TURF GRASS WINTER STRESS MANAGEMENT

Golf course managers' handbook

Sterf

PREFACE

This text is an attempt to summarize results and experiences from several research projects related to turf grass winter stress. The funders of these projects were mainly the Nordic golfers, through their contributions to the Scandinavian Turfgrass and Environment Research Foundation (STERF), and the Norwegian Research Council.

Producing this text was included in Norwegian Golf Federations' innovation project *"Autumn application of fertilizer"*, which was concluded this year. Some figures show data from these experiments. In order to keep the text short, and not to repeat ourselves, we have described the experiments in appendix 1.

When developing this handbook we first had golf course managers in mind. During the work, we consulted many scientific papers, and the list of references became long. We hope this can help turf grass researchers and others who want to delve deeper into the subject.

More ready to use information about winter stress related topics is available in facts sheets and handbooks on www.sterf.org. We link to relevant STERF publications from this text.

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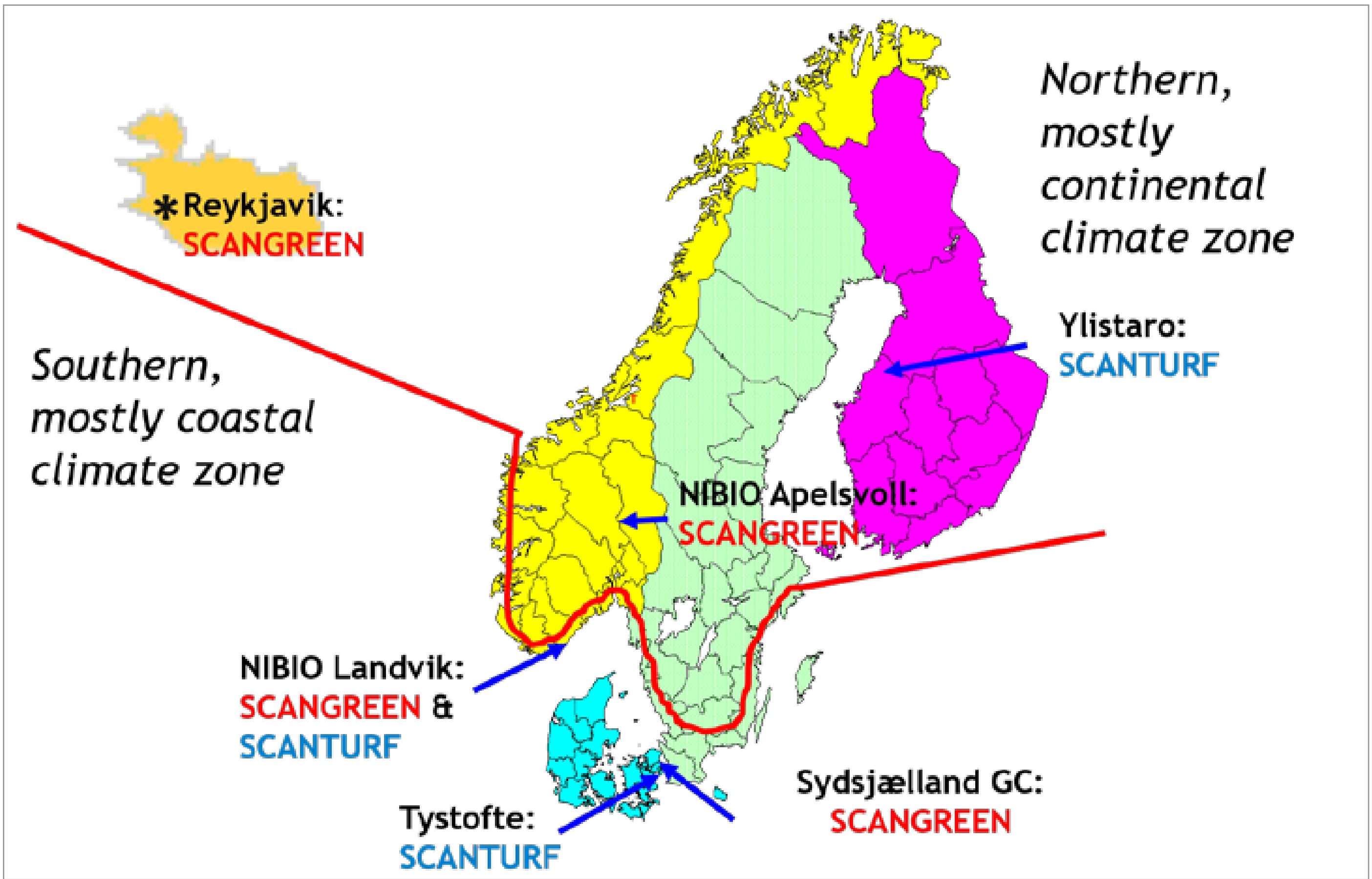


***Figure 1**. The two climatic zones and test locations that are used in SCANGREEN and SCANTURF variety trials.*

GEOGRAPHICAL DIFFERENCES

The Nordic countries include Iceland, Norway, Sweden, Finland (with Åland) and Denmark (with Greenland and the Faroe Island). Some Estonians also claim to be Nordic, and from a winter climatic point of view, all three Baltic States should be included.

The climate varies a lot between countries and regions. The warm Golf stream makes the coastline of Norway much milder than expected from the high latitude. Dominating western winds deliver large amounts of precipitation to the west part of Norway. This is in sharp contrast to the rain shadow on the east side of the mountains, where the annual precipitations is less than 300 mm.

A coastal climate with small variation between summer and winter temperatures is very different from the inland climate where the winter temperature can go below -40 °C. Normally snow cover protects turf grass from the extreme temperatures in these areas. The most challenging climate, from the turf grass point of view, is unstable snow cover, warm spells during winter and risk of ice formation.

The turf grass variety-testing programs SCANGREEN and SCANTURF operate with two climatic zones in the Nordic countries. See this simplification in figure 1.

OVERVIEW OF WINTER STRESSES

STERF's research program for winter stress management lists the complexity of winter stresses that grass plants can encounter, and outlines the factors that are important for successful winter survival.

In this text, we will group the winter stresses into three:
1. winter diseases,
2. ice and water damages and
3. desiccation

The stress events are to a large extent related to the location of the golf course and the time of the year. Microdochium patch caused by the winter-active fungus *Microdochium nivale* is the economically most severe problem in the southern part of Scandinavia.

Further north ice encasement is more common. Lethal desiccation is difficult to distinguish from freezing injuries or damages caused by high light intensity. We presume these stresses mainly occur in the spring when solar radiation is much higher than in the autumn.

Based on this, we present three chapters called 'Winter disease management', 'Ice and water management' and 'Spring challenges'. But first we start with the genetic component.

