

3.1 Experimental sites, climate, and soil conditions

Within the SUSPHOS-project, this P fertilization study was conducted on golf course putting greens in four European countries (Germany, Norway, Sweden, The Netherlands) and one Asian country (China) from 2017 to 2020. In Germany, the experimental putting green was located at the 18-hole golf course Golfclub Osnabrück-Dütetal e.V. (Duete-DE), in Norway at the NIBIO turfgrass research center Landvik (Landvik-NO), in Sweden at the 18-hole golf course Falkenbergs Golfklubb (Falken-SE), and in The Netherlands at the 27-hole golf course Golfclub Princenbosch (Princen-NL). For the field trial in China, a putting green at the 18-hole golf course Jingshan Lake Golf Club (Jingshan-CN) was used. A geographical overview of all sites is shown in Fig. 4, while detailed GPS-coordinates and information about elevation are composed in Tab. 2.

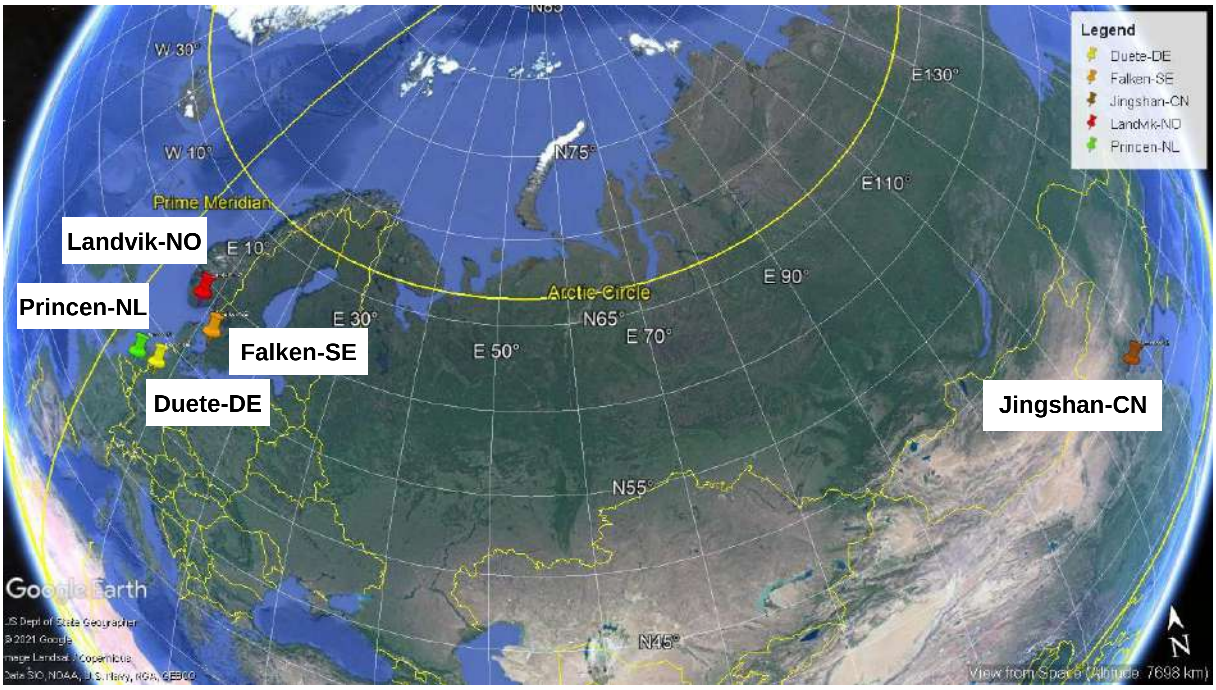


Fig. 4: Geographical location of the five experimental sites (GOOGLE EARTH 2021, modified). For experimental site description, see Tab. 2.

The climate at Duete-DE, Falken-SE and Princen-NL is temperate oceanic (Cfb), at Landvik-NO and Jingshan-CN, humid continental with warm summers in Norway (Dfb) and hot summers in China (Dwa) according to the Köppen-Geiger climate classification modified by BECK et al. (2018). Long-term average annual air temperatures had a maximum difference of 4.2 °C between the five experimental sites, being coldest at Landvik-NO (7.8 °C) and warmest at Jingshan-CN (12.0 °C, Tab. 2). The maximum difference in long-term average annual precipitation was ≈ 900 mm, with a minimum average annual precipitation of 507 mm recorded for Jingshan-CN and the highest for Landvik-NO with 1,416 mm (Tab. 2). For the other three experimental sites at Duete-DE, FALKEN-SE, and Princen-NL, the long-term average annual precipitation was ≈ 830 – 870 mm.

Tab. 2: Site characteristics and climate conditions. Climate data according to CLIMATE-DATA (2021) for Duete-DE, according to DONKERS (2021) for Princen-NL, according to VACKERTVÄDER (2021) for Falken-SE, according to their own stationary weather stations for Jingshan-CN and for Landvik-NO.

Exper. site	Location	Coordinates N	E	Elevation (m.a.s.l.)	Long-term annual AIR TEMP (°C)	PCPN (mm)	Climate classification[a]
Duete-DE	Dütetal, Germany	52°18'	7°55'	60	9,1	830	Cfb
Falken-SE	Falkenberg, Sweden	56°89'	12°57'	48	9,0	872	Cfb
Jingshan-CN	Jingshan Lake, China	40°19'	116°43'	68	12,0	507	Dwa
Landvik-NO	Landvik, Norway	58°20'	8°31'	12	7,8	1416	Dfb
Princen-NL	Princenbosch, The Netherlands	51°32'	4°87'	10	10,9	834	Cfb

Exper. site = Experimetal site; AIR TEMP = Long-term average annual air temperature;
PCPN = Long-term average annual precipitation; m.a.s.l. = metres above sea level;
[a] Climate classification according to Köppen-Geiger modified by BECK et. al. (2018);
Cfb = Temperate oceanic climate; Dwa = Hot-summer humid continental climate;
Dfb = Warm-summer humid continental climate.

The putting green soil profiles at Jingshan-CN, Landvik-NO, and Princen-NL were constructed according to the United States Golf Association (USGA) specifications (USGA 2018, Tab. 3). These USGA profiles feature a layered design including a stable subgrade with a pipe drainage system overlaid by a 10 cm gravel layer and a ≥ 30 cm sand-based rootzone mixture. In the case of Jingshan-CN, calcareous sand was used for the rootzone mixture. Corresponding to these USGA profiles without intermediate layer, the profile at Duete-DE was built as a K3-Drainage layer construction, following FLL (2008) guidelines. From top to bottom, the K3 profile contains a ≥ 25 cm thick rootzone mixture, a gravel layer of ≥ 12 cm, and a subgrade of ≥ 37 cm (FLL 2008). Since turf planting in 2000, this sand-based rootzone mixture has built up a sandy-organic maintenance horizon in the upper portion. Deviating from USGA and FLL putting green constructions, the profile at Falken-SE is specified as a ‘push-up green‘, designed by using the native soil.

The long-established putting greens were characterized for different soil physical and chemical properties (Tab. 3). The site-specific rootzone mixtures had an average soil bulk density of 1.37 g cm^{-3} (Jingshan-CN) to 1.56 g cm^{-3} (Duete-DE). The average loss on ignition was between 1.1 % (Jingshan-CN) and 1.6 % (Falken-SE). Average soil pH measured in distilled water ranged between pH 5.9 (Landvik.NO) and pH 6.7 (Duete-DE), except of a very high pH of 8.3 at Jingshan-CN. Depending on the putting green location the total carbon (C) concentration in the rootzone mixtures was determined to be 0.31 – 0.80 %, while the total nitrogen (N) concentration was 0.02 – 0.05 %.

Tab. 3: Putting green construction and initial soil physical and chemical properties determined in the rootzone mixture of all experimental sites. One representative sample (0 – 20 cm depth) across all plots on each experimental site. Concentrations of total carbon (Tot. C) and total nitrogen (Tot. N) in %. For experimental site description, see Tab. 2.

Exper. site	Putting green construction	Soil bulk density[a] (g cm^{-3})	Soil dry matter[a] (%)	Loss on ignition[a] (%)	pH_{H2O}[a] (-)	Tot. C[b] (%)	Tot. N[b] (%)
Duete-DE	FLL K3 profile	1.56	99.84	1.5	6.7	0.80	0.04
Falken-SE	Push-up / modified USGA profile	1.39	99.78	1.6	6.0	0.62	0.04
Jingshan-CN	USGA profile	1.37	99.81	1.1	8.3	0.31	0.02
Landvik-NO	USGA profile	1.40	99.83	1.4	5.9	0.63	0.05
Princen-NL	USGA profile	1.42	99.76	1.3	6.3	0.53	0.04

[a] *Analytical methods according to KROGSTAD (1992);* [b] *Detection limit: 0.05 %;*
pH measured in distilled water; Tot. C and Tot. N according to NELSON and SOMMERS (1996);
FLL = Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau e.V.;
USGA = United States Golf Association.

The initial Degree of Phosphorus Saturation (DPS) in the rootzone mixture was low at Jingshan-CN and Princen-NL (15 % and 17 %, respectively) compared to Duete-DE and Falken-SE (36 % and 37 %, respectively, Tab. 4). In four sites, the initial Soil Cation Exchange Capacity (CEC) was between 2.56 and 3.31 cmol c^+ kg^{-1} soil. In the rootzone mixture at Jingshan-CN the CEC was higher at 6.10 cmol c^+ kg^{-1} soil. Further soil P sorption properties and detailed CEC calculations are shown in Tab. 4.

Tab. 4: Initial soil P sorption properties and Soil Cation Exchange Capacity (CEC) determined in the rootzone mixture. One representative sample (0 – 20 cm depth) across all plots on each experimental site. Oxalate extractable Aluminum (Al_{ox}), Iron (Fe_{ox}) and Phosphorus (P_{ox}) in g kg^{-1} soil. Phosphorus Sorption Capacity (PSC) in mmol kg^{-1} soil. Degree of Phosphorus Saturation (DPS) in %. CEC in cmol c^+ kg^{-1} soil = ∑ Calcium (Ca) + Potassium (K) + Magnesium (Mg) + Sodium (Na) + Hydrogen (H).

Exper. site	**Soil phosphorus sorption**					**Soil Cation Exchange Capacity (CEC)**					
	Al_{ox} (g kg^{-1} soil)	**Fe_{ox}**	**P_{ox}**	**PSC (mmol kg^{-1} soil)**	**DPS (%)**	**Ca** (cmol c^+ kg^{-1} soil)	**K**	**Mg**	**Na**	**H**	**CEC**
Duete-DE	0.08	0.36	0.05	**4.60**	**36**	2.30	0.09	0.46	< LD	0.00	**2.85**
Falken-SE	0.17	0.40	0.08	**6.72**	**37**	0.93	0.22	0.22	0.03	2.58	**3.73**
Jingshan-CN	0.14	0.61	0.04	**8.04**	**15**	4.60	0.22	0.98	0.10	0.42	**6.10**
Landvik-NO	0.24	0.22	0.05	**6.41**	**24**	0.50	0.22	0.10	0.04	2.67	**3.31**
Princen-NL	0.10	0.27	0.02	**4.26**	**17**	1.00	< LD	0.48	0.03	1.08	**2.56**

Exper. site = Experimental site; LD = Detection limit; ox = Oxalate extractable; PSC = Phosphorus Sorption Capacity (= (Al_{ox} (mmol kg^{-1} soil) + Fe_{ox} (mmol kg^{-1} soil)) x 0.5); DPS = Degree of Phosphorus Saturation (= P_{ox} (mmol kg^{-1} soil) / PSC (mmol kg^{-1} soil) x 100 (%)); Al_{ox}, Fe_{ox} and P_{ox} according to "Acid oxalate extractable Al, Si method" according to VAN REEUWIJK (1995); CEC: "Ammonium-acetat method", pH 7.00, ICP-OES; H^+ using titration with 0.05 M NaOH according to SUMNER and MILLER (1996).

3.2 Grass species composition and turfgrass management

Due to turfgrass species composition the long-established putting greens at Duete-DE, Falken-SE, Jingshan-CN and Landvik-NO were characterized as *Agrostis stolonifera* (creeping bentgrass) greens with no *Poa annua* (annual bluegrass) encroachment at Jingshan-CN and up to 55 % at Duete-DE (Tab. 5). The mowing height was at 2.5 – 4.0 mm during season. At Princen-NL, the putting green was a mixed *Festuca rubra* (red fescue) and *Agrostis capillaris* (colonial bentgrass) green with 5 % *Poa annua*, cut at a height of 4.5 – 5.5 mm (Tab. 5).

Tab. 5: Grass species composition and mowing conditions on each experimental site (Exper. site). For experimental site description, see Tab. 2.

Exper. site	**Species compostion**				**Mowing**
	Agrostis stolonifera	***Agrostis capillaris*** (%)	***Poa annua***	***Festuca rubra***	**Cutting height (mm)**
Duete-DE	45	-	55	-	4.0
Falken-SE	50	-	50	-	2.7 – 3.0
Jingshan-CN	100	-	-	-	2.5 – 3.0
Landvik-NO	90	-	10	-	3.0
Princen-NL	-	35	5	60	4.5 – 5.5

In addition to mowing procedures, practical putting green maintenance included regular aeration, scarifying and sanding, pest management, use of wetting agents, and overseeding according to the course managers' schedule. For details about operations and date on the example of Duete-DE, see Appx. 1 (dates for overseeding are unknown). All nutrients, except P, were calculated according to common practice on putting greens, and were spread evenly throughout the entire experimental putting green (e.g. Duete-DE, Appx. 2). In the case of N fertilization, the nutrient amount applied referred to the course managers' preferred N level. For the *Agrostis stolonifera* putting greens the applied N rate ranged between 11.8 and 27.0 g m^{-2} y^{-1}, for the *Festuca rubra* + *Agrostis capillaris* (*Fr + Ac)* mixture between 2.6 and 5.5 g m^{-2} y^{-1} (Tab. 6) during the entire trial period. On each individual experimental site, N rates usually differed only slightly between the years (maximum 3 g m^{-2} $y^{-1)}$, except of two years at Landvik-NO and one year at Falken-SE and Duete-DE (Tab. 6). At Landvik-NO, N rates had to be increased from 12.0 to 25.0 g m^{-2} y^{-1} for the 2nd and 3rd year of trial due to the green´s reestablishment after a severe damage during winter 2017 / 2018. At Falken-SE, a breakdown of the irrigation system caused dry spots/patches of 10 – 60 % in some plots in the 4th year of trial. The reestablishment of the green after this event increased N fertilization (+ 6 g m^{-2} y^{-1}). At Duete-DE, a new course manager started in the 3rd year of trial and applied crucial more N than the years before (+ 8 g m^{-2} y^{-1}).

Tab. 6: N rates (g m^{-2} y^{-1}) for each experimental site (Exper. site) and trial year. For experimental site description, see Tab. 2.

Exper. site	N rate (g m^{-2} y^{-1})				
	1st Year	2nd Year	3rd Year	4th Year	SUM
Duete-DE	18.0	19.0	27.0	-	**64.0**[a]
Falken-SE	19.0	19.0	19.0	25.0	**82.0**
Jingshan-CN	9.9	11.8	12.1	12.1	**45.9**
Landvik-NO	12.0	25.0	25.0	18.0	**80.0**
Princen-NL	2.6	3.7	5.5	5.5	**17.3**

[a] *Applied N in total of three years at Duete-DE, all other sites of four years.*

3.3 Experimental design and treatments

The field trials on each experimental site had the same Latin square design with four treatments and four replicates (Duete-DE: Fig. 5, all others: Fig. 6), in which each treatment occurs exactly once in each row and each column. Thus, the experiment consisted of 16 plots in total (Duete-DE: each 2.0 m x 2.0 m; all others: 2.0 m x 1.5 m; the central 1.0 m x 1.5 m was used for assessments). The trials were laid out in June 2017 (Duete-DE: December 2017) with the P fertilization treatments described as:

- **MLSN** – “Minimum Levels for Sustainable Nutrition” recommending to establish or maintain a soil P concentration of > 18 mg kg^{-1} soil (Mehlich-3 extraction)
- **SPF** – “Scandinavian Precision Fertilization” P rates adequate to 12 % of annual N input
- **SLAN** – “Sufficiency Level of Available Nutrients” recommending to establish or maintain a Mehlich-3 soil P concentration of > 54 mg kg^{-1} soil (Mehlich-3 extraction).

Additionally, a control treatment with no P application (**Control**) was included.

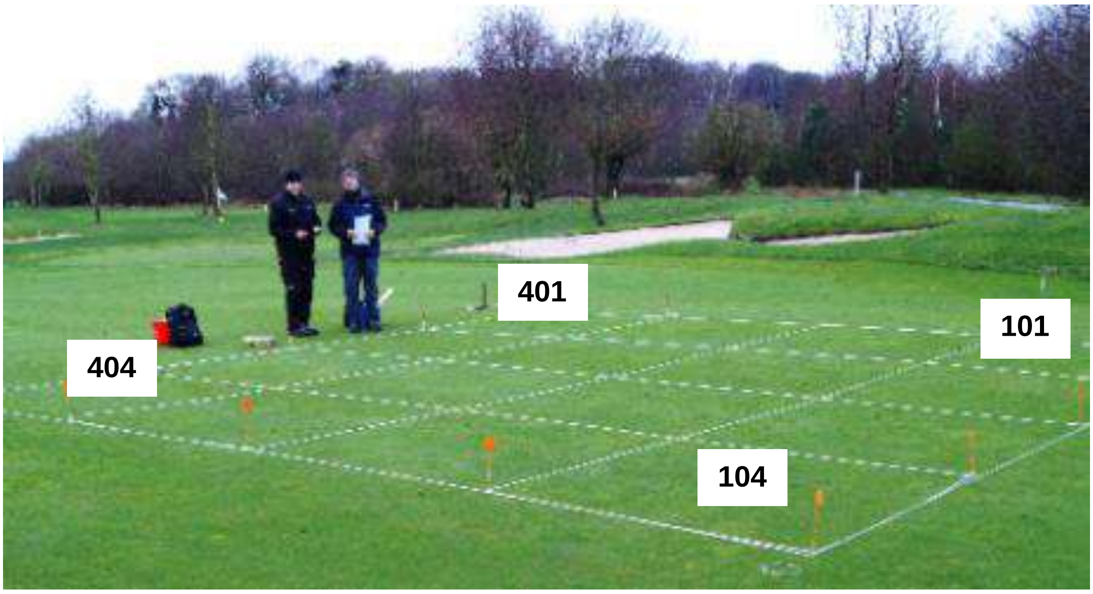


Fig. 5: Experimental site Duete-DE with plot numbers (Photo: PRÄMAßING).

Fig. 6: Experimental sites Falken-SE (a), Jingshan-CN (b), Landvik-NO (c), Princen-NL (d; Photos: SINTORN (a), CHEN (b), AAMLID (c), DOKKUMA (d)).

At the beginning of each growing season, the P rates for MLSN, SPF, and SLAN treatment were calculated according to their P fertilization recommendations. For SPF, the required P rate (g m^{-2}) corresponded to the expected turfgrass annual P removal, which according to Ericsson et al. (2010) is equivalent to 12 % of the N input for the respective growing season. In addition it was assumed that the entire applied N was removed in clippings (KUSSOW et al. 2012). Thus, in spring each year N fertilization plans were set up and mostly followed by the course manager´s. Only in the 4th year of trial at Falken-SE and in the 3rd year at Duete-DE they increased the N rates without informing the project manager.

For MLSN and SLAN treatment, the required P reserve in the soil (g m^{-2}) at the end of the growing season (18 or 54 mg kg^{-1} soil, respectively) was added to the expected annual P removal (g m^{-2}). For this, the site-specific bulk soil density and a soil depth of 20 cm were taken into account. To finally calculate the required P rates (g m^{-2}), the P amount in soil (g m^{-2}) at the end of the previous growing season was subtracted. For 2017 (1st year of trial, July – October), P rates for the MLSN and SLAN treatments at Falken-SE, Jingshan-CN, Landvik-NO, and Princen-NL were calculated from soil analyses taken in June 2017, while from 2018 soil samples taken at the end of the growing season in November were taken into account. Tab. 7 gives an example of how the annual P rates were calculated.

Tab. 7: Calculation of the annual P rate on the example of P fertilization at Duete-DE in the 2nd year of trial (2019).

Treatment	P in soil Nov. 2018[a]	P in soil Nov. 2018[b]	Expected P removal in clippings in 2019[c]	Required P reserve at the end of the growing season 2019[b]	Annual P rate given in 2019
	(mg kg^{-1} soil)	(g m^{-2})			
Control	21	6.6	2.5	-	0.0
MLSN	23	7.2	2.5	5.6	1.0
SPF	27	8.3	2.5	-	2.5
SLAN	37	11.6	2.5	16.9	7.8

[a] *Mehlich-3 extraction, mean of four samples.*

[b] *At 0 - 20 cm soil depth; 1.56 g cm^{-3} soil bulk density.*

[c] *12 % of N fertilizer rate (21.0 g N m^{-2}).*

Conclusively, each treatment received different P rates not only between each experimental site but also in each of the three or four years of trial. Annual added P rates for MLSN, SPF and SLAN treatments are shown in Fig. 7. In the practical implementation, those annual P rates per treatment were equally split up to six or seven applications per year, approximately once a month from April/May to September/October (2017: four or five applications as the first application was in June). As P fertilizer, a triple phosphate (ICL Fertilizers Europe C. V.) with a P concentration of 20 % (water-soluble P: 19.3 %) was used. In addition to P, this granular fertilizer contained 14.4 % Ca, and 1.2 % sulfur (S). The fertilizer had been grinded and dissolved in water, before spreading with e.g. the Birchmeier battery-operated backpack sprayer REC 15 ABZ at Duete-DE. Consequently, a four-minute irrigation followed the fertilizer application to wash the fertilizer from leaves.

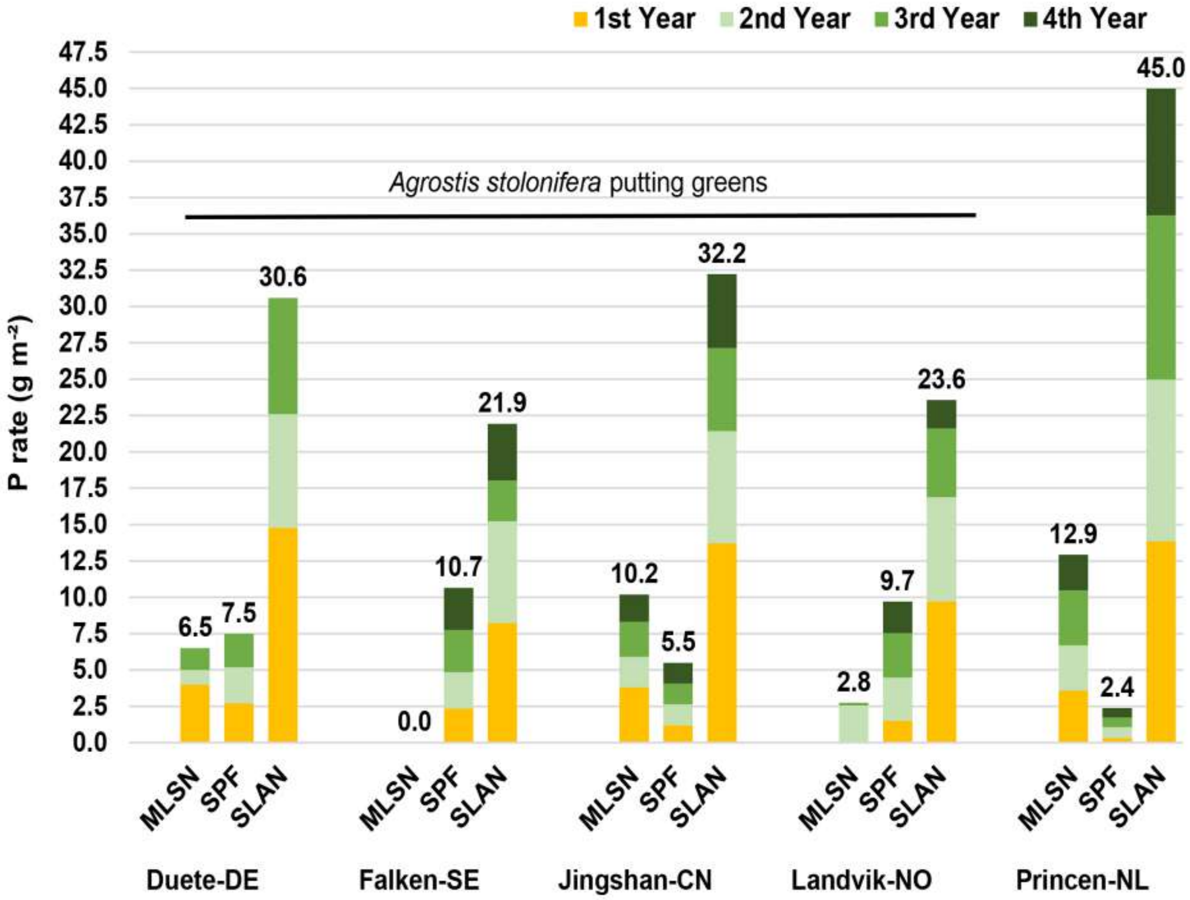


Fig. 7: Applied P rates per treatment and year (g m^{-2}) at each experimental site. Value on top of the column = sum of all P rates applied during trial per treatment. 3-year trial at Duete-DE, 4-year trials on all other sites. Control (not shown): no P application; MLSN: Minimum Levels for Sustainable Nutrition = > 18 mg kg^{-1} soil (Mehlich-3 extraction); SPF: Scandinavian Precision Fertilization = 12 % of N input; SLAN: Sufficiency Level of Available Nutrients = > 54 mg kg^{-1} soil (Mehlich-3 extraction). For experimental site description, see Tab. 2.

3.4 Soil sampling and analyses

To determine different soil physical and chemical properties in the rootzone mixture before the trials started and after each growing season (annually in November), one composite soil sample per plot was taken at a depth of 0 – 20 cm using an auger or a cylinder on each experimental site. To get a representative soil sample per plot (plot sample), 20 subsamples were pooled, obtaining ≈ 250 – 350 g of soil (Fig. 8). Turfgrass residues were removed, while thatch remained in the sample. The air-dried soil samples were shipped to the soil laboratory at the Norwegian University of Life Sciences (NMBU) in Ås (Norway) where the soil samples were dried at 40 °C and passed through a 2-mm sieve prior to analyses. For initial soil bulk density, soil dry matter, loss on ignition, soil pH, total C, total N, CEC, and oxalate extractable aluminum (Al_{ox}), iron (Fe_{ox}), and P_{ox} determination, the plot samples for each experimental site taken before the trials started, were pooled on volume basis to one sample (pooled sample). For Mehlich-3 soil P and soil pH analyses the plot samples were analyzed.

Fig. 8: Example of soil sampling for P and pH analysis on plot scale at the Duete-DE experimental site. Jan Rosenbusch taking the samples with an auger in November 2020 (a). Punctures after soil sampling in one plot and the composite plot sample in the plastic bag for soil analysis (b).

Soil bulk density was calculated as an average of five weighing of 10 mL soil using the formula for sand according to KROGSTAD (1992). Loss on ignition was measured as the difference between dry weight after drying at 105 °C for 48 hours and ash weight after burning over night at 550 °C (HOOGSTEEN et al. 2015).

Total C and total N was analyzed according to NELSON and SOMMERS (1996) using a LECO Truspec in which the soil sample is combusted at 1050 °C (carrier gas: helium). The cations in soil for CEC calculation (Ca, K, Mg, Na and H) were analyzed at pH 7.00 by ICP-OES or titration with 0.05 M NaOH for H^+ according to the Ammonium-acetate method by SUMNER and MILLER (1996).

