PRECISION FERTILISATION

– From theory to practice

UPDATE 2021

ABOUT THE FERTILISATION HANDBOOK

The first (2011) edition of this handbook summarised the knowledge and experiences gained in three research projects on fertilisation funded by STERF in the period 2003-2011:

- Effect of precision fertilisation on the growth, appearance and nitrogen utilisation of turfgrasses
- Fertiliser strategies for golf turf: Implications for physiology-driven fertilisation
- Impact of mowing height and autumn fertilisation on winter survival of golf greens in the Nordic countries

The current (2021) handbook has been updated with the results from the STERF projects *Optimal application of nitrogen and sulphur in autumn for better winter survival of turfgrasses* and *SUSPHOS: Sustainable phosphorus (P) fertilization on golf courses*. While former STERF projects mostly focused on nitrogen (N), the aim of SUSPHOS was to investigate if P fertilization can be reduced on golf course putting greens without negative implications on turf quality. Information about these projects and popular and scientific papers can be found at **www.sterf.org**

FIND OUT MORE

Demand-driven fertilization. Part I: Nitrogen productivity in four high-maintenance turf grass species. T. Ericsson, K. Blombäck & A. Neumann 2012. - Acta Agriculturae Scandinavica, 62(1):113-121.

Demand-driven fertilization. Part II: Influence of demand-driven fertilization on shoot nitrogen concentration, growth rate, fructan storage and playing quality of golf turf. T. Ericsson, K. Blombäck & A. Neumann 2012. - Acta Agriculturae Scandinavica, 62(1):139-149.

Reduced phosphorus fertilization on golf courses: A comparison of three fertilizer recommendations for putting greens. K. J. Hesselsøe, A. F. Borchert, A. F. Øgaard, T. Krogstad, Y. Chen, W. Pramässing & T.S. Aamlid. 2021: Submitted to Int. Turfgrass Soc. Res. Jour. June 2021

Temperature effects on phosphorus requirements for creeping bentgrass establishment and spring growth. A.F. Øgaard & T.S. Aamlid 2020. Agronomy Journal 112:3478–3490. https://doi.org/10.1002/agj2.20288

Einfluss unterschiedlicher P-Düngeempfehlungen auf die Nährstoffgehalte im Boden und die Qualität von Golfgrüns am Beispiel des Golfplatzes Dütetal (Osnabrück). A. F. Borchert, J. Rosenbusch, K.J. Hesselsøe, T.S. Aamlid & W. Prämaßing. 2020. European Journal of Turfgrass Science (RASEN · TURF · GAZON) 3: 61-66

Green fertilization the Scandinavian way. A. Kvalbein & T. S. Aamlid 2012.
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Phosphorus for turfgrass – the SUSPHOS project. K. J. Hesselsøe, A.F. Øgaard & T.S. Aamlid 2020
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MLSN fertilization on golf courses. T. S. Aamlid & K. J. Hesselsøe 2020
http://www.sterf.org/Media/Get/3444/mlsn-fertilization-english.pdf

TOWARDS A MORE SUSTAINABLE FERTILISATION

Long before the beginning of the modern age, it was known that all plants need some form of nutrients in order to grow and develop in a satisfactory way. However, it was only discovered in the mid-1800s that the 'food' used by plants consists primarily of basic elements from the Earth's crust. Today, we know that all plants require the same 14 elements and we have good knowledge of why these elements are required. Supplying nutrients has now become the most effective measure for controlling the growth and influencing the quality of crops, including golf turf. The underlying theory and the methods used for applying fertiliser to fairways and greens are strongly influenced by the methods used in agriculture. However modern golf courses, particularly in terms of green constructions, differ from the soils in which arable crops are grown. Greens built according to USGA norms have a very restricted nutrient storage capacity. Fertilisation in excess is therefore a method that should be avoided from both an economic and environmental perspective. Instead, fertilisation of greens should be based around small, frequently occurring doses, the size of which is determined by the actual nutrient requirements of the grass and knowledge of how these requirements vary during the season. This is the underlying reasoning for the concept 'precision fertilisation'.

Precision fertilisation is based on the assumption that the grass requires nutrients in constant relative proportions. The same fertiliser can therefore be used from spring until autumn and fertilisation can be adapted based on the nitrogen requirement of the grass and soil analyses.

Through precision fertilisation, the nitrogen content of the grass and therefore growth and quality characteristics are determined by the genetic composition of the grass and the climate conditions found at the site. By matching fertilisation to requirements during the season, it is possible to avoid undesirable fluctuations in grass growth and playing quality.

This handbook presents the theory behind this fertilisation concept, together with simple instructions on how to carry out precision fertilisation.

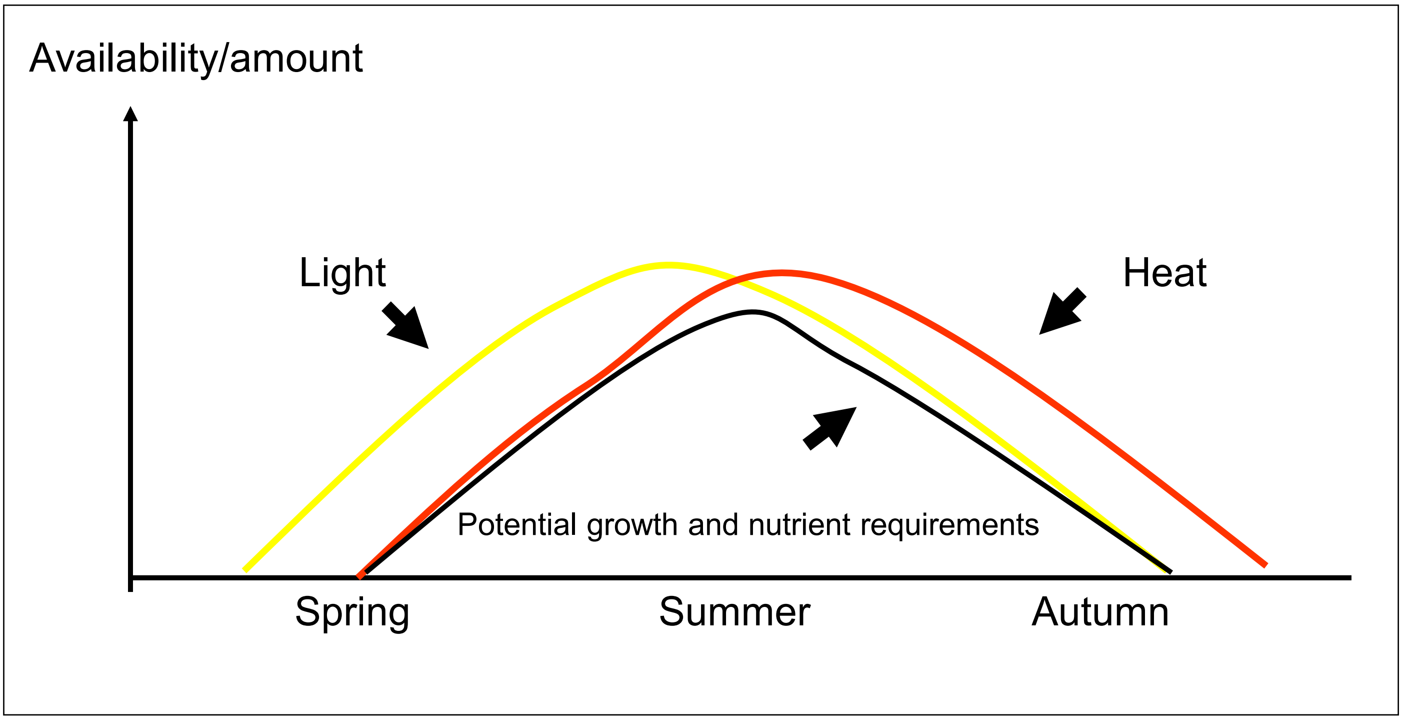


Figure 1 - Seasonal dynamics – light, heat and potential growth/nutrient requirement of turfgrass.

LIGHT AND HEAT CONTROL - THE GROWTH POTENTIAL OF GRASS

It is becoming increasingly common for nutrients to be applied to greens in weekly or biweekly doses, but the shape of the fertilisation curve during the growing season can vary widely between golf courses. There are many possible explanations for this variation, but the factors determining the potential growth of grass, and therefore its nutrient requirements, are the availability of light, heat and water. Water availability is usually the only one of these factors that can be controlled by the greenkeeper on a daily basis. Water availability is critically important for the ability of the grass to cool its leaves by transpiration on hot summer days. Good access to water is also vital for cell division and elongation, and thereby leaf growth, which is fundamental for the ability of the grass to capture solar energy and carry out photosynthesis.

Daylength and light intensity determine the amount of solar energy available to the grass for use in the energy-demanding processes in photosynthesis. The temperature controls the rate of all biochemical reactions and thus how rapidly new leaves and roots are formed during the season. In spring, it is generally the temperature that restricts grass growth and development, while in autumn it is lack of light that causes growth to decline and thus also the nutrient requirement (Figure 1). Therefore, the availability of light together with the area of green leaves determines the amount of solar energy that can be captured by the plant and converted into carbohydrates via photosynthesis. These carbohydrates provide fuel for the plant and building materials for new shoots and roots. The growth potential and the associated fertiliser requirement are therefore greatest when the light availability is at maximum (Figure 1).

It is not possible to force growth in the spring with the help of large doses of nutrients when the machinery of the grass is operating in a low gear due to lack of heat. Likewise, it is not possible to compensate for lack of light with increasing doses of nutrients as the days become shorter in autumn.