GRASS SPECIES AND THE ACQUISITION OF WINTER STRESS TOLERANCE

***Picture 1**. A test-green seeded with different seed mixtures of red fescue and brown-top bent. To the right is a mix of international varieties. To the left are varieties based on Norwegian ecotypes. The picture was taken on 18 December 2003. Photo: A. Kvalbein.*

PLANT ACCLIMATION AND DE-ACCLIMATION

Grass plants can change between two different physiological states. In the growing state, the cell membranes are waterproof, which means that hydraulic pressure can make new cells expand. Impermeable and flexible membranes are a prerequisite for plant growth. (You cannot blow up a balloon with holes.)

In the acclimated state, water can easily percolate through the cell membranes. This allows ice crystals to form and grow mainly outside the plant cells.

Enhanced concentrations of sugars and other osmolytes lower the freezing temperature inside the plant cells. Special anti-freeze proteins effectively limit ice crystal growth (Griffith & Yaish, 2004).

There seems to be a general contradiction between growth and winter stress tolerance. This means that growing plants are less tolerant to winter stress than acclimated plants. Perennial ryegrass (*Lolium perenne* L.) and annual meadow-grass (*Poa annua* L.) tend to continue growing in the autumn. These species are the least winter stress tolerant cool-season grasses used on golf courses.

***Picture 2.** Losby GC, fairway 16. Patches of local grass survived, top rated seeded varieties died. A flooding river to the right frequently causes ice cover and winterkill on this fairway. Photo: A. Kvalbein.*

Turf managers should keep in mind that any action that stimulates growth, like nitrogen fertilization, irrigation (if dry) or covers that enhance temperature might increase the risk of winter injuries. This is the case both in the autumn and in the spring.

Temperature and light conditions[1] are the key signals for plant acclimation or de-acclimation. Two weeks with day temperatures below 4 °C in combination with some days below zero, will gradually make the plant stop growing and acclimate. Turf grass usually reaches maximum acclimation status towards the end of December. De-acclimation occurs when depletion of carbohydrates (due to darkness, anoxia or diseases) and warm spells reduce the acclimation status as winter passes. De-acclimation happens faster than acclimation and it can be completely reversible, partly reversible or completely irreversible depending on the temperature and duration of the de-acclimation period (Pomeroy et al., 1975; Gusta & Fowler, 1976a,b; Espevig et al., 2014a). Read more about acclimation and de-acclimation in the fact sheets Acclimation and winter stresses and Warm spells during the winter, respectively.

Local grass ecotypes are slightly less affected by maintenance and temperature than varieties developed for an international market. While day temperature is controlling the commercial varieties, northern - adapted grasses respond to day length in addition to day temperature. We think this makes local ecotypes more robust in a changing climate where mild autumns might reduce acclimation (Dalmannsdottir, 2017). Canadian and US ecotypes of annual meadow-grass differ in winter stress tolerance depending on their origin (Dionne et al., 2009).

FREEZING TOLERANCE AS AN INDICATOR OF PLANT ACCLIMATION STATUS

The tolerance to winter stresses differs very much among turf grass species and varieties. Generally, red fescue (*Festuca rubra* L.) is more resistant to disease than bents (*Agrostis* sp.) The disease resistance of the grass species also depends on their acclimation status. Tronsmo et al. (2013) showed that velvet bent (*A. canina* L.) is more vulnerable than creeping bent (*A. stolonifera* L.) to microdochium patch during the growing season. In contrast, velvet bent resists microdochium patch better than creeping bent when both species are acclimated.

1) The relative impact of temperature versus photoperiod and light intensity on acclimation of grass is poorly investigated. Woody perennials are mapped more thoroughly (Malyshev et al., 2014). A recent study into perennial ryegrass and timothy (Phleum pratense L.) of northern and southern origin discussed the relations between temperature and irradiance / photoperiod, and underlined the importance of incoming radiation for development of freezing tolerance (Dalmannsdottir et al., 2017).

Freezing tolerance can be determined in laboratory tests. The most common method is sampling of ten plants for regrowth as the temperature is lowered gradually in a freezing chamber. The temperature at which 50% of the plants survive is the LT_{50} value (lethal temperature for 50% of the plants (e.g. Espevig et al., 2010; Espevig et al., 2014a). This test method cannot predict the grass plants' survival under cold conditions in the field, but it can be used to rank different grass species or varieties, or to evaluate effects of shade or due to the application of biostimulants or fertilizers.

It is a common assumption that freezing tolerance is positively correlated resistance to winter fungi, both being induced by acclimation. Several experiments with various plant species, including cereals and grasses, have shown this relationship (Ergon et al., 1998; Gaudet et al., 1999; Kuwabara & Imai, 2009; Huang et al., 2014).

SPECIES USED ON GOLF COURSES IN THE NORDIC COUNTRIES

An overview of grass species is presented in STERF's handbook: The Grass Guide 2015 - Amenity Turf Grass Species for the Nordic Countries. The fact sheet Grass species and varieties for severe winter climates gives more specific information.

Nordic golf courses have many different grass species on their greens, and there are interesting differences between the countries. While red fescue is the predominant species in Iceland, bents are more widely used in the other countries. It is important to know the actual species composition, not only which species that was seeded. A survey for the Norwegian Golf Federation and STERF in 2015 gave data about the grass sward composition on "a typical green on your course". By analysing the answers on the dominant and second most dominant species, we could set up figure 2.

Please note that data from Finland only represent 12% of the golf courses. For the other countries, the numbers are, probably, representative: Denmark - 30%, Iceland - 41%, Norway - 35%, and Sweden - 22%. There are some national specialities. In Finland, you find velvet bent on many greens. In Sweden, many Poa greens are re-seeded with rough-stalked meadow-grass (*Poa trivialis* L.) in the spring.

The contamination with annual meadow-grass can be related to the average age of the golf courses. Golf developed earlier in Sweden and Finland than in Denmark and Norway.

We have no corresponding data about grass species on fairways and tees, but based on information from seed suppliers, the most commonly used mixture on fairways is red fescue and smooth-stalked meadow-grass (*Poa pratensis* L.). Tees are usually established with smooth-stalked meadow-grass and over-seeded with perennial ryegrass. Creeping bent fairways and tees are found only on a few high-budget courses.