Al_{ox}, Fe_{ox}, and P_{ox} were determined in an acid ammonium oxalate solution according to VAN REEUWIJK (2002). These results for Al_{ox}, Fe_{ox}, and P_{ox} were used to calculate the Degree of Phosphorus Saturation (DPS) in percent as the molar ratio between P_{ox} and P Sorption Capacity (PSC) where PSC was the sum of Al_{ox} and Fe_{ox} multiplied by 0.5 for non-calcareous soils (MAGUIRE et al. 2001; SCHOUMANS 2000). Al_{ox}, Fe_{ox} and P_{ox} values in equation (1) and (2) are in mmol kg^{-1} soil:

$$PSC\ (mmol\ kg^{-1}\ soil) = (Al_{ox} + Fe_{ox}) * 0{,}5 \quad (1)$$

$$DPS\ (\%) = \left(\frac{P_{ox}}{PSC}\right) * 100 \quad (2)$$

To determine plant available P (PO_4-P) in soil, the nutrient was extracted according to the Mehlich-3 method described in CARTER and GREGORICH (2008) at a 1 : 10 soil : solution ratio (*w/v*). The solution consisted of 0.2 M CH_3COOH + 0.25 M NH_4NO_3 + 0.015 M NH_4F + 0.13 M HNO_3 + 0.001 M EDTA (pH 2.3 ± 0.2). To detect the orthophosphate forms of P (PO_4-P), the soil extract was then colorimetrically measured using the Molybdenum (Mo) blue method (MURPHY and RILEY 1962).

In the pooled sample as well as in the plot samples on each experimental site, soil pH was measured with a glass pH electrode according to KROGSTAD (1992) in a 1 : 2.5 ratio soil (air dried) : distilled water (*v/v*). For this method, 10 mL soil and 25 mL water were mixed and stored until next day. After one extra mixing procedure, pH in soil was determined at least 15 minutes later.

3.5 Assessments and rooting depth measurement

To evaluate turfgrass quality, nine visual registrations were done on plot-scale before the trial started and just before each P application. Thus, approximately every four weeks from April/May to October/November (2017: July until October at all sites, except Duete-DE) overall impression, density and color ratings were collected based on a scale from 1 – 9. In addition, percent coverage of *Agrostis stolonifera* or *Festuca rubra* and *Agrostis capillaris* (depending on the putting green species), *Poa annua*, dicot weeds, moss, diseased turf, and bare soil was estimated. For each parameter, a maximum of 32 values per treatment (8 rating dates * 4 replicates) were listed per year and experimental site, resulting in 96 values during the 3-year experiment or 128 after 4 years of trial (Tab. 8). In this master thesis, only the results of overall impression, coverage (*Poa annua*), and rooting depth are going to be presented.

Overall impression is a rating for living ground cover, uniformity, greenness, fineness, disease resistance and shoot density. A rating of 9 is best and 1 being poorest. A rating of ≥ 6 is generally considered acceptable (MORRIS 2004). Coverage was assessed in percent (%) of plot area taking into account that the percent of non-diseased turf of the sown species (e.g. *Agrostis stolonifera*), *Poa annua*, dicot weeds, moss, diseased turf, and bare soil made up 100 % of the plot area.

Tab. 8: Assessments and their performing dates for each year and experimental site. Season from April to November (A – N). Grey dot = Assessment has been performed in this month. Number of ratings / values per treatment and year (n) and over the entire trial (∑). For experimental site description, see Tab. 2.

Exper. site	Assessment	Performed in the																																				
		1st Year									2nd Year									3rd Year									4th Year									
		A	M	J	J	A	S	O	N	**n**	A	M	J	J	A	S	O	N	**n**	A	M	J	J	A	S	O	N	**n**	A	M	J	J	A	S	O	N	**n**	∑
Duete-DE	Overall imp.		●	●	●	●	●	●	●	**28**	●	●	●	●	●	●	●	●	**32**	●	●	●	●	●	●	●	●	**32**									**0**	**92**
	P. annua		●	●	●	●	●	●	●	**28**	●	●	●	●	●	●	●	●	**32**	●	●	●	●	●	●	●	●	**32**									**0**	**92**
	Root. depth		●	●	●	●	●	●	●	**28**	●	●	●	●	●	●	●	●	**32**	●	●	●	●	●	●	●	●	**32**									**0**	**92**
Falken-SE	Overall imp.					●	●	●	●	**16**		●	●	●	●	●	●	●	**28**		●	●	●	●	●	●	●	**28**		●	●	●	●	●	●	●	**28**	**100**
	P. annua					●	●	●	●	**16**		●	●	●	●	●	●	●	**28**		●	●	●	●	●	●	●	**28**		●	●	●	●	●	●	●	**28**	**100**
	Root. depth					●	●	●	●	**16**		●	●	●	●	●	●	●	**28**		●	●	●	●	●	●	●	**28**		●	●	●	●	●	●	●	**28**	**100**
Jingshan-CN	Overall imp.						●	●	●	**12**	●	●	●	●	●	●	●	●	**32**		●	●	●	●	●	●		**24**		●	●	●	●	●	●		**24**	**92**
	P. annua						●	●	●	**12**	●	●	●	●	●	●	●	●	**32**		●	●	●	●	●	●		**24**		●	●	●	●	●	●		**24**	**92**
	Root. depth						●	●	●	**12**	●	●	●	●	●	●	●	●	**32**		●	●	●	●	●	●		**24**		●	●	●	●	●	●		**24**	**92**
Landvik-NO	Overall imp.				●	●	●	●		**16**				●	●	●	●		**16**			●	●	●	●	●	●	**24**	●	●	●	●	●	●	●		**28**	**84**
	P. annua				●	●	●	●		**16**				●	●	●	●		**16**			●	●	●	●	●	●	**24**	●	●	●	●	●	●	●		**28**	**84**
	Root. depth				●	●	●	●		**16**				●	●	●	●		**16**			●	●	●	●	●	●	**24**	●	●	●	●	●	●	●		**28**	**84**
Princen-NL	Overall imp.					●	●	●	●	**16**			●	●	●	●	●	●	**24**		●	●	●	●	●	●		**24**		●	●	●	●	●	●		**24**	**88**
	P. annua					●	●	●	●	**16**			●	●	●	●	●	●	**24**		●	●	●	●	●	●		**24**		●	●	●	●	●	●		**24**	**88**
	Root. depth					●	●	●	●	**16**			●	●	●	●	●	●	**24**		●	●	●	●	●	●		**24**		●	●	●	●	●	●		**24**	**88**

Overall imp. = Overall impression; Root. depth = Rooting depth; P. annua = Poa annua;
n = Number of ratings / values per treatment and year (number of assessment dates multiplied with the 4 replicates for each treatment).

To determine rooting depth, two soil cores per plot were collected using e.g. a root cylinder with a diameter of about 5 cm (Fig. 9). The intact hanging root cylinder was measured in millimeter (mm).

Fig. 9: Root cylinder (a) and soil core with roots (b) taken at the Landvik-NO experimental site for rooting depth measurement.

3.6 Statistical analysis

To evaluate the present dataset of each experimental site, descriptive and inferential statistics for all soil and turf quality parameters were computed using Microsoft Excel and R version 3.6.3 (R CORE TEAM 2013). An overview of the selected statistical methods and tests is given in Tab. 9. For rooting depth analysis, the two subsamples per plot were arithmetically averaged and their means were used for further calculations.

Tab. 9: Overview of descriptive and inferential statistics.

Parameter	Measurement scale	Descriptive	Inferential	Post-Hoc Tests
Soil samples				
PO_4-P, pH	Interval	Average	ANOVA, repeated measurements with mixed model	HSD, emmeans, contrasts
Assessments				
Overall impression	Ordinal	Median, Minimum, Maximum, Q1, Q3	Kruskal-Wallis rank sum test, Friedman rank sum test	Nemenyi-Test
Coverage (*Poa annua*)	Interval	Average, Median, Minimum, Maximum, Q1, Q3	ANOVA, repeated measurements with mixed model	HSD, LSD, emmeans, contrasts
Rooting depth	Interval	Average, Minimum, Maximum, Q1, Q3	ANOVA, repeated measurements with mixed model	HSD, LSD, emmeans, contrasts

HSD:Tukey´s Honest Significant Difference; LSD: Fischer´s Least Significant Difference; Q1: Quantile 1; Q3: Quantile 3.

Average soil PO_4-P concentration, soil pH, *Poa annua* coverage, and rooting depth were evaluated with a one-way analysis of variance (ANOVA) to determine if there were statistical differences in response to the different P fertilization recommendations for each sampling or assessment date (GOMEZ and GOMEZ 1984; KÖHLER et al. 2002). The required preconditions, i.e. normal distribution and variance homogeneity, were tested via the Kolmogorov-Smirnov test, respectively the Levene test (DALLAL and WILKINSON 1986; FOX and WEISBERG 2011; FOX 2016; STEPHENS 1974; THODE 2011). All data fulfilled these preconditions. For the ANOVA, the function "aov" in R package "stats" was performed as a Latin square taking into account:

$$aov\ (Response \sim ROW\ +\ COL\ +\ Fertilization)$$

with the arguments Response = analyzed parameters in soil, *Poa annua* coverage, and rooting depth; ROW = row and COL = column as random variables. In order to define significant differences between the fertilization treatments within the individual dates, the Honestly

Significant Difference test (Tukey HSD) and the Least Significant Difference test (LSD) were used as Post-Hoc tests. Those multiple comparison tests were performed using the function "HSD.test" (α = 0.05 and 0.10) and "LSD.test" (α = 0.05) in R package "agricolae" according to HSU (1996) and STEEL et al. (1997).

Among the P treatments, differences were determined using a mixed model including the effect of time as repeated measurements and considering rows and columns as random variables. For soil PO_4-P concentration and soil pH, all sampling dates were considered, while, in addition to this, for *Poa annua* coverage and rooting depth each trial year was computed separately. For mixed modeling with repeated measurements, the function "lmer" in package "car" was used taken into account:

$$lmer\left(Response \sim COL + ROW + Fertilization * Time + (1|individual\, plot)\right), \\ type = "II", test.statistic = "F")$$

with the arguments Response = parameters in soil, *Poa annua* coverage, and rooting depth; ROW = row; COL = column; type II = provided p-values in type II anova, test.statistic; F = F-tests (FREEDMAN 2006; LONG and ERVIN 2000; WHITE 1980). As preconditions, all data fulfilled the criteria of normal distribution, variance homogeneity, and sphericity, after performing Kolmogorov-Smirnov test, Levene test, and Mauchly's Test of Sphericity (ANDERSON 2003; DALLAL and WILKINSON 1986; FOX 2016; FOX and WEISBERG 2011; STEPHENS 1974; THODE 2011). To denote significant differences, contrasts were calculated for pairwise comparison at 5 % level adjusted by "Tukey" performing the function "cld/emmeans" in the package "multcomp" according to PIEPHO (2004).

Kruskal-Wallis rank sum test was used to determine significant differences between P treatments for the ordinal-scaled ratings of overall impression. This non-parametric test for independent variables compares the distribution location parameters of each treatment for each rating date. To perform the Kruskal-Wallis rank sum test, the function "kruskal.test" in R package "stats" was used (HOLLANDER et al. 2014). Nemenyi-Test for multiple comparisons of mean rank sums of independent samples (function "posthoc.kruskal.nemenyi.test" in R package "PMCMR", SACHS 2004) was chosen to do pairwise multiple comparisons depending on:

$$kruskal.test\ (Response \sim Fertilization)$$

$$posthoc.kruskal.nemenyi.test\ (Response \sim Fertilization, p.adjust.method = "none", \\ dist = "Tukey")$$

with the arguments Response = rating values and dist = distance, Tukey method.

To indicate significant differences in overall impression ratings between the trial years within each P treatment, the Friedman rank sum test for dependent samples in combination with the Post-Hoc Nemenyi-Test for multiple comparisons was computed for each treatment (R package “stats” version 3.6.2) as

$$friedman.test\ (Response \sim Date \mid BLK)$$

$$posthoc.friedman.nemenyi.test\ (Response, Date, BLK, p.adjust.method\ =\ "none")$$

with the arguments Response = rating values, Date = trial years and BLK = blocks.

4 Results

4.1 Phosphorus in soil

In general, soil PO_4-P concentrations differed due to MLSN, SPF and SLAN treatment on all five experimental sites (Tab. 10). Thus, soil PO_4-P concentrations across all sampling dates were lower in the treatment order MLSN < SPF < SLAN at Duete-DE, Falken-SE, and Landvik-NO. This resulted in soil PO_4-P concentrations of 23 – 41 mg kg^{-1} soil (MLSN and SLAN, respectively) at Duete-DE, of 28 – 45 mg kg^{-1} soil (MLSN and SLAN, respectively) at Falken-SE, and of 25 – 46 mg kg^{-1} soil (MLSN and SLAN, respectively) at Landvik-NO. At Jingshan-CN and Princen-NL, MSLN treatment (18 and 9 mg kg^{-1} soil, respectively) resulted in higher PO_4-P concentrations than SPF treatment (16 and 8 mg kg^{-1} soil, respectively) but also in lower values compared to SLAN treatment (40 and 23 mg kg^{-1} soil, respectively). SPF and MSLN treatment reduced soil PO_4-P concentrations significantly compared to SLAN treatment on all experimental sites, but did not show significant differences in soil PO_4-P concentrations among each other (Tab. 10). No P application according to the Control treatment did not result in considerably lower soil PO_4-P concentrations compared to MLSN or SPF treatment, except at Duete-DE (Control < SPF) and Jingshan-CN (Control < MLSN). In terms of time, significant differences between sampling dates could be computed for each experimental site ($p < 0.05$; Appx. 3). Interactions between sampling dates and treatments could were also identified, except at Landvik-NO ($p = 0.289$; Appx. 3)

Tab. 10: Average soil PO_4-P concentration (mg kg^{-1} soil) across all sampling dates for each experimental site (n = 16, except for Duete-DE with n = 12) in response to different P treatments. Treatments = P fertilization recommendations: Control: no P application; MLSN: Minimum Levels for Sustainable Nutrition = > 18 mg kg^{-1} soil (Mehlich-3 extraction); SPF: Scandinavian Precision Fertilization = 12 % of annual N input; SLAN: Sufficiency Level of Available Nutrients = > 54 mg kg^{-1} soil (Mehlich-3 extraction). Different letters indicate differences between treatments (Tukey contrasts, α = 0.05). For experimental site description, see Tab. 2.

Treatment	**PO_4-P (mg kg^{-1} soil)**				
	Duete-DE	Falken-SE	Jingshan-CN	Landvik-NO	Princen-NL
Control	16 **a**	29 **a**	9 **a**	25 **a**	8 **a**
MLSN	23 **ab**	28 **a**	18 **b**	25 **a**	9 **a**
SPF	27 **b**	29 **a**	16 **ab**	31 **a**	8 **a**
SLAN	41 **c**	45 **b**	40 **c**	46 **b**	23 **b**
p-value	0.001	0.007	0.000	0.003	0.000

On the four *Agrostis stolonifera* putting greens, initial soil PO_4-P concentrations were at different levels ranging between 7 – 9 mg kg^{-1} soil at Jingshan-CN, between 14 – 17 mg kg^{-1} soil at Duete-DE, between 25 – 29 mg kg^{-1} soil at Landvik-NO, and between 33 – 37 mg kg^{-1}

soil at Falken-SE (Fig. 10 and Tab. 11). These differences in initial soil PO_4-P concentrations between the treatments were insignificant, except at Duete-DE (Tab. 11). Initial soil PO_4-P values at this experimental site and at Jingshan-CN were also lower than the MLSN threshold (18 mg kg^{-1} soil). In comparison, initial soil PO_4-P concentrations at Landvik-NO and Falken-SE were higher than MLSN threshold but lower than SLAN threshold (54 mg kg^{-1} soil).

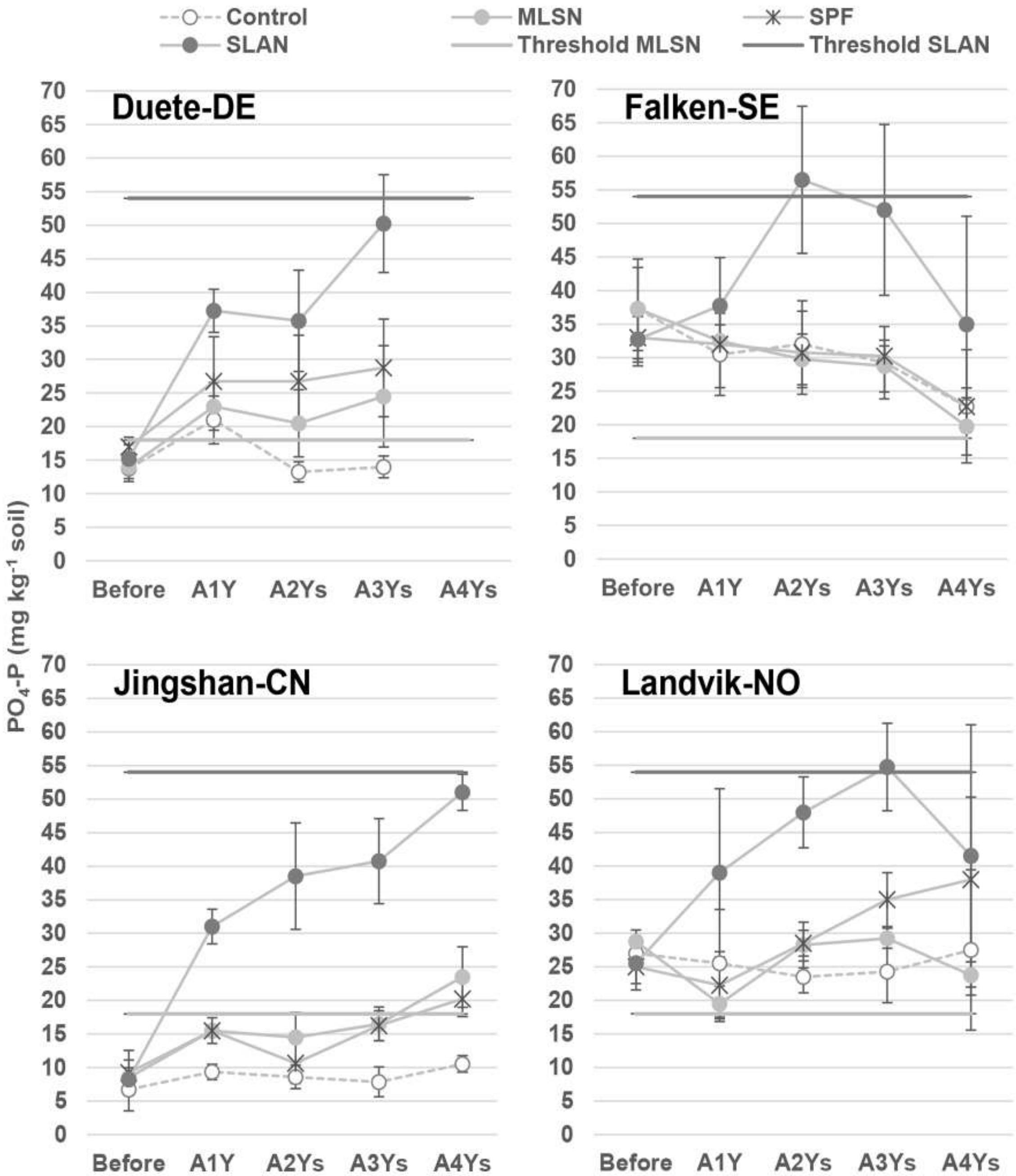


Fig. 10: Changes in soil PO_4-P concentration (mg kg^{-1} soil) in response to different P treatments on the four *Agrostis stolonifera* experimental greens. Five sampling dates: before the trial started (Before), after 1 year of trial (A1Y), after 2 years (A2Ys), after 3 years (A3Ys), and after 4 years (A4Ys, no data for Duete-DE). Light grey line = threshold for MLSN (18 mg kg^{-1} soil); dark grey line = threshold for SLAN (54 mg kg^{-1} soil). Error bars represent the spatial variation at plot scale (n = 4). For treatment description, see Tab. 10, for exper. site description see Tab. 2.

On the *Agrostis stolonifera* experimental sites with initial soil PO_4-P below MLSN threshold, soil PO_4-P concentrations had nearly quadrupled to 31 mg kg^{-1} soil (Jingshan-CN) and more than doubled to 37 mg kg^{-1} soil (Duete-DE) due to SLAN treatment after the 1st trial year in comparison to the individual start values (8 and 15 mg kg^{-1} soil, respectively; Fig. 10). In response to SLAN recommendation, the highest soil PO_4-P concentration for these two experimental sites was found after the 3rd trial year at Duete-DE (50 mg kg^{-1} soil) and after the 4th year at Jingshan-CN (51 mg kg^{-1} soil). SLAN threshold of 54 mg kg^{-1} soil was not reached (Fig. 10). SPF and MLSN treatment also increased the soil PO_4-P concentrations to the end of the 1st year, but not as much as the SLAN treatment. In the following years soil PO_4-P concentrations ranged between 15 – 24 mg kg^{-1} soil for MLSN treatment and between 11 – 20 mg kg^{-1} soil for SPF treatment at Jingshan-CN (Fig. 10). Thus, soil PO_4-P concentrations were mostly below MLSN threshold. At Duete-DE, soil PO_4-P concentrations ranged around MLSN threshold between 21 – 25 mg kg^{-1} soil for MLSN treatment and between 27 – 29 mg kg^{-1} soil for SPF treatment in the 2nd and 3rd year of trial. Despite to no P application in the Control treatment, soil PO_4-P increased by the end of the first growing season (21 mg kg^{-1} soil; Tab. 11) at Duete-DE but decreased in the following two years. At the end of the trial after three years with no P application, the soil PO_4-P concentrations nearly reached initial values (14 mg kg^{-1} soil). At Jingshan-CN, no P fertilization resulted in soil PO_4-P concentrations almost equal to the initial values, except of after the last year of trial (11 mg kg^{-1} soil). Control and MLSN treatment reduced soil PO_4-P significantly compared to SLAN treatment after the 1st trial year, all the same did SPF treatment at Jingshan-CN (Tab. 11). At Duete-DE, this was not the case before the end of the trial.

On the *Agrostis stolonifera* experimental sites with initial soil PO_4-P above MLSN threshold, Landvik-NO and Falken-SE, soil PO_4-P concentrations increased by 13 mg kg^{-1} soil and 5 mg kg^{-1} soil respectively due to SLAN treatment after one year of trial (Tab. 11). After two years of trial soil PO_4-P concentrations reached SLAN threshold at Falken-SE (57 mg kg^{-1} soil) and after three years at Landvik-NO (55 mg kg^{-1} soil; Fig. 10), which was not the case at Duete-DE and Jingshan-CN. Regardless of sampling date or treatment, soil PO_4-P concentrations were above MLSN threshold, except after one year of trial for MLSN treatment at Landvik-NO. However, at both experimental sites no P application (Control), MLSN and SPF treatment reduced soil PO_4-P significantly by ≈ 30 –50 % after two years of trial compared to SLAN treatment (Tab. 11). The same situation was found in the following years, but after the 4th trial year there were no significant differences between the treatments at Landvik-NO and at Falken-SE (p = 0.499 and 0.057, respectively; HSD α = 0.05). Significant differences between soil PO_4-P concentrations for SPF and MLSN treatment could not be determined for any of the two experimental sites (Tab. 11).

Tab. 11: Influence of different P treatments on soil PO_4-P concentration (mg kg^{-1} soil) for each sampling date on the four *Agrostis stolonifera* experimental greens. Experimental sites (Exper. site) sorted by initial soil PO_4-P level. Before = before the trial started. Different letters indicate differences between treatments within each sampling date (HSD, α = 0.05 (bold) and 0.10 (italic), ns = not significant). For treatment description, see Tab. 10, for site description see Tab. 2.

Exper. site	Treatment	PO_4-P (mg kg^{-1} soil)				
		Before	After1Y	After2Ys	After3Ys	After4Ys
Jingshan-CN	Control	7	9 **a**	9 **a**	8 **a**	11 **a**
	MLSN	9	16 **b**	15 **a**	17 **a**	24 **b**
	SPF	9	16 **b**	11 **a**	16 **a**	20 **b**
	SLAN	8	31 **c**	39 **b**	41 **b**	51 **c**
	ANOVA p-value	0.537	0.000	0.001	0.000	0.000
	HSD (α=0.05)	**ns**	**5.4**	**12.5**	**9.0**	**7.6**
	HSD (α=0.10)					
Duete-DE	Control	14 **a**	21 **a**	13 **a**	14 **a**	-
	MLSN	14 **a**	23 **a**	21 **ab**	25 **a**	-
	SPF	17 **b**	27 **ab**	27 **bc**	29 **a**	-
	SLAN	15 **ab**	37 **b**	36 **c**	50 **b**	-
	ANOVA p-value	0.013	0.015	0.001	0.003	-
	HSD (α=0.05)	**2.4**	**12.3**	**9.5**	**18.2**	-
	HSD (α=0.10)					
Landvik-NO	Control	27	26 *ab*	24 **a**	24 **a**	28
	MLSN	29	20 *a*	28 **a**	29 **a**	24
	SPF	25	22 *ab*	29 **a**	35 **a**	38
	SLAN	26	39 *b*	48 **b**	55 **b**	42
	ANOVA p-value	0.101	0.065	0.000	0.000	0.499
	HSD (α=0.05)	**ns**	**ns**	**8.8**	**11.0**	**ns**
	HSD (α=0.10)		*17.3*			
Falken-SE	Control	37	31	32 **a**	29 **a**	23 *ab*
	MLSN	37	33	30 **a**	29 **a**	20 *a*
	SPF	33	32	31 **a**	30 **a**	23 *ab*
	SLAN	33	38	57 **b**	52 **b**	35 *b*
	ANOVA p-value	0.613	0.431	0.004	0.002	0.057
	HSD (α=0.05)	**ns**	**ns**	**16.4**	**12.6**	**ns**
	HSD (α=0.10)					*13.0*

Y =Year/Years

On the *Festuca rubra* + *Agrostis capillaris* (*Fr* + *Ac*) experimental putting green at Princen-NL, initial soil PO_4-P concentrations were below MLSN threshold (6 – 7 mg kg^{-1} soil; Fig. 11). After the 1st trial year, the soil PO_4-P concentration for SLAN treatment was three times higher with 18 mg kg^{-1} soil compared to the initial values and increased to 30 mg kg^{-1} soil after four years of trial. Thus, SLAN threshold was not reached during trial. Soil PO_4-P concentrations for MLSN treatment ranged between 7 and 12 mg kg^{-1} soil not reaching MLSN threshold during trial (Fig. 11). Neither did SPF treatment, revealing even lower soil PO_4-P (6 – 9 mg kg^{-1} soil). No P application led to a consistent soil PO_4-P level (7 – 9 mg kg^{-1} soil).

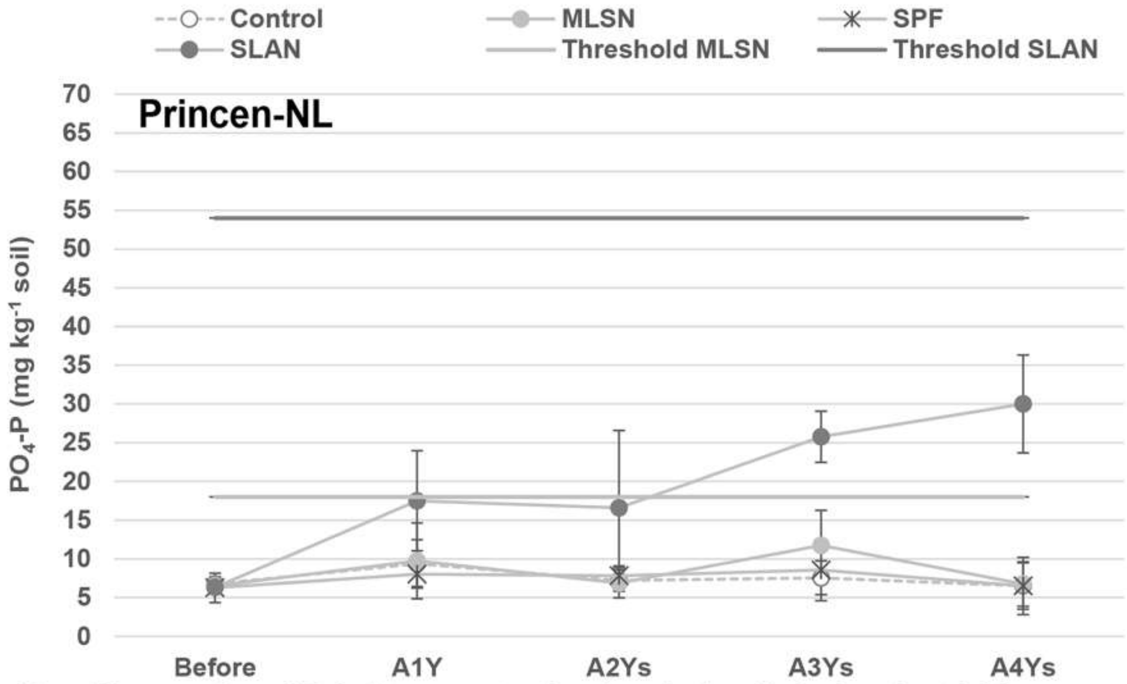


Fig. 11: Changes in soil PO_4-P concentration (mg kg^{-1} soil) during the trial in response to different P treatments on the *Fr + Ac* experimental green at Princen-NL. Five sampling dates: before the trial started (Before), after 1 year of trial (A1Y), after 2 years (A2Ys), after 3 years (A3Ys), and after 4 years (A4Ys). Light grey line = threshold MLSN (18 mg kg^{-1} soil); dark grey line = threshold SLAN (54 mg kg^{-1} soil). Error bars represent the spatial variation at plot scale (n = 4). For treatment description see Tab. 10, for experimental site description see Tab. 2.