Warm summer days lower the nutrient requirement

It is not only low temperatures that inhibit grass growth. As the temperature approaches 30 °C, the efficiency of photosynthesis is reduced in plants adapted to the Nordic climate. This means that the growth-determining role of light decreases in warm weather. When photosynthesis is slower, there is a decrease in the growth capacity of grass and thus also in its nutrient requirement. The fertiliser level may therefore need to be lowered in the middle of summer if a hot spell continues for more than a week.

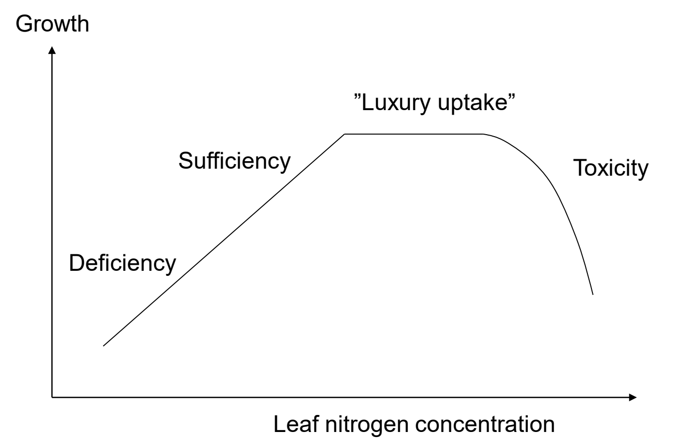


Figure 2 – Relationship between leaf nitrogen concentration and growth..

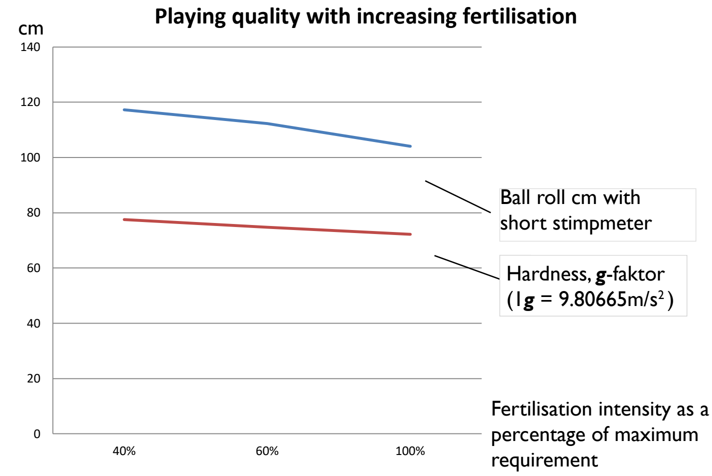


Figure 5 – Effect of increasing fertilisation on playing quality. Mean of six species in fertiliser trials at Landvik 2009.

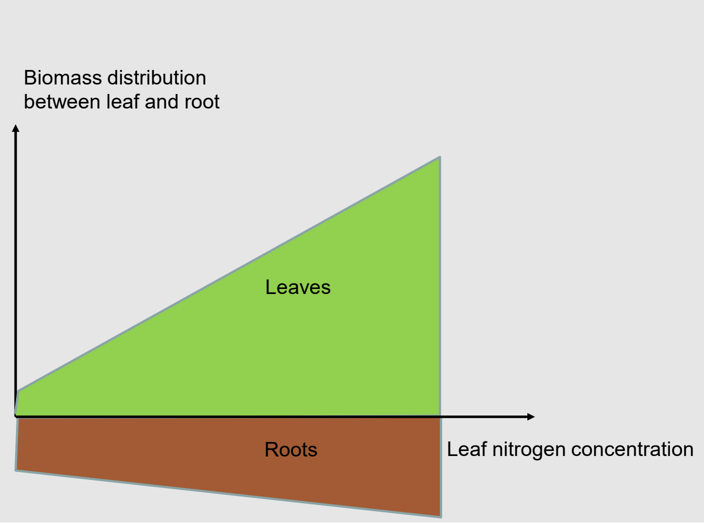


Figure 3 – Effect of leaf nitrogen concentration on leaf and root development.

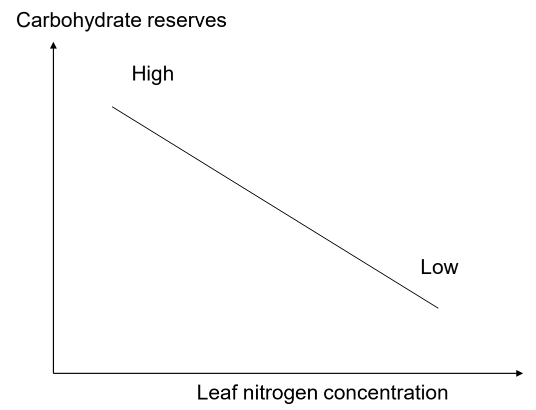


Figure 6 – Effect of leaf nitrogen concentration on the amount of carbohydrate reserves.

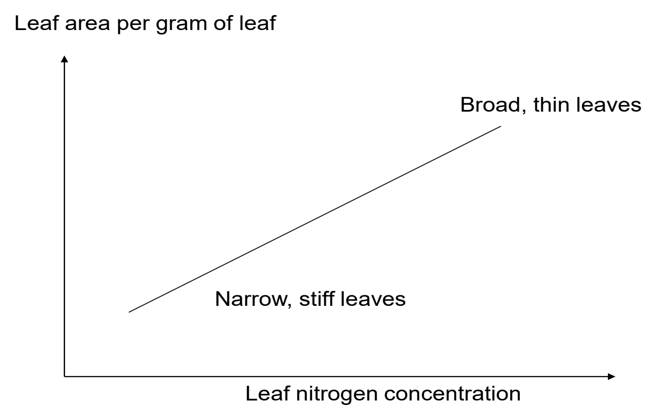
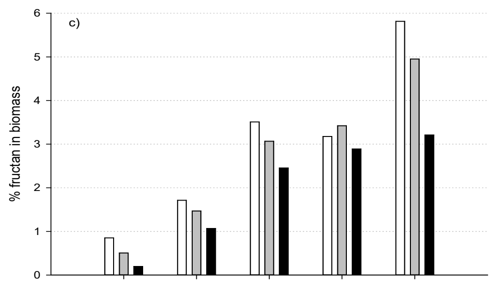


Figure 4 – Effect of leaf nitrogen concentration on leaf formation.



White = 40% of max. requirement
Grey = 60% of max. requirement
Black = 100% of max. requirement

Figure 7 – Effect of fertilisation intensity on carbohydrate storage in the leaves of different cultivars of fescue and bents.

Nitrogen is important for growth. This picture shows how the nitrogen content in the leaves affected shoot growth in uncut 40-day-old creeping bent plants in a climate chamber. Photo: Tom Ericsson

NITROGEN CONTENT IN LEAVES CONTROLS MANY IMPORTANT PROCESSES

Nitrogen is the nutrient that grass plants require the most. It is a component of amino acids and proteins, and therefore of enzymes, the compounds that control all chemical reactions in the plant. Nitrogen is also an important component of plant DNA and hormones, thereby playing a central role in the plant's 'machinery'. It is a well-known fact that supplying nitrogen has a powerful impact on plant growth (Figure 2). However, nitrogen supply also affects a range of other important functions and characteristics.

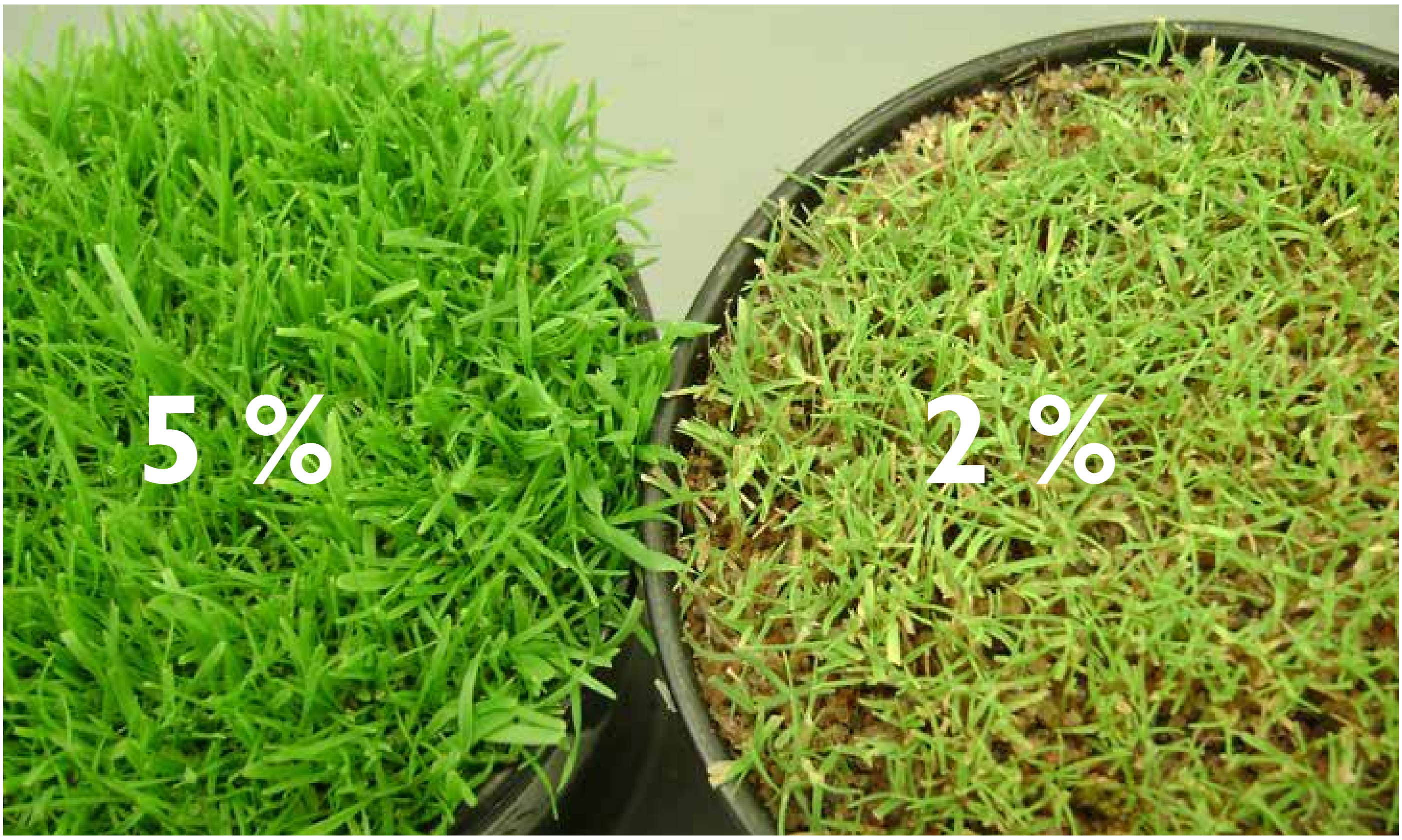
Nitrogen availability determines the distribution of aboveground and belowground growth, i.e. the distribution between shoots and roots and thereby also the respective capacity of the plant to bind solar energy and take up water and nutrients (Figure 3). Nitrogen also affects leaf morphology (Figure 4). The better the nitrogen availability and the higher the growth rate, the thinner (softer) and larger (wider) are the leaves. The nitrogen status of the grass is therefore important for ball roll and thus playing quality (Figure 5).