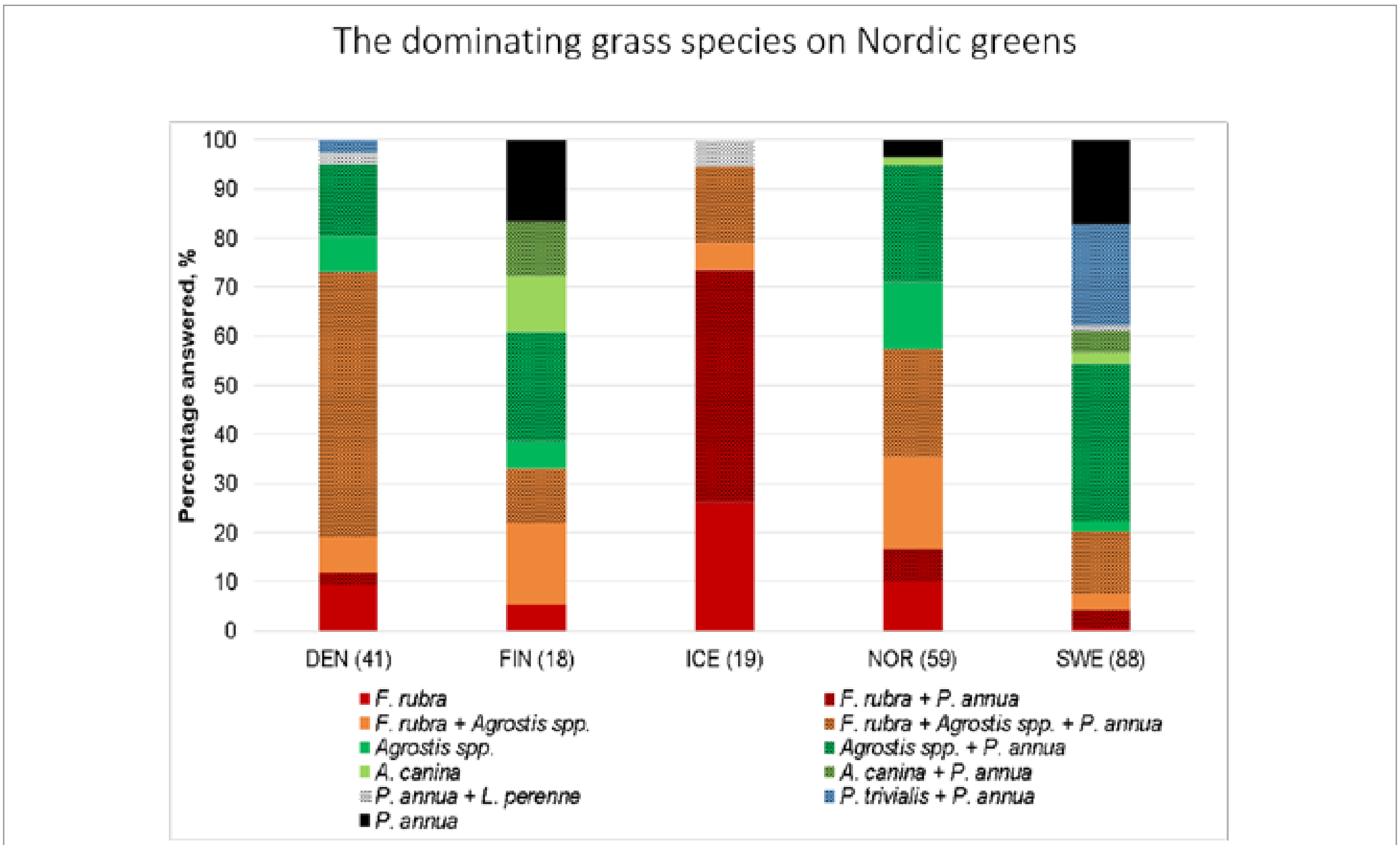


Figure 2. *Data based on a survey on Nordic golf courses in 2015.The number of informants in parentheses (Kvalbein et al., 2017).*

WINTER STRESS TOLERANCE SPECIES BY SPECIES

Velvet bent grass (*Agrostis canina* L.)
In the acclimated state, this species is more resistant to microdochium patch than other Agrostis species (Espevig, 2011; Tronsmo et al., 2013). In the growing phase though, it is very susceptible to microdochium patch and take all patch (Gaeumannomyces graminis).

Velvet bent greens have in our field experiments demonstrated extreme ice encasement tolerance, surviving 119 days of ice encasement without significantly reduced quality compared to normal winter conditions (snow cover) (Waalen et al., 2017). This species seems to have low respiration rate when acclimated (Espevig et al., 2013). In spring, some varieties protect themselves from photoinhibition (damages due to a combination of low temperature and high light intensity) by producing anthocyanin, which gives the turf a dark purple colour.

We recommend STERF's handbook Potential for velvet bentgrass on Nordic golf greens. It discusses advantages and disadvantages of using this very winter hardy species.

Brown-top bent / Common bent (*Agrostis capillaris* L. = *A. tenuis* Sibth.)
There are fewer varieties within this species compared to creeping bent, but the winter stress tolerance is more variable. Browntop varieties from Denmark, Netherlands and – in particular - New Zealand usually have inferior tolerance to freezing temperatures and ice and water damage than Norwegian varieties and some American ones.

When it comes to microdochium patch (and a number of other diseases occurring during the growing season, e.g. take all patch) the resistance of browntop bent is usually poor, especially in the un-acclimated stage. We find more microdochium patch in browntop bent than in creeping bent in our variety trials where we use no fungicides.

Seeding a mixture of red fescue and browntop bent is common on UK and Nordic golf greens (figure 2). One of the rationales for including browntop is, according to some British turf grass agronomists, increased wear resistance to winter play. This is relevant for southern Sweden and Denmark. Depending on browntop variety, the mixture may also be also more robust to ice and water damages and the (re)establishment rate is faster than when seeding pure fescue.

Creeping bent (*Agrostis stolonifera* L.)
The market for this species is large and the number of varieties is very high. The breeders include disease resistance into their programs, but the most severe fungus in the Nordics, *Microdochium nivale*, is not always highly prioritized.
The freezing tolerance and the ability to survive ice encasement is generally good for this species. Acceptable turf quality has been reported after three months ice cover (Thompkins et al., 2004; Waalen et al., 2017). The snow mould resistance varies between varieties.

Tufted hair-grass / tussock grass (*Deschampsia caespitosa* L.)
This is one of the most winter stress tolerant species on the market. Native genotypes survive on severely winter damaged (often poorly drained) fairways. Tufted hair-grass has been recommended for shaded lawns, but it is not a good alternative for tees and football stadiums due to limited wear tolerance and recuperative capacity. We know of some golf courses that seeded this species on roughs and green surroundings, but without success: It formed tufts and the playing quality was not acceptable.

Red fescue (*Festuca rubra* L.)
We categorize this species into three subspecies, based on the existence and length of rhizomes. Strong creeping red fescue (*F. rubra* ssp. *rubra*) is native in Northern Scandinavia and local genotypes are well adapted to cold winters. The Norwegian variety 'Frigg' has superior winter stress tolerance compared with other varieties, but the winter colour is brownish and very dull.

Chewings fescue (*F. rubra* ssp. *commutata*) does not produce rhizomes, but a relatively dense sward. It grows wild in Denmark and Southern Sweden. The commercial varieties are generally more winter hardy than those of slender creeping red fescue (*F. rubra* ssp. *lithoralis* = *trichophylla*). These two subspecies also differ when it comes to winter or off-season colour. Slender creeping red fescue keeps the green colour better than Chewings fescue. For golf greens these two subspecies should be mixed. Our recommendation is to use a 50/50 seed mixture in the southern climatic zone, but 75% Chewings fescue and 25% slender creeping red fescue in the northern climatic zone.