At the end of the trial (After3Ys and After4Ys) Control, MLSN, and SPF treatment revealed considerable lower soil PO_4-P concentrations than SLAN treatment at Princen-NL. Thus, those three P treatments reduced PO_4-P concentrations to 7 – 12 mg kg^{-1} soil depending on the treatment and sampling date compared to 26 – 30 mg kg^{-1} soil for SLAN treatment (Tab. 12).

Tab. 12: Influence of different P treatments on soil PO_4-P concentration (mg kg^{-1} soil) on the *Fr + Ac* experimental green at Princen-NL. Before = before the trial started. Different letters indicate differences between treatments for each sampling date (HSD, α = 0.05 (bold) and 0.10 (italic), ns = not significant). For treatment description see Tab. 10, for experimental site description see Tab. 2.

Exper. site	Treatment	PO_4-P (mg kg^{-1} soil)				
		Before	After1Y	After2Ys	After3Ys	After4Ys
	Control	7	9	7	8 **a**	7 **a**
	MLSN	7	10	7	12 **a**	7 **a**
	SPF	6	8	8	9 **a**	7 **a**
Princen-NL	SLAN	6	18	17	26 **b**	30 **b**
	ANOVA p-value	0.403	0.097	0.099	0.000	0.000
	HSD (α=0.05)	**ns**	**ns**	**ns**	**5.5**	**6.6**
	HSD (α=0.10)					

Y =Year/Years

4.2 Soil pH

Average soil pH across all sampling dates varied among the experimental sites (Tab. 13). Lowest soil pH was measured at Falken-SE ranging between pH 5.6 (SPF) and 5.7 (Control, MLSN, SLAN). Plots at Jingshan-CN had the highest soil pH in a range of 7.7 (MLSN and SLAN) to 7.9 (Control). The different P treatments did not influence soil pH significantly on any experimental site, except at Duete-DE ($p = 0.039$). On this experimental putting green, plots with no P application had the highest soil pH of 7.1 (Control), while SLAN treatment reduced soil pH slightly but significantly to 7.0. In terms of time, sampling dates influenced soil pH significantly for all sites, while interactions between treatments and sampling dates were not present for any other site ($p > 0.05$; Appx. 4).

Tab. 13: Average soil pH across all sampling dates for each experimental site (n = 16, except Duete-DE with n = 12) in response to different P treatments. Different letters indicate differences between treatments (Tukey contrasts, α = 0.05). For treatment description see Tab. 10, for experimental site description see Tab. 2.

Treatment	**pH_{H2O}**				
	Duete-DE	Falken-SE	Jingshan-CN	Landvik-NO	Princen-NL
Control	7.1 **b**	5.7	7.9	6.1	6.5
MLSN	7.1 **ab**	5.7	7.7	6.1	6.5
SPF	7.1 **ab**	5.6	7.8	6.2	6.4
SLAN	7.0 **a**	5.7	7.7	6.1	6.5
p-value	0.039	0.329	0.225	0.396	0.658

Before the trials started, soil pH was lower than pH 7.0 on the *Agrostis stolonifera* putting greens Duete-DE, Falken-SE, and Landvik-NO and higher at Jingshan-CN (pH 8.3; Fig. 12). On the *Fr* + *Ac* experimental putting green at Princen-NL, initial soil pH was also < pH 7.0 and ranged slightly but insignificantly between 6.2 (MLSN and SLAN) and 6.3 (Control and SPF, Fig. 12). At Jingshan-CN (initial soil pH 8.3), soil pH decreased by approx. one pH unit to pH 7.3 (SLAN) – 7.7 (Control) until the end of the trial. At Falken-SE (initial soil pH 6.0) soil pH also declined to 5.3 (MLSN) – 5.4 (Control, SPF, SLAN) until the end of trial. In contradiction, at Duete-DE soil pH increased to a range of 7.1 (SLAN) to 7.3 (Control) after the 2nd trial year and at Landvik-NO to 6.3 (SPF and SLAN) to 6.4 (Control, MLSN) after the 4th trial year. Landvik-NO was the only *Agrostis stolonifera* experimental green with soil pH in the optimum range of pH 6.0 – 6.5 (Fig. 12) according to AMELUNG (2018) for P mobilization and P plant uptake. This was also the case on the *Fr* + *Ac* experimental green at Princen-NL, except after the 3rd trial year (Appx. 5). Initial soil pH ranged between 6.2 (MLSN, SLAN) and 6.3 (Control, SPF), increased after three years of trial to a range of 6.7 (Control, MLSN, SPF) to 6.8 (SLAN) and declined to a range of 6.4 (SLAN) to 6.6 (Control) until the end of trial.

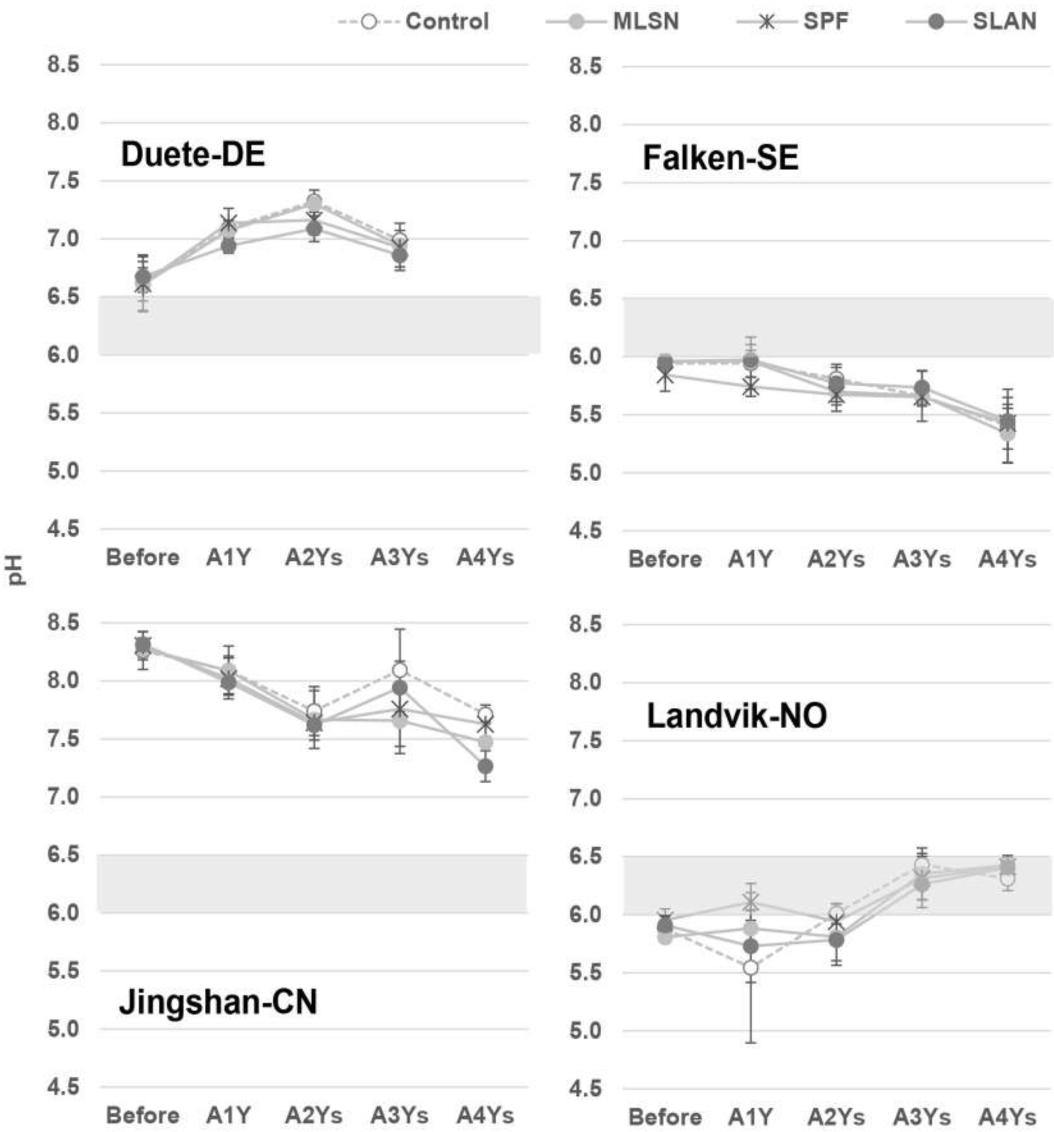


Fig. 12: Changes in soil pH according to different P treatments on the four *Agrostis stolonifera* experimental greens. Soil pH was analyzed before the trials started (Before), after 1 year of trial (A1Y), after 2 years (A2Ys), after 3 years (A3Ys), and after 4 years (A4Ys, no data for Duete-DE). Error bars represent the spatial variation at plot scale (n = 4). Grey highlighted area shows the soil pH range for optimum P availability (pH 6.0 – 6.5; AMELUNG 2018). For treatment description see Tab. 10, for experimental site description see Tab. 2.

Differences in soil pH at a significant level of 5 % in response to P treatments could not be computed for any experimental site with initial soil pH < pH 7.0 for any sampling date (Tab. 14). The only exception was the experimental green at Duete-DE, where SLAN treatment declined soil pH to 7.1 compared to Control and MSLN treatment (7.3, respectively) after two years of trial (p = 0.079). At a significant level of 10 %, SLAN treatment led to a lower soil pH of 6.4 in comparison to no P application (pH 6.6) at the end of the trial at Princen-NL, but not to MLSN and SPF treatment.

Tab. 14: Influence of different P treatments on soil pH at the experimental sites with initial soil pH < 7.0 (Duete-DE, Falken-SE, Landvik-NO, Princen-NL). Experimental sites sorted by initial soil pH value. Before = before the trial started. Different letters indicate differences between treatments for each sampling date (HSD, α = 0.05 (bold) and 0.10 (italic), ns = not significant). For treatment description see Tab. 10, for experimental site description see Tab. 2.

Exper. site	Treatment	pH				
		Before	After1Y	After2Ys	After3Ys	After4Ys
Falken-SE	Control	5.9 *ab*	5.9	5.8	5.7	5.4
	MLSN	6.0 *b*	6.0	5.7	5.7	5.3
	SPF	5.8 *a*	5.7	5.7	5.7	5.4
	SLAN	6.0 *b*	6.0	5.8	5.7	5.4
	ANOVA p-value	0.057	0.111	0.438	0.807	0.898
	HSD (α=0.05)	**ns**	**ns**	**ns**	**ns**	**ns**
	HSD (α=0.10)	*0.1*				
Landvik-NO	Control	5.9	5.5	6.0	6.4	6.3
	MLSN	5.8	5.9	5.8	6.4	6.4
	SPF	6.0	6.1	5.9	6.3	6.4
	SLAN	5.9	5.7	5.8	6.3	6.4
	ANOVA p-value	0.128	0.274	0.273	0.632	0.324
	HSD (α=0.05)	**ns**	**ns**	**ns**	**ns**	**ns**
	HSD (α=0.10)					
Princen-NL	Control	6.3	6.3	6.4	6.7	6.6 *b*
	MLSN	6.2	6.3	6.4	6.7	6.5 *ab*
	SPF	6.3	6.3	6.2	6.7	6.5 *ab*
	SLAN	6.2	6.3	6.4	6.8	6.4 *a*
	ANOVA p-value	0.427	0.815	0.675	0.548	0.091
	HSD (α=0.05)	**ns**	**ns**	**ns**	**ns**	**ns**
	HSD (α=0.10)					*0.1*
Duete-DE	Control	6.6	7.1 *ab*	7.3 **b**	7.0	-
	MLSN	6.6	7.1 *ab*	7.3 **b**	6.9	-
	SPF	6.6	7.1 *b*	7.2 **ab**	6.9	-
	SLAN	6.7	6.9 *a*	7.1 **a**	6.9	-
	ANOVA p-value	0.880	0.079	0.011	0.665	-
	HSD (α=0.05)	**ns**	**ns**	**0.2**	**ns**	-
	HSD (α=0.10)		*0.2*			

Y =Year/Years

On the Jingshan-CN experimental site (initial soil pH > 8.0), SLAN treatment displayed significantly lower values (pH 7.3) than SPF and Control treatment (pH 7.6 and 7.7, respectively) at the end of the trial, but not compared to MLSN treatment (pH 7.5; Tab. 15). At the end of the trial considerable differences in soil pH did exist among treatments on this site.

Tab. 15: Influence of different P treatments on soil pH at Jingshan-CN (initial soil pH > 7.0). Before = before the trial started. Different letters indicate differences between treatments for each sampling date (HSD, α = 0.05 (bold) and 0.10 (italic), ns = not significant). For treatment description, see Tab. 10.

Exper. site	**Treatment**	**pH**				
		Before	After1Y	After2Ys	After3Ys	After4Ys
	Control	8.3	8.1	7.7	8.1	7.7 **b**
	MLSN	8.3	8.1	7.7	7.7	7.5 **ab**
	SPF	8.3	8.0	7.6	7.8	7.6 **b**
Jingshan-CN	SLAN	8.3	8.0	7.6	7.9	7.3 **a**
	ANOVA p-value	0.862	0.761	0.802	0.446	0.020
	HSD (α=0.05)	**ns**	**ns**	**ns**	**ns**	**0.4**
	HSD (α=0.10)					

Y =Year/Years

4.3 Turfgrass overall impression

Turfgrass overall impression was assessed with median ratings between 6.0 and 8.0 for all experimental sites regardless P treatment (Fig. 13). For each site, median overall impression ratings across all assessment dates were above the threshold for acceptable visual turfgrass quality (≥ 6.0; MORRIS 2004) but could at individual assessment dates degrade to a rating of 2.0. Highest individual rating values were registered with 9.0 at individual dates (Appx. 7).

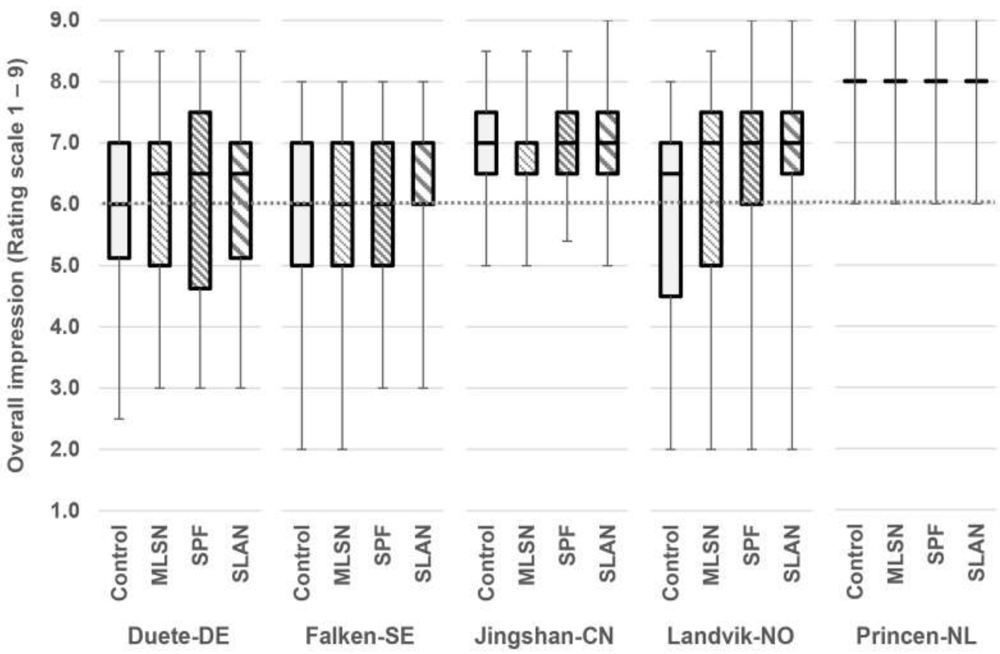


Fig. 13: Impact of different P treatments on overall impression (Rating scale 1 – 9) across all dates for each experimental site. For n, see Tab. 8. A rating of ≥ 6 is considered acceptable (MORRIS 2004; grey dashed line). Boxplot with median as vertical bold line inside the box, the ends of the box represent the upper and lower quartiles (Q3 - Q1 = interquartile range) and the two lines outside the box (whiskers) show highest and lowest rating values. For treatment description see Tab. 10, for experimental site description see Tab. 2.

Control treatment showed lower median ratings (6.0) than all other treatments (6.5) at Duete-DE, which was also the case at Landvik-NO (Control: 6.5, all others 7.0; Fig. 13). At Duete-DE the middle 50 % of the rating values for Control and SLAN treatments ranged between 5.1 (Q1) and 7.0 (Q3) with an interquartile range (IQR) of 1.9, while ratings on SPF treatment plots scattered even more (IQR 2.9). This was not the case at any other site. At Falken-SE and Landvik-NO, SLAN treatment had the smallest IQR (1.0) compared to all other treatments. On the *Fr* + *Ac* experimental green at Princen-NL, overall impression ratings did not show any variation among the treatments (IQR: 0.0), revealing a median rating of 8.0 for each treatment.

At Jingshan-CN, median overall impression rating across all assessment dates was 7.0 for all treatments (Fig. 13). During the 4-year trial period, median ratings increased for MLSN, SPF and SLAN treatment revealing significant differences between the years within each treatment (Tab. 16). MLSN treatment plots were evaluated with a value of 6.3 for the 1st trial year and with a significantly higher value of 7.0 at the end of trial (4th Year), while SPF treatment increased significantly from 6.5 to 7.8, and SLAN treatment from 6.3 to 8.0. The same increase in overall impression could be found at Duete DE, but not at any other site (Appx. 6).

Tab. 16: Mean overall impression (Rating scale 1 – 9) in response to different P treatments before the trial started and for each trial year at Duete-DE and Jingshan-CN. Mean ratings were calculated as median. For n in each trial year, see Tab. 8. Different letters indicate differences between the trial years for each P treatment (p-value < 0.05). For treatment description, see Tab. 10.

Exper. site	**Treatment**	**Overall impression (Rating scale 1 - 9)**					**Friedman rank test**
		Before[a]	1st Year	2nd Year	3rd Year	4th Year	p-value
Duete-DE	Control	2.5	5.5 **a**	6.0 **ab**	7.0 **b**	-	0.018
	MLSN	2.5	5.5 **a**	6.5 **ab**	7.0 **b**	-	0.022
	SPF	2.5	5.0 **a**	6.5 **ab**	7.5 **b**	-	0.018
	SLAN	2.5	5.5 **a**	6.5 **ab**	7.3 **b**	-	0.018
Jingshan-CN	Control	5.8	6.3	7.0	7.0	7.0	0.100
	MLSN	5.3	6.3 **a**	7.0 **ab**	7.0 **ab**	7.0 **b**	0.044
	SPF	5.0	6.5 **a**	7.0 **ab**	7.0 **ab**	7.8 **b**	0.010
	SLAN	5.3	6.3 **a**	7.0 **ab**	7.0 **ab**	8.0 **b**	0.010

[a] *Results reported at the first assessment date (Jingshan-CN: July 2017, Duete-DE: April 2018) before the trial started. Values not used for statistical analysis (Friedman test).*

Among the individual year, turfgrass overall impression ratings varied regardless of P treatment, often starting with the lowest rating values in spring (Appx. 7 and Appx. 8). Significant differences between the treatments could be determined for individual dates at some experimental sites (Appx. 7 and Appx. 8). At Jingshan-CN, MLSN and Control treatment showed significant lower ratings in June, August, and September in the 4th trial year compared to SLAN treatment, but not to SPF treatment (Tab. 17). A comparison with August, September, and October in 1st year showed that overall impression rating values did not differ significantly at that time, and were all in all lower (5.0 – 6.8), while in the 4th trial year the overall impression ratings ranged between 7.0 and 8.0.

Tab. 17: Overall impression (Rating scale 1 – 9) in response to different P treatments recorded monthly from August until November in the 1st trial year and from May until October in the 4th trial year at Jingshan-CN. Mean ratings as median from four plots per treatment. Different letters indicate differences between treatments (p-value < 0.05; ns = not significant). For treatment description, see Tab. 10.

Treatment	Overall impression (Rating scale 1 - 9)							
1st Year	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.
Control	-	-	-	-	5.8	6.0	6.8	6.3
MLSN	-	-	-	-	5.3	6.5	6.3	6.0
SPF	-	-	-	-	5.0	6.3	6.5	6.0
SLAN	-	-	-	-	5.3	6.3	6.5	6.3
Kruskal-Wallis rank test	**-**	**-**	**-**	**-**	**ns**	**ns**	**ns**	**ns**
p-value	-	-	-	-	0.374	0.826	0.791	1.000

Treatment								
4th Year	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.
Control	-	7.0	7.5 **ab**	7.5	7.0 **a**	7.0 **a**	7.0 **a**	-
MLSN	-	7.5	6.5 **a**	7.0	7.0 **a**	7.3 **ab**	7.5 **a**	-
SPF	-	7.5	8.0 **b**	7.5	7.3 **ab**	7.8 **ab**	7.8 **a**	-
SLAN	-	7.0	8.0 **b**	8.5	7.8 **b**	8.0 **b**	7.0 **a**	-
Kruskal-Wallis rank test	**-**	**ns**		**ns**				**-**
p-value	-	0.753	0.009	0.079	0.009	0.034	0.044	-

4.4 *Poa annua* coverage

In contrast to Jingshan-CN experimental green, which had 100 % *Agrostis stolonifera* coverage, the other four experimental greens revealed varying percentages of *Poa annua* encroachment during the trial. *Poa annua* coverage in response to the different P treatments did not show significant differences across all dates at any of these sites ($p > 0.05$; Tab. 18). Average percent of *Poa annua* ranged between 37.2 % (Control) and 38.3 % (SLAN) at Duete-DE, between 47.8 % (Control) and 50.7 % (SLAN) at Falken-SE, between 5.9 % (Control) and 12.1 % (SPF) at Landvik-NO, and between 6.1 % (Control) and 7.1 % (SPF) at Princen-NL. The *Fr* + *Ac.* putting green at Princen-NL had the lowest *Poa annua* percentage and *Agrostis stolonifera* putting green at Falken-SE the highest.

Before the trials started, *Poa annua* encroachment intensity was assessed in the experimental site order of Princen-NL (5.0 %; *Fr* + *Ac* putting green) < Landvik-NO (4.3 – 8.8 %) < Falken-SE (47.3 – 53.3 %), and Duete-DE (48.8 – 51.5 %; Tab. 18). The differences in initial *Poa annua* coverage between the P treatments were insignificant at Landvik-NO, Falken-SE, and

Duete-DE. On the sites initially less covered with *Poa annua* (< 10 %), Princen-NL and Landvik-NO, the different P treatments did not influence *Poa annua* growth significantly in any trial year, except in 4th year at Landvik-NO (p = 0.054, Tab. 18). In that year, no P application depressed *Poa annua* growth in the sward significantly to 3.3 % compared to SPF (9.4 %). MLSN and SLAN treatment had higher but insignificant coverage percentages (6.0 %, respectively) than Control treatment, and insignificant lower values than SPF treatment.

Tab. 18: Influence of different P treatments on *Poa annua* coverage (%) at all experimental sites, except Jingshan-CN (no *Poa annua* found; Duete-DE 3-year trial, all others four years). Average across all assessment dates of each individual year and across all assessment dates. For n, see Tab. 8. Before = first assessment before the trials started. Different letters indicate differences between treatments for each trial year or across all dates (Tukey contrasts, α = 0.05; ns = not significant). For treatment description see Tab. 10, for experimental site description see Tab. 2.

Exper. site	Treatment	*Poa annua* (%)					
		Before[a]	1st Year	2nd Year	3rd Year	4th Year	All years[c]
Duete-DE	Control	49.1	44.4	35.5	32.6	-	37.2
	MLSN	51.5	46.7	36.8	33.3	-	38.6
	SPF	48.8	45.4	38.2	32.2	-	38.3
	SLAN	50.5	45.7	36.3	33.8	-	38.3
	p-value	0.816[b]	0.764	0.213	0.183	-	0.274
	Tukey (α=0.05)	**ns**	**ns**	**ns**	**ns**	-	**ns**
Falken-SE	Control	47.3	48.2	48.4 **a**	47.1 **a**	47.5	47.8
	MLSN	50.0	50.3	47.9 **a**	47.9 **ab**	46.7	47.9
	SPF	49.0	49.7	49.0 **a**	50.1 **ab**	47.3	48.9
	SLAN	53.3	53.6	50.8 **b**	50.6 **b**	49.1	50.7
	p-value	0.195[b]	0.316	0.005	0.023	0.407	0.077
	Tukey (α=0.05)	**ns**	**ns**			**ns**	**ns**
Landvik-NO	Control	6.3	5.5	7.6	8.1	3.3 **a**	5.9
	MLSN	8.8	7.7	14.6	14.5	6.0 **ab**	10.4
	SPF	6.5	7.4	12.6	18.1	9.4 **b**	12.1
	SLAN	4.3	4.7	10.1	8.8	6.0 **ab**	7.3
	p-value	0.408[b]	0.620	0.154	0.179	0.054	0.066
	Tukey (α=0.05)	**ns**	**ns**	**ns**	**ns**		**ns**
Princen-NL	Control	5.0	2.7	2.5	8.9	8.2	6.1
	MLSN	5.0	2.6	2.8	11.1	6.5	6.3
	SPF	5.0	2.6	3.0	13.7	6.5	7.1
	SLAN	5.0	2.4	3.3	12.9	6.5	6.9
	p-value	-	0.972	0.445	0.462	0.950	0.803
	Tukey (α=0.05)	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**

[a] Poa annua registered at the first assessment date (Duete-DE = April, Falken-SE = July, Landvik-NO = June, Princen-NL = July). [b] Statistics: ANOVA and HSD (α=0.05). [c] Duete-DE 3-year trial, all others 4-year trials.

On the experimental sites with initially higher *Poa annua* coverage of ≈ 50 % (Falken-SE and Duete-DE), P treatments influenced *Poa annua* percentage differently (Tab. 18). At Falken-SE, the Control, MLSN, and SPF treatment plots showed significantly less *Poa annua* than

SLAN treatment plots in the 2nd trial year. In the 3rd trial year, there was only a significant difference between Control and SLAN treatment (47.1 and 50.6 %, respectively). At Duete-DE, the different P treatments did not have a significant effect on *Poa annua* growth but decreased the percent *Poa annua* coverage from the beginning to the end of trial regardless of treatment (Fig. 14). Falken-SE showed some significant differences between the treatments in individual months, especially in 2nd year (Appx. 9). In May, June, July, and August MLSN treatment plots had significantly less *Poa annua* ranging between 47 – 48 % compared to SLAN treatment plots (50 – 52 %).