The hardness of the greens is also an important factor. Fertilising above the optimum increases thatch formation and makes the greens softer. Growth is stimulated by nitrogen fertilisation primarily because aboveground growth is stimulated, so the grass becomes better at capturing solar energy, and also because the amount of carbohydrates required to form a certain leaf area is lower when access to nitrogen is good.

Fertilisation intensity also affects the capacity of the grass to store carbohydrates in shoots and roots. As the amount of nitrogen available to the grass increases, a greater proportion of the carbohydrates formed is used for growth and thus a lower proportion is available for storage in tissues and for use in other vital functions (Figures 6 and 7). Wide and thin leaves have limited wear tolerance, and the production of defence compounds may be sacrificed for higher growth rates.

Even when the nitrogen availability is relatively low and only allows plants to grow at half capacity, plants develop healthy green leaves as long as the nitrogen supply is constant and harmonised with the growth potential. Creating stable internal nitrogen concentrations in grass leaves and roots is therefore one of the central targets in precision fertilisation. The nitrogen concentration in the tissues sometimes needs to be high for rapid repair of damage occurring during the winter or after intensive use.

When playing quality is the main focus and fast surfaces are desired, the leaves of the grass need to be stiffer, which can be achieved by decreasing the fertilisation rate and thus reducing the nitrogen concentration in leaves and roots.



Effect of nitrogen addition on leaf nitrogen concentration (dry matter), shape and colour in creeping bent. Photo: Tom Ericsson

THREE PER CENT NITROGEN IN LEAVES IS ENOUGH

In precision fertilisation, the aim is to provide nutrient conditions that give a relatively constant nitrogen concentration in the plant over time. By controlling the nitrogen level in the plant with the aid of fertilisation, various desirable qualities of the grass can be achieved.

Trials carried out in the greenhouse (Swedish University of Agricultural Sciences (SLU)) and in the field (Landvik, Norway) show that a nitrogen concentration of 3.1-3.5% in dried grass clippings is sufficient to achieve good colour and playing quality in annual meadowgrass, creeping bent, common (browntop) bent, velvet bent and red fescue. With this concentration of nitrogen in the leaves, the growth rate was approx. 60% of the maximum rate and all species tested had better root development, stiffer leaves and larger carbohydrate reserves than when nitrogen availability allowed higher nitrogen concentrations and thus maximum growth.

However, if high growth is required in order to repair damage quickly, nitrogen concentrations of around 6% in dried clippings of annual meadowgrass and the bentgrasses can be accepted without exceeding the uptake capacity of the grass. In contrast, the fescues reach their full growth potential at a nitrogen concentration of approx. 5% in dried leaves.

An experienced greenkeeper can judge from the colour of the grass whether the fertilisation level is right or wrong. The amount of clippings produced also sends a clear signal about the nitrogen status of the grass. However, when it is uncertain how the fertilisation programme is working, leaf analysis can be a great help. Leaf analysis in this case involves determining the percentage content of nitrogen in grass clippings. Inclusion of dressing sand in the sample submitted for analysis should be avoided, since the high weight of the sand grains leads to underestimation of the actual nitrogen content in the grass.

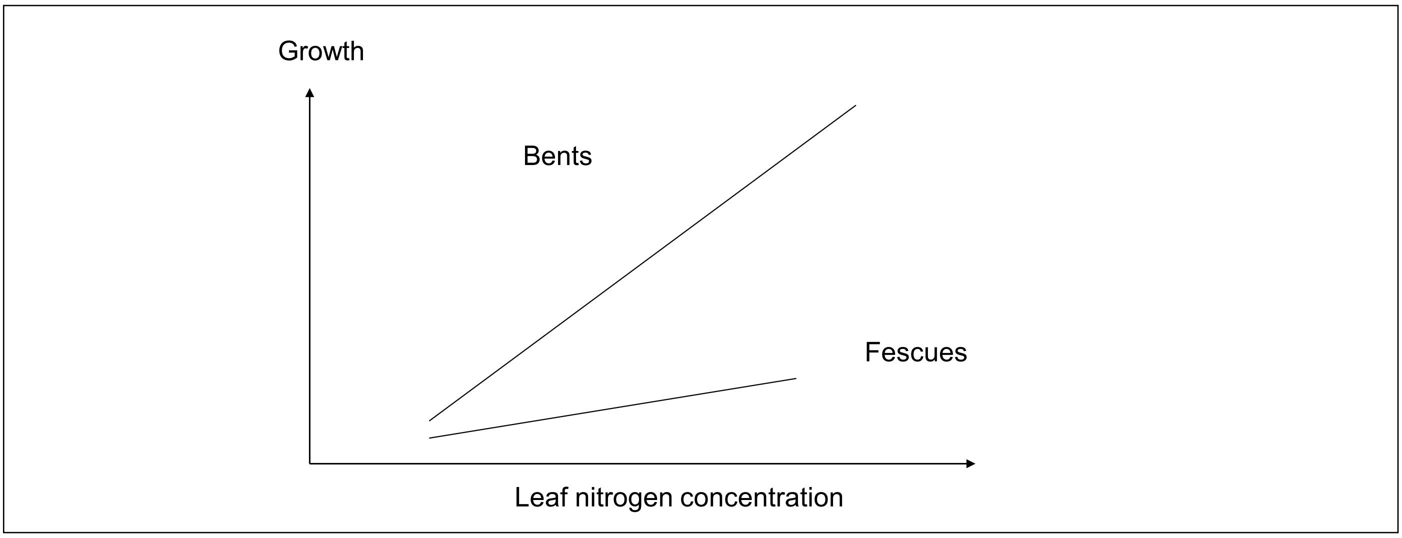


Figure 8 – Capacity of turfgrasses to utilise nitrogen for growth

DIFFERENCES BETWEEN TURFGRASSES

There are differences in the capacity of different turfgrass species to utilise nitrogen. Fast-growing species (meadowgrasses and bentgrasses) grow faster at a given nitrogen concentration in the leaves than slow-growing species (fescues) (Figure 8). The reason for this is that the amount of carbohydrates needed to produce a given amount of leaf area is higher for slow-growing species than for fast-growing. The thicker the leaves and therefore the higher the carbohydrate consumption for leaf growth, the lower the nitrogen productivity, i.e. the growth rate per unit nitrogen taken up. This observation is general and applies for all plants.

It is well known that turfgrasses grow at different rates and therefore have different nutrient requirements. Less is known about the magnitude of the differences between species, which limits the precision in formulation of fertilisation plans. A STERF study completed in 2011 ranked the growth capacity and relative nutrient requirements of established plants of annual meadowgrass, creeping bent, common bent, velvet bent and red fescue. The results showed that annual meadowgrass had just over 10% higher, and common bent and velvet bent approx. 30% lower, nutrient requirements than creeping bent. Chewings fescue and slender creeping red fescue ended up last in the ranking with nutrient requirements 45% and 67% lower than those of creeping bent. Experiences from later STERF projects have mostly confirmed this ranking but based on experiences from the 'Fescue Green' project (Box 1 on page 21) we now recommend a fertiliser level to pure red fescue (both subspecies) greens and mixed fescue and common (browntop) bent greens corresponding to 60 % of that used in creeping bent (Table 1).

In absolute terms, our trials have shown that approx. 1.6 kg N per 100 m^2 is sufficient for creeping bentgrass greens in central and southern (lowland) parts of the Nordic countries. This fertiliser level gives a nitrogen concentration of approx. 3% in leaf dry matter and the growth rate is approx. 60 % of the maximum rate.

It must be emphasized that these recommendations apply to mature greens with an established well-balanced microbial community in the upper rootzone. During the 6-10 week grow-in period after seeding or reseeding greens, the fertiliser requirement is usually twice as high as for established greens.