Red fescue is a low input grass, which means that the need for fertilizer is 40-60% compared with creeping bent and annual meadow-grass. This holds also for autumn fertilization. Experiments has shown that spring growth was significantly improved when red fescue received late autumn nitrogen fertilization before winter (Kvalbein & Aamlid, 2012).
Red fescue is significantly more resistant to snow moulds than bents. For this reason, it ranks higher than bents for winter survival in the SCANGREEN trials, which are not sprayed with any fungicides (Aamlid et al., 2012b). It can, however, be infected with microdochium patch when not acclimated.

Ice and water damage encasement is the biggest concern for red fescue growers in the northern climatic zone. Chewings fescue and slender creeping red fescue are weaker than velvet bent and creeping bent on greens (Waalen et al., 2017), and Chewings fescue is weaker than smooth-stalked meadow grass on fairways (Espevig et al., 2014b). Because of the slow germination and recovery of red fescue (Waalen & Kvalbein, 2016; Waalen et al., in prep), we are reluctant to recommend this species seeded alone on greens in districts with high risk of ice build-up in the winter.

Guidelines for red fescue management and discussions about fescue/ bent mixes can be found in STERF's handbook Red fescue management.

Perennial ryegrass (*Lolium perenne* L.)
This species will not survive winters in most parts of the northern climatic zone, but it usually performs well in Denmark and some coastal climates further north. The genetic variability for winter hardiness is small among the ordinary diploid varieties, but tetraploid varieties have improved resistance to winter diseases and perhaps also to freezing temperatures and ice and water damage (www.scanturf.org).

Annual meadow-grass/ annual bluegrass (*Poa annua* L.)
This genetically flexible and adaptive species is difficult to describe. It shows great variation in winter stress tolerance, and Canadian researchers have proven that the most tolerant genotypes for greens grow in districts with variable winter temperatures, not in the colder inland districts where stable

snow cover occurs (Dionne et al., 2009). Observations from field trials in Massachusetts (DaCosta, 2012, pers. comm.) indicate that annual meadow-grass can survive the winter better than perennial ryegrass. In spite of this, we rank annual meadow-grass as the least winter stress tolerant turf grass on sports fields and golf courses. It is highly susceptible to snow moulds, and it will normally not survive more than one month under ice cover (Aamlid et al., 2009b; Waalen et al., 2017). The shallow root system provides little water in the critical, dry spring period. Poa greens with acceptable putting surface in the spring are not common in northern parts of Scandinavia, and fungicides are commonly used to improve spring performance even in the southern climatic zone. Annual meadow-grass is the only grass that produce seed at green's mowing height. Because a certain percentage of the seed are dormant, the species usually forms a large seed bank (Thompson & Grime, 1979). Together with perennial ryegrass, annual meadow-grass usually germinates at lower temperatures than other grasses used on greens (Waalen & Kvalbein, 2016).

None of the rather few commercial varieties of *Poa annua* has performed well in the SCANGREEN trials, so those who want annual meadow-grass on their greens should rather preserve and develop their local ecotypes.

Annual meadow-grass is far less winter tolerant than the seeded species. This makes annual meadow-grass a serious weed in the northern part of the Nordic countries. However, because it is superior in re-establishment situations, every year with severe winterkill is likely to increase the contamination of Poa into greens and fairways seeded with other species. For this reason, it is important to avoid maintenance practices that promote annual meadow-grass. One of the clues is that it is less heat and drought stress tolerant than other grasses, and summer maintenance can therefore make a difference in favour of the preferred grasses. This text is not about Poa control, but headlines would be:

- Avoid mechanical disturbance of the green surface
- Keep the rootzone dryer
- Limit the fertilizer rates

If Poa dominates parts of the greens, a strict regime following the bullet points above can reduce the playing quality to unacceptable levels due to anthracnose (*Colletotricum graminicola*) and seed head production. This makes Poa reduction a delicate balance, and good results are hard to achieve.

Smooth-stalked meadow-grass/ Kentucky bluegrass (*Poa pratensis* L.)
The excellent winter stress tolerance of smooth-stalked meadow-grass has been demonstrated in several variety tests under lawn maintenance. In some cases, we have also found surviving plants of smooth-stalked meadow-grass on otherwise winterkilled greens. As a forage grass, Icelandic smooth-stalked meadow grass ranked higher for freezing tolerance and ice encasement tolerance than Canadian creeping bent (Gudleifsson et al., 1986).

Recently we have included smooth-stalked meadow-grass in the SCANGREEN trials. It survives winter and looks nice at 5 mm mowing height, but we have not measured the playing quality on the relatively course, stiff and upright leaves. For fairways and tees, this species is an obvious choice. Because of slow germination, smooth-stalked meadow-grass will rarely establish when seeded into established turf. Seed of smooth-stalked meadow grass is expensive, and we recommend investing in this species only if you can seed into open soil (Aamlid et al., 2012a)

Creeping or prostrate meadow-grass/ Supina bluegrass (*Poa supina* Schrad.)
This shade and wear tolerant species has also shown very good winter stress tolerance. Creeping meadow-grass grows aggressively and the light green, almost yellowish plants have a tendency to spread to areas where they are not supposed to be. We are therefore reluctant to recommend this species except in special cases, e.g. on enclosed soccer fields and or isolated and shaded tees. Finnish experiences suggest that creeping meadow-grass can replace annual meadow-grass on greens at locations where winterkill occurs regularly (Hakamäki, 2014).

Rough-stalked meadow-grass/ Rough bluegrass (*Poa trivialis* L.)
In some US textbooks, this species counts among the most freezing stress tolerant species. Nordic trials have not confirmed this, and we rank it slightly more winter tolerant than ryegrass. In the SCANGREEN trials, especially in the southern climatic zone, pure stands of *Poa trivialis* often have low density and a purple or almost brownish colour, but it blends well with other species in seed mixtures.