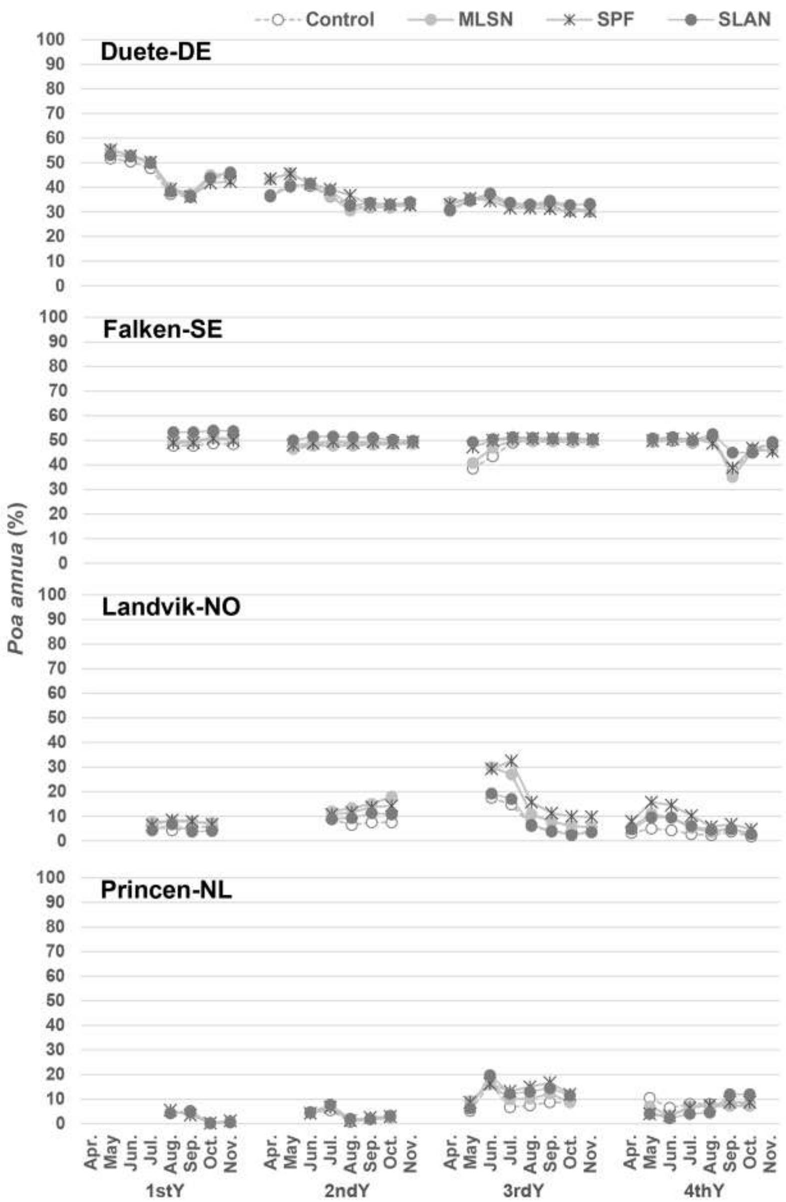


Fig. 14: ***Poa annua*** **coverage (%) in response to different P treatments at all experimental sites, except Jingshan-CN. Monthly average per treatment (n = 4) from April until November in the 1st trial year (1stY), in the 2nd trial year (2ndY), in the 3rd trial year (3rdY), and in the 4th trial year (4thY, except Duete-DE). Some dates missing due to experimental site related vegetation period. For treatment description see Tab. 10, for experimental site description see Tab. 2.**

4.5 Rooting depth

On the four *Agrostis stolonifera* putting greens, regardless of the different P treatments rooting depth varied in extension and pattern within each trial year and among the experimental sites (Fig. 15). At Duete-DE, the rooting depth was the lowest of all sites with < 100 mm revealing only small changes in rooting depth within each year, except of in the 2nd year with longer roots in early summer. Almost the same situation could be found at Landvik-NO but with a slight increase in rooting depth from the beginning to the end of trial. At Falken-SE and Jingshan-CN, rooting depth was > 100 mm with more variation within each year (Fig. 15).

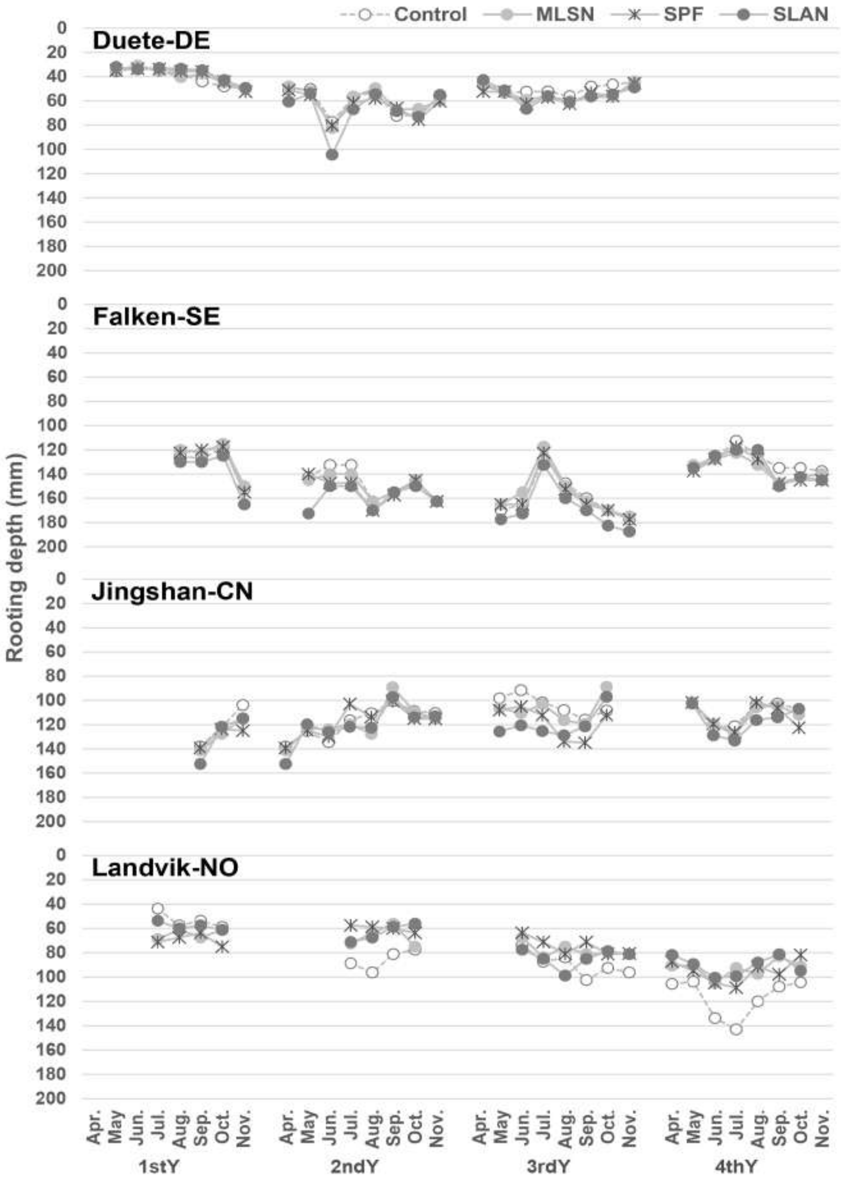


Fig. 15: Development in rooting depth (mm) in response to different P treatments at the four *Agrostis stolonifera* experimental greens. Monthly average per treatment (n = 4) from April until November in the 1st year of trial (1stY), in the 2nd year (2ndY), in the 3rd year (3rdY), and in the 4th year (4thY, except Duete-DE). Some dates are missing due to experimental site related vegetation period. For treatment description see Tab. 10, for experimental site description see Tab. 2.

On the *Fr* + *Ac* experimental green at Princen-NL, rooting depth was ≈ 70 – 130 mm (Fig. 16). In the 1st trial year rooting depth varied between ≈ 70 – 90 mm within the year regardless of P treatment, afterwards the differences between the months were up to 40 mm (Appx. 11).

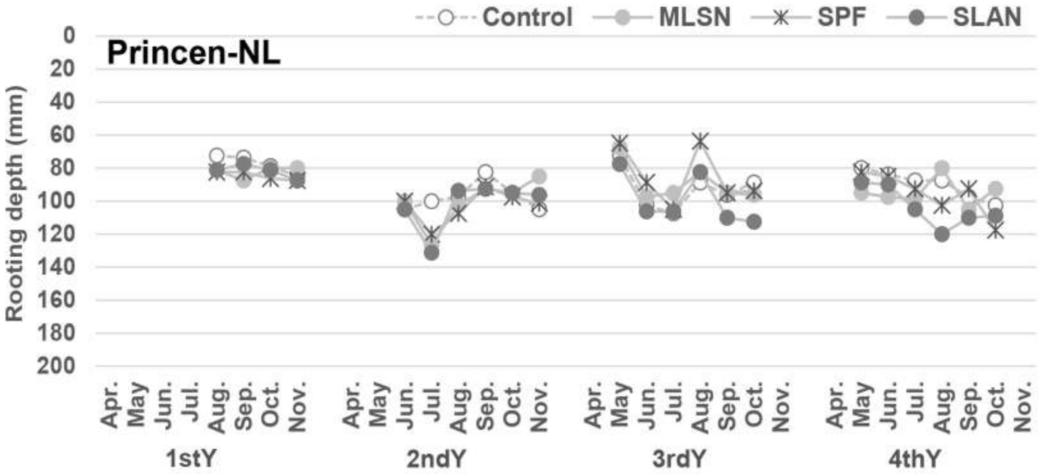


Fig. 16: Development in rooting depth (mm) in response to different P treatments on the *Fr* + *Ac* experimental green at Princen-NL. Monthly average per treatment (n = 4) from April until November in the 1st year of trial (1stY), in the 2nd year (2ndY), in the 3rd year (3rdY), and in the 4th year (4thY). Some dates are missing due to vegetation period. For treatment description, see Tab. 10.

Average rooting depth across all dates was not affected by the different treatments at any experimental site (p = > 0.05), except at Jingshan-CN (p = 0.04; Tab. 19). At this experimental site, no P application resulted in significantly shorter roots (111 mm) compared to SLAN treatment (121 mm). Rooting depth measured on MLSN and SPF plots was higher compared to Control plots and shorter compared to SLAN plots but not significantly (115 and 118 mm, respectively). MLSN and SPF did not significantly differ either.

In terms of the individual trial years, P treatments did not influence rooting depth neither on the *Agrostis stolonifera* experimental greens at Duete-DE and at Landvik-NO (Tab. 19), nor on the *Fr* + *Ac* experimental putting green at Princen-NL. There were no significant differences in rooting depth at Landvik-NO, but rooting depth measured in Control treatment plots was higher than for all other treatments in 2nd, 3rd, and especially in 4th trial year (p = 0.088, Tab. 19). At Falken-SE in the 3rd year of trial, MSLN treatment decreased rooting depth significantly to 156 mm compared to SLAN treatment (169 mm) but not to Control and SPF (160 mm, respectively). This was also the case at Jingshan-CN, except of that the Control (105 mm) and MLSN (108 mm) treatment revealed shorter roots than SPF (118 mm) and SLAN (120 mm). At the 4th trial year, rooting depth was also significantly different between Control (110 mm) and SLAN (117 mm) treatment but not compared to MLSN and SPF.

Tab. 19: Influence of different P treatments on rooting depth (mm) for each trial year and for all years at all experimental sites (Duete-DE 3-year trial, all other four years). Before = first assessment before the trial started. Different letters indicate differences between treatments for each trial year and across all measurement dates (Tukey contrasts, α = 0.05, ns = not significant). For treatment description see Tab. 10, for experimental site description see Tab. 2.

Exper. site	**Treatment**	**Rooting depth (mm)**					
		Before[a]	1st Year	2nd Year	3rd Year	4th Year	All years[c]
Duete-DE	Control	30	41	61	50	-	51
	MLSN	30	39	61	54	-	52
	SPF	28	39	64	55	-	53
	SLAN	27	37	67	55	-	54
	p-value	0.714[b]	0.110	0.168	0.349	-	0.518
	Tukey (α=0.05)	**ns**	**ns**	**ns**	**ns**	-	**ns**
Falken-SE	Control	130	131	148	160 **ab**	130	143
	MLSN	125	127	150	156 **a**	135	144
	SPF	125	129	153	160 **ab**	135	146
	SLAN	130	138	159	169 **b**	134	151
	p-value	0.834[b]	0.414	0.341	0.029	0.619	0.100
	Tukey (α=0.05)	**ns**	**ns**	**ns**		**ns**	**ns**
Jingshan-CN	Control	159	122	118	105 **a**	110 **a**	111 **a**
	MLSN	149	128	119	108 **a**	112 **ab**	115 **ab**
	SPF	142	130	118	118 **b**	113 **ab**	118 **ab**
	SLAN	157	130	121	120 **b**	117 **b**	121 **b**
	p-value	0.366[b]	0.273	0.715	0.012	0.034	0.037
	Tukey (α=0.05)	**ns**	**ns**	**ns**			
Landvik-NO	Control	50	53	86	89	117	91
	MLSN	78	65	67	78	93	78
	SPF	56	69	60	75	95	78
	SLAN	66	58	63	84	91	78
	p-value	0.536[b]	0.691	0.163	0.224	0.088	0.159
	Tukey (α=0.05)	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**
Princen-NL	Control	81	78	98	93	90	90
	MLSN	84	82	100	89	95	92
	SPF	86	85	103	85	95	93
	SLAN	88	82	102	99	104	98
	p-value	0.726[b]	0.195	0.724	0.079	0.159	0.095
	Tukey (α=0.05)	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**

[a] *Values measured at the first assessment date (Duete-DE = April, Falken-SE = July, Landvik-NO = June, Princen-NL = July).* [b] *Statistics: ANOVA and HSD (α=0.05).* [c] *Duete-DE 3-year trial, all others 4-year trials.*

An impact of the different P treatments on rooting depth at individual measurement dates was found for all experimental sites (Appx. 10 and Appx. 11). The differences were mostly insignificant, except in the 3rd trial year at Falken-SE and Jingshan-CN corresponding to the differences found across all measurement dates for that year (Tab. 20). In June, MSLN treatment led to significantly shorter roots (Falken-SE: 155 mm, Jingshan-CN: 92 mm) compared to SLAN treatment (Falken-SE: 173 mm; Jingshan-CN: 121 mm) on both sites. Control (92 mm) and SPF (105 mm) treatment decreased rooting depth compared to SLAN treatment only at Jingshan-CN but were insignificant among each other. The same situation was found in July, except of that MLSN and SPF treatment significantly differed in rooting depth. In August at Falken-SE, rooting depth on Control (148 mm), MLSN (150 mm), and SPF (153 mm) plots was significantly lower than on SLAN plots (160 mm). In comparison, the Jingshan-CN experimental site showed significant differences between Control (108 mm) and SLAN (129 mm) as well as SPF (134 mm) treatment. In October, the situation was almost the opposite as Control (108 mm) and SPF (112 mm) treatment had significantly longer roots than SLAN (97 mm) and MLN (89 mm) treatment. Significant differences in rooting depth in the same month could not be found at Falken-SE. In addition revealed the experimental green at Jingshan-CN significant differences in rooting depth in August, September, and October in the 4th trial year with longer roots in SLAN treatment plots than in MLSN plots (not significant in October; Appx. 10).

Tab. 20: Rooting depth (mm) measured monthly from April to November in the 3rd year of trial at Falken-SE and Jingshan-CN. Some dates are missing due to experimental site related vegetation period. Different letters denote significant differences between treatments for each measurement date (HSD, α = 0.05; ns = not significant). For treatment description see Tab. 10, for experimental site description see Tab. 2.

Exper. site	**Treatment**	**Rooting depth (mm)**							
		Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.
Falken-SE	Control	-	170	165 **ab**	128	148 **a**	160	170	178
	MLSN	-	165	155 **a**	118	150 **a**	163	170	175
	SPF	-	165	165 **ab**	123	153 **a**	165	170	178
	SLAN	-	178	173 **b**	133	160 **b**	170	183	188
	ANOVA p-value	-	0.294	0.061	0.216	0.004	0.240	0.341	0.110
	HSD (α=0.05)	**-**	**ns**	**16.9**	**ns**	**7.1**	**ns**	**ns**	**ns**
Jingshan-CN	Control	-	99	92 **a**	102 **a**	108 **a**	116	108 **c**	-
	MLSN	-	107	111 **b**	103 **a**	116 **ab**	120	89 **a**	-
	SPF	-	108	105 **b**	112 **b**	134 **b**	135	112 **c**	-
	SLAN	-	126	121 **c**	125 **c**	129 **b**	122	97 **b**	-
	ANOVA p-value	-	0.105	0.000	0.000	0.017	0.207	0.000	-
	HSD (α=0.05)	**-**	**ns**	**9.9**	**5.6**	**20.6**	**ns**	**4.2**	**-**

5 Discussion

Sustainable P fertilization on golf course putting greens must ensure to (a) minimize P fertilizer input to save this non-renewable resource, (b) decrease P losses by erosion and leaching, and (c) provide sufficient P availability for high turfgrass and playing quality. A recently conducted survey by GELERNTER et al. (2016) already documented an annual 53 % reduction in P use on US golf courses from 2006 to 2014 due to lower P rates, but also less fertilized acres and golf course closures. At the same time, no significant negative impact on turfgrass quality was reported. Regarding reduced P application reduction, the selected fertilization recommendation plays an important role. According to an overview by JORDAN-MEILLE et al. (2012) and other literature sources (Tab. 1), many different P fertilization recommendations exist for arable crops and were adopted or modified for putting green nutrition. However, there is little research on how useful these recommendations are to decrease P input on golf course putting greens and what influence such a reduction has on turfgrass quality. Two recommendations are currently of particular interest: the newly in the USA developed fertilization recommendation MLSN according to WOODS et al. (2014; 2016; 2020) and the Scandinavian SPF fertilization recommendation according to ERICSSON et al. (2015) and KVALBEIN and AAMLID (2016). These recommendations are assumed to decrease P fertilization compared to traditional SLAN recommendation according to CARROW et al. (2004a, b), while at the same time maintaining good turfgrass quality under different climate and management conditions. In the present SUSPHOS-project study, MSLN and SPF recommendations were tested against SLAN recommendation on five putting greens to get profound understanding of the short-term and long-term soil P and turfgrass quality response to reduced P fertilization.

On golf course putting greens, P interactions in soil (Chapter 2.1) and turfgrass P availability (Chapter 2.2) depend on climatic conditions, putting green construction, and soil chemical properties. The sward composition is also of interest because turfgrass species vary in e.g. P uptake efficiency according to LIU et al. (1995). Before discussing soil and turfgrass response to different P fertilization recommendations, it is therefore first necessary to evaluate whether the trials were carried out on comparable putting greens and under the same climate conditions at the five experimental sites. For a short overview of the most important site-specific characteristics, see Tab. 21. Climate conditions at Duete-DE and Falken-SE are quite similar with long-term average annual air temperature of ≈ 9 °C and long-term annual precipitation of ≈ 800 mm representing average conditions compared to the other sites (Tab. 2). The climate conditions at Princen-NL are comparable to those sites due to quite similar precipitation with slightly higher temperatures (10.9 °C). Jingshan-CN can be considered as warm (12 °C) with low precipitation (< 510 mm), Landvik-NO as cold (7.8 °C) with high precipitation (> 1400 mm).

Tab. 21: Selected descriptive characteristics of the five experimental sites. Exper. site = Experimental site; Character. = Characteristic; AIR TEMP = Long-term annual air temperature (°C); PCPN = Long-term average annual precipitation; PSC = Phosphorus Sorption Capacity; DPS = Degree of Phosphorus Saturation; N = Nitrogen; Ca = Calcium. Evaluation of the values: bold = high; grey = low.

Exper. site / Character.	Duete-DE	Falken-SE	Jingshan-CN	Landvik-NO	Princen-NL
Climate conditions					
AIR TEMP (°C)	9.1	9.0	**12.0**	7.8	10.9
PCPN (mm)	830	872	507	**1416**	834
Putting green construction	FLL K3	Push-up / USGA	USGA	USGA	USGA
Sown species	*Agrostis stolonifera*	*Agrostis stolonifera*	*Agrostis stolonifera*	*Agrostis stolonifera*	*Festuca rubra* + *Agrostis capillaris*
***Poa annua* coverage (%)**	**55**	**50**	0	10	5
Annual N rates ($g\ m^{-2}$)	18 – 27	19 – 25	10 – 12	12 – 25	3 – 6
Soil pH	6.7	6.0	**8.3**	5.9	6.3
Soil PO_4-P concentration ($mg\ kg^{-1}$ soil)	14 – 17	**33 – 37**	7 – 9	**25 – 29**	6 – 7
PSC ($mmol\ kg^{-1}$ soil)	4.60	6.72	**8.04**	6.41	4.26
DPS (%)	**36**	**37**	15	24	17
Ca ($cmol\ c^{+}\ kg^{-1}$ soil)	**2.30**	0.93	**4.60**	0.50	1.00

FLL = Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau e.V.;
USGA: United States Golf Association

The experimental putting greens can be categorized into four *Agrostis stolonifera* greens at Duete-DE, Jingshan-CN, Falken-SE, and Landvik-NO and into one *Festuca rubra* + *Agrostis capillaris* (*Fr* + *Ac*) putting green at Princen-NL differing in initial *Poa annua* coverage in the order Jingshan-CN (0 %) < Princen-NL (5 %), Landvik-NO (≈ 10 %) < Falken-SE (≈ 50 %) < Duete-DE (≈ 55 %). Most of the experimental greens were constructed according to USGA guidelines associated with a sandy-rootzone mixture and drainage layer (USGA 2018). The putting green at Falken-SE is also a USGA green but built on top of native soil. The initial soil PO_4-P concentrations on the *Agrostis stolonifera* greens at Jingshan-CN and Duete-DE ranged between 7 – 9 mg kg^{-1} soil and 14 – 17 mg kg^{-1} soil, respectively (Tab. 11). According to the P supply levels by CARROW et al. (2001) these initial values have to be considered as very low (0 – 12 mg kg^{-1} soil) and low (13 – 26 mg kg^{-1} soil), respectively. On the other two *Agrostis stolonifera* greens at Falken-SE and Landvik-NO, P levels can be interpreted as medium (27 – 54 mg kg^{-1} soil) according to CARROW et al. (2001). Accordingly, the *Agrostis stolonifera* experimental greens are to be classified into greens with low (Duete-DE, Jingshan-CN) and medium (Falken-SE, Landvik-NO) initial soil P, which corresponds to below and above MLSN threshold (18 mg kg^{-1} soil). The *Fr + Ac* green at Princen-NL had the lowest initial PO_4-P concentrations of 6 – 7 mg kg^{-1} soil (Tab. 12) compared to all greens, which can be evaluated as very low according to CARROW et al. (2001).

The ability of a soil or in this case the rootzone-mixture to fix the P applied to the reactive forms of Al and Fe is expressed by the PSC according to MAGUIRE et al. (2001) and SCHOUMANS (2000). Comparable PSC values for putting greens from previous studies are not present so that those values have to be evaluated among the experimental sites. On the *Agrostis stolonifera* greens with medium initial soil P, Falken-SE and Landvik-NO, the PSC of > 6 mmol kg^{-1} soil was medium. On the *Agrostis stolonifera* greens low in initial soil P, the PSC of > 8 mmol kg^{-1} soil was higher at Jingshan-CN compared to Falken-SE and Landvik-NO and lower at Duete-DE (< 5 mmol kg^{-1} soil; Tab. 4). At Duete-DE, this low PSC went along with a high DPS of 36 % revealing that a high proportion of the binding sites were already occupied, as the DPS is the ratio between accumulated P in soil and the PSC. Soils with a DPS of > 30 % are associated with an increased risk of P losses (DESMET et al. 1996; LEINWEBER et al. 1997; LOOKMAN et al. 1996). With 37 % the DPS was comparably high despite medium PSC at Falken-SE. A low DPS (15 and 24 %, respectively) along with a higher PSC was found at Jingshan-CN and Landvik-NO. The *Fr + Ac* green at Princen-NL showed a low PSC (4.26 mmol kg^{-1} soil) and low DPS (17 %). Initial soil pH ranged between 5.9 and 6.7 among all experimental sites. At Jingshan-CN, soil pH was 8.3 and clearly above optimum range of 6.0 – 6.5 according to AMELUNG (2018). At the same time, Ca (4.60 cmol c^+ kg^{-1} soil) makes up a high proportion of the CEC (6.10 cmol c^+ kg^{-1} soil) because of the calcareous sand used to build the green. In soils with high pH, P is increasingly bound to Ca instead of Al and Fe (AMELUNG 2018). The Ca proportion of the CEC on the other sites ranged in the order of Duete-DE > Princen-NL > Falken-SE > Landvik-NO (Tab. 4).

P rates according to SPF are based on the N fertilization. According to BÜRING (1989) annual N rates of 20 – 40 g m^{-2} (clippings removed) are common practice. Compared to this range the

N fertilization levels were similar or lower on the *Agrostis stolonifera* sites (9.9 – 27.0 g m^{-2}) and very low with annual N rates of 2.6 – 5.5 g m^{-2} on the *Fr* + *Ac* green at Princen-NL (Tab. 6). In summary, the five experimental sites have to be considered as different and clustering was only possible to a certain extent. However, it can be assumed that the experimental greens responded differently to the fertilizer recommendations.

MLSN and SLAN are both fertilization recommendations based on soil analysis but differ in the soil P concentration that is considered sufficient. MLSN recommends to maintain a soil PO_4-P concentration of > 18 mg kg^{-1} soil, which is two-thirds lower than for SLAN with > 54 mg kg^{-1} soil (Chapter 2.4). As expected, this resulted in less P fertilizer being applied over the entire trial period for MLSN recommendation compared to SLAN on all experimental sites. The total P amounts applied on the *Agrostis stolonifera* greens were 0.0 – 10.2 g P m^{-2} for MLSN, which was 70 – 100 % lower than those due to SLAN recommendation (21.9 – 32.2 g P m^{-2}, Fig. 7). On the *Fr* + *Ac* putting green at Princen-NL, a total P amount of 12.9 g P m^{-2} was applied according to MLSN recommendation. This P amount was comparable to the highest total P amounts for MLSN on the *Agrostis stolonifera* experimental sites. Nevertheless, it was still below the total P application due to SLAN recommendation, which turned out to be the highest application with 45.0 g P m^{-2} compared to all other sites (Fig. 7). For all experimental sites, SPF recommendation, which does not consider soil P concentration, reduced the total P amounts applied to 2.4 – 10.7 g P m^{-2}, which were lower than those according to SLAN. As SPF disregards soil P level and turf type described in NIBIO (2017), it was assumed that SPF recommendation would result in higher total P application compared to MLSN at all experimental greens. This assumption was confirmed for Duete-DE, Falken-SE, and Landvik-NO, but not on the other two putting greens. On the calcareous *Agrostis stolonifera* green at Jingshan-CN and the *Fr* + *Ac* putting green at Princen-NL, the SPF recommendation reduced total P application by ≈ 50 % (Jingshan-CN) and ≈ 80 % (Princen-NL) compared to MLSN (Fig. 7). These results indicate that both MLSN and SPF recommendations reduce long-term P use on putting greens compared to SLAN recommendation, but as expected due to experimental site characteristics, total P rates varied within the treatments between the greens.

With the decreasing total P application due to MLSN and SPF recommendations, average soil PO_4-P concentrations decreased significantly across all years compared to SLAN on each putting greens (Tab. 10). On the *Agrostis stolonifera* greens at Duete-DE, Falken-SE, and Landvik-NO, soil PO_4-P concentrations were 41 – 46 mg kg^{-1} soil for SLAN, whereas they were lower by a factor of 1.5 to 1.8 for MLSN (23 – 28 mg kg^{-1} soil) and SPF (27 – 31 mg kg^{-1} soil, Tab. 10), depending on the experimental site. Due to high total P application for SLAN, the differences in soil PO_4-P concentrations were even higher at Jingshan-CN (SLAN: 40 mg kg^{-1} soil; MLSN: 18 mg kg^{-1} soil; SPF: 16 mg kg^{-1} soil) and the *Fr* + *Ac* putting green Princen-NL (SLAN: 23 mg kg^{-1} soil; MLSN: 9 mg kg^{-1} soil; SPF 8 mg kg^{-1} soil, Tab. 10). Although in general, the MLSN and SPF recommendations reduced soil P concentration and total P rates compared to SLAN recommendation, these two recommendations do not seem to be suitable to decrease annual P rates lower than usual for common practice. Depending on the experimental site and trial year, annual P rates according to MLSN and SPF recommendation ranged between 0.0 – 4.0 g P m^{-2} y^{-1} (Fig. 7). Those P rates were quite similar to the standard requirements for normal growth of 2.9 g P m^{-2} y^{-1} according to THIEME-HACK (2018) or the recommended P rate of up to 10.0 g P m^{-2} y^{-1} by BÜRING (1989). In contrary, the annual P rates based on SLAN recommendation, which mainly ranged between > 5.0 g P m^{-2} y^{-1} and up to 14.8 g P m^{-2} y^{-1}, have to be considered as high (Fig. 7). Consequently, annual P rates decreased due to MLSN and SPF recommendation compared to SLAN on each experimental site. Like for the total P rates, annual rates also varied clearly within the treatments between the years and experimental greens. The reasons are to be expected in the different characteristics of the experimental sites and the relationship between P rate and P concentration in soil, especially for recommendations based on soil samples.