Table 1 – Ranking of the growth capacity of some common turfgrasses

Species/variety	Ranking
Annual meadowgrass	1.12
Creeping bent	1
Pure red fescue and fescue/bentgrass (common, velvet and creeping) mixtures	0.60

ADAPTATION TO VARIATIONS IN GROWING CONDITIONS

Since the potential growth of grass is controlled by the availability of light, heat and water, the fertilisation level must be adapted to the growing conditions. Shade, high temperature or drought reduce the growth capacity. When one of these situations arises, the fertilisation level should be lowered to prevent the nitrogen concentration in the leaves from increasing. If the fertilisation level is not reduced, shoot growth will be promoted at the expense of root growth. The leaves will become softer and the carbohydrate reserves in the tissues will decrease. This is not good for playing quality or for the ability of the grass to withstand attacks by fungi and other pests.

The same argument applies when the cutting height of the turf is lowered before tournaments. When the leaf area is reduced, the capacity of the grass to capture solar energy is also reduced. This decreases the growth capacity and the nutrient requirement (Figure 9). In order to avoid changes in the growth pattern of the grass above and below the ground and to maintain leaf structure and carbohydrate levels in the tissues, the fertilisation intensity must be decreased during the period when the cutting height is lowered.

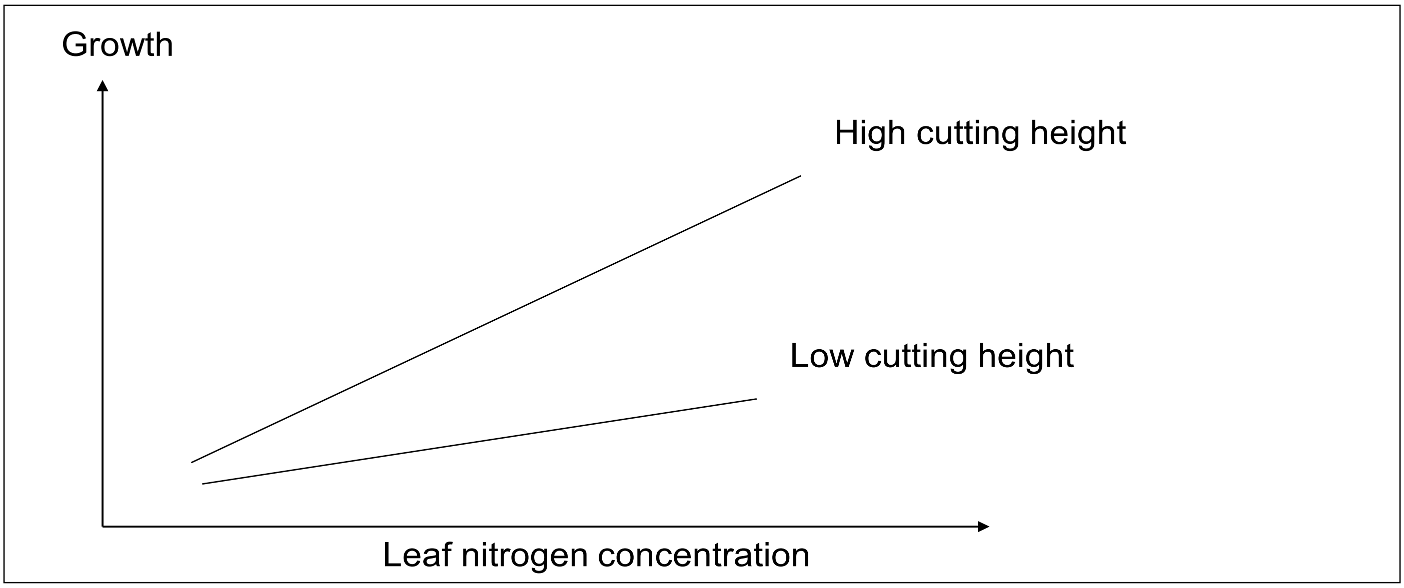


Figure 9 – Effect of cutting height on the capacity of grass to utilise nitrogen for growth.

WHAT MAKES A GOOD FERTILISER?

Greens built according to USGA norms have a low capacity to bind and supply nutrients to the grass. In order to avoid undesirable nutrient leaching, both the amount and the relative proportions of the nutrients should reflect the actual requirements of the grass. A wide range of fertiliser products are available for golf turf and the composition of these products varies depending on their intended use.

Comprehensive studies of plants' nutrient requirements at SLU show that species are very similar with regard to the optimal balance between the different nutrients. As long as there are no reserves in the soil, a good fertiliser product for sand-based greens should therefore contain all the nutrients that the grass requires and in the proportions shown in Table 2 (column A). For all nutrients except nitrogen, the proportions in that column are somewhat higher than required for growth. Since plants are opportunists in terms of nutrient uptake, some degree of 'luxury' uptake will occur when a fertiliser product with the composition shown in column A is used. This excess uptake is beneficial and provides the plant with the ability to cope with brief periods of restricted nutrient supply. If a fertiliser product containing the proportions listed in column A is applied in growth-restricting amounts, the grass will interpret this situation as growth restriction by nitrogen. The growth rate will therefore decline in order to adjust to the lower nitrogen availability without deficiency symptoms appearing, since all the nutrients will be present in proportions matching the lower growth.

When the growth rate declines, the relationship between biomass and nitrogen is adjusted so that the nitrogen concentration in the leaves is lowered. Nitrogen-limiting growth conditions are desirable when playing quality is the main focus, since stem stiffness and the formation of narrower leaves is stimulated. When fast growth is desired, for example to repair damage, nitrogen limitation should be avoided. It is easy to achieve this by increasing the dose of the regular fertiliser rather than by changing to a fertiliser product with a higher nitrogen content.

Same balance between nutrients throughout the year

There is no evidence to suggest that the relationship between the different nutrients in turfgrasses needs to be altered depending on season, as long as the grass is in its vegetative phase. Thus, there is no biological reason for altering the composition of the fertiliser product used during the year. When a fertiliser with the proportions between nutrients shown in Table 2, column A, is applied in growth-restricting amounts, the grass will always experience the situation primarily as nitrogen-restricted. Other elements, for example potassium, will then be taken up in 'luxury' amounts, i.e. in amounts exceeding the requirements for growth. Adding extra potassium in late summer/autumn to turf which already contains a surplus of this compound has no effect on the ability of the grass to resist diseases or survive the winter. As discussed, a moderate lack of nitrogen poses no serious problems for the health of turfgrass and in fact increases the playing quality of the turf. It is, on the other hand, important to avoid deficiency of elements such as potassium, magnesium, iron and manganese, i.e.

Table 2 - Nutrient proportions in fertiliser (A) and for diagnosis of deficiencies (B).

Macronutrients	A	B	Micronutrients	A	B
Nitrogen (N)	100	100	Iron (Fe)	0.7	0.2
Potassium (K)	65	30	Manganese (Mn)	0.4	0.06
Phosphorus (P)	14	8	Boron (B)	0.2	0.04
Sulphur (S)	9	5	Zinc (Zn)	0.06	0.05
Calcium (Ca)	7	4	Copper (Cu)	0.03	0.02
Magnesium (Mg)	6	4	Chlorine (Cl)	0.03	*
			Molybdenum Mo)	0.003	*
			Nickel (Ni)**	*	*

* Lack of reliable data ** Very low requirement, can be omitted from fertiliser

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

Do turfgrass seedlings need extra phosphorus (P) in spring?

Seedling growth is a critical stage for turfgrass establishment. Compared with established turf, grow-in turf is usually considered more sensitive to low soil P values because of less and shorter roots, and thus less soil volume to explore for P uptake. Seedling growth often occurs in spring at low soil temperatures after reseeding turfgrass due to winter damage. Under these circumstances, it is often recommended to apply 'start fertilisers' with an equal or even higher concentration of P than of N prior to reseeding.

One of the major findings in the SUSPHOS project was that low temperatures did not justify higher P applications, and that a fertiliser P/N ratio of 6-12% was sufficient for turfgrass establishment on a sandy soil low in P (see photo, above).
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As shown in figure 10 (a) temperature was the most critical factor for rapid establishment of a turfgrass sward. P application promotes turfgrass establishment, but a P rate corresponding to 6-12% of N was as good as a higher rate (18-24% of N), figure 10 (b). Low temperature was more limiting to turfgrass growth than to turfgrass P-uptake. This suggests that the optimal proportion between N and P in turfgrass fertiliser (Table 2, p 11) applies not only for established turf, but even at the grow-in stage.