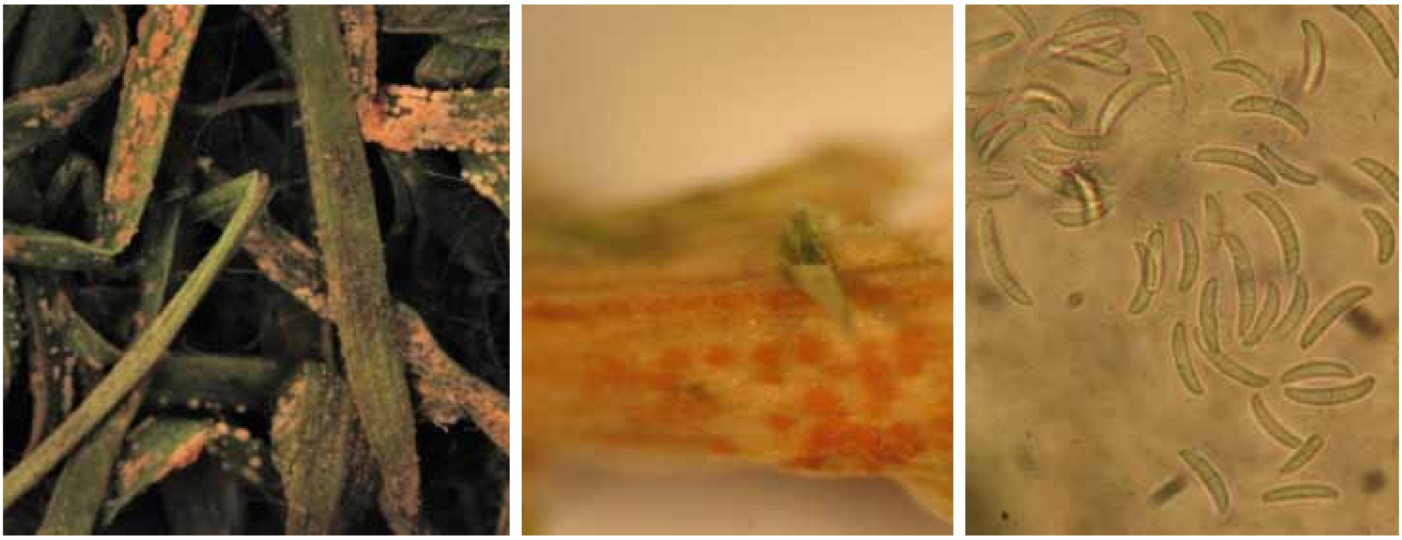
HOW TO FIND THE BEST VARIETY WITHIN EACH SPECIES ?

When evaluating winter survival on test greens, there are often eye-catching differences between grass varieties. On golf courses, these quality differences are hard to discover. In areas with severe winter climate or high risk of snow mould, it is very important to use the most winter stress tolerant varieties. STERF has supported variety testing as a part of their research program on winter stresses. The updated results are available at www.scanturf.org. Here you can rank the varieties within each species according to overall winter hardiness or other characters. We highly recommend this information. You can also look up details about the varieties in the tables published at STERF web.

TEMPORARY NURSE GRASSES FOR QUICKER RE-ESTABLISHMENT AFTER WINTER DAMAGE

Some greenkeepers re-seed winter killed greens with a mixture of the durable species and a species that establishes more quickly. Perennial ryegrass and rough-stalked meadow-grass are alternatives. In our trials comparing the two species as companions for creeping bent, the establishment rate has usually been slightly faster for perennial ryegrass, but the ryegrass has also been more competitive and persistent, even at 3 mm mowing height. Ryegrass also has a higher growth rate, it continues to grow late in autumn, and it can spoil the playing quality and visual impression for many years after being introduced into greens or surroundings. Rough-stalked meadow-grass will usually blend into the sward and fade out more gradually during the summer, thus leaving the space to creeping bent or annual meadow-grass.

WINTER DISEASE MANAGEMENT



***Picture 3a-c**. Sporodochia of Microdochium nivale on leaves of annual meadow-grass (left and middle) and spores of M. nivale (magnification 400x) (right). Photos: T. Espevig.*

PLANT DEFENCE

Resent research on plant genetics opens a tide of new information about the complex battle between plants and fungi. Plants can recognize intruding fungi and activate several defence systems including building physically stronger cell walls and producing chemicals that are toxic to the pathogens. The intruders, on the other hand, are able to react on these contra-attacks and break through. Plant scientists agree that sugars are important in this fight between the host and the fungi. Some greenkeepers are aware of their role as 'carbohydrate managers'. They focus on the carbohydrate or sugar status of the turf throughout the growing season and during hardening period. We think this approach is very good. It provides a key to understand some of our observations on golf greens.

Horsfall & Dimons (1957) distinguished between 'low sugar diseases' and 'high sugar diseases'. They showed that plants low in sugar became more susceptible to certain diseases, and they used Fusarium wilt (the old name for Microdochium was also Fusarium) as an example of a 'low sugar disease'. In contrast, rust (*Puccinia* sp.) and powdery mildew (*Blumeria graminis*) were examples of 'high sugar diseases'.

Although interactions between sugar status and winter diseases are not completely understood, it has been shown that the resistance to snow moulds increases with higher levels of sugars in the plant tissue (Vanderplank, 1984; Gaudet et al., 1999) and that it is induced by hardening (Tronsmo et al., 2001). Hardened plants and cultivars with a high sugar content usually show fair resistance to snow moulds. In addition, not only the total amount of sugars plays a role in snow mould resistance, but the resistance also increases with a higher content of reserve carbohydrates - fructans (see next paragraph) or/and with a slower rates of sugar metabolism in the more resistant species and cultivars (Yoshida et al., 1997; Gaudet et al., 1999; Bertrand et al., 2011).

Sucrose from photosynthesis is the energy source for plant growth and life. Sucrose molecules can be transformed into reserve sugars by linking together in long chains like cellulose, fructans, starch and the more complex lignin molecule. Fructans are the most important sugars for long-term energy storage in grass plants of temperate origin (Smith, 1972). The ratio between sucrose and fructans in grasses is dynamic and it depends on photosynthesis rate and growth rate. When plants are under snow cover and the production of sucrose stops due to absence of photosynthesis, the fructans will be converted to sucrose as energy for grass respiration and defence against snow moulds. A higher fructan content in the plant means higher energy storage.

Sucrose does not only deliver energy, but together with other sugars, it is also an important cryoprotectant (Olien, 1967; Anchordoguy et al., 1987; Livingston et al., 2009). It also serves as a controller and signalling molecule (Rolland et al., 2006; Ruan, 2014) activating genes that set up the defence system in the plants (Morkunas & Ratajczak, 2014; Moghaddam & Van den Ende, 2012). When a fungus invades a plant cell, the cell becomes like a battlefield. Quick transport of energy into the fight is crucial, and the content of water-soluble sugar in the neighbour cells is important. Plants that are low in sugar become the losers.

Low sugar content can have many reasons. Shade is obviously bad, and oxygen shortage in the soil (due to compaction, thatch problems or bad drainage) can make the root cells burn sugar in a very inefficient way. Too high nitrogen fertility especially in the late summer and early autumn will stimulate growth, and attract sugars to the production and elongation of new cells and not to the storage.

During cold acclimation, grass plants nearly stop growing and, thus, accumulate more sugar in their cells. This increases their resistance to attack from winter fungi and many other winter stresses.