It is known that the P amount applied influences soil P concentration. At the same time, soil P concentration has a major influence on the P rates according to fertilization recommendations, such as MLSN and SLAN, which are based on soil P analysis and maintaining a certain P concentration in soil. The P rates are expected to decrease until they reach the threshold and then settle there. Thus, the P rate and the soil P concentration reciprocally influence each other. This is not the case, when using SPF recommendation, which calculates the P rate as 12 % of the applied N rate. Thus, the P rate depends on the N fertilization. These relationships were also determined in this study. At Jingshan-CN, the calcareous *Agrostis stolonifera* green with a very low initial soil P level, MLSN treatment resulted in almost doubling the soil PO_4-P concentrations in 1st year (16 mg kg^{-1} soil) and then in very slowly increasing values reaching MLSN threshold first after the 4th trial year (24 mg kg^{-1} soil, Fig. 10). This indicates that reducing P rates due to MLSN recommendation might not be appropriate to supply P sufficiently on such a putting green. As PO_4-P concentrations increased only slowly, annual P rates decreased only slightly from 3.8 to 1.9 g m^{-2} y^{-1} from the beginning to the end of the trial. Due to the highest P rates, fertilization according to SLAN recommendation increased PO_4-P concentrations from 8 mg kg^{-1} soil (before trial) to 51 mg kg^{-1} soil (after the 4th year) above MLSN threshold but still below SLAN threshold (Fig. 10). Thus, for both recommendations based on soil samples there was a gap - small for MLSN and larger for SLAN - between the present soil PO_4-P concentration and the calculated concentration to remain after the vegetation period (MLSN: 18 mg kg^{-1} soil and SLAN: 54 mg kg^{-1} soil, respectively).

Possible reasons might be (a) higher plant P uptake as predicted, (b) the soil P extraction method used and (c) P losses due to leaching. In this study, P uptake was calculated corresponding to SPF recommendation as 12 % of the N input according to ERICSSON et al. (2015) and KUSSOW et al. (2012). A significant higher plant P uptake than calculated, seems to be unlikely, as PO_4-P concentration for SPF treatment increased by 7 mg kg^{-1} soil in 1st year and was then quite constant. On the other hand, no P application resulted in constant or even slightly increasing soil PO_4-P concentrations during trial. This allows the conclusion that a certain amount of P might be released from the soil, what might have influenced the real P uptake. Previous studies by NUS et al. (1993) have documented in a 5-year study that *Poa pratensis* (Kentucky bluegrass) increased the P concentration in clippings under increasing P supply of up 25.8 g m^{-2} y^{-1}. Whether this was the case at Jingshan-CN cannot be validated, as clipping analysis and biomass yields are missing.

According to NEYROUD and LISCHER (2003), WUENSCHER et al. (2016) and MÜLLER-BECK and LAWSON (2017) different P extraction methods lead to different results for soil P concentrations. This is due to different extraction mechanisms and extracted soil P pools (WUENSCHER et al. 2016). Accordingly, the present PO_4-P results might indicate that soil P extraction with Mehlich-3 underestimates soil P levels in calcareous soils. FRANK et al. (1998) and SIMS (2000) describe the method as suitable for most soils as it extracts P bonded to Ca, Al, and Fe, while other studies recommend the Olsen extracting method according to OLSEN et al. (1954) for calcareous soils (ZORN and KRAUSE 1999). However, both methods do not analyze the complete P pool in soil. Thus, the gap between expected and measured soil P level might rather not be caused by the extraction methods but by the calculation of the P rates. The methods might only be better or worse suited to determine the plant available P. However, MLSN and SLAN sufficient levels are probably not valid for P extracted by Olsen, although Olsen and Mehlich-3 are highly correlated according to EBELING et al. (2008).

As reported in a review by SOLDAT and PETROVIC (2008), P leaching is a relevant loss process on golf courses. Although, over many years the general opinion was the contrary as stated for example by GUERTAL (2006). At Jingshan-CN, leaching was probably the main reason why the soil PO_4-P concentration was lower than expected based on recommendation thresholds. However, this cannot be completely answered because studies from lysimeters are lacking. Nevertheless, USGA golf greens, like the one at Jingshan-CN, are designed to drain rain or irrigation water, and thus the nutrients dissolved in it, as quickly as possible. According to the USGA (2018) specification, the infiltration rate defined as Saturated Hydraulic Conductivity should be ≥ 150 mm $hour^{-1}$. Therefore, it is likely that the applied water-soluble P in this trial might be rapidly translocated to deeper layers in the rootzone-mixture and finally to the drainage. It is probably no longer detected by soil sampling in a depth of 0 – 20 cm as in this trial. Depending on the conditions right after P fertilization, the applied P might not have enough time to bind to the soil due to the high infiltration rate on USGA greens. This might be the reason why soil PO_4-P concentrations only increased slowly over time, especially for SLAN recommendation. However, information about precipitation and irrigation amounts are missing.

The high PSC and low DPS at Jingshan-CN initially seemed to ensure good P sorption (Tab. 4). However, due to the high soil pH of 8.3, the PSC might not be a convincing criterion. In soils with high pH, P is adsorbed more likely to Ca according to KREUSER et al. (2012). Thus, the applied P probably rather formed complexes with Ca, as the nutrient's concentration was high (Tab. 4), than was bonded to Al and Fe oxides. An interesting observation was that since soil pH decreased during trial to pH < 7.7 (Fig. 12), PO_4-P increased in the Control treatment indicating an improvement in P sorption to Al and Fe. In summary, recommendations based on soil analysis might not be convincing due to possible P losses for such putting greens. For sustainable P application, it is worth to consider, whether the SPF recommendation might be more appropriate to reduce P application. At Jingshan-CN, the total P rates were twice as low for SPF compared to MLSN and even more compared to SLAN (Fig. 7).

At Duete-DE, SPF recommendation caused higher P rates (Fig. 7), although this *Agrostis stolonifera* green had low initial soil P levels similar to Jingshan-CN. Due to the fast increase in PO_4-P concentration above MLSN threshold after the first year (23 mg kg^{-1} soil, Fig. 10), MLSN treatment resulted in the lowest total P rates compared to SPF < SLAN. Only in the 1st trial year, annual P rates for MLSN were higher (4.0 g m^{-2}) compared to SPF (2.7 g m^{-2}; Fig. 7) because soil PO_4-P was below MLSN threshold. Afterwards the P rates were on a certain but lower level. As expected, SLAN recommendation resulted in the highest annual P rates (up to 14.8 g m^{-2}) and highest soil PO_4-P concentrations increasing over time, although not reaching SLAN threshold similar to Jingshan-CN experimental site. In contrast to Jingshan-CN, Duete-DE had initially low PSC and high DPS (36%; Tab. 4). According to DESMET et al. (1996) DPS > 30 % indicates a higher risk of P losses. In conclusion, on putting greens like Duete-DE, such high P rates due to SLAN recommendation will cause certain P amounts to get lost because the soil cannot sorb more P. This will probably not be the case for MLSN recommendation, as in this trial there was almost no gap between the determined soil PO_4-P and the MLSN threshold. Except in 1st year, after switching to MLSN, the P rate might be too high due to the low PSC (Fig. 7). SPF recommendation will be a better choice to reduce P application than SLAN but probably not compared to MLSN depending on the N fertilization level. This site also demonstrated that P increasingly binds to Ca, when pH increases (Fig. 10 and Fig. 12).

On the *Agrostis stolonifera* greens with initial medium soil P levels above MLSN threshold, Falken-SE and Landvik-NO, soil PO_4-P concentrations in response to MLSN recommendation were expected to decrease during trial. At Falken-SE, PO_4-P concentrations decreased from 37 to 29 mg kg^{-1} soil (MLSN) until the end of the trial, but were still above MLSN threshold (Fig. 10). This resulted in no P application at all due to MLSN recommendation explaining why SPF recommendation would have significantly higher P rates on such greens. Due to the higher PSC on this green (Tab. 4), soil PO_4-P concentrations were constant for SPF recommendation (≈ 30 mg kg^{-1} soil) and increased for SLAN treatment from 33 (before trial) to 57 mg kg^{-1} soil (after 3rd year; Fig. 10). Subsequently the soil appeared to retain P by Al and Fe oxides, but since it is essential for sustainable P nutrition to avoid P losses according to BELL (2011) and SCHOLZ et al. (2014), this cannot be recommended. Especially, as the DPS was > 30 % already before the trial started. Special was, that in the last year of trial soil PO_4-P concentration decreased in all treatments, probably caused by the breakdown of the irrigation (Chapter 3.2).

At Landvik-NO, the P rates directly affected soil PO_4-P concentrations and vice versa, probably due similar PSC and lower DPS compared to Falken-SE. In most cases, P was not or only in low rates applied due to MLSN recommendation, as P levels were slightly above the MLSN threshold (20 – 29 mg kg^{-1} soil; Fig. 10). Thus, for such a putting green the MLSN recommendation seems to a good choice to reduce P fertilization, especially as the soil pH was in optimum range for P availability. The higher P rates due to SPF treatment increased soil PO_4-P slightly from 25 to 38 mg kg^{-1} soil (Fig. 10) revealing a certain P retention in soil. The increase in soil PO_4-P concentration due to SLAN treatment, even if slowly, underlines this conclusion (Fig. 10). For sand-based putting greens, previous studies have proven considerable P losses with runoff processes e.g. RICE and HORGAN (2010). Due to high precipitation at Landvik-NO (Tab. 2), it is not useful to increase P rates higher than necessary.

Compared to the four *Agrostis stolonifera* greens, the *Fr* + *Ac* green at Princen-NL had the lowest initial soil PO_4-P concentrations (≈ 7 mg kg^{-1} soil; Tab. 12). Soil PO_4-P concentrations due to MLSN recommendation varied between the trial years, but never reached MLSN threshold with values of 7 – 10 mg kg^{-1} soil. At the same time, this effect caused consistent P rates of 2.4 – 3.6 g m^{-2} y^{-1}, significantly higher than those rates for SPF (0.3 – 0.7 g m^{-2} y^{-1}; Tab. 7). The very low N fertilization level < 6.0 g m^{-2} y^{-1} magnified the differences in P rates. SLAN recommendation increased soil PO_4-P concentrations from 6 to 30 mg kg^{-1} soil from the beginning to the end of the trial. Thus, this site showed a comparable picture to the experimental site at Jingshan-CN site. At Princen-NL, however, it can also be assumed that the differences between target soil PO_4-P concentrations and analyzed concentration were probably caused by P losses. Compared to the calcareous sand at Jingshan-CN, P sorption to Ca is not to be assumed due to low Ca in soil (Tab. 4) and a soil pH of 6.2 – 6.7 (Tab. 14). In addition, the PSC was as low as for Duete-DE. Thus, on an extensive putting green like Princen-NL, SPF recommendation seems to be best suitable to reduce P rates and recommendations based on soil sampling might provide unnecessarily high rates.

According to BELL (2001), low soil P concentrations are usually not the reason why P deficiency occurs in turfgrass swards. It is more likely caused by insufficient P availability. As shown, soil pH plays an important role for soil P availability. Inappropriate soil pH is closely associated with insufficient P supply as a too low pH (< 5.5) or too high pH (> 7.5) limits P availability (CARROW et al. 2001). The question remains to what extent the different fertilization recommendations influenced soil pH in this study. It was not found that soil pH did not respond to the different P treatments in general, except on the *Agrostis stolonifera* green at Duete-DE. At this experimental site, no P application showed a significantly higher soil pH of 7.1 compared to SLAN recommendation with 7.0 (Tab. 13). Nevertheless, this deviation of 0.1 pH units seems to be negligible in practice. It should rather be kept in mind that when considering the mean pH value, pH changes between years might remain unnoticed. In this study, only few significant differences between the P treatments could be found in individual years for each experimental site (Tab. 14 and Tab. 15). Due to the use of triple phosphate ($Ca(H_2PO_4)$), which is generally considered to have an acidic effect in the soil (TROTT 2008), it was assumed that the soil pH would be higher due to less or no P application for MLSN, SPF or Control treatment compared to higher P rates due to SLAN. This effect was confirmed in the 1st and 2nd trial year at Duete-DE. Soil pH was significantly (10 % and 5 % level, respectively) higher by 0.2 pH units, when P was not applied (Control: pH 7.3) compared to SLAN recommendation (pH 7.1). On the *Fr* + *Ac* green at Princen-NL, significant 0.2 pH units differences (10 % significant level) were first observed in the last trial year despite highest P rates for SLAN recommendation compared to all other sites. This might indicate a high buffering capacity in the soil or that other management factors played a more important role (e.g. irrigation with water high in pH). The green at Jingshan-CN showed the highest response to P fertilization on soil pH, as no P fertilization had a 0.4 pH units higher soil pH compared to SLAN after the last trial year. This was not expected, since triple phosphate was supposed to have a pH increasing effect in soils with wide Ca : P ratios according to TROTT (2008). Compared to all sites, Jingshan-CN had the highest CEC dominated by Ca but a low initial P level (Tab. 4 and Tab. 11), which should at least explain the delayed pH differences. Why the soil pH in response to no P fertilization was higher than for SLAN, could not be clarified.

These results show that MSLN and SPF recommendations compared to SLAN reduced long-term and short-term P application on the putting greens and kept soil PO_4-P concentrations at a lower level, but did not prevent P losses with high probability. The general influence on soil pH was limited. Nevertheless, noteworthy differences between the putting greens were found, indicating that the putting green characteristics, e.g. putting green construction, soil, climate, and maintenance practices, influence the response to the different P fertilization recommendations. Additionally, although not expected, none of the tested P recommendations enabled sufficient P supply considering SLAN threshold (Fig. 10 and Fig. 11). Using MLSN threshold, all treatments except the unfertilized Control were classified sufficient at Duete-DE, Landvik-NO, and Falken-SE. At Jingshan-CN and Princen-NL, mainly the SLAN recommendation revealed soil PO_4-P concentrations above MLSN threshold. However, based on this evaluation it cannot adequately predicted, whether the reduced P application due to MLSN and SPF recommendations ensured sufficient P supply on all putting greens. In order to answer this question, turfgrass quality in response to P fertilization has to be evaluated, as P availability has a considerable influence according to CHRISTIANS et al. (1979).

Acceptable turfgrass quality is expressed by visual overall impression ratings ≥ 6.0 according to MORRIS (2004). In this study, the median ratings across all trial years ranged between 6.0 and 8.0 regardless of P application on all experimental sites (Fig. 13). Consequently, visual turfgrass quality was high, even when P was not applied. This indicates that the P rates applied and/or the soil PO_4-P concentrations were sufficient to meet turfgrass quality requirements. Regarding P rates, JOHNSON et al. (2003) have shown that P rates of 2.8 – 11.0 g m^{-2} y^{-1} were sufficient for acceptable turfgrass quality for a calcareous sand-based *Agrostis stolonifera* putting green in the western USA. Similar P rates of 1.2 – 13.7 g P m^{-2} y^{-1} were applied based on MLSN, SPF, and SLAN recommendation (Fig. 7) on the comparable constructed green at Jingshan-CN resulting in mean overall impression ratings of 7.0 (Fig. 13) and thus good visual turfgrass quality. The study by JOHNSON et al. (2003) also pointed out that reducing P application to 0.6 g m^{-2} y^{-1} worsened visual turfgrass quality. This could not be verified in the present trial because the annual P rates were not that low according to MLSN, SPF, or SLAN recommendation at Jingshan-CN (Fig. 7). Nevertheless, there was a tendency that no P application over several years may reduce visual turfgrass quality on calcareous sand-based putting greens. The median overall impression was rated 7.0 for no P application, for SLAN recommendation 8.0 in the last trial year (Tab. 16). Whether or not these differences were significant, could not be computed based on the ordinal-scaled data. However, significant differences in June (Control: 7.0; SLAN: 8.0) and in August (Control: 7.0; SLAN: 7.8; Appx. 7) the same year allow this assumption. In general, all ratings - even if lower - could still be considered as good turfgrass quality.

At Falken-SE and Landvik-NO an acceptable visual turfgrass quality (ratings ≥ 6.0) was expected because soil PO_4-P concentrations for MLSN, SPF, and Control treatment were continuously above MLSN threshold (Fig. 10). Poorer turfgrass quality was assumed at Duete-DE, where soil PO_4-P concentrations fell below MLSN threshold after two years of trial due to no P application (Fig. 10). At Jingshan-CN and Princen-NL, soil PO_4-P concentrations for MLSN, SPF, and Control treatment were continuously below MLSN threshold (except at Jingshan-CN for MLSN and SPF after the 4th trial year) leading to the same expectation as for Duete-DE (Fig. 10 and Fig. 11). The fact that the turfgrass swards revealed high overall impression ratings, thus low soil PO_4-P concentrations below MLSN threshold, indicates that even lower soil P levels and/or P rates might be appropriate for sufficient turfgrass P fertilization. A study by KREUSER et al. (2012) on a sand-based *Agrostis stolonifera* green points in the same direction. It suggests critical points for visual turfgrass quality ranging between 6 and 11 mg P kg^{-1} soil (Mehlich-3). Thus, those critical points were even lower than MLSN threshold of > 18 mg kg^{-1} soil but might be not completely comparable as soil samples according to KREUSER et al. (2012) were taken to a depth of 0 – 8 cm (SUSPHOS-project: 0 – 20 cm) and soil P measurement was done by ICP-OES instead of spectrophotometry. However, on the *Agrostis stolonifera* green at Jingshan-CN no P application resulted in soil PO_4-P concentrations of 7 – 11 mg kg^{-1} soil quite similar to the critical points along with acceptable visual turfgrass quality (≥ 6.0). This might indicate that even lower soil PO_4-P concentrations than MLSN threshold are sufficient for turfgrass P nutrition. On the other hand, visual turfgrass quality was improved, when P was applied regardless of recommendation, at Jingshan-CN (Tab. 17). These critical soil P points proposed by KREUSER et al. (2012) could also be confirmed by the results at Princen-NL. The *Fr* + *Ac* putting green responded with a high mean overall impression rating of 7.0 (Fig. 13) to low soil PO_4-P concentrations of 7 – 12 mg kg^{-1} soil (Tab. 12). This indicates that very low P levels might be particularly suitable for extensive *Fr* + *Ac* putting greens, especially because of the good visual turfgrass quality, even though when no P was applied. This agrees to findings by CHANG et al. (2014), which showed that *Festuca rubra* had lower critical P levels than *Agrostis stolonifera* during establishment from seeds. Nonetheless, the results of the current study do not allow the conclusion to completely stop P fertilization on putting greens because soil PO_4-P decreased, even if slowly, over time on most of the experimental greens (Fig. 10).

As mentioned, median overall impression ratings across all years did not differ much in response to P fertilization on any experimental site. On the *Agrostis stolonifera* greens at Jingshan-CN and Duete-DE, however, an improvement of visual turfgrass quality was observed, as the overall impression ratings increased significantly within each P treatment over time (Tab. 16). At Jingshan-CN, each P treatment regardless of recommendation had up to 1.7 units higher rating values at the end of trial than after the 1st year. This might be explained by a better P availability due to constantly P application and increase in soil PO_4-P concentration for MLSN, SPF (even though below MLSN threshold), and SLAN recommendation (Fig. 10). In contrast, at Duete-DE, this effect was likely due to changes in turfgrass composition. *Poa annua* coverage decreased from ≈ 50 % to 30 % regardless of the P treatment (Fig. 14 and Tab. 18). Accordingly, the putting green probably appeared more uniform due to higher turfgrass density and darker color, resulting in significantly higher overall impression ratings at the end of the 3-year trial. This influence on visual ratings by changes in turfgrass composition should be considered, when using rating values to assess turfgrass quality. Another problem is that overall impression ratings are subjective. Thus, it was not useful to compare the ratings between the experimental sites because different persons assessed the rating values. For future trials, handheld optical sensor measurements or remote sensing could be a reliable alternative to obtain objective turfgrass responses to P application. BELL et al. (2009) successfully tested handheld optical sensor measurements (Greenseeker) to estimate turfgrass quality, and previous studies by KRUSE et al. (2005) found that remote sensing was suitable to identify P deficiencies in *Agrostis stolonifera* swards.

Poa annua growth does not only affect the visual turfgrass quality of a putting green, as studied in this trial, but also the playing quality. According to NOLAN (2015) a high coverage with *Poa annua* on *Agrostis stolonifera* putting greens lead to a softer surface, an increased ball bounce according to TOLER (2007), and a reduced ball roll distance (green speed). Therefore, management practices that suppress *Poa annua* are of great interest to ensure high playing quality. In this context, low P supply can be beneficial and reduce *Poa annua* in the sward according to HÄHNDEL (2019). In contrast, a very high P supply promotes *Poa annua* according to several studies, e.g. GUERTAL and MC ELROY (2018). However, the trials conducted in the SUSPHOS-project did not convincingly confirm any of these theories. Regardless of the P rates due to the fertilization recommendations, no significant differences (5 % level) in average *Poa annua* coverage across all years were assessed on the *Agrostis stolonifera* greens at Duete-DE, Falken-SE, and Landvik-NO (Tab. 18). Thus, neither did less P fertilization reduce *Poa annua*, nor did high P rates favor the undesirable grass in general. Nevertheless, no P application due to Control and MLSN treatment, as well as lower P rates for SPF treatment resulted in 2 – 3 % less *Poa annua* coverage in 2nd trial year (significantly) and 3rd trial year (insignificantly for MLSN and SPF) compared to SLAN at Falken-SE. This is in agreement with the suppressing effect of no P application described in a 2-year study by RALEY et al. (2013). It was investigated that 0.0 g P m^{-2} y^{-1} resulted in a 2 % decline of *Poa annua* coverage, whereas P rates ≥ 4.3 g P m^{-2} y^{-1} enhanced *Poa annua* encroachment by 2.9 to 6.8 % on a 2-year-old *Agrostis stolonifera* green. Furthermore, these results explain why significant differences were found only in the 2nd trial year on the putting green at Falken-SE. In 2nd year, the P rates of the Control, MLSN and SPF treatments were below 4.3 g P m^{-2} y^{-1} and for the SLAN treatment with 7.0 g P m^{-2} y^{-1} clearly above (Fig. 7). In the 3rd year of trial, the P rates for all treatments were below 4.3 g m^{-2} y^{-1} and differed barely (2.9 g m^{-2} y^{-1} and 2.8 g m^{-2} y^{-1} for SPF and SLAN, respectively). Nevertheless, on a putting green with initial 50 % *Poa annua* a reduction of 2 – 3 % is likely irrelevant for playing quality. The situation is different on a green like Landvik-NO. For the 4th trial year, the results revealed significant differences of 6 % in *Poa annua* coverage between no P application and SPF recommendation, which had the highest P rate (2.2 g m^{-2} y^{-1}). While the Control treatment had 3 % *Poa annua* coverage, SPF treatment had 9 % (Tab. 18). As *Poa annua* growth at Landvik-NO was generally low, this difference would almost certainly have had an impact on turfgrass playability.

In addition to critical P rates, RALEY et al. (2013) proposed a threshold of > 12.9 mg kg^{-1} soil (Mehlich-3) associated with *Poa annua* encroachment, which could not be confirmed at any of the current experimental sites. RALEY et al. (2013) also concluded that soil test P may not be a good indicator of *Poa annua* encroachment because soil P concentrations (Mehlich-3) correlated with *Poa annua* growth in only one year of this 2-year trial. Also in the present trials, no correlation between soil PO_4-P concentrations and *Poa annua* could be found. Nonetheless, another interesting observation regarding *Poa annua* growth was made at Duete-DE. On this experimental site, the unusually warm weather conditions during trial and subsequent overseeding with *Agrostis stolonifera* seem to have had a significantly stronger effect on *Poa annua* than P fertilization. Regardless of P application *Poa annua* covered only ≈ 30 % of the sward at the end of the trial, which was significantly less compared to ≈ 51 % at the beginning (Fig. 14). According to VARGAS (1994) *Poa annua* is known to be sensitive to high temperatures and limited water supply, which was obviously the case. In addition, the course manager recorded dry patches and insufficient irrigation in 2nd year, which resulted in overseeding with *Agrostis stolonifera* according to common practice.

Another important criteria for turfgrass quality is rooting depth, as it has an influence on the tolerance to drought and on shear strength for high playing quality according to LYONS et al. (2008). Rooting depth response to P fertilization is discussed controversially in several studies. On the one hand, P is important for root growth, mentioned by literature sources, such as MARSCHNER and RENGEL (2012). On the other hand, it is known that lower P rates or P fertilizer that is placed further away from the roots, stimulates root growth (LYONS et al. 2008). Due to varying P rates and different soil PO_4-P concentrations on all experimental sites, significant differences in rooting depth were expected in the current study. However, the results rarely showed significant differences, only at Jingshan-CN for the 3rd and 4th trial year, as well as across all years, and at Falken-SE in the 3rd trial year (Tab. 19). This was mainly due to the high distribution of the subsamples and highly variable mean plot values related to each treatment. To solve this problem, more samples should have been taken.

The inconsistent influence of P application on root growth could be confirmed in parts in the present study. At Jingshan-CN, the highest P rate due to SLAN recommendation significantly increased average rooting depth to 121 mm compared to no P application (111 mm) but insignificantly to MLSN (115 mm) and SPF (118 mm) recommendation (Tab. 19). The opposite was the case at Landvik-NO, where no P application resulted in the longest roots (91 mm) compared to MLSN, SPF and SLAN recommendation (78 mm). However, the differences were insignificant. A possible explanation, why the two *Agrostis stolonifera* experimental sites showed contrary effects on P application could be due to their different soil properties. The calcareous green at Jingshan-CN had a higher PSC, a higher soil pH > 7.5, and soil PO_4-P concentrations mostly below MLSN threshold compared to the green at Landvik-NO. Thus, the application of higher P rates increased plant available soil P associated with increasing PO_4-P concentrations at Jingshan-CN (Tab. 11), promoting root growth. At Landvik-NO, soil PO_4-P concentrations were already above MLSN threshold before the trial started, thus root growth seems to be stimulated by less or no P application in agreement to LYONS et al. (2008). In summary, reduced P application due to MLSN or SPF recommendation might lead to lower or higher rooting depth depending on the putting green characteristics.

Regardless of P application, this study also showed that rooting depth varies between putting greens. On the *Agrostis stolonifera* putting greens, the average rooting depth across all trial years ranged between 51 – 151 mm in the order Duete-DE < Landvik-NO < Jingshan-CN, and Falken-SE (Tab. 19). One reason could be the turfgrass composition as *Poa annua* has shorter roots compared to *Agrostis stolonifera* (TURGEON 2012). At Duete-DE, this explanation seems to be convincing, as rooting depth increased during trial and *Poa annua* decreased (Fig. 14 and Fig. 15). Nevertheless, turfgrass composition cannot be the only reason. Falken-SE, the experimental site with the highest coverage of *Poa annua*, had the highest average rooting depth (Tab. 19). It is also of interest that Jingshan-CN had the second longest roots, while at the same time the lowest soil PO_4-P concentrations for all *Agrostis stolonifera* greens. At Duete-DE, the situation was the opposite. Thus, other factors appear to have a greater influence on rooting depth than P fertilization. One might be soil compaction. The highest soil bulk density compared to all experimental sites at Duete-DE (1.56 g cm^{-3}; Tab. 3) might indicate that this green tends to be more compact und thus affects root growth. If considerable soil compaction was present, was not assessed, but could have been clarified using a penetrometer. On the *Fr + Ac* putting green at Princen-NL, the noticed changes in rooting depth between the trial years were rather to explain by the climate conditions (e.g. hot summers) and management practices (e.g. overseeding, irrigation). Unlike, it could not be confirmed that turfgrass under high temperatures in summer responds positively to higher P supply as CARROW et al. (2001) proposed. Thus, lower P rates due to MLSN and SPF do not seem not to be disadvantageous. However, it could be of interest to apply the P fertilizer adapted to the season in individual years, as i.g. rooting depth could be improved by higher P rates due to SLAN treatment in June, July, and August at Falken-SE or Jingshan-CN in a range of 10 – 20 mm. However, it is not known what consequence this would have for nutrient uptake.