Leaf analysis as a diagnostic tool

If a well-balanced fertiliser that contains all essential nutrients is used (Table 2) there is little risk of the turf suffering nutrient imbalances. When there is uncertainty about the nutrient status of the grass, a leaf analysis can reveal potential deficiencies. Analysing the nutrient content in dried grass clippings is a simple procedure, but correct

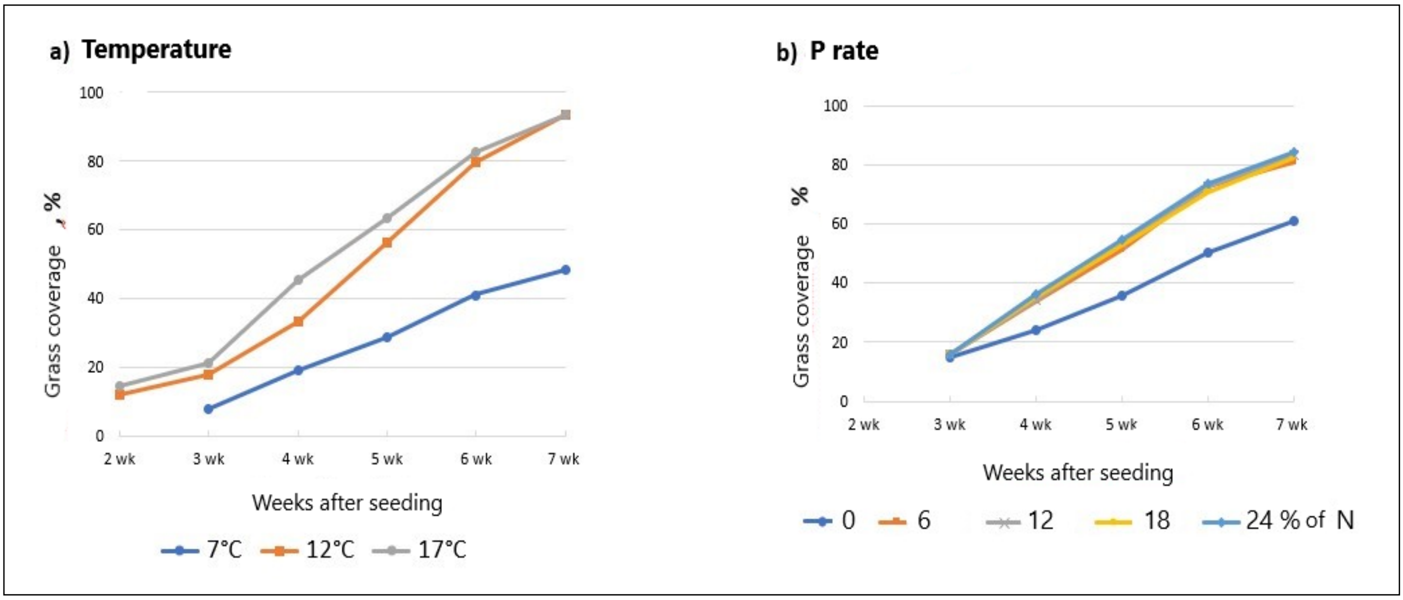
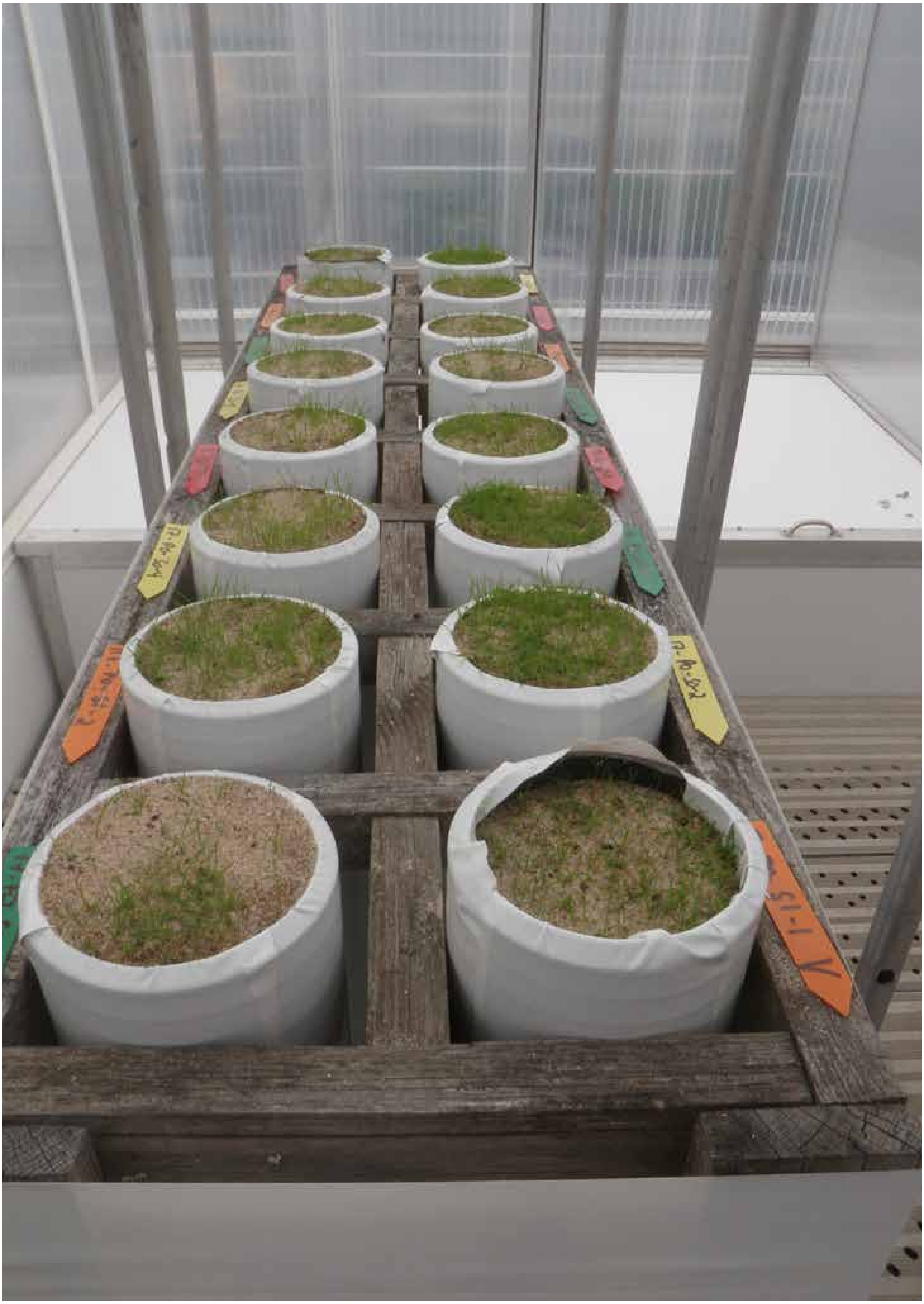


Figure 10 – Effect of temperature (7, 12 and 17°C) and P rate (0, 6, 12, 18 or 24% of N rate) on establishment of creeping bentgrass in a climate chamber.

interpretation of the data requires reliable reference values. Since measured values of the total amount of nutrients in grass dry matter can show large variations, it is more reliable to observe the relative proportions of the different elements. Since the relative proportions of the elements do not differ significantly between species, imbalances and deficiencies can easily be detected, irrespective of grass species. Column B in Table 2 shows the lowest proportions relative to nitrogen (N=100) at which the other elements can be present without causing serious disruptions in growth or other vital processes. A value lower than this reference value indicates that the element has taken over from nitrogen as the most growth-limiting factor. This situation must be avoided and the reasons for the deficiency identified and eliminated.

Increasing fertilisation level (left to right) affects thatch development, here in common (browntop) bent. Photo: Agnar Kvalbein.

Soil nitrogen content has a strong influence on the root system of turfgrass in terms of appearance and quantity.
Photo: Tom Ericsson



HOW TO TAKE SOIL PROPERTIES INTO ACCOUNT

The soil material also affects nutrient availability. Old, established greens, particularly soil-based or push-up greens, and fairways established on the topsoil of former arable land often have abundant nutrient reserves which are available to the grass. These nutrients are released from soil particles through weathering, decomposition of organic matter and chemical processes such as cation exchange.

The organic material is broken down by microorganisms and the nutrients released through mineralisation. If the soil content of organic material is high, relatively large amounts of nitrogen can be released by mineralisation and this decreases the need for nitrogen in fertilisers.

Phosphorus, which is released during the growing season through chemical and biological processes in the soil, is often low in sandy soils such as USGA constructed greens. Sandy soils have low specific surface area of the particles and thereby relatively few binding sites for phosphate ions. This can result in leaching of P when added in surplus and P may also be lost as surface run-off, either as particulate P from bare soils due to erosion or from green surfaces after fertilisation or freezing events. The pH of the soil is also critical for the availability of P – it is best in the range 6.0-6.5 (determined in H_2O solution) but decreases when the pH is lower or higher.

Experimental sites in the SUSPHOS project.

Sustainable phosphorus nutrition (The SUSPHOS project)

Currently, there are no common European recommendation for turfgrass fertilisation as a function of the soil's content of plant available P. The recommendations based on soil analyses differ from country to country depending on the analytical methods used in agriculture. In Sweden, Norway and in The Netherlands the standard laboratory method for P in soil is the P-AL method, in Denmark it is the Olsen-P method and in Germany the CAL method.

In Swedish and Norwegian agriculture the recommendation is to apply extra P (more than removed in yield) when the P-AL concentration is lower than 40 mg/kg soil (4 mg/100 g soil). In Denmark the recommendation is to apply extra P (more than removed in yield) when the Olsen P is lower than 25 mg/kg soil (2.5 mg/100 g soil, P-tal: 2.5). In Germany it is recommended to keep the CAL-P concentration between 31 and 60 mg/kg soil.

Table 3. Climate, soil properties and annual N-rates at the golf courses in the SUSPHOS project.

Location	Long-term average annual		pH	Start Mehlich-3 P	Average annual N rate
	air temperature	precipitation			2017-2020
	°C	mm	-	mg/kg soil	kg N/100 m2
Dütetal, Germany	9.1	830	6.7	15	2.1
Falkenberg, Sweden	9.0	872	6.0	35	2.0
Jingshan Lake, China	12.0	507	8.3	8	1.2
Landvik, Norway	7.8	1416	5.9	26	2.0
Princenbosch, The Netherlands	10.9	834	6.3	7	0.4

One of the aims of the SUSPHOS project was to investigate if P fertilisation can be reduced on golf course putting greens without negative implications on turf quality. Here we used the Mehlich-3 method for analysing P because the US fertiliser guidelines 'Sufficiency Level of Available Nutrients' (SLAN) and 'Minimum Level of Sustainable Nutrition' (MLSN) are based on this method. At soil pH less than 7.0, approximate conversions of analyses conducted at European laboratories to Mehlich 3 are:

- Mehlich-3 (mg/kg) = P-AL (mg/kg) x 1.47 + 0.1
- Mehlich-3 P (mg/kg) = 4.37 x Olsen-P (mg/kg) – 39.5

When converting P-AL to Mehlich-3 the traditional recommendation in Norway and Sweden is to apply extra P when Mehlich-3 P is 59 or lower or in Denmark to to apply extra P when Mehlich-3 P is 69 or lower. The fertiliser guideline MLSN prescribes to maintain a Mehlich-3 soil P of 18 mg/kg soil as the minimum 'safety' limit for 'good looking turf'. This is less than 1/3 of the Scandinavian guidelines used in agriculture.