THE MOST COMMON WINTER DISEASES

Some fungi are active at low temperature and attack plants in the humid microclimate under snow. A common name for these pathogens are snow moulds as they leave white mycelium on the turf when the snow disappears. Some of these diseases can be active even without snow. Keep in mind that you sometimes might find other fungi attacking plants under low temperature than those described in the following.

Microdochium patch

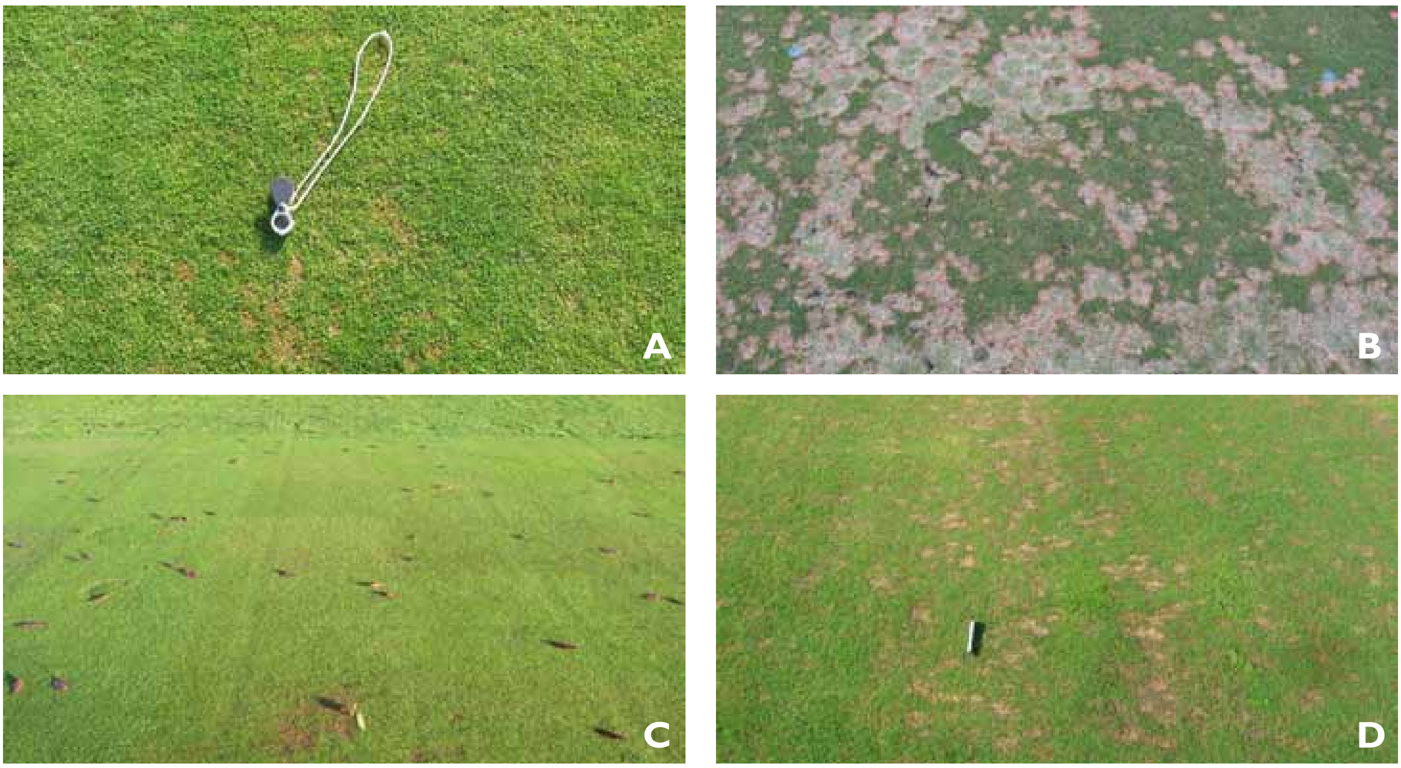
Microdochium patch caused by *Microdochium nivale* (called *Fusarium nivale* from 1901 to 1983), is the most economically important turf grass disease in the Nordics (Tronsmo et al., 2001). Different from the other snow moulds, it can attack grass without snow cover. During moist and cool periods, even in summer and typically in autumn, microdochium patch can destroy the putting quality of golf greens. Well-fertilized turf can also suffer from massive attack in spring even at temperatures above 10 °C.

After a snow cover, the middle of the patches is often tan while the margins are reddish, brown or pink. This is due to the spores of *M. nivale* being borne in sporodochia (fruiting structures consisting of clusters with a mass of spores and mycelium) which are orange in colour (picture 3a,b). Pink snow mould is the name of these "spring symptoms".

M. nivale attacks all grass species used on golf greens. Annual meadow-grass is the most susceptible species (picture 4a,b), followed by browntopbent, creeping bent and red fescue (picture 4c). Velvet bent is susceptible in the growing season, but becomes more resistant than creeping bent after cold acclimation in the autumn (picture 4d).

M. nivale spreads with spores, but the fungi can survive in the thatch and attack the grass from growing mycelium. Spores spreading from contaminated thatch is supposed to be the main infection source (Tronsmo et al., 2001). This probably explains why some greens have a higher disease pressure than others. Shade or a higher percentage of annual meadow-grass can also be factors increasing the amount of microdochium patch infection.

Microdochium patch is a typical low sugar disease. In the late summer high soil temperature will enhance the mineralization of nitrogen from the thatch, stimulate growth and lower the sugar content in plant tissue. In combination with dewfall and moist leaves, which allow spores to germinate, the environment becomes perfect for development of microdochium patch. Excessive nitrogen fertilization in the autumn will also stimulate disease development. See the following chapter on fertilization.



***Picture 4.** Microdochium patch on annual meadow-grass in July 2011 (a) and after a mild winter 2016-17 with six short periods of snow cover lasting from 2 hours to 2 days (b); on red fescue in October 2013 (c) and on velvet bent in October 2007 (d). All photos are from NIBIO's turfgrass research centre Landvik. Photos: T. Espevig.*

Typhula snow moulds

The snow moulds caused by the *Typhula* species are often superficial in the sense that they kill the grass leaves only. However, the crowns may also be injured and the turf may die in districts with a certain period of snow cover (Årsvoll, 1973). *Typhula ishikariensis* (speckled snow mould) needs at least three months of snow cover in order to cause significant damage. The snow requirements of *Typhula incarnata* (grey snow mould) are lower. Thus, in our experimental plots at Landvik on the Norwegian south coast (on/off winter, often with only a few weeks of snow cover), we often see superficial attacks of *T. incarnata* in perennial ryegrass and creeping bent, but *T. ishikariensis* has not been detected to date.