For practical putting green P fertilization, it can be concluded that MLSN and SPF recommendations are appropriate to reduce P input compared to SLAN fertilization having no impact on turfgrass quality. This will minimize P fertilizer input and save this non-renewable resource. Nevertheless, this study has shown that different recommendations might be more suitable than others for different putting greens. For sand-based *Agrostis stolonifera* putting greens, SLAN recommendation seems to be inappropriate. It caused unnecessary high P rates that did not improve visual turfgrass quality but led to higher soil PO_4-P concentrations, and thus increased the risk of environmentally harmful P losses. Conversely, reduced P rates and soil PO_4-P concentrations due to MLSN recommendations are suitable to ensure good visual turfgrass quality under a wide range of climate and management conditions. Nevertheless, fertilization according to MLSN recommendation can also lead to too high P rates, if the soil cannot retain P and thus the MLSN threshold is not reached. For sand-based *Fr* + *Ac* putting greens with extensive N fertilization, soil PO_4-P concentrations might even decrease to 7 mg kg^{-1} soil (Mehlich-3) without any negative impact on visual turfgrass quality. In contrast, calcareous sand-based putting greens with high soil pH > 7.5 are more sensitive to too low PO_4-P concentrations (< 18 mg kg^{-1} soil; Mehlich-3) and may be negatively affected on visual turfgrass quality and rooting depth. The SPF recommendation, which does not consider soil analysis, seems to be appropriate to reduce P rates and soil PO_4-P concentrations compared to SLAN recommendation on putting greens. Still, SPF recommendation may lead to unnecessary high P application rates and thus higher P losses due to higher soil PO_4-P concentrations compared to MLSN recommendation, if soil PO_4-P concentrations are already above MLSN threshold and N fertilization is medium or high.

For future research, the ability of the soil to retain P, e.g. determined as PSC, and the amount of P accumulated in soils, e.g. determined as DPS, have not yet been taken into account in any P fertilization recommendation. However, the current study has shown that parameters like these might be an important factor to optimize sufficient and sustainable P fertilization on golf course putting greens, even if not yet optimal. Further research should be done.

6 Summary

High turfgrass quality, i.e. high tiller density, few areas with weeds or bare soil, is essential to meet the golfer´s needs. To ensure this, golf course managers perform regular maintenance practices, such as mowing, scarifying, and fertilization. It is especially important to focus on P fertilization as this nutrient stimulates root and shoot growth. However, an oversupply with P is disadvantageous as this increases the risk of eutrophication of surface waters. A lower P supply might be beneficial as it is known to suppress *Poa annua* (annual bluegrass), but might on the other hand lead to shallower rooting depth. Consequently, sustainable P fertilization for putting green management must ensure to (a) minimize P fertilizer input to save this non-renewable resource, (b) reduce P in soil to decrease P losses by erosion and leaching to prevent eutrophication and (c) provide sufficient P availability for high turfgrass and playing quality. Currently, there are many country-specific P fertilization recommendations common for putting greens, which are based either on P concentrations in soil or on a certain N : P ratio equivalent to the expected P removal. Nevertheless, only little is known about their ability to fulfill the above-mentioned criteria and how reduced P fertilization influences soil P and turfgrass quality.

The international research project "Sustainable phosphorus fertilization on golf courses 2017 – 2020 (SUSPHOS)" funded by the Scandinavian Turfgrass and Environment Research Foundation (STERF) compared three of these P fertilization recommendations at five golf course putting greens. The fertilization recommendations were "Minimum Levels for Sustainable Nutrition" (MLSN), "Scandinavian Precision Fertilization" (SPF), and "Sufficiency Level of Available Nutrients" (SLAN). MLSN recommends maintaining a P level in soil of above 18 mg kg^{-1} soil (Mehlich-3 extraction), which is three times lower than for SLAN corresponding to a soil P level of above 54 mg kg^{-1} soil (Mehlich-3 extraction). SPF recommendation acclaims applying P as 12 % of the annual N rate corresponding to the expected P removal. The subject of this master thesis was to evaluate the impact of these selected P fertilization recommendations on different soil and turfgrass quality parameters. The hypotheses were that a lower P rate due to MSLN and SPF recommendations in comparison to a higher P rate due to SLAN recommendation would decrease soil PO_4-P concentrations without negatively affecting turfgrass quality, suppress the undesirable turfgrass species *Poa annua* in the sward, but might adversely decrease turfgrass rooting depth. It was also expected that the SPF recommendation, which does not consider P concentrations in soil, might result in higher P rates and thus unnecessarily higher soil PO_4-P concentrations compared to MLSN recommendation, while turfgrass quality would remain the same.

The field trials were set up on established *Agrostis stolonifera* (creeping bentgrass) putting greens, one each in China (Jingshan-CN), Germany (Duete-DE), Norway (Landvik-NO), and Sweden (Falken-SE), and additionally on one mixed *Festuca rubra* + *Agrostis capillaris* (red fescue x colonial bentgrass; *Fr* + *Ac*) putting green in The Netherlands (Princen-NL). Initial soil PO_4-P concentrations were low (< 18 mg kg^{-1} soil) at Duete-DE, Jingshan-CN, and Princen-NL, and were high (> 18 mg kg^{-1} soil) at Falken-SE and Landvik-NO. Initial soil pH ranged between 5.9 and 6.7, while a pH of 8.3 was found at the calcareous sand-based green at Jingshan-CN. The greens had varying encroachment of *Poa annua* with ≈ 50 % at Duete-DE and Falken-SE, < 10 % at Landvik-NO and no growth at all at Jingshan-CN. At each experimental site, the 4-year or 3-year (Germany) trials were conducted as a Latin square with four P treatments (Control without P fertilization and the three fertilization recommendations MLSN, SPF, and SLAN) with four replicates. On the four *Agrostis stolonifera* greens, the plots received 0.0 – 10.2 g P m^{-2} in total of the entire trial period for the MLSN treatment, 5.5 – 10.7 g P m^{-2} for the SPF treatment, and 21.9 – 30.6 g P m^{-2} for the SLAN treatment as triple phosphate. On the *Fr* + *Ac* green, the total P rates were 12.9 g m^{-2} (MLSN), 2.4 g m^{-2} (SPF), and 45 g m^{-2} (SLAN). In principal, once a month from April to November the plots were assessed for turfgrass overall impression as visual ratings from 1 – 9 and coverage percentage for *Poa annua*. Rooting depth was measured on a hanging cylinder. A representative soil sample per plot (0 – 20 cm) was collected before the trials started and after each of the growing seasons for soil PO_4-P (Mehlich-3 extraction) and soil pH (H_2O) analysis. Statistical analyses were performed with non-parametric tests, one-way analysis of variance (ANOVA), or a mixed model for repeated measurements using the software R version 3.6.3.

Regardless of the experimental site, reduced P application due to MLSN and SPF recommendations resulted in significantly lower average soil PO_4-P concentrations compared to SLAN recommendation. On the *Agrostis stolonifera* greens, the by 50 – 100 % lower total P rates for MLSN and SPF reduced the average soil PO_4-P concentration to 16 – 31 mg kg^{-1} soil compared to 40 – 46 mg kg^{-1} soil for SLAN. The reduction in P application by 70 – 95 % on the *Fr* + *Ac* green led to average soil PO_4-P concentrations of 9 and 8 mg kg^{-1} soil (MLSN and SPF, respectively) compared to 23 mg kg^{-1} soil (SLAN). Significant differences in soil PO_4-P concentrations between MLSN and SPF recommendations did not exist. These lower soil PO_4-P concentrations had no considerable impact on turfgrass quality, because median overall impression ratings were ≥ 6.0 during the entire trial at all experimental sites. Nevertheless, at Jingshan-CN on the calcareous sand-based green with low initial soil PO_4-P concentrations (7 – 9 mg kg^{-1} soil) and high soil pH (pH 8.3) any P application regardless of fertilization recommendation improved the overall impression by approximately one unit until the end of the trial. On each experimental site, lower P rates due to MLSN or SPF recommendations did not suppress *Poa annua* significantly. Only at Falken-SE, there was a significant decline of 2 – 3 % in the 2nd trial year. Rooting depth was not negatively affected by lower P rates due to MLSN or SPF recommendations, but at Jingshan-CN, the high P rates of SLAN recommendation led to ≈ 10 mm longer roots compared to no P application. The opposite was the case at Landvik-NO revealing ≈ 20 mm longer roots due to no P application compared to SLAN recommendation after the 2nd trial year. However, the differences were not significant on the 5 % significant level.

The current study confirmed that lower P rates due to MSLN and SPF recommendations in comparison to higher P rates due to SLAN recommendation decreased soil PO_4-P concentrations without negatively affecting turfgrass quality under a wide range of climate and management conditions. Unlike expected, the lower P rates did not significantly suppress the undesirable turfgrass species *Poa annua* in the sward. The results also showed that turfgrass rooting depth did not decrease with lower P rates in general. It was also not the case that SPF recommendation resulted generally in higher P rates and thus unnecessarily higher soil PO_4-P concentrations compared to MLSN recommendation due to very low soil PO_4-P concentrations or low N fertilizer input.

For P fertilization practices on golf course putting greens, it can be noted that reduced P rates corresponding to soil PO_4-P concentrations of > 18 mg kg^{-1} soil (Mehlich-3) due to MLSN recommendation are sufficient to ensure good turfgrass quality. For sand-based *Fr* + *Ac* putting greens with extensive N fertilization, soil PO_4-P concentrations might even decrease to 7 mg kg^{-1} soil (Mehlich-3) without any impact on turfgrass quality. In contrast, calcareous sand-based putting greens with soil pH > 7.5 seem to be more sensitive to lower soil PO_4-P concentrations and might be negatively affected in turfgrass quality and rooting depth. Thus, regular soil sampling and P analysis are an important tool to maintain the desired soil P level and to apply only as much P as necessary. Course managers, who want to rely on a fertilizer recommendation without soil samples but certain N : P ratios such as SPF, risk unnecessary high P rates on intensively managed putting greens but can be successful on extensive managed greens. So far, the ability of the soil to retain P, also known as P Sorption Capacity (PSC) and the amount of P accumulated in soils (DPS) have not been taken into account in any P fertilization recommendation. However, the current study has shown that parameters like these might be an important factor to optimize sufficient and sustainable P fertilization on putting greens. Further research should be done.

7 Zusammenfassung

Die Düngung mit Phosphor (P) ist eine wichtige Pflegemaßnahme, um die Rasenqualität eines Golfgrüns sicherzustellen und damit dem Golfer ein optimales Spiel zu ermöglichen. Gleichzeitig soll im Zuge der aktuellen Diskussion um Nachhaltigkeit und Umweltschutz der Einsatz von P durch angepasste Düngeempfehlungen reduziert werden. Von 2017/18 bis 2020 untersuchte das internationale STERF-Projekt „Sustainable phosphorus fertilization on golf courses (SUSPHOS)“ auf fünf Golfgrüns, welche praxisübliche Empfehlung eine reduzierte P-Düngung bei gleichbleibender Rasenqualität ermöglicht. Verglichen wurden dabei: „Minimum Levels for Sustainable Nutrition“ (MLSN; Ziel: > 18 mg P kg^{-1} Boden), „Skandinavian Precision Fertilisation“ (SPF; P-Menge: 12 % der jährlichen N-Menge) und „Sufficiency Level of Available Nutrients“ (SLAN; Ziel: > 54 mg P kg^{-1} Boden). Ziel der Masterarbeit war es, den Einfluss reduzierter P-Düngung durch die ausgewählten Düngeempfehlungen auf verschiedene Bodenparameter und die Rasenqualität zu bewerten. Die Versuche wurden auf je einem *Agrostis stolonifera* (Weißes Straußgras) Golfgrün in China, Deutschland, Norwegen und Schweden sowie einem *Festuca rubra* + *Agrostis capillaris* Golfgrün (Rot-Schwingel + Rotes Straußgras; *Fr* + *Ac*) in den Niederlanden als lateinisches Quadrat mit den Varianten Kontrolle ohne P, MLSN, SPF und SLAN sowie vier Wiederholungen angelegt. Folgende Parameter wurden erfasst: PO_4-P-Gehalt (Mehlich-3 Extraktion) und pH-Wert (H_2O) im Boden, Rasenaspekt (Boniturnote), *Poa annua* (Deckungsgrad in %) und Durchwurzelungstiefe (mm).

Die geringeren P-Gaben nach MLSN- und SPF-Düngeempfehlungen im Vergleich zu den höheren Gaben nach SLAN verringerten die P-Gehalte im Boden signifikant auf allen Standorten. Auf den *Agrostis stolonifera* Golfgrüns führten die um 50 – 100 % geringeren Gesamt-P-Gaben durch MLSN und SLAN zu P-Gehalten von 16 – 31 mg kg^{-1} Boden (SLAN: 40 – 46 mg kg^{-1} Boden). Die um 70 – 95 % reduzierten P-Gaben auf dem *Fr* + *Ac* Golfgrün reduzierten die P-Gehalte auf 9 und 8 mg kg^{-1} Boden bei MLSN bzw. SPF (SLAN: 23 mg kg^{-1} Boden). Gleichzeitig war der mittlere Rasenaspekt auf allen Standorten als gut einzustufen (Boniturnoten: ≥ 6). Das Wachstum von *Poa annua* wurde durch die reduzierten P-Gaben nach MLSN und SPF nicht signifikant unterdrückt, außer um 2 – 3 % auf dem Golfgrün in Schweden (2. Versuchsjahr). Die Durchwurzelungstiefe wurde durch weniger P nicht nachteilig reduziert, jedoch ließen sich in China durch höhere P-Gaben nach SLAN-Empfehlung um ≈ 10 mm längere Wurzeln im Vergleich zur Kontrolle nachweisen. Das Gegenteil war in Norwegen ab dem 2. Versuchsjahr der Fall. Die SPF-Empfehlung, die keine P-Bodenanalysen berücksichtigt, sorgte nicht automatisch für höhere P-Gaben und damit unnötig höhere P-Gehalte im Boden im Vergleich zur MLSN-Empfehlung. Für die Praxis bedeutet dies, dass eine reduzierte P-Düngung nach MLSN- oder SPF-Empfehlung die Qualität von Golfgrüns nicht nachteilig beeinträchtigt. Ob sich die P-Düngung weiter optimieren lässt, gilt es zu prüfen.

8 References

AAMLID, T. S., SANDELL, B. (2018): MLSN-gjødsling av golfgress. Gressforum 3, 15 – 17.

AMELUNG, W. (2018): Böden als Pflanzenstandorte. In: Amelung, W., Blume, H.-P., Fleige, H., Horn, R., Kandeler, E., Kögel-Knabner, I., Kretzschmar, R., Stahr, K., Wilke, B.-M. (eds.) "Scheffer/Schachtschabel Lehrbuch der Bodenkunde". Berlin, Germany: Springer Spektrum, 536 – 547.

ANDERSON, T. W. (2003): An Introduction to Multivariate Statistical Analysis. Hoboken, NJ, USA: John Wiley & Sons.

BAKER, S. W. (2004): Cononstruction methods for public sector and professional sports pitches: A review. Acta Horticulturae 661, 27 – 37.

BARIS, R. D., COHEN, S. Z., BARNES, N. L., LAM, J., MA, Q. (2010): Quantitative analysis of over 20 years of golf course monitoring studies. Environmental toxicology and chemistry 29, 1224 – 1236.

BECK, H. E., ZIMMERMANN, N. E., MC VICAR, T. R., VERGOPOLAN, N., BERG, A., WOOD, E. F. (2018): Present and future Köppen-Geiger climate classification maps at 1-km resolution. Scientific Data 5, 180 – 214.

BELL, G. E. (2011): Turfgrass Physiology and Ecology – Advanced Management Principles. Wallingford, Oxfordshire, Great Britain: CABI.

BELL, G. E., MARTIN, D. L., KOH, K., HAN, H. R. (2009): Comparison of turfgrass visual quality ratings with ratings determined using a handheld optical sensor. HortTechnology 19, 309 – 316.

BOCK, E. M., EASTON, Z. M. (2020): Export of nitrogen and phosphorus from golf courses: A review. Journal of Environmental Management 255, 109 – 817.

BÜRING, W. (1989): Golfplätze und Umwelt - Fakten und Daten zur Umweltverträglichkeit fachgerechter Golfplatzpflege. Zeitschrift Rasen - Turf - Gazon 3, 81 – 83.

CARROW, R. N., WADDINGTON, D. V., RIEKE, P. E. (2001): Turfgrass Soil Fertility and Chemical Problems – Assessment and Management. Hoboken, NJ, USA: John Wiley & Sons.

CARROW, R. N., STOWELL, L. J., GELERNTER, W. D., DAVIS, S., DUNCAN, R. R., SKORULSKI, J. (2004a): Clarifying soil testing: II. Choosing SLAN extractants for macronutrients. Golf Course Management 72, 189 – 193.

CARROW, R. N., STOWELL, L. J., GELERNTER, W. D., DAVIS, S., DUNCAN, R. R., SKORULSKI, J. (2004b): Clarifying soil testing: III. SLAN sufficiency ranges and recommendations. Golf Course Management 72, 194 – 198.

CARTER, M. R., GREGORICH, E. G. (2008): Soil Sampling and Methods of Analysis. Boca Raton, FL, USA: CRC Press.

CHANG, Z., JIN, X., LI, D. (2014): Phosphorus responses vary among cool-season turfgrasses during establishment from seed. Agronomy Journal 106, 1975 – 1980.

CHRISTIANS, N. E., MARTIN, D. P., WILKINSON, J. F. (1979): Nitrogen, phosphorus, and potassium effects on quality and growth of kentucky bluegrass and creeping bentgrass. Agronomy Journal 71, 564 – 567.

CHRISTIANS, N. E. (2007): Fundamentals of Turfgrass Management. Hoboken, NJ, USA: John Wiley & Sons.

CLIMATE-DATA (2021): Climate in Osnabrück (Germany). https://de.climate-data.org/europa/deutschland/niedersachsen/osnabrueck-2121/#climate-table (last accessed June 5, 2021).

CORDELL, D., DRANGERT, J.-O., WHITE, S. (2009): The story of phosphorus: Global food security and food for thought. Global Environmental Change 19, 292 – 305.

DACOSTA, M., HUANG, B. (2006): Osmotic adjustment associated with variation in bentgrass tolerance to drought stress. Journal of the American Society for Horticultural Science 131, 338 – 344.

DAHL JENSEN, A. M. (2012): Playing quality on the golf course. Sterf brochure. http://www.sterf.org/Media/Get/1223/playing-quality-on-the-golf-course.pdf (last accessed October 5, 2021).

DALLAL, G. E., WILKINSON, L. (1986): An analytic approximation to the distribution of Lilliefors's test statistic for normality. The American Statistician 40, 294 – 296.

DESMET, J., HOFMAN, G., VANDERDEELEN, J., VAN MEIRVENNE, M., BAERT, L. (1996): Phosphate enrichment in the sandy loam soils of West-Flanders, Belgium. Fertilizer Research 43, 209 – 215.

DEST, W. M., GUILLARD, K. (1987): Nitrogen and phosphorus nutritional influence on bentgrass-annual bluegrass community composition. Journal of the American Society for Horticultural Science 112, 769 – 773.

DONKERS, K. (2021): Compiled weather data of the weather station Gilze-Rijen 1990 – 2020 (The Netherlands). Email from April 20, 2021. Royal Netherlands Golf Federation.

DRG (2020): Grundlagen – Golfrasen – Pflegemaßnahmen. Fachinformationen von Deutsche Rasengesellschaft e. V. https://www.rasengesellschaft.de/golfrasen-pflegemassnahmen.html (last accessed October 5, 2021).

EBELING, A. M., BUNDY, L. G., KITTELL, A. W., EBELING, D. D. (2008): Evaluating the Bray P1 test on alkaline, calcareous soils. Soil Science Society of America Journal 72, 985 – 991.

EGNÉR, H., RIEHM, H., DOMINGO, W. R. (1960): Untersuchungen über die chemische Bodenanalyse als Grundlage für die Beurteilung des Nährstoffzustandes der Böden. II Chemische Extraktionsmethoden zur Phosphor- und Kaliumbestimmung. Kungliga Lantbrukshögskolans Annaler 26, 199 – 215.

ERICSSON, T., BLOMBÄCK, K., KVALBEIN, A. (2015): Precision fertilisation – from theory to practice. Sterf brochure. http://www.sterf.org/Media/Get/1228/precision-fertilisation-from-theory-to-practice.pdf (last accessed October 5, 2021).

EUROFINS (2021): Veiledning til jordanalyser. Evaluation sheet P-AL methode. https://cdn media.eurofins.com/european-east/media/356784/veiledning-jord.pdf (last accessed June 5, 2021).

FLL (2008): Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau e. V. (FLL)-Richtlinie für den Bau von Golfplätzen – Golfplatzbaurichtlinie. Troisdorf, Germany: FLL.

FOX, J., WEISBERG, S. (2011): An R Companion to Applied Regression. Los Angeles, London, New Delhi, Singapore, Washington DC: Sage.

FOX, J. (2016): Applied Regression Analysis and Generalized Linear Models. Los Angeles, London, New Delhi, Singapore, Washington DC: Sage.

FRANK K., BEEGLE D., DENNING J. (1998): Phosphorus. In: BROWN, J. R. (ed.) "Recommended Chemical Soil Test Procedures for the North Central Region". Columbia North Central Regional Research Publication 221, Missouri Agricultural Experiment Station, 21 – 30.

FRANK, K. W., GUERTAL, E. A. (2013): Potassium and phosphorus research in turfgrass. In: Stier, J. C., Horgan, B. P., Bonos, S. A. (eds.) "Turfgrass: Biology, Use, and Management". Madison, WI, USA: American Society of Agronomy; Crop Science Society of America; Soil Science Society of America, 493 – 519.

FREEDMAN, D. A. (2006): On the So-Called “Huber Sandwich Estimator” and “Robust Standard Errors”. The American Statistician 60, 299 – 302.

FRY, J., HUANG, B. (2004): Applied Turfgrass Science and Physiology. Hoboken, NJ, USA: John Wiley & Sons.

GELERNTER, W. D., STOWELL, L. J., JOHNSON, M. E., BROWN, C. D. (2016): Documenting tends in nutrient use and conservation practices on US golf courses. Crop, Forage and Turfgrass Management 2, 1 – 10.

GILBERT, N. (2009): Environment: The disappearing nutrient. Nature 461, 716 – 718.

GOMEZ, K. A., GOMEZ, A. A. (1984): Statistical Procedures for Agricultural Research. New York, NY, USA: John Wiley & Sons.

GOOGLE EARTH (2021): Map of the earth. Google Earth version 7.3.3.7786 (last accessed October 10, 2021).

GROSS, R. L., BRAUEN, S. E., ORTON, S. P. (1975): The effects of N, P, K and S on Poa annua L. in bentgrass putting green turf. Journal of the Sports Turf Research Institute 51, 74 – 82.

GUERTAL, E. A. (2006): Phosphorus movement and uptake in bermudagrass putting greens. USGA Turfgrass and Environmental Research Online 5, 1 – 7.

GUERTAL, E. A., MC ELROY, J. S. (2018): Soil type and phosphorus fertilization affect Poa annua growth and seedhead production. Agronomy Journal 110, 2165 – 2170.

HAWKESFORD, M., HORST, W., KICHEY, T., LAMBERS, H., SCHJOERRING, J., SKRUMSAGER MØLLER, I., WHITE, P. (2012): Functions of macronutrients. In: Marschner, P. (ed.): Marschner's Mineral Nutrition of Higher Plants. Amsterdam, The Netherlands; Boston, MA, USA: Academic Press, 158 – 165.

HÄHNDEL, R. (2019): Rasen. In: Wissemeier, A., Olfs, H.-W. (eds.) "Diagnose des Ernährungszustands von Kulturpflanzen". Clenze, Germany: ERLING Verlag, 180 – 189.

HOLLANDER, M., WOLFE, D. A., CHICKEN, E. (2014): Nonparametric Statistical Methods. Hoboken, NJ, USA: John Wiley & Sons.

HOLSTEN, B., PFANNERSTILL, M., TREPEL, M. (2016): Phosphor in der Landschaft – Management eines begrenzt verfügbaren Nährstoffes. Kiel, Germany: Institut für Ökosystemforschung, Christian-Albrechts-Universität zu Kiel.

HOOGSTEEN, M. J. J., LANTINGA, E. A., BAKKER, E. J., GROOT, J. C. J., TITTONELL, P. A. (2015): Estimating soil organic carbon through loss on ignition: effects of ignition conditions and structural water loss. European Journal of Soil Science 66, 320 – 328.

HSU, J. (1996): Multiple Comparisons – Theory and Methods. Boca Raton, FL, USA: Chapman and Hall/CRC Press.

HULL, R. J. (1997): Phosphorus usage by turfgrasses. Turfgrass Trends 6, 1 – 12.

JASINSKI, S. (2014): Phosphate rock statistics and information. U.S. Department of the Interior: National minerals information center. https://www.usgs.gov/centers/nmic/phosphate-rock-statistics-and-information (last accessed October 5, 2021).

JOHNSON, P. G., KOENIG, R. T., KOPP, K. L. (2003): Nitrogen, phosphorus, and potassium responses and requirements in calcareous sand greens. Agronomy Journal 95, 697 – 702.

JORDAN-MEILLE, L., RUBAEK, G. H., EHLERT, P. A. I., GENOT, V., HOFMAN, G., GOULDING, K., RECKNAGEL, J., PROVOLO, G., BARRACLOUGH, P. (2012): An overview of fertilizer-P recommendations in Europe: soil testing, calibration and fertilizer recommendations. Soil Use and Management 28, 419 – 435.

JUSKA, F. V., HANSON, A. A. (1969): Nutritional requirements of Poa annua L.. Agronomy Journal 61, 466 – 468.

KING, J. W., SKOGLEY, C. R. (1969): Effect of nitrogen and phosphorus placements and rates on turfgrass establishment. Agronomy Journal 61, 4 – 6.

KIRKBY, E. (2012): Introduction, definition and classification of nutrients. In: Marschner, P. (ed.): Marschner's Mineral Nutrition of Higher Plants. Amsterdam, The Netherlands; Boston, MA, USA: Academic Press, 3 – 5.

KÖHLER, W., SCHACHTEL, G., VOLESKE, P. (2002): Biostatistik – Eine Einführung für Biologen und Agrarwissenschaftler. Berlin, Heidelberg, Germany: Springer.

KREUSER, W. C., PAGLIARI, P. H., SOLDAT, D. J. (2012): Creeping bentgrass putting green Mehlich-3 soil test phosphorus requirements. Crop Science 52, 1385 – 1392.

KROGSTAD, T. (1992): Metoder for jordanalyser. Issue 6/1992. Ås, Norwegen: Norges Landbrukshøgskule.

KRUSE, J. K., CHRISTIANS, N. E., CHAPLIN, M. H. (2005): Remote sensing of phosphorus deficiencies in Agrostis stolonifera. International Turfgrass Society Research Journal 10, 923 – 928.

KUSSOW, W. R., SOLDAT, D. J., KREUSER, W. C., HOULIHAN, S. M. (2012): Evidence, regulation, and consequences of nitrogen-driven nutrient demand by turfgrass. International Scholarly Research Network Agronomy 2012, 1 – 9.

KVALBEIN, A., AAMLID, T. S. (2016): Gjødsling som ledd i integrert plantevern. Faktablad - Integrert plantevern. Sterf broschure. http://www.sterf.org/Media/Get/2433/gjodsling-norsk-160420.pdf.pdf (last accessed October 5, 2021).

LEINWEBER, P., LÜNSMANN, F., ECKHARDT, K. U. (1997): Phosphorus sorption capacities and saturation of soils in two regions with different livestock densities in northwest Germany. Soil Use and Management 13, 82 – 89.

LIU, H., HULL, R. J., DUFF, D. T. (1995): Comparing cultivars of three cool-season turf-grasses for phosphate uptake kinetics and phosphorus recovery in the field. Journal of Plant Nutrition 18, 523 – 540.

LONG, J. S., ERVIN, L. H. (2000): Using heteroscedasticity consistent standard errors in the linear regression model. The American Statistician 54, 217 – 224.