In SUSPHOS the MLSN guideline was tested on five different golf courses around the world in comparison with the old American SLAN guideline of 54 mg P/kg soil, which has often been used on US golf courses and which is close to the recommendations for P in Scandinavian agriculture. A third treatment was the recommendation for Precision Fertilisation (SPF) previously explained in this handbook, i.e. to always apply P corresponding to 12 % of the N rate. The three guidelines were compared with a control treatment (no P) in field trials from 2017 to 2020 on USGA-greens at golf courses in Germany, Sweden, China, Norway and the Netherlands with different climatic conditions and management practices (Table 3).

The experimental greens in Germany and Sweden were very alike with a 50/50 sward of creeping bentgrass and annual meadowgrass, while the creeping bentgrass greens in Norway and China had low proportions of annual meadowgrass (0-10%). The green in the Netherlands was a mixed fescue/bentgrass green with a very low N-rate.

The experimental green at Dütetal Golf Club in Germany divided into 16 2x2 m plots receiving four different rates of P-fertiliser.

P was given monthly from April to October as a liquid solution of triple phosphate ($Ca(H_2PO_4)_2$, 20 % elemental P). All plots within one experiment received the same amounts of N (Table 3) and other nutrients except P. Soil samples taken from all plots in November were used to calculate the next year's P-rate in the MLSN and SLAN treatments.

P-fertilization was done with a handheld sprayer applying a liquid solution of triple phosphate according to the different P-rates. Photo: Majvor Sintorn.

Development of soil P levels

As shown in figure 11 and 12 the SLAN treatment increased the soil P level significantly compared to the other treatments with less or no input of P. After two-four years with high P applications on the creeping bentgrass greens (Figure 11), the soil P almost reached the threshold of 54 mg P/kg soil, but at the fescue/bent green in the Netherlands the same high application only resulted in a small and slow increase of the soil P-level.

Further soil analyses showed that all greens had a low P sorption capacity, i.e. few binding sites for phosphate ions. The high P applications provided more P than was removed in the clippings, and such high applications of P will inevitably increase the risk for leaching of P. Even for the Precision Fertilisation (SPF) treatment, applied with 12% of P relative to N input, it is likely to assume that a certain leaching of P occurred since the soil P levels were not taken into account.

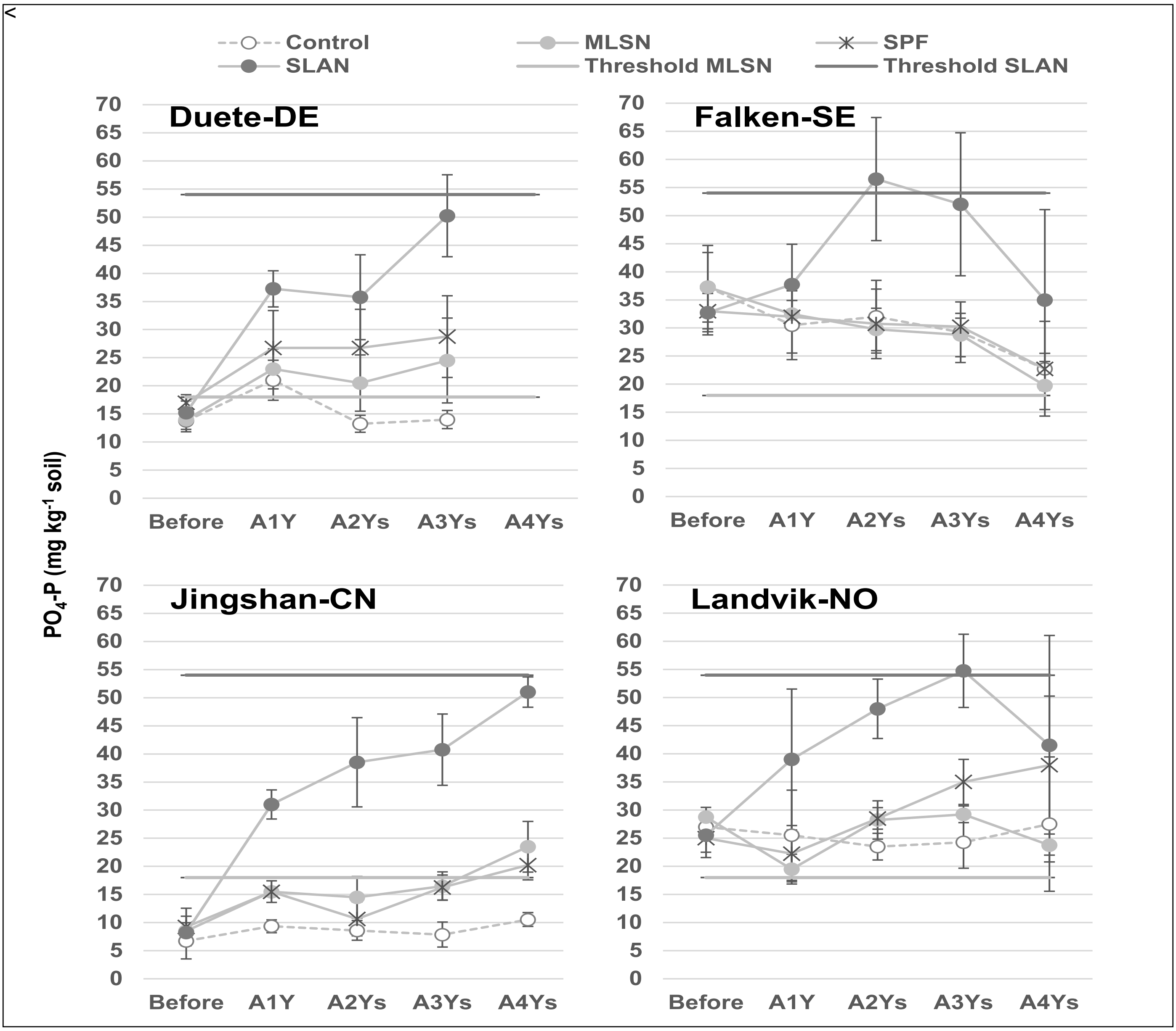


Figure 11. Changes in soil P levels during the trial in response to different P fertilization recommendations on the four creeping bentgrass greens. Before the trial started (Before), after 1 year of trial (A1Y), after 2 years (A2Ys), after 3 years (A3Ys), and after 4 years (A4Ys, no data for Duete-DE). Light grey line = threshold MLSN (18 mg/kg soil); dark grey line = threshold SLAN (54 mg/kg soil).

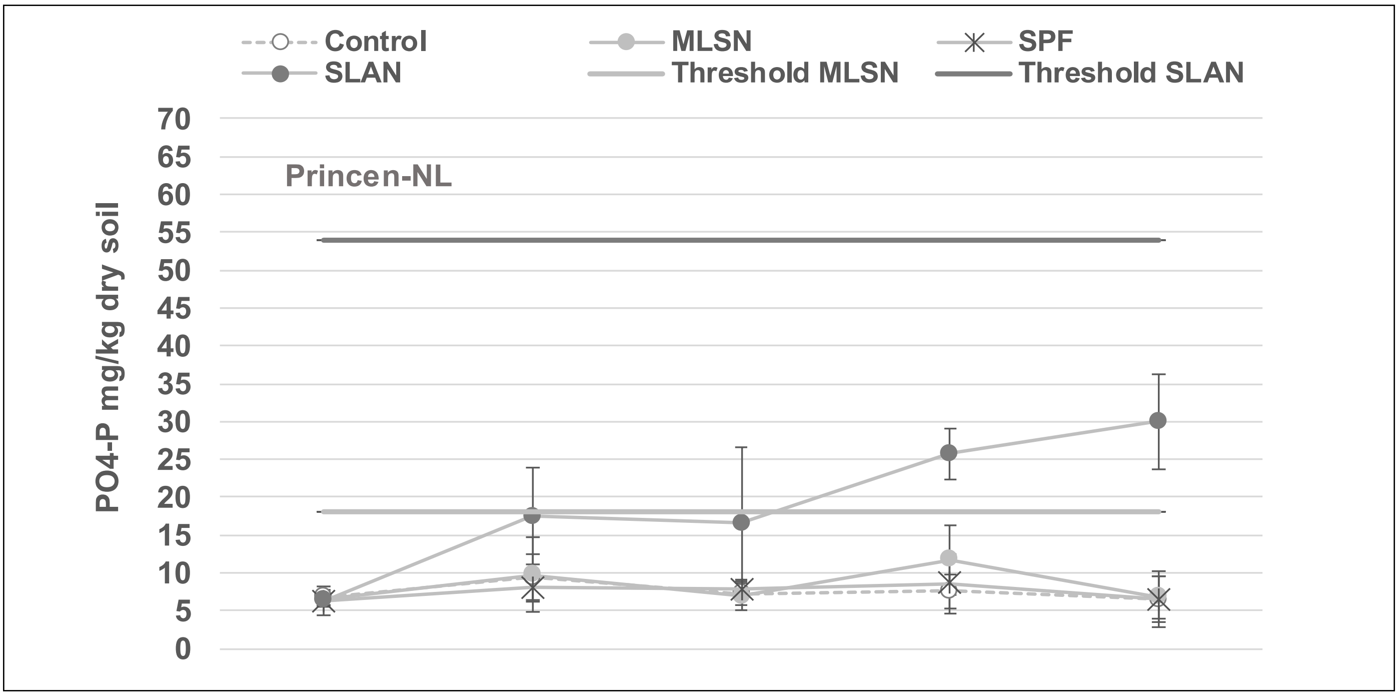


Figure 12 – Changes in soil P levels during the trial in response to different P fertilization recommendations on the fescue/bent green at Princenbosch, the Netherlands. Before the trial started (Before), after 1 year of trial (A1Y), after 2 years (A2Ys), after 3 years (A3Ys), and after 4 years (A4Ys). Light grey line = threshold MLSN (18 mg/kg soil); dark grey line = threshold SLAN (54 mg/kg soil).