Common to the two *Typhula* species is that that they develop greyish spring patches (picture 5). It can be difficult to distinguish between the two *Typhula* snow moulds in the field unless you find the sclerotia (a compact mass of hyphae that are formed by the fungi to survive the summer). The sclerotia are reddish brown in *T. incarnata* (picture 6) and nearly black and smaller in *T. ishikariensis*, and they are embedded in the dead grass leaves in the spring (picture 7). In the autumn the sclerotia geminate into fruiting bodies which are pink in *T. incarnata* (picture 6 b,c) and white in *T. ishikariensis.* If you see these fruiting bodies, it tells that the fungus is present, but the weather conditions and the acclimation status of your turf determine whether there will be an outbreak of disease or not.

Together with mushrooms, *Typhula* belongs to a group of fungi called Basidiomycetes, while *Microdochium* belong to a group called Ascomycetes. This means that some of the fungicides that are effective to control *Microdochium* will not affect *Typhula* (Hsiang et al. 1999).

Picture 5. *Grey snow mould on velvet bent in April 2010 at Kongsberg GC. Photo: T. Espevig*

Other winter diseases

Some other fungi can also attack turf grasses under snow cover. *Typhula phacorrhiza* exists in North Europe. The oomycetes (non-true-fungi) *Phythium iwayamai* grows quickly in ice-cold water under snow. *Sclerotinia borealis* can kill grass if the snow cover lasts about half a year. Be aware that rare and new diseases may occur. If you have any doubt, please send samples to our disease laboratory for identification.

Picture 6a-c. *Typhula incarnata: Sclerotia (left), Sclerotia germinating into fruiting body (middle) and fruiting bodies in late autumn on a creeping bent golf green. Photos: T. Espevig (left & middle) and T. Haugen (right).*

Picture 7. *Sclerotia of Typhula incarnata embedded in a leaf of browntop-bent in spring. Photo: A. Kvalbein.*

Picture 8. *Fruiting bodies of Typhula incarnata in the late autumn. Photo: T. Espevig.*

AUTUMN PREPARATIONS TO AVOID WINTER DISEASES

Fertilization

Some greenkeepers apply fertilizer according to their practical experiences or recommendations from the fertilizer suppliers . "If it works it works". There are several statements in the fertilizer catalogues that are in conflict with relevant research. Even some textbooks seem to copy each other without checking the relevance of the experiments cited. The most common misunderstanding is that enhanced levels of potassium in the autumn will improve the winter stress tolerance of cool season turf grasses, or more diffuse: Strengthen the turf for winter. The lack of solid research on effects of potassium on turf grass was recently reviewed in a master thesis from Clemson University (Mirmow, 2016). We find several other claims indicating that the turf needs extra supply of a single nutrient to be prepared for winter stresses. Calcium, sulphate and iron are examples.

Our fertilization strategy has for the past ten years been based on some simple principles learned from a team of plant nutrition researchers at the Swedish University of Agricultural Sciences They worked on this for three decades. The baselines are in short:

- All plants need the same mix of nutrients throughout the year, and the optimal ratio between these nutrients is well defined.
- Nutrients, with nitrogen as the minimum factor controlling growth, should be applied frequently in rates corresponding to the plants' growth potential, determined by the turf grass species (genetics) and environmental conditions such as temperature, light and water availability.

You can read more about fertilization of turf grass in STERF's handbook Precision fertilization.

Plants are extremely flexible and able to adapt to variations in nutrient availability by rebuilding the ports and pumps in their root cell membranes. This adaptation is, however, an energy consuming process. In order to save energy (sugar) you should keep the nutrient mix in the soil stable and as optimal as possible. On a USGA green the easiest way to fertilize is to spoon-feed weekly with "the optimal fertilizer". See table 1.

The weekly application should be adapted to the grass species' growth capacity (on greens: Poa > bents > fescues) and the environmental conditions. Mineralization of nutrients from thatch degradation will fill some of the plants' needs when soil temperature is high. See figure 3. The plants' growth potential will be reduced in summer if the mean diurnal temperature is higher than 20 °C. In the Nordic countries, we rarely experience serious summer decline because of heat stress as long as the water supply is good.

Nitrogen	100
Potassium	65
Phosphorus	14
Sulphur	9
Magnesium	6
Calcium	7
Iron	0.7
Manganese	0.4
Boron	0.2
Zink	0.06
Copper	0.03
Chlorine	0.03
Molybdenum	0.003
Nickel	*

* Lack of reliable data

Table 1. *The optimal plant fertilizer.* *Each element by weight relative to nitrogen (=100)*

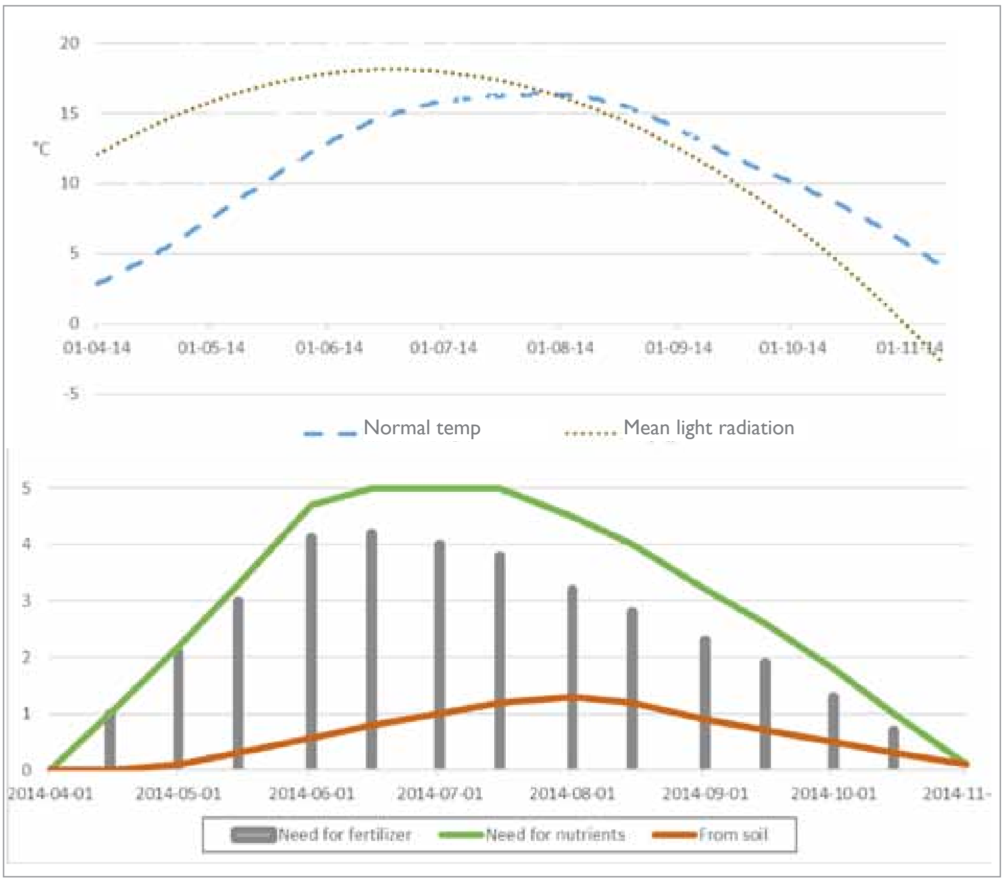


Figure 3 and 4. *Above: Normal irradiance and air temperature (°C) curve in South Norway. Below: Example of fertilizer distribution related to growth conditions and soil fertility (degradation of soil organic matter).*