LOOKMAN, R., JANSEN, K., MERCKX, R., VLASSAK, K. (1996): Relationship between soil properties and phosphate saturation parameters a transect study in northern Belgium. Geoderma 69, 265 – 274.

LYONS, E. M., SNYDER, R. H., LYNCH, J. P. (2008): Regulation of root distribution and depth by phosphorus localization in Agrostis stolonifera. HortScience 43, 2203 – 2209.

MAGUIRE, R. O., FOY, R. H., BAILEY, J. S., SIMS, J. T. (2001): Estimation of the phosphorus sorption capacity of acidic soils in Ireland. European Journal of Soil Science 52, 479 – 487.

MARSCHNER, P., RENGEL, Z. (2012): Nutrient availability in soils. In: Marschner, P. (ed.): Marschner's Mineral Nutrition of Higher Plants. Amsterdam, The Netherlands; Boston, MA, USA: Academic Press, 3 – 5.

MC CARTY, L. B. (2011): Best Golf Course Management Practices – Construction, Watering, Fertilizing, Cultural Practices, and Pest Management Strategies to Maintain Golf Course Turf with Minimal Environmental Impact. Upper Saddle River, NJ, USA: Prentice Hall.

MEHLICH, A. (1984): Mehlich-3 soil test extractant: A modification of Mehlich-2 extractant. Communications in Soil Science and Plant Analysis 15, 1409 – 1416.

MENGEL, K., KIRKBY, E. A. (2001): Principles of Plant Nutrition. Dodrecht, The Netherlands: Kluwer Academic Publishers.

MORRIS, K. N. (2004): A guide to NTEP turfgrass ratings. National Turfgrass Evaluation Program http://www.ntep.org/reports/ratings.htm#quality (last accessed October 5, 2021).

MÜLLER-BECK, K., LAWSON, P. (2017): Bodenanalysen bilden Grundlage für Düngepläne in der Golf- und Sportplatzpflege. Turfgrass topic November 2017. https://www.rasengesell schaft.de/rasenthema-detailansicht/rasenthema-november-2017.html (last accessed July 5, 2021).

MÜLLER-BECK, K. (2019): Grünsqualität – Smoothness, Trueness, Firmness. Presentation at the GVD-Jahrestagung 2019. https://www.rasengesellschaft.de/files/downloads/rasenthema/2019/Vortrags-Handout%20K.%20Müller-Beck_08_2019.pdf (last accessed July 5, 2021).

MURPHY, J., RILEY, J. P. (1962): A modified single solution method for the determination of phosphate in natural waters. Analytica Chimica Acta 27, 31 – 36.

NELSON, D. W., SOMMERS, L. E. (1996): Total carbon, organic carbon, and organic matter. In: Sparks, D. L. (ed.) "Methods of Soil Analysis". Madison, WI, USA: American Society of Agronomy, Soil Science Society of America, 961 – 1010.

NEYROUD, J.-A., LISCHER, P. (2003): Do different methods used to estimate soil phosphorus availability across Europe give comparable results? Journal of Plant Nutrition and Soil Science 166, 422 – 431.

NIBIO (2017): Optimal gjødsling av planter – Om sammenhenger mellom næringstilgang, vekst og kvalitet. NIBIO BOK, Issue 7/2017. Ås, Norway: Norwegian Institute of Bio-economy Research (NIBIO).

NOLAN, C. (2015): Greens playing quality. Sterf Seminar Copenhagen and Hoor. http://www.sterf.org/Media/Get/2179/nolan-greens-playing-quality.pdf (last accessed June 10, 2021).

NUS, J. L., CHRISTIANS, N. E., DIESBURG, K. L. (1993): High phosphorus applications influence soil-available potassium and kentucky bluegrass copper content. HortScience 28, 639 – 641.

ØGAARD, A. F., AAMLID, T. S. (2020): Temperature effects on phosphorus requirements for creeping bentgrass establishment and spring growth. Agronomy Journal 112, 3478 – 3490.

OLSEN, S. R., COLE, C. V., WATANABE, F. S., DEAN, L. A. (1954): Estimation of available phosphorus in soils by extraction with sodium bicarbonate. Washington D.C, USA: U.S. Department of Agriculture.

PESSARAKLI, M. (2008): Handbook of Turfgrass Management and Physiology. Boca Raton, FL, USA: CRC Press.

PIEPHO, H.-P. (2004): An algorithm for a letter-based representation of all-pairwise comparisons. Journal of Computational and Graphical Statistics 13, 456 – 466.

R CORE TEAM (2013): R: A language and environment for statistical computing. http://www.R-project.org/ (last accessed October 5, 2021).

RALEY, R., LANDSCHOOT, P., BROSNAN, J. T. (2013): Influence of phosphorus and nitrogen on annual bluegrass encroachment in a creeping bentgrass putting green. International Turfgrass Society Research Journal 12, 649 – 655.

RICE, P., HORGAN, B. (2010): Nutrient Loss of Runoff from Turf: Effect on Surface Water Quality. USGA Turfgrass and Environmental Research Online 9, 1 – 10.

SACHS, L. (2004): Angewandte Statistik – Anwendung statistischer Methoden. Berlin, Heidelberg, Germany: Springer.

SCHILLING, G. (2000): Pflanzenernährung und Düngung. Stuttgart (Hohenheim), Germany: Ulmer.

SCHINDLER, D. W. (1971): Carbon, nitrogen, and phosphorus and the eutrophication of freshwater lakes. Journal of Phycology 7, 321 – 329.

SCHOLZ, R. W., ROY, A. H., BRAND, F. S., HELLUMS, D. T., ULRICH, A. E. (2014): Sustainable Phosphorus Management – A Global Transdisciplinary Roadmap. Dordrecht, The Netherlands: Springer Netherlands.

SCHOUMANS, O. (2000): Determination of the degree of phosphate saturation in non-calcareous soils. In: Pierzynski, G. M. (ed.) "Methods of Phosphorus Analysis for Soils, Sediments, Residuals, and Waters". Manhattan, KS, USA: SERA-IEG 17, 31 – 34.

SCHÜLLER, H. (1969): Die CAL-Methode, eine neue Methode zur Bestimmung des pflanzenverfügbaren Phosphates in Böden. Zeitschrift für Pflanzenernährung und Bodenkunde 123, 48 – 63.

SEGES (2017): Jordbundsanalyser - hvad gemmer sig bag tallene? https://www.havelab.dk/wp-content/uploads/2019/01/jordbundsanalyser-hvad-gemmer-sig-bag-tallene_pl_14_1955.pdf (last accessed October 5, 2021).

SHEN, J., YUAN, L., ZHANG, J., LI, H., BAI, Z., CHEN, X., ZHANG, W., ZHANG, F. (2011): Phosphorus dynamics: from soil to plant. Plant physiology 156, 997 – 1005.

SHUMAN, L. M. (2004): Runoff of nitrate nitrogen and phosphorus from turfgrass after watering-in. Communications in Soil Science and Plant Analysis 35, 9 – 24.

SIMS, J.T. (2000): Soil test phosphorus: Mehlich 3. In: Pierzynski, G. M. (ed.) "Methods of Phosphorus Analysis for Soils, Sediments, Residuals, and Waters". Manhattan, KS, USA: SERA-IEG 17, 17 – 19.

SOLDAT, D. J., PETROVIC, A. M. (2007): Soil phosphorus levels and stratification as affected by fertilizer and compost applications. Applied Turfgrass Science 4, 1 – 6.

SOLDAT, D. J., PETROVIC, A. M. (2008): The fate and transport of phosphorus in turfgrass ecosystems. Crop Science 48, 2051 – 2065.

STAHNKE, G. K., MILTNER, E. D., COGGER, C. G., LUCHTERHAND, R. A., BEMBENEK, R. E. (2013): Phosphorus availability in turfgrass root zones after applications of organic and synthetic nitrogen fertilizers. Applied Turfgrass Science 10, 1 – 7.

STEEL, R. G. D., TORRIE, J. H., DICKEY, D. A. (1997): Principles and Procedures of Statistics – A Biometrical Approach. New York, NY, USA: McGraw-Hill.

STEPHENS, M. A. (1974): EDF statistics for goodness of fit and some comparisons. Journal of the American Statistical Association 69, 730.

SUMNER, M. E., MILLER, W. P. (1996): Cation exchange capacity and exchange coefficients. In: Sparks, D. L. (ed.) "Methods of Soil Analysis". Madison, WI, USA: American Society of Agronomy, Soil Science Society of America, 1201 – 1229.

THIEME-HACK, M. (2018): Handbuch Rasen. Stuttgart (Hohenheim), Germany: Ulmer.

THODE, H. C. (2011): Normality tests. In: Lovric, M. (ed.) "International Encyclopedia of Statistical Science". Berlin, Germany: Springer, 999 – 1000.

TOLER, J. E. (2007): Postemergent annual bluegrass control in dormant non-overseeded bermudagrass turf. HortScience 42, 670 – 672.

TÖNJES, H. (2021a): Schedule for maintenance of green 18 at Duete-DE. Email from January 4, 2021. Golfclub Osnabrück-Düteltal e. V..

TÖNJES, H. (2021b): Non-P fertilizer application at Duete-DE. Email from January 10, 2021. Golfclub Osnabrück-Düteltal e. V..

TROTT, H. (2008): Kalkwert von Düngemitteln - eine Bewertung von Düngesystemen -. Presentation at the conference of the "Düngekalk-Hauptgemeinschaft" February 19, 2008 in Fulda. https://docplayer.org/178101073-Kalkwert-von-duengemitteln-eine-bewertung-von-duengesystemen.html (last accessed October 10, 2021).

TURGEON, A. J. (2012): Turfgrass management. Boston, MA, USA: Prentice Hall.

TURNER, T. R., WADDINGTON, D. V. (1983): Soil test calibration for establishment of turfgrass monostands. Soil Science Society of America Journal 47, 1161 – 1166.

TURNER, T. R., HUMMEL, N. W. (1992): Nutritional requirements and fertilization. In: Waddington, D. V., Carrow, R. N., Shearman, R. C. (eds.) "Turfgrass". Madison, WI, USA: American Society of Agronomy; Crop Science Society of America; Soil Science Society of America, 385 – 439.

ULÉN, B., BECHMANN, M., FÖLSTER, J., JARVIE, H. P., TUNNEY, H. (2007): Agriculture as a phosphorus source for eutrophication in the north-west European countries, Norway, Sweden, United Kingdom and Ireland: a review. Soil Use and Management 23, 5 – 15.

USGA (2018): A guide to constructing the USGA putting green. https://archive.lib.msu.edu/tic/usgamisc/monos/2018recommendationsmethodputtinggreen.pdf (last accessed July 5, 2021).

VACKERTVÄDER (2021): Climate in Falkenberg (Sweden). https://www.vackertvader.se/falkenberg (last accessed October 5, 2021).

VAN REEUWIJK, L. P. (2002): Procedures for Soil Analysis. Wageningen, The Netherlands: International Soil Reference and Information Centre.

VARCO, J. J., SARTAIN, J. B. (1986): Effects of phosphorus, sulfur, calcium hydroxide, and pH on growth of annual bluegrass. Soil Science Society of America Journal 50, 128 – 132.

VARGAS, J. M. (1994): Management of Turfgrass Diseases. Boca Raton, FL, USA: CRC Press.

VARGAS, J. M., TURGEON, A. J. (2004): Poa annua – Physiology, Culture, and Control of Annual Bluegrass. Hoboken, NJ, USA: John Wiley & Sons.

VDLUFA (2012): Methodenbuch I – Bestimmung von Phosphor und Kalium im Calcium-Acetat-Lactat-Auszug A 6.2.1.1. Darmstadt, Germany: VDLUFA-Verlag.

WADDINGTON, D. V., TURNER, T. R., DUICH, J. M., MOBERG, E. L. (1978): Effect of fertilization on Penncross creeping bentgrass. Agronomy Journal 70, 713 – 718.

WHITE, H. (1980): A heteroskedasticity-consistent covariance matrix estimator and a direct test for heteroskedasticity. Econometrica 48, 817.

WIESLER, F., APPEL, T., DITTERT, K., EBERTSEDER, T., MÜLLER, T., NÄTSCHER, L., OLFS, H.-W., REX, M., SCHWEITZER, K., STEFFENS, D., TAUBE, F., ZORN, W. (2018): Standpunkt: Phosphordüngung nach Bodenuntersuchung und Pflanzenbedarf. Speyer, Germany: Verband Deutscher Landwirtschaftlicher Untersuchungs- und Forschungs-anstalten e.V. (VDLUFA).

WISSEMEIER, A. (2019): Pflanzennährstoffe. In: WISSEMEIER, A., OLFS, H.-W. "Diagnose des Ernährungszustands von Kulturpflanzen". Clenze, Germany: ERLING Verlag, 14 – 15.

WOODS, M. S., STOWELL, L. J., GELERNTER, W. D. (2014): Just what the grass requires. Using minimum levels for sustainable nutrition. Golf Course Management 82, 132 – 136, 138.

WOODS, M. S., STOWELL, L. J., GELERNTER, W. D. (2016): Minimum soil nutrient guidelines for turfgrass developed from Mehlich 3 soil test results. PeerJ Preprints 4:e2144v1. https://peerj.com/preprints/2144v1/ (last accessed October 5, 2021).

WOODS, M. S., STOWELL, L. J., GELERNTER, W. D. (2020): A survey of soil nutrient analyses from turfgrass sites in Asia, Europe, and North America. https://mfr.osf.io/render?url=https://osf.io/ej58z/?direct%26mode=render%26action=download%26mode=render (last accessed October 5, 2021).

WUENSCHER, R., UNTERFRAUNER, H., PETICZKA, R., ZEHETNER, F. (2016): A comparison of 14 soil phosphorus extraction methods applied to 50 agricultural soils from Central Europe. Plant, Soil and Environment 61, 86 – 96.

ZORN, W., KRAUSE, O. (1999): Untersuchungen zur Charakterisierung des pflanzen-verfügbaren Phosphats in Thüringer Carbonatböden. Journal of Plant Nutrition and Soil Science 162, 463 – 469.

Appendix

Appx. 1: Putting green maintenance according to the course manager's schedule on the example of Duete-DE. Begin. = Beginning; + = in combination with (TÖNJES 2021a).

Practices	1st Year 2018		2nd Year 2019		3rd Year 2020*	
	Date	Operation	Date	Operation	Date	Operation
Aeration	Mid Jan.	Maredo 2.5 cm	End Feb.	+ Sanding	Sep.	Cross spoons
	Mid Mar.	Maredo 2.5 cm	End May	+ Topdressing	Oct.	Cross spoons
	End Mar.	Hollow spoons + sanding	Mid Sep.	+ Sanding		
	End May	Cross spoons	End Oct.	Maredo 2.5 cm + topdressing		
	Mid Aug.	Cross spoons				
	Begin. Mar.	Solid spoons + sanding				
	Mid Oct.	Maredo 2.5 cm				
Scarifying	Mid Apr.	No Topdressing	Mid Feb.	+ Topdressing	Mid Aug.	No Topdressing
	End Jun.	+ Topdressing	Begin. Jul.	No Topdressing	Oct.	Slitting
	End Aug.	+ Topdressing			Begin. Dec.	Slitting
Mowing		No information		Daily in season Cutting height during season 4.0 mm, post season up to 6.0 mm		Daily in season Cutting height during season 4.5 mm, post season 5.0 mm
Pest Management		-		No information	Begin. Oct.	Fungicide Medaillon against Fusarium (3,0 L/ha)
Wetting Agents	May	H2 Pro Tablets		No information		No information
	Jul.	Kick (0.2 mL/m²)				
	Aug.	Kick (1.7 mL/m²)				

*No information about practises in the period January to July 2020.

Appx. 2: Application practices of non-P fertilizer to all plots referring to the course manager's schedule on the example of Duete-DE (TÖNJES 2021b, modified).

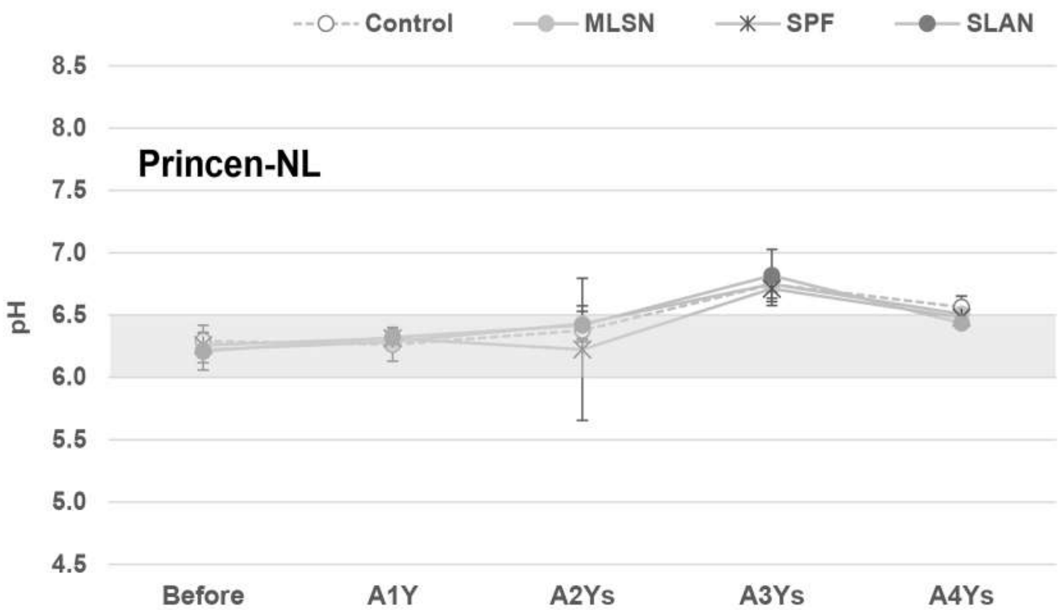
Date	Fertilizer type	Product ($g\ m^{-2}$)	N	K	Mg	S	Ca	Fe	Mn
			Nutrients added ($g\ m^{-2}$)						
1st Year 2018									
Begin. Apr.	Greenmaster NK 12-0-12	25.0	3.0	3.0	0.8	0.0	0.0	0.5	0.0
End Apr.	Sportsmaster WSF High N 35-0-14	3.0	1.1	0.4	0.0	0.0	0.0	0.0	0.0
May	Sierraform GT Spring Start 16-0-16	20.0	3.2	3.2	0.0	0.0	0.0	0.2	0.1
Aug.	Sierraform GT Spring Start 16-0-16	20.0	3.2	3.2	0.0	0.0	0.0	0.2	0.1
Sep.	Sierraform GT Anti Stress 15-0-26	20.0	3.0	5.2	0.0	0.0	0.0	0.2	0.0
Oct.	Greenmaster NK 12-0-12	20.0	2.4	2.4	0.6	0.0	0.0	0.4	0.0
Mid Oct.	Tour Turf FDC Autumn 5-0-0	4.0	0.2	0.0	0.0	0.0	0.0	0.2	0.0
Begin. Nov.	RenoSan 1 1,4-0,1-0,2	6.4	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Nov.	Tour Turf FDC Autumn 5-0-0	4.0	0.2	0.0	0.0	0.0	0.0	0.2	0.0
Nov.	Sierraform GT K Step 6-0-27	25.0	1.5	6.8	0.8	0.0	0.0	0.5	0.0
Dec.	Tour Turf FDC Autumn 5-0-0	4.0	0.2	0.0	0.0	0.0	0.0	0.2	0.0
SUM whole season 2018			**18.0**	**24.2**	**2.1**	**0.0**	**0.0**	**2.6**	**0.1**
2nd Year 2019									
End Feb.	E.Marker FDC liquid fertiliser	4.0	0.2	0.0	0.0	0.3	0.0	0.2	0.0
Mid Mar.	Granulated fertiliser 12-0-12	25.0	3.0	3.0	0.8	0.0	0.5	0.5	0.0
Begin. Apr.	Granulated fertiliser 15-0-26	20.0	3.0	5.2	0.0	0.0	0.0	0.2	0.0
Mid May	Granulated fertiliser 16-0-16	20.0	3.2	3.2	0.0	0.0	0.0	0.2	0.1
Mid Jun.	Granulated fertiliser 16-0-16	20.0	3.2	3.2	0.0	0.0	0.0	0.2	0.1
Mid Jul.	Granulated fertiliser 16-0-16	20.0	3.2	3.2	0.0	0.0	0.0	0.2	0.1
End Sep.	E.Marker FDC liquid fertiliser	4.0	0.2	0.0	0.0	0.3	0.0	0.2	0.0
Mid Oct.	Granulated fertiliser 15-0-26	20.0	3.0	5.2	0.0	0.0	0.0	0.2	0.0
End Nov.	E.Marker FDC liquid fertiliser	4.0	0.2	0.0	0.0	0.3	0.0	0.2	0.0
SUM whole season 2019			**19.2**	**23.0**	**0.8**	**0.8**	**0.5**	**2.1**	**0.2**
3rd Year 2020									
Mar.	Sierraform GT 16-0-16	25.0	4.0	4.0	0.0	0.0	0.0	0.3	0.1
Apr.	Sierraform GT 16-0-16	25.0	4.0	4.0	0.0	0.0	0.0	0.3	0.1
May	Sierraform GT 16-0-16	25.0	4.0	4.0	0.0	0.0	0.0	0.3	0.1
Jun.	Sierraform GT 16-0-16	25.0	4.0	4.0	0.0	0.0	0.0	0.3	0.1
Jul.	Sierraform GT 16-0-16	25.0	4.0	4.0	0.0	0.0	0.0	0.3	0.1
Aug.	Sierraform GT 16-0-16	25.0	4.0	4.0	0.0	0.0	0.0	0.3	0.1
End Aug.	Granulated fertiliser 7-0-7	30.0	2.1	2.1	0.0	0.0	0.0	0.0	0.0
Mid Oct.	Liquid fertilizer 5-0-0	4.0	0.2	0.0	0.0	0.0	0.0	0.2	0.0
Mid Nov.	Granulated fertiliser 4-0-0	30.0	1.2	0.0	0.0	0.0	0.0	1.8	0.0
SUM whole season 2020			**27.5**	**26.1**	**0.0**	**0.0**	**0.0**	**3.5**	**0.5**

Appx. 3: Statistical results for soil PO_4-P concentration (mg kg^{-1} soil). Mixed model with repeated measurements. F1 = treatments, F2 = time, F1:F2 = interactions. Pr (> F) = p-value. Significant levels: * = 0.05, ** = 0.01, * = 0.001.**

```
Anova(model.lmer <- lmer(PO4-P ~ COL + ROW + F1*F2 + (1|ID), daten1), type="II",
test.statistic="F"
Analysis of Deviance Table (Type II Wald F tests with Kenward-Roger df)
COl = Column
ROW = Row
F1 = Fertilization
F2 = Time

"Duete-DE"
              F Df Df.res    Pr(>F)
COL      0.7449  3      6 0.563377
ROW      1.6695  3      6 0.271308
F1      23.1754  3      6 0.001064 **
F2       7.5437  2     24 0.002871 **
F1:F2    5.2321  6     24 0.001438 **

"Falken-SE"
              F Df Df.res     Pr(>F)
COL      1.5777  3      6  0.290029
ROW      2.0232  3      6  0.212225
F1      11.4669  3      6  0.006754 **
F2      15.3102  3     36 1.391e-06 ***
F1:F2    2.8287  9     36  0.012653 *

"Jingshan-CN"
              F Df Df.res     Pr(>F)
COL      0.7523  3      6     0.5599
ROW      0.2889  3      6     0.8322
F1      99.3038  3      6 1.671e-05 ***
F2      29.1156  3     36 9.813e-10 ***
F1:F2    6.1062  9     36 3.526e-05 ***

"Landvik-NO"
              F Df Df.res    Pr(>F)
COL      0.8244  3      6 0.526540
ROW      0.1484  3      6 0.927021
F1      16.8073  3      6 0.002523 **
F2       3.5580  3     36 0.023614 *
F1:F2    1.2651  9     36 0.288921

"Princen-NL"
              F Df Df.res     Pr(>F)
COL      6.7741  3      6 0.0235814 *
ROW      5.1155  3      6 0.0431283 *
F1      70.2541  3      6 4.591e-05 ***
F2       3.5914  3     36 0.0227857 *
F1:F2    4.4328  9     36 0.0005906 ***
```

Appx. 4: Statistical results for soil pH. Mixed model with repeated measurements. F1 = treatments, F2 = time, F1:F2 = interactions. Pr (> F) = p-value. Significant levels: * = 0.05, ** = 0.01, * = 0.001.**

```
Anova(model.lmer <- lmer(soil pH ~ COL + ROW + F1*F2 + (1|ID), daten1), type="II",
test.statistic="F"
Analysis of Deviance Table (Type II Wald F tests with Kenward-Roger df)
COl = Column
ROW = Row
F1 = Fertilization
F2 = Time

"Duete-DE"
             F Df Df.res     Pr(>F)
COL     0.0309  3      6     0.9919
ROW     3.0368  3      6     0.1146
F1      5.3628  3      6     0.0391 *
F2     39.4117  2     24 2.615e-08 ***
F1:F2   1.3313  6     24     0.2820

"Falken-SE"
             F Df Df.res     Pr(>F)
COL     0.8051  3      6     0.5352
ROW     2.7705  3      6     0.1332
F1      1.4073  3      6     0.3294
F2     27.0685  3     36 2.436e-09 ***
F1:F2   0.5707  9     36     0.8118

"Jingshan-CN"
             F Df Df.res     Pr(>F)
COL     0.5193  3      6    0.68437
ROW     1.0546  3      6    0.43483
F1      1.9391  3      6    0.22463
F2     24.8315  3     36 6.952e-09 ***
F1:F2   1.8345  9     36    0.09546 .

"Landvik-NO"
             F Df Df.res     Pr(>F)
COL     1.3925  3      6     0.3331
ROW     1.1468  3      6     0.4036
F1      1.1706  3      6     0.3960
F2     29.1500  3     36 9.668e-10 ***
F1:F2   1.6264  9     36     0.1447

"Princen-NL"
             F Df Df.res     Pr(>F)
COL     1.1123  3      6    0.41498
ROW     3.7379  3      6    0.07953 .
F1      0.5647  3      6    0.65801
F2     25.5173  3     36 5.008e-09 ***
F1:F2   0.5568  9     36    0.82266
```



Appx. 5: Changes in soil pH during the trial in response to different P fertilization recommendations on the *Fr + Ac* experimental green at Princen-NL. Soil pH was analyzed before the trial started (Before), after 1 year of trial (A1Y), after 2 years (A2Ys), after 3 years (A3Ys), and after 4 years (A4Ys). Error bars represent the spatial variation at plot scale (n = 4). Grey highlighted area shows optimum soil pH for P availability (pH 6.0 – 6.5; AMELUNG 2018). For treatment description see Tab. 10, for experimental site description see Tab. 2.

Appx. 6: Mean overall impression (Rating scale 1 – 9) in response to different P fertilization recommendations before the trial started and for each trial year at Falken-SE, Landvik-NO, and Princen-NL. Mean ratings calculated as median. For n in each trial year, see Tab. 8. Different letters indicate differences between the trial years for each P treatment (p-value < 0.05). For treatment description see Tab. 10, for experimental site description see Tab. 2.

Exper. site	Treatment	Overall impression (Rating scale 1 - 9)					Friedman rank test
		Before[a]	1st Year	2nd Year	3rd Year	4th Year	p-value
Falken-SE	Control	6.5	6.5 **ab**	6.0 **ab**	7.0 **b**	5.0 **a**	0.050
	MLSN	5.0	5.5	6.0	7.0	5.0	0.116
	SPF	4.5	5.0 **a**	6.5 **ab**	7.0 **b**	5.0 **ab**	0.020
	SLAN	4.5	6.0 **a**	7.0 **a**	7.0 **a**	5.0 **a**	0.045
Landvik-NO	Control	6.0	7.0 **a**	3.5 **a**	6.3 **a**	6.5 **a**	0.047
	MLSN	7.0	7.0	4.0	7.3	6.8	0.091
	SPF	8.0	7.3 **a**	4.3 **a**	7.8 **a**	7.0 **a**	0.048
	SLAN	7.0	7.0 **ab**	4.5 **a**	8.0 **b**	7.0 **ab**	0.045
Princen-NL	Control	9.0	8.0 **a**	8.0 **a**	8.0 **a**	8.0 **a**	0.026
	MLSN	9.0	8.0 **a**	8.0 **a**	8.0 **a**	7.5 **a**	0.012
	SPF	9.0	8.0 **a**	8.0 **a**	8.0 **a**	7.8 **a**	0.043
	SLAN	9.0	8.0	8.0	8.0	8.0	0.100

[a] Results reported at the first assessment date (Falken-Se and Princen-NL: July 2017, Landvik-NO: June 2017) before the trial started. Values not used for statistical analysis (Friedman test).