Turfgrass quality was not affected by the different P rates

Visual turf quality rated monthly from 2017 to 2020 on the five experimental greens did not show any significant difference between the different P treatments. At all sites, the turfgrass quality varied through the seasons, and in some years it decreased due to winter damages or hot summers, but it never differed due to the P applications or the P level in the soil.

Soil samples were taken at the experimental greens every year in November from 2017 to 2020. Here at Dütetal Golf Club in Germany. Photo: Anne F. Borchert

P influenced the proportion of annual meadowgrass in only one of five experiments

Many studies have shown that that P fertilisation and subsequently high soil P levels can promote annual meadowgrass. It was only on the experimental green at Falkenberg in Sweden that this finding was confirmed in the SUSPHOS project. Here the 50/50 mixed creeping bentgrass/annual meadowgrass green showed a 2-3 % increase in annual meadowgrass coverage with P fertilisation relative to the treatments that did not receive P. Weather conditions and management (notably irrigation) had a much stronger impact on annual meadowgrass encroachment than the P treatments.

At Falkenberg, Sweden the high applications of P resulted in a 2-3 % increase in annual meadowgrass. Photo: Kim Sintorn.

Growth chamber experiment with established turf

Cores with a Mehlich-3 P soil value of 34 mg/kg soil from a 4 to 6 years old creeping bentgrass green were taken to a growth chamber to be fertilised with increasing rates of P (phosphoric acid) as foliar or granular applications. The growth chamber experiments confirmed the field trials as the results showed no improvement in colour or spring green-up with increasing P rates and no differences between foliar and granulated fertiliser.

Does P fertilisation affect the rooting depth?

Rooting depth was measured monthly at all experimental greens (see photo) in the whole project period. Regardless of the different P treatments rooting depth varied in extension and pattern during each year of the trial between the experimental sites. The results suggests that other factors than low or high P fertilisation does affect the rooting depth.

Soil core with roots taken at the Landvik-NO experimental site for rooting depth measurement. Photo: Anne F. Borchert.

The SUSPHOS project – conclusion

The SUSPHOS project has shown that maintenance of the soil P level of 18 mg P/kg soil (Mehlich-3 P) can be recommended for putting greens with low P sorption capacity under a wide range of climatic and management conditions. Higher soil P values increased the risk for P losses to the environment without improving turfgrass quality. The SPF recommendation to apply 12% P relative to N irrespective of soil P values was a safe guideline for all turfgrass situations including establishment, but it resulted in redundant P application on soils with high P levels. At low N-input greens as exemplified by the fescue/bentgrass green at Princenbosch, the recommendation to maintain soil Mehlich-3 P at 18 mg/kg can be followed or even lowered as the removal of P in clippings is low. At higher N-input as on the creeping bentgrass/annual meadow grass greens in this project, the recommendation to maintain soil Mehlich-3 P at 18 mg/kg shall be followed. Remember to do soil sampling and analyses regularly to check the soil P levels. If the P-AL or Olsen-P methods are used by the laboratory, the conversion to Mehlich-3 P (explained on page 16) can be used when the soil pH is less than 7.0.

GUIDELINES FOR SEASONAL FERTILISER DISTRIBUTION

In this section, we suggest guidelines for precision fertilisation and for achieving high playing quality of the turf. The proposed nitrogen rate during the season is intended to permit growth corresponding to approx. 60% of maximum growth and a nitrogen concentration in the leaves of around 3% in dried samples. These values should be regarded merely as guidelines. Owing to different circumstances, e.g. variations in weather conditions, type of green construction and choice of turfgrass, it can sometimes be necessary to deviate from the guidelines and increase or decrease the fertiliser rate. The fertiliser quantities listed apply for established greens in which the microflora has reached an equilibrium.

The first (2011) edition of this handbook suggested a symmetrical fertiliser distribution curve with a constant weekly 'summer' rate from 15 June to 1 September throughout the Nordic countries. The constant maximum summer rate on putting greens was recommended to be 0.6-0.7 g N/m²/week (0.06-0-07 kg N/100m²/week) for creeping bent; higher rates were recommended for annual meadowgrass and lower rates for common (browntop) bent, velvet bent and red fescue according to Table 1 (page 9). Spring fertilisation was recommended to start when soil temperatures exceeded 7°C with linearly increasing weekly rates until 15 June, while autumn fertilisation to decrease linearly with the last application about two weeks after the last mowing for the season.

While most of these recommendations are still valid, we have now revised the shape of the fertiliser distribution curve (Figure 13) based on new knowledge in the STERF projects 'Fescue green' (2012-2015, box 1) and 'Autumn fertilisation' (box 2). Part of the explanation for this is the mineralisation, primarily of N, but also of P and S from soil organic matter that commonly occur at high soil temperatures and sufficient soil moisture in late summer. The mineralisation rate will of course depend on the organic matter content and type of substrate/microbial activity in the rootzone. Substrates amended with compost have a higher mineralisation potential than substrates amended with Sphagnum peat, and old greens which have accumulated a thatch/mat layer have a higher potential than young greens. Frequent aeration will stimulate aerobic bacteria that degrade organic matter into a form that can be taken up by the plants.

Another modification that we made when revising the handbook is that the threshold soil temperature for giving the first fertiliser application in spring has been changed from 6-7 to 5-6 °C. A temperature of 5 or 6 °C is the threshold often used in agricultural models.

It is important to remember that the fertiliser distribution curve recommended in Figure 13 is based on experiences

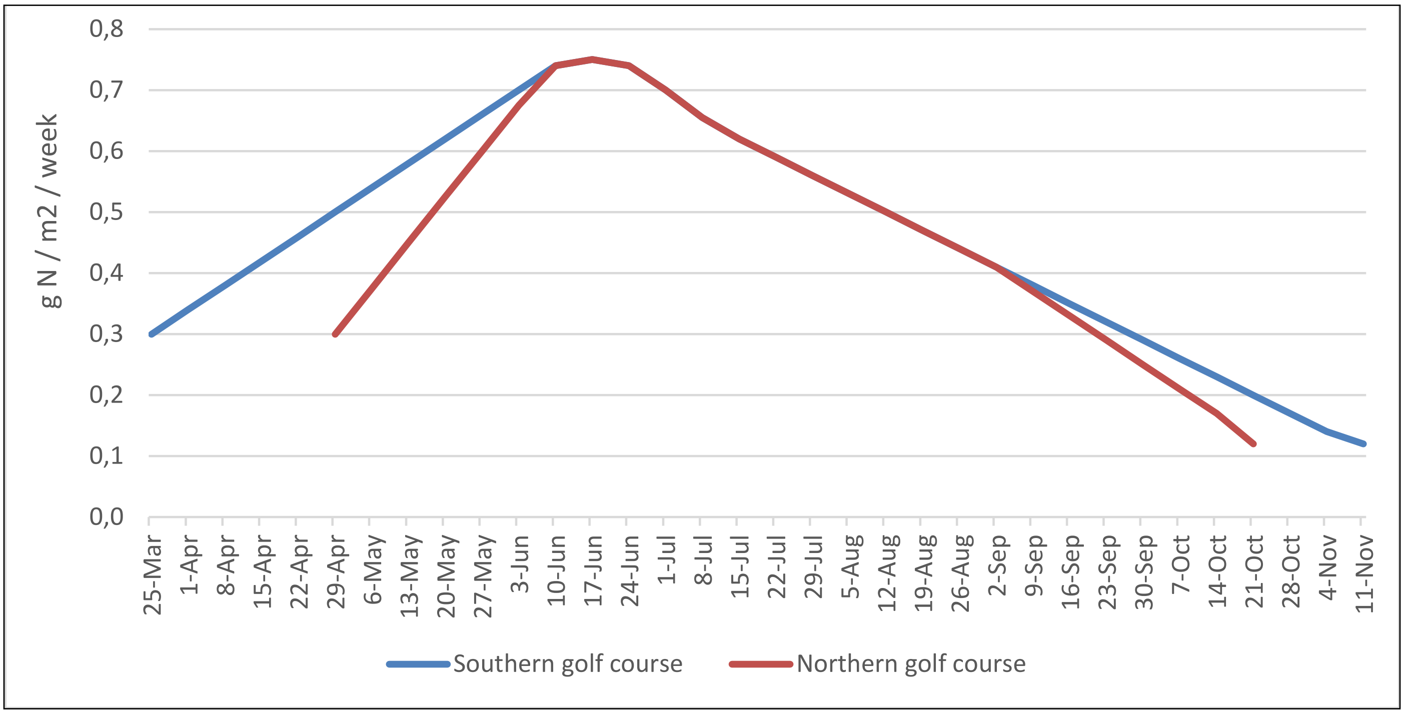


Figure 13. Suggested fertilisation rates to established, sand-based creeping bentgrass greens in the southern and northern part of the Nordic countries. The weekly fertiliser inputs add up to 15 and 12 g N/m², respectively.

with creeping bentgrass growing on sand-based greens. The shape of the distribution curve should, however, be valid also for pure red fescue or mixed fescue/bentgrass greens. In that case, the weekly fertiliser rates can be reduced by approximately 40 % relative to creeping bentgrass.