Appx. 7: Overall impression ratings (Rating scale 1 – 9) recorded monthly from April until November each year of trial on the *Agrostis stolonifera* putting greens at Duete-DE, Falken-SE, Jingshan-CN, and Landvik-NO. Mean ratings as median from four plots per treatment. Some dates are missing due to experimental site related vegetation period. Different letters indicate differences between treatments (p-value < 0.05; ns = not significant). For treatment description see Tab. 10, for experimental site description see Tab. 2.

Overall impression (Ratings 1 - 9)	Duete-DE								Falken-SE								Jingshan-CN								Landvik-NO							
1st Year	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.
Control	2.5	5.3	6.3	5.5	5.3	4.8	5.3	6.5	-	-	-	6.5	6.0	6.0	7.0	7.5	-	-	-	-	5.8	6.0	6.8	6.3	-	-	6.0	6.0	6.8	7.0	7.0	-
MLSN	2.5	4.5	5.5	5.3	5.0	4.3	5.5	6.5	-	-	-	5.0	4.5	4.5	5.5	7.0	-	-	-	-	5.3	6.5	6.3	6.0	-	-	7.0	7.3	7.3	7.0	7.0	-
SPF	2.5	4.5	5.0	5.0	5.0	4.5	5.5	6.0	-	-	-	4.5	4.5	4.5	5.5	6.0	-	-	-	-	5.0	6.3	6.5	6.0	-	-	8.0	7.5	7.3	7.0	7.3	-
SLAN	2.5	5.3	5.5	5.5	5.5	5.0	6.0	6.3	-	-	-	4.5	5.0	5.0	6.0	7.0	-	-	-	-	5.3	6.3	6.5	6.3	-	-	7.0	7.0	7.0	7.0	7.0	-
Kruskal-Wallis rank test	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**-**	**-**	**-**	**ns**	**ns**	**ns**	**ns**	**ns**	**-**	**-**	**-**	**-**	**ns**	**ns**	**ns**	**ns**	**-**	**-**	**ns**	**ns**	**ns**	**ns**	**ns**	**-**
p-value	0.996	0.265	0.414	0.974	0.968	0.921	0.824	0.906	-	-	-	0.195	0.414	0.414	0.264	0.388	-	-	-	-	0.374	0.826	0.791	1.000	-	-	0.187	0.236	0.235	0.976	0.942	-
2nd Year	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.
Control	3.5	4.8	6.3	6.8	7.0	7.0	6.3	5.8	-	6.0	6.5	6.0	5.5	7.0	6.5	7.0	5.8	7.0	7.0	7.0	7.5	8.0	7.0	7.0	-	-	-	3.5	3.5	4.3	4.8	-
MLSN	3.3	4.5	6.5	7.0	7.5	7.8	6.8	6.5	-	5.5	7.0	5.5	5.5	7.0	6.0	7.0	6.0	6.8	7.0	6.8	7.3	8.0	7.3	6.5	-	-	-	3.5	4.0	4.8	5.3	-
SPF	3.0	4.5	6.0	7.0	7.5	7.3	7.0	6.5	-	5.5	6.5	5.5	6.5	7.5	6.5	8.0	6.0	6.5	7.0	6.8	7.0	7.5	7.0	7.0	-	-	-	3.8	4.5	5.3	5.5	-
SLAN	3.3	4.3	6.3	6.3	7.3	7.0	6.8	6.5	-	6.0	6.5	6.0	6.5	7.0	6.5	7.5	6.0	6.5	7.3	7.0	7.0	7.8	7.0	7.0	-	-	-	3.5	5.0	5.5	5.8	-
Kruskal-Wallis rank test	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**-**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**-**	**-**	**-**	**ns**	**ns**	**ns**	**ns**	**-**
p-value	0.826	0.527	0.595	0.057	0.874	0.536	0.572	0.407	-	0.127	0.957	0.648	0.207	0.370	0.516	0.716	0.173	0.444	0.160	0.801	0.271	0.339	0.966	0.342	-	-	-	0.915	0.831	0.664	0.687	-
3rd Year	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.
Control	3.0	5.0	7.0	7.5	8.0	8.0	7.5	7.0	-	4.5	6.0	6.5	7.0	7.5	7.5	8.0	-	5.4	6.8	7.3	6.8	7.3	7.0	-	-	-	5.3	7.5	6.5	6.3	6.0	5.8
MLSN	3.3	5.5	7.3	7.8	7.5	8.0	7.5	7.0	-	5.0	6.0	6.5	7.5	7.0	8.0	8.0	-	5.6	6.4	7.3	7.0	7.0	7.0	-	-	-	7.3	8.0	7.3	7.0	7.3	6.8
SPF	3.5	6.3	7.5	7.8	7.5	7.8	7.8	7.3	-	5.5	7.5	7.0	7.5	7.0	8.0	8.0	-	5.5	7.0	7.0	7.4	7.0	7.3	-	-	-	7.0	8.3	7.8	7.3	7.5	7.3
SLAN	3.3	6.0	7.3	7.5	7.5	7.8	7.8	7.3	-	6.0	7.0	7.0	7.5	7.0	8.0	8.0	-	5.4	7.0	7.0	6.9	7.5	7.0	-	-	-	7.5	8.3	8.0	8.0	8.0	8.0
Kruskal-Wallis rank test	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**-**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**-**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**-**	**-**	**-**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**
p-value	0.464	0.251	0.295	0.652	0.714	0.866	0.711	0.605	-	0.064	0.187	0.288	0.760	0.843	0.845	0.764	-	0.643	0.249	0.730	0.421	0.149	0.802	-	-	-	0.324	0.126	0.230	0.462	0.168	0.130
4th Year	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.
Control	-	-	-	-	-	-	-	-	-	6.0	5.0	5.0	3.5	3.5	5.0	5.5	-	7.0	7.5 **ab**	7.5	7.0 **a**	7.0 **a**	7.0 **a**	-	4.0	5.5	6.5	7.0	7.3	7.0	7.3	-
MLSN	-	-	-	-	-	-	-	-	-	6.0	6.0	5.0	3.5	3.5	4.5	5.0	-	7.5	6.5 **a**	7.0	7.0 **a**	7.3 **ab**	7.5 **a**	-	4.8	5.0	6.8	7.0	7.3	7.0	7.3	-
SPF	-	-	-	-	-	-	-	-	-	6.0	5.5	5.5	4.0	4.0	4.5	5.5	-	7.5	8.0 **b**	7.5	7.3 **ab**	7.8 **ab**	7.8 **a**	-	5.3	5.0	7.5	7.5	7.3	7.3	7.3	-
SLAN	-	-	-	-	-	-	-	-	-	6.0	5.5	6.0	4.0	4.0	5.0	6.0	-	7.0	8.0 **b**	8.5	7.8 **b**	8.0 **b**	7.0 **a**	-	5.5	6.3	7.0	7.5	7.5	7.3	7.5	-
Kruskal-Wallis rank test	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**-**	**ns**		**ns**				**-**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**-**
p-value	-	-	-	-	-	-	-	-	-	0.543	0.599	0.788	0.717	0.735	0.911	0.464	-	0.753	0.009	0.079	0.009	0.034	0.044	-	0.083	0.430	0.361	0.684	0.927	0.930	0.927	-

Appx. 8: Overall impression (Rating scale 1 – 9) recorded monthly from April until November on the *Fr* + *Ac* experimental green at Princen-NL. Mean ratings as median from four plots per treatment. Some dates are missing due to experimental site related vegetation period. Different letters indicate differences between treatments (p-value < 0.05; ns = not significant). For treatment description, see Tab. 10.

Overall impression (Rating scale 1 - 9)								
1st Year	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.
Control	-	-	-	9.0	8.0	8.0	9.0	8.0
MLSN	-	-	-	9.0	8.0	8.0	9.0	8.0
SPF	-	-	-	9.0	8.0	8.0	9.0	8.0
SLAN	-	-	-	9.0	8.0	8.0	9.0	8.0
Kruskal-Wallis rank test	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
p-value	-	-	-	-	-	-	-	-
2nd Year	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.
Control	-	-	8.3	7.5	9.0	8.5	8.0	8.0
MLSN	-	-	8.0	7.5	9.0	8.5	8.0	8.0
SPF	-	-	8.0	7.0	9.0	8.5	8.0	8.0
SLAN	-	-	8.3	7.0	9.0	8.5	8.0	8.0
Kruskal-Wallis rank test	**-**	**-**	**ns**	**ns**	**-**	**-**	**-**	**ns**
p-value	-	-	0.801	0.975	-	-	-	0.392
3rd Year	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.
Control	-	8.0	7.5	7.5	8.0	8.0	8.0	-
MLSN	-	8.0	8.0	7.5	8.0	8.0	8.0	-
SPF	-	8.0	8.0	7.0	8.0	8.0	7.5	-
SLAN	-	8.0	8.0	7.5	8.5	8.0	7.5	-
Kruskal-Wallis rank test	**-**	**-**	**ns**	**ns**	**ns**	**-**	**ns**	**-**
p-value	-	-	0.845	0.930	0.475	-	0.801	-
4th Year	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.
Control	-	6.8	7.5	7.8	8.0	8.0	8.0	-
MLSN	-	7.0	7.5	8.0	8.0	7.5	8.0	-
SPF	-	7.0	7.5	8.0	7.8	7.5	8.0	-
SLAN	-	8.0	7.5	8.0	7.5	7.8	8.0	-
Kruskal-Wallis rank test	**-**	**ns**	**ns**	**ns**	**ns**	**ns**	**-**	**-**
p-value	-	0.072	0.764	0.845	0.175	0.325	-	-

Appx. 9: ***Poa annua*** **coverage (%) assessed monthly from April to November in each year of trial at Duete-DE, Falken-SE, Landvik-NO, and Princen-NL. Some dates are missing due to experimental site related vegetation period. Different letters denote significant differences between treatments for each measurement date (HSD or LSD α = 0.05; ns = not significant). For treatment description see Tab. 10, for experimental site description see Tab. 2.**

Poa annua (%)

	Duete-DE								Falken-SE							
1st Year	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.
Control	49.1	51.8	50.5	47.8	37.3	36.0	44.4	43.5	-	-	-	47.3	47.8	47.8	48.8	48.5
MLSN	51.5	55.5	53.0	50.5	39.8	37.3	44.9	45.8	-	-	-	50.0	49.8	49.8	51.0	50.8
SPF	48.8	55.3	52.8	50.3	39.3	36.3	41.8	42.3	-	-	-	49.0	49.0	49.0	50.8	50.0
SLAN	50.5	53.1	52.5	49.8	38.3	36.5	43.8	46.0	-	-	-	53.3	53.3	53.3	54.0	53.8
ANOVA p-value	0.816	0.381	0.735	0.639	0.808	0.911	0.726	0.710	-	-	-	0.195	0.279	0.279	0.341	0.379
HSD (α=0.05)	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	-	-	-	**ns**	**ns**	**ns**	**ns**	**ns**
LSD (α=0.05)																
2nd Year	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.
Control	36.8 **ab**	41.0 *ab*	40.5	36.3	32.8	32.0	31.8	33.0	-	47.5 **ab**	48.5 **a**	48.5 **a**	48.5 **ab**	48.5	48.5 *a*	48.8
MLSN	43.3 **b**	45.8 *b*	41.3	36.5	30.5	32.3	31.8	33.5	-	46.5 **a**	47.8 **a**	47.8 **a**	47.8 **a**	48.3	48.5 *a*	48.5
SPF	43.5 **b**	45.5 *b*	41.5	39.3	36.8	33.0	33.0	32.8	-	48.0 **b**	48.8 **a**	49.5 **ab**	49.0 **ab**	49.3	49.0 *ab*	49.3
SLAN	36.3 **a**	40.3 *a*	41.5	38.8	32.5	33.8	33.0	34.0	-	50.0 **c**	51.5 **b**	51.5 **b**	51.3 **b**	51.0	50.3 *b*	49.8
ANOVA p-value	0.017	0.066	0.985	0.618	0.389	0.587	0.874	0.688	-	0.001	0.008	0.014	0.023	0.060	0.048	0.230
HSD (α=0.05)	**7.0**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	-	**1.4**	**2.4**	**2.7**	**4.9**	**ns**	**ns**	**ns**
LSD (α=0.05)		*4.9*													*1.3*	
3rd Year	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.
Control	30.5	34.5	36.5	33.8	32.8	32.3 *ab*	30.5	30.3 *a*	-	38.5 a	43.5	49.0	49.8	50.0	49.5 **a**	49.5
MLSN	34.0	35.5	36.0	32.8	32.0	34.0 *b*	31.5	30.5 *a*	-	40.8 ab	47.0	50.0	49.5	49.5	49.3 **a**	49.3
SPF	33.0	35.5	34.5	31.5	31.5	31.3 *a*	30.3	30.3 *a*	-	47.3 bc	50.0	50.8	50.8	50.8	50.5 **ab**	50.5
SLAN	31.0	35.0	37.5	33.8	33.0	34.5 *b*	32.8	33.3 *b*	-	49.3 c	50.5	51.3	51.0	50.8	51.0 **b**	50.5
ANOVA p-value	0.362	0.709	0.271	0.346	0.121	0.050	0.083	0.037	-	0.011	0.107	0.240	0.216	0.387	0.048	0.198
HSD (α=0.05)	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	-	**8.2**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**
LSD (α=0.05)						*2.4*		*2.2*							*1.3*	
4th Year	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.
Control	-	-	-	-	-	-	-	-	-	49.5	49.8	49.0	51.3	37.5	46.3	49.3
MLSN	-	-	-	-	-	-	-	-	-	49.3	50.3	49.3	51.3	35.0	45.5	46.3
SPF	-	-	-	-	-	-	-	-	-	49.8	50.5	50.8	48.8	38.8	46.8	45.5
SLAN	-	-	-	-	-	-	-	-	-	50.8	51.3	50.0	52.5	45.0	45.0	49.3
ANOVA p-value	-	-	-	-	-	-	-	-	-	0.141	0.413	0.061	0.367	0.316	0.935	0.489
HSD (α=0.05)	-	-	-	-	-	-	-	-	-	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**
LSD (α=0.05)																

	Landvik-NO								Princen-NL							
1st Year	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.
Control	-	-	6.3	6.5	4.3	5.5	5.8	-	-	-	-	5.0	4.3	5.3	0.3	1.0
MLSN	-	-	8.8	7.8	8.0	7.8	7.3	-	-	-	-	5.0	4.5	4.5	0.3	1.0
SPF	-	-	6.5	6.5	8.5	8.0	6.8	-	-	-	-	5.0	5.5	3.5	0.3	1.3
SLAN	-	-	4.3	4.3	6.8	3.8	4.0	-	-	-	-	5.0	4.3	4.8	0.3	0.5
ANOVA p-value	-	-	0.401	0.620	0.659	0.474	0.327	-	-	-	-	-	0.622	0.147	0.537	0.138
HSD (α=0.05)	-	-	**ns**	**ns**	**ns**	**ns**	**ns**	-	-	-	-	-	**ns**	**ns**	**ns**	**ns**
LSD (α=0.05)																
2nd Year	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.
Control	-	-	-	8.8	6.5	7.5	7.5 **a**	-	-	-	4.5	5.5	0.8	1.8	2.5	-
MLSN	-	-	-	12.0	13.3	15.0	18.0 **b**	-	-	-	4.3	7.0	1.3	1.8	2.3	-
SPF	-	-	-	10.8	11.5	13.8	14.3 **ab**	-	-	-	4.3	6.8	1.3	2.5	3.0	-
SLAN	-	-	-	9.0	9.3	11.3	10.8 **ab**	-	-	-	4.8	7.8	2.0	2.0	3.3	-
ANOVA p-value	-	-	-	0.822	0.201	0.137	0.028	-	-	-	0.082	0.779	0.187	0.638	0.552	-
HSD (α=0.05)	-	-	-	**ns**	**ns**	**ns**	**8.9**	-	-	-	**ns**	**ns**	**ns**	**ns**	**ns**	-
LSD (α=0.05)																
3rd Year	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.
Control	-	-	17.5	14.8	6.0	3.8	3.3	3.5	-	5.3	16.3	6.8	7.5	8.8	8.8	-
MLSN	-	-	30.0	27.0	10.8	7.8	6.0	5.5	-	9.3	16.3	10.0	10.3	12.3	8.8	-
SPF	-	-	29.3	32.5	15.8	11.3	10.0	9.8	-	8.8	16.3	13.3	15.0	16.8	12.0	-
SLAN	-	-	19.3	17.0	6.5	4.0	2.3	3.5	-	6.3	19.8	12.3	13.0	14.5	11.5	-
ANOVA p-value	-	-	0.331	0.162	0.271	0.359	0.220	0.265	-	0.217	0.704	0.503	0.398	0.269	0.511	-
HSD (α=0.05)	-	-	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	-	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	-
LSD (α=0.05)																
4th Year	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.
Control	3.3	5.0	4.3 **a**	2.8	2.3 **a**	3.8	1.8 **a**	-	-	10.5	6.5	8.0	8.0	8.0	8.0	-
MLSN	5.5	11.0	9.3 **ab**	5.3	3.5 **ab**	5.0	2.8 **ab**	-	-	7.0	3.3	7.0	7.3	7.3	7.3	-
SPF	8.0	15.8	14.5 **b**	10.3	5.8 **b**	6.8	4.8 **b**	-	-	4.0	3.3	6.5	7.5	8.8	8.8	-
SLAN	4.8	9.5	9.5 **ab**	6.0	4.5 **ab**	4.8	2.8 **ab**	-	-	4.0	2.3	4.0	4.5	12.0	12.0	-
ANOVA p-value	0.111	0.060	0.054	0.186	0.058	0.093	0.038	-	-	0.384	0.608	0.648	0.731	0.778	0.778	-
HSD (α=0.05)	**ns**	**ns**	**9.6**	**ns**	**3.5**	**ns**	**2.6**	-	-	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	-
LSD (α=0.05)																

Appx. 10: Rooting depth (mm) measured monthly from April to November in each year of trial on the *Agrostis stolonifera* putting greens at Duete-DE, Falken-SE, Jingshan-CN, and Landvik-NO. Some dates are missing due to experimental site related vegetation period. Different letters denote significant differences between treatments for each measurement date (HSD or LSD, α = 0.05; ns = not significant). For treatment description see Tab. 10, for experimental site description see Tab. 2.

	Rooting depth (mm)																															
	Duete-DE								Falken-SE								Jingshan-CN								Landvik-NO							
1st Year	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.
Control	29	36	33	35	38 **ab**	44 **b**	48	50	-	-	-	130	125	128	118	153	-	-	-	-	159	138	122	104 **a**	-	-	50	44	58	54	59	-
MLSN	29	35	31	35	41 **b**	38 **ab**	45	50	-	-	-	125	120	123	115	150	-	-	-	-	149	141	128	114 **ab**	-	-	78	69	61	68	61	-
SPF	26	35	34	34	36 **ab**	36 **a**	44	53	-	-	-	125	123	120	118	155	-	-	-	-	142	139	124	125 **b**	-	-	56	71	68	64	75	-
SLAN	27	32	34	33	34 **a**	35 **a**	43	49	-	-	-	130	130	130	125	165	-	-	-	-	158	153	122	115 **ab**	-	-	66	54	60	58	61	-
ANOVA p-value	0.714	0.579	0.630	0.683	0.051	0.026	0.353	0.621	-	-	-	0.834	0.744	0.645	0.561	0.675	-	-	-	-	0.366	0.472	0.452	0.053	-	-	0.536	0.127	0.713	0.785	0.385	-
HSD (α=0.05)	**ns**	**ns**	**ns**	**ns**	**6.8**	**8.2**	**ns**	**ns**	**-**	**-**	**-**	**ns**	**ns**	**ns**	**ns**	**ns**	**-**	**-**	**-**	**-**	**ns**	**ns**	**ns**	**19.5**	**-**	**-**	**ns**	**ns**	**ns**	**ns**	**ns**	**-**
LSD (α=0.05)																																
2nd Year	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.
Control	51	50	78	57	53	72	72	57	-	143	133	133	163	155	145	163	138	125	134	116	111	101	109	111	-	-	-	89	96	81	78	-
MLSN	48	52	83	57	50	67	67	60	-	145	140	140	163	155	145	163	141	123	124	120	128	89	109	115	-	-	-	73	64	56	75	-
SPF	51	55	80	62	58	66	76	60	-	140	148	148	170	158	145	163	139	125	130	103	114	100	115	115	-	-	-	58	59	60	64	-
SLAN	61	54	104	67	55	69	73	55	-	173	150	150	170	155	150	163	153	120	126	122	123	97	114	113	-	-	-	71	68	59	56	-
ANOVA p-value	0.067	0.791	0.099	0.643	0.145	0.486	0.522	0.617	-	0.077	0.356	0.356	0.411	0.977	0.802	1.000	0.472	0.660	0.342	0.118	0.205	0.242	0.621	0.753	-	-	-	0.354	0.082	0.212	0.253	-
HSD (α=0.05)	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**-**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**-**	**-**	**-**	**ns**	**ns**	**ns**	**ns**	**-**
LSD (α=0.05)																																
3rd Year	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.
Control	45	53	53	52	56	48	47 **a**	44	-	170	165 **ab**	128	148 **a**	160	170	178	-	99	92 **a**	102 **a**	108 **a**	116	108	-	-	-	74	88	84	103	93	96 *b*
MLSN	48	53	59	56	60	57	57 **b**	44	-	165	155 **a**	118	150 **a**	163	170	175	-	107	111 **b**	103 **a**	116 **ab**	119	89	-	-	-	68	84	75	81	80	81 *a*
SPF	53	52	63	57	62	53	56 **b**	46	-	165	165 **ab**	123	153 **a**	165	170	178	-	108	105 **b**	112 **b**	134 **b**	135	112	-	-	-	64	71	81	71	81	81 *a*
SLAN	43	51	67	56	61	56	55 **b**	49	-	178	173 **b**	133	160 **b**	170	183	188	-	126	121 **c**	125 **c**	129 **b**	122	97	-	-	-	78	85	99	85	79	81 *a*
ANOVA p-value	0.376	0.995	0.223	0.778	0.381	0.387	0.012	0.755	-	0.294	0.061	0.216	0.004	0.240	0.341	0.110	-	0.105	0.000	0.000	0.017	0.207	0.000	-	-	-	0.507	0.466	0.153	0.342	0.627	0.051
HSD (α=0.05)	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**7.6**	**ns**	**-**	**ns**	**16.9**	**ns**	**7.1**	**ns**	**ns**	**ns**	**-**	**ns**	**9.9**	**5.6**	**20.6**	**ns**	**4.2**	**-**	**-**	**-**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**
LSD (α=0.05)																																*11.9*
4th Year	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.
Control	-	-	-	-	-	-	-	-	-	135	128	113	125	135	135	138	-	102	122	121	103 **a**	103 **a**	108 **a**	-	106	104	134	143 **b**	120	108	104	-
MLSN	-	-	-	-	-	-	-	-	-	133	128	123	133	148	143	140	-	101	119	129	106 **a**	104 **a**	112 **a**	-	91	91	105	93 **a**	98	83	91	-
SPF	-	-	-	-	-	-	-	-	-	138	128	118	128	148	145	145	-	102	119	126	102 **a**	106 **ab**	123 **b**	-	88	95	105	109 **ab**	91	98	82	-
SLAN	-	-	-	-	-	-	-	-	-	135	125	120	120	150	143	145	-	103	129	133	116 **b**	114 **b**	107 **a**	-	82	89	101	99 **ab**	88	81	95	-
ANOVA p-value	-	-	-	-	-	-	-	-	-	0.878	0.843	0.642	0.554	0.603	0.494	0.455	-	0.980	0.407	0.274	0.002	0.018	0.003	-	0.143	0.432	0.233	0.028	0.351	0.140	0.375	-
HSD (α=0.05)	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**-**	**ns**	**ns**	**ns**	**7.1**	**9.2**	**9.1**	**-**	**ns**	**ns**	**ns**	**43.9**	**ns**	**ns**	**ns**	**-**
LSD (α=0.05)																																

Appx. 11: Rooting depth (mm) measured monthly from April to November on the *Fr + Ac* experimental green at Princen-NL. Some dates are missing due to experimental site related vegetation period. Different letters denote significant differences between treatments for each measurement date (HSD or LSD, α = 0.05; ns = not significant). For treatment description, see Tab. 10.

			Rooting depth (mm)					
1st Year	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.
Control	-	-	-	81	73	74	79	85
MLSN	-	-	-	84	81	88	80	80
SPF	-	-	-	86	83	83	86	88
SLAN	-	-	-	88	81	78	81	88
ANOVA p-value	-	-	-	0.726	0.416	0.133	0.375	0.702
HSD (α=0.05)	**-**	**-**	**-**	**ns**	**ns**	**ns**	**ns**	**ns**
LSD (α=0.05)								
2nd Year	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.
Control	-	-	105	100	98	83	95	105
MLSN	-	-	100	126	103	93	95	85
SPF	-	-	100	120	108	91	98	101
SLAN	-	-	105	131	94	93	95	96
ANOVA p-value	-	-	0.970	0.094	0.460	0.306	0.974	0.241
HSD (α=0.05)	**-**	**-**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**
LSD (α=0.05)								
3rd Year	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.
Control	-	73	103	108	89	96	89	-
MLSN	-	68	98	95	83	95	96	-
SPF	-	65	89	105	64	95	94	-
SLAN	-	78	106	106	83	110	113	-
ANOVA p-value	-	0.794	0.617	0.134	0.378	0.212	0.138	-
HSD (α=0.05)	**-**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**-**
LSD (α=0.05)								
4th Year	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.
Control	-	80	84	88	88 **a**	98	103	-
MLSN	-	95	98	99	80 **a**	105	93	-
SPF	-	83	85	93	103 **ab**	93	118	-
SLAN	-	89	90	105	120 **b**	110	109	-
ANOVA p-value	-	0.819	0.535	0.468	0.010	0.535	0.516	-
HSD (α=0.05)	**-**	**ns**	**ns**	**ns**	**27.4**	**ns**	**ns**	**-**
LSD (α=0.05)								

Statement of Authentication

I hereby declare that I have written the present thesis independently, without assistance from external parties and without use of other resources than those indicated. The ideas taken directly or indirectly from external sources (including electronic sources) are duly acknowledged in the text. The material, either in full or in part, has not been previously submitted for grading at this or any other academic institution.

Osnabrück, 20th of October 2021

Place, Date Signature

Acknowledgement

To write my master thesis was exciting in the beginning, frustrating in the middle, and hard work at the end. It would have never been possible to write 97 pages without many people. Now it is time for me to say "**THANK YOU**" to…

…**Wolfgang Prämaßing** for giving me the possibility to write my master thesis about the results of this great international project, for his advice during writing, and not to forget for getting me in contact with the NIBIO research station in Landvik (Norway).

…**Hans-Werner Olfs** for taking the chance to learn more about turfgrass fertilization and for "first aid" when I got lost in English writing and too many results. Diploma thesis, master thesis – we will see what comes next ;-)

…**Karin Juul Hesselsøe** for helping me to find my way through the jungle of all SUSPHOS data, good discussions about the results, and for all your positive support during writing.

…**Eva Brand** – what would I have done without your humor? Thanks for finding all my mistakes in figures and tables. I still think it is time to get on a cruise together.

…**Jan Cordel** for being my most important turfgrass expert and motivator. We still have a project to work on – I have not forgotten it.

…**Klaudia and Michael Klindtworth** for last-minute table header support and encouragement during master studies.

…**Herbert Pralle** for all advice and discussion about statistics. Numbers will never be my thing, but I know where to find someone who knows all about them.

…**Brian Wiedenfeld** and **Ann-Christin Sanner** for making my English a lot better.

…**Trygve S. Åmlid** for encouragement during writing.

...all **greenkeepers, technicians,** and **researchers** that conducted these trials and accurately recorded all observations. It was a pleasure to work with the data you collected.

...my **family** and **friends** for being patient with me, reading my text, and supporting me with lots of chocolate.