Annual meadowgrass has a higher fertiliser requirement than creeping bentgrass, and it also keeps growing at lower temperatures in autumn. Many greenkeepers have experienced that annual meadowgrass at green's mowing height can be infected with anthracnose (*Colletotricum graminicola*) if fertiliser rates are reduced too much in July and August. For greenkeepers aiming to make the best out of annual meadowgrass, a somewhat flatter distribution curve with a higher proportion of the N rate in late summer and early autumn may therefore have certain advantages compared with the one shown in Figure 13. This is an aspect that warrants further research.

Good root development in common (browntop) bent that has received 60% of the maximum fertiliser rate. Photo: Agnar Kvalbein.

Box 1: Fertiliser distribution trial in the STERF project 'Fescue green'

A fertiliser distribution trial was conducted from mid August 2013 to mid August 2015 on a USGA-green with an initial botanical composition of 84 % red fescue and 16 % annual meadowgrass at NIBIO Landvik Turfgrass Research Center. A fertiliser rate of 11 g N/m^2 in total was applied as weekly inputs of a balanced liquid fertiliser according to the ratios given in Table 2 (page 11). Percent of the annual fertiliser amount given in various seasons varied as follows:

	Season				
Fertiliser distribution treatment	Early spring: 31 Mar.– 4 May	Late spring / early summer: 5 May – 22 June	High summer: 23 June – 10 Aug.	Late summer / early autumn: 11 Aug – 29 Sep.	Late autumn: 30 Sep – 17 Nov.
1. Spring+	6.2 %	43.2 %	28.9 %	14.6 %	7.2 %
2. Flat rate	6.2 %	28.9 %	28.9 %	28.9 %	7.2 %
3. Autumn+	6.2 %	14.6 %	28.9 %	43.2 %	7.2 %

Results showed that treatments 1) 'Spring+' and 2) 'Flat rate' produced higher turf quality than 3) 'Autumn+' on average for the entire trial period. The only exception was in late autumn and early spring where 'Autumn+' resulted in higher turf quality and faster green-up. From 15 May till 10 Aug, i.e during most of the playing season, the highest quality was achieved with 'Spring+' fertilisation.

Box 2: Autumn fertilisation

In STERF's autumn fertilisation project, four rates of the same balanced fertiliser (Table 2) were applied from 1 Sep to 1 Dec. on sand-based greens with a turf cover of annual meadowgrass or creeping bentgrass. The weekly rates started at at 0.4, 0.8, and 1.2 g N/m^2/week on 1 Sep. (week 37) and decreased linearly to zero with the last applications around 1 Dec. (week 49). The total N rate over the thirteen-week period amounted to 2.8, 5.6 and 8.4 g N/m^2, respectively. A treatment not receiving autumn fertilisation was included as control.

The experiment is explained in detail in Appendix 1 in STERFs handbook 'Turfgrass Winter Stress Management'. The main conclusions were:

1. Autumn fertilisation resulted in faster green-up in spring
2. The lowest fertiliser rate (starting at 0.4 g N/m^2/week) on 1 Sep. did not increase N leaching compared with the unfertilised control treatment. Higher fertiliser rates increased N leaching significantly up to almost 50 % of applied N at the highest rate.
3. Increasing fertiliser rates in autumn caused a linear reduction in the freezing tolerance of creeping bentgrass from about -36°C in the unfertilised control treatment to about -26°C at the highest rate. The corresponding decrease in freezing tolerance with increasing fertiliser level in annual meadowgrass was only from -20 to -16 °C.
4. In both species, there was a four to five fold increase in microdochium attack during winter as the accumulated fertiliser rate increased from 2.8 to 5.6 g N/m^2. In contrast, the lowest rate of 2.8 g N/m^2 did not result in more microdochum patch than in the unfertilized control treatment.

All in all, these results lend strong support to the latter part of the fertiliser distribution curve in Figure 13, i.e. to continue fertilisation with small and decreasing amounts until 2-3 weeks after the last mowing for the season.

HOW TO CONSTRUCT A PRECISION FERTILISER DISTRIBUTION CURVE FOR GOLF COURSE PUTTING GREENS?

1. Choose a fertiliser or a combination of fertilisers that contains all macronutrients and micronutrients. If the Mehlich-3 P level in the soil is 18 mg P/kg soil or higher a fertiliser without P can be recommended on established greens. Just be aware to maintain the Mehlich-3 P level in the soil not lover than 18 mg P/kg. The balance between the nutrients should be approximately the same as in Table 2, column A. Liquid fertiliser are convenient for small and frequent applications, but combinations of granular and liquid formulation are also feasible.

   This is how to convert the nutrient content stated as percentages of a fertiliser product to proportions by weight. Nitrogen, N, forms the basis for the comparison between the different nutrients, so N is given a value of 100. Assume that a fertiliser product contains N-P-K in proportions 11-2-5. Giving N a value of 100, the proportion by weight of phosphorus, P, is then 2/11 multiplied by 100 = 18P and the proportion by weight of potassium, K, is 5/11 multiplied by 100 = 45K.

2. Precision fertilisation is based around fertilising often and in small amounts. A one week interval is preferable, and a fertilisation interval of two weeks is an absolute maximum. Short intervals make it possible to adjust fertilisation during the season at short notice if the weather, grass development or playing qualities so require.

3. Successful application of a liquid fertiliser in small doses requires a modern sprayer with a suitable nozzle. An area meter is also recommended. The sprayer must always be a type which is possible to calibrate.

4. Start fertilisation in spring when the mean daily temperature in the upper 5 cm of the soil is 5-6 °C and when the grass has started to grow (Figure 13).

5. For creeping bent, the starting dose in the spring should be 0.3 g N /m^2/week (0.03 kg N/100 m^2/week) Calculate the fertiliser dose for other species according to Table 1 (p 9).

6. Increase the fertiliser dose gradually during the spring from the starting dose to the max. dose, according to the increased growth rate of the grass.

7. For creeping bent, the max. dose can be 0.75 g N/m^2/week (0.075 kg N/100 m^2/week). If turf repair is required, the dose can be increased by 60%.

8. From approximately 1 July, the weekly fertiliser rate can be reduced little by little to 0.4 g N/m^2/week (0.04 kg N/100 m^2/week) on 1 Sep. depending on the green's potential for mineralisation of organic matter.

9. A stable colour and stable clipping yields throughout the summer is a good indication that the fertiliser program works appropriately. If there is uncertainty about the precision of the programme, samples of grass clippings can be analysed for nitrogen concentration. With the help of a loss on ignition test, the presence of dressing sand in the sample can be corrected for. Otherwise, there is a risk for nitrogen concentration to be underestimated.

10. From 1 Sep. the fertiliser rates can be reduced until the last application approximately two weeks after the last seasonal clippings.

11. Adjust fertilisation to the microclimate on the course. Greens in shady positions grow more slowly and therefore have lower nutrient requirements than greens in full sun.

12. When changing from one fertilisation strategy to another, e.g. to precision fertilisation, it is important to record the changes made and the effects on the grass. This allows the method to be refined in coming seasons.

    The following documentation is useful when evaluating the fertiliser programme:
    - Grass colour
    - Root development
    - Soil temperature
    - Air temperature
    - Cutting heights
    - Ball roll
    - Treatments for disease, time and compound used.
    - Irrigation and other management inputs.

MANY ADVANTAGES WHEN BIOLOGY DECIDES

Hauger GC, Oslo. Photo: Agnar Kvalbein

The suggested fertiliser curve in Figure 13 is an idealised picture of how turfgrass growth rates and soil mineralisation, and thus fertiliser requirements, change during the season. Of course fluctuations arise in the availability of light, heat and rainfall, but if these are of a short-term nature (approx. one week), there is no reason to deviate from the original fertilisation schedule. This is particularly true when fertilising under nutrient restriction to depress the growth rate and promote root growth.

A fertilisation programme that is carried out frequently and in rates adapted to cover the requirement is usually easy to adjust. By lowering or increasing the fertiliser rate, the grass can be quickly influenced to change its growth rate in the direction required by the situation. 'Growth-driven' fertilisation can therefore be an appropriate term for the concept 'precision fertilisation'. Growth is controlled to the level that best suits the conditions at the time.

Fertilisation affects not only the grass plant, but also the microorganisms in the soil that help in the uptake of nutrients and water. These mainly comprise the mycorrhiza, a group of fungi that is very susceptible to high nutrient concentrations in the soil. Steady, controlled nutrient application therefore also helps to create a positive microflora in the greens.

Applying nutrients in liquid form increases the precision in fertilisation and reduces the need for post-fertilisation irrigation. This fertilisation method therefore saves time and disruptions to playing quality because irrigation is minimised.

Adjusting the nutrient supply to the desired level of growth dramatically reduces the risk of leaching. By creating 'hungry' grass, the carbohydrate reserves in the tissues can be increased, thereby improving the ability of the grass to defend itself against pests. Growth-driven fertilisation is therefore good for turf quality, the environment and club finances.

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