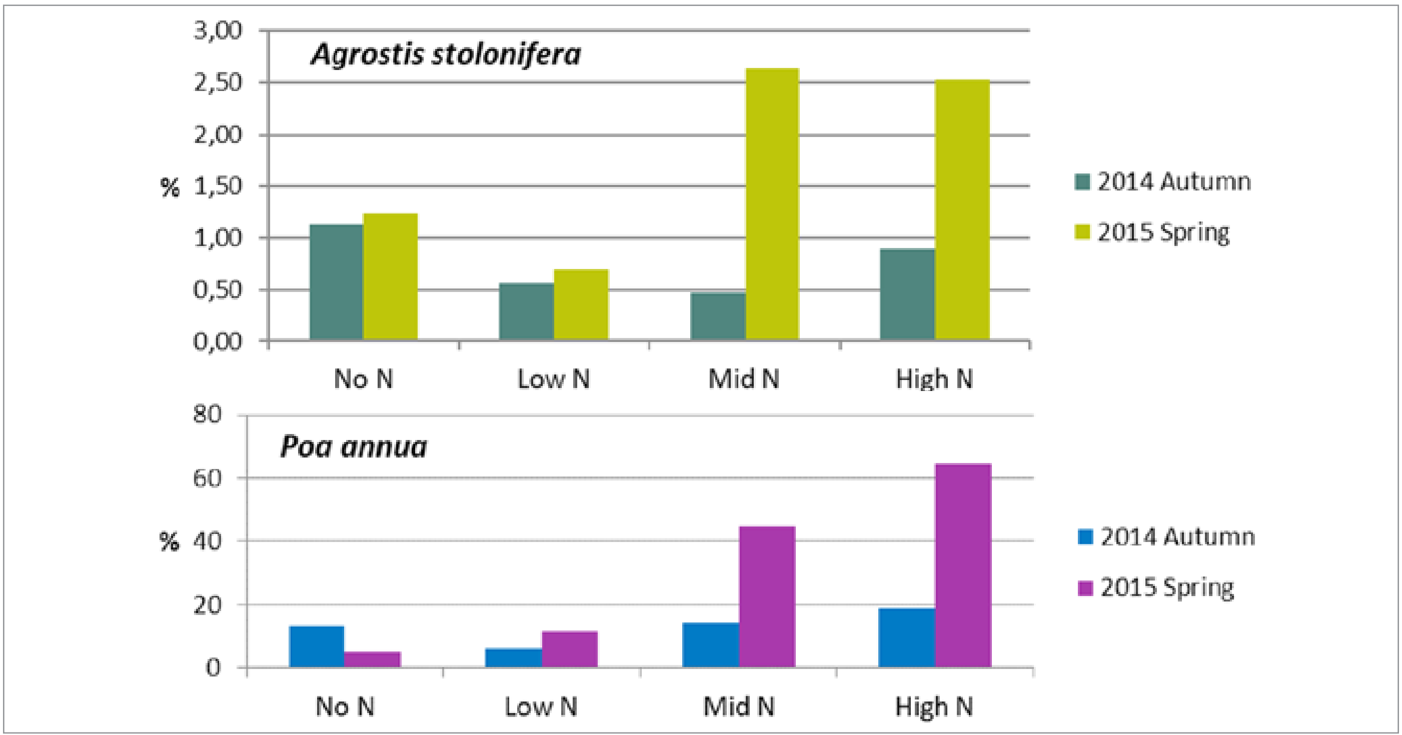


Figure 5. *Microdochium patch (% of plot area) at Landvik in response to four nitrogen levels (0, 2.8, 5.5, 8.4 g/m2) from medio September to the end of November. Note the different scales on the Y-axes.*

Autumn fertilization experiment
In 2014-2016 we performed fertilization experiments in annual meadow-grass and creeping bent. Detailed information can be found in appendix 1.

Figure 5 shows results from one of the experiments at Landvik with regard to microdochium patch. The two higher nitrogen rates caused significantly more disease in spring in both species. The low N rate showed, on the other hand, a tendency to less disease than in the treatment only fertilized with other nutrients than nitrogen. We used no fungicides in this trial.

The positive effects of nitrogen application in the autumn is good colour and growth until low day temperatures make the turf acclimate. Autumn fertilization also accelerates spring growth. Several studies, nicely reviewed by Bauer et al. (2012), confirm these positive effects. However, the experimental evidence from Landvik presented in figure 5 clearly shows that the nitrogen rate in autumn ought to be moderate.

Some other nutrients

Sulphur / Sulphate
Elementary sulphur is an old fungicide. Rausch & Wachter (2005) made a review of the role sulphur plays in the defence mechanisms in plants and used the term "sulphur-induced resistance". However, the experiments at Apelsvoll (inland climate, shorter autumn) showed no effect on microdochium patch in either autumn or spring of excessive sulphate application in the autumn (N:S rate = 100:160) compared to no sulphate or the recommended rate (N:S= 100:9, Ericsson et al., 2013). At Landvik (costal climate, longer autumn), no sulphate and excessive sulphate led to more microdochium patch compared to the recommended S-rate (Ericsson et al., 2013).

We will not recommend to exclude sulphate from the autumn applications but the higher rates should be avoided. Our experiments also gave some indications that excessive amounts of sulphate may reduce spring growth.

Iron
Many Nordic greenkeepers apply extra iron in the autumn (unpublished data from survey 2015, see figure 6 - next page). The rationale for this may vary, but iron improves colour. Mattox et al. (2017) reported that iron sulphate helped to control Microdochium nivale if combined with other management strategies, but iron sulphate alone did not provide acceptable winter quality on annual meadow-grass greens in the North-West United States.

Excessive use of iron can have serious negative impact on USGA greens. Between the root zone mixture and the gravel, iron can be oxidized and form rust layer which can effectively prevent drainage from the green. We have seen this in Norway, and there are reports from other parts of the world (Obear & Soldat, 2014).

Copper / pigments
Copper-solutions were considered fungicides many years ago. Today, some copper products provide an intense green colour to the turf. Other pigments or colorants are also on the marked. The effects of some of these products on heat-stressed creeping bent greens have been tested. The conclusion was that they were without any benefits for the turf (McCarty et al., 2013).

We have tested the effects of some experimental pigments on winter diseases. Some of them appeared to have a certain effect, but we are not sure if it was a real effect or if the pigment only masked the symptoms of the fungi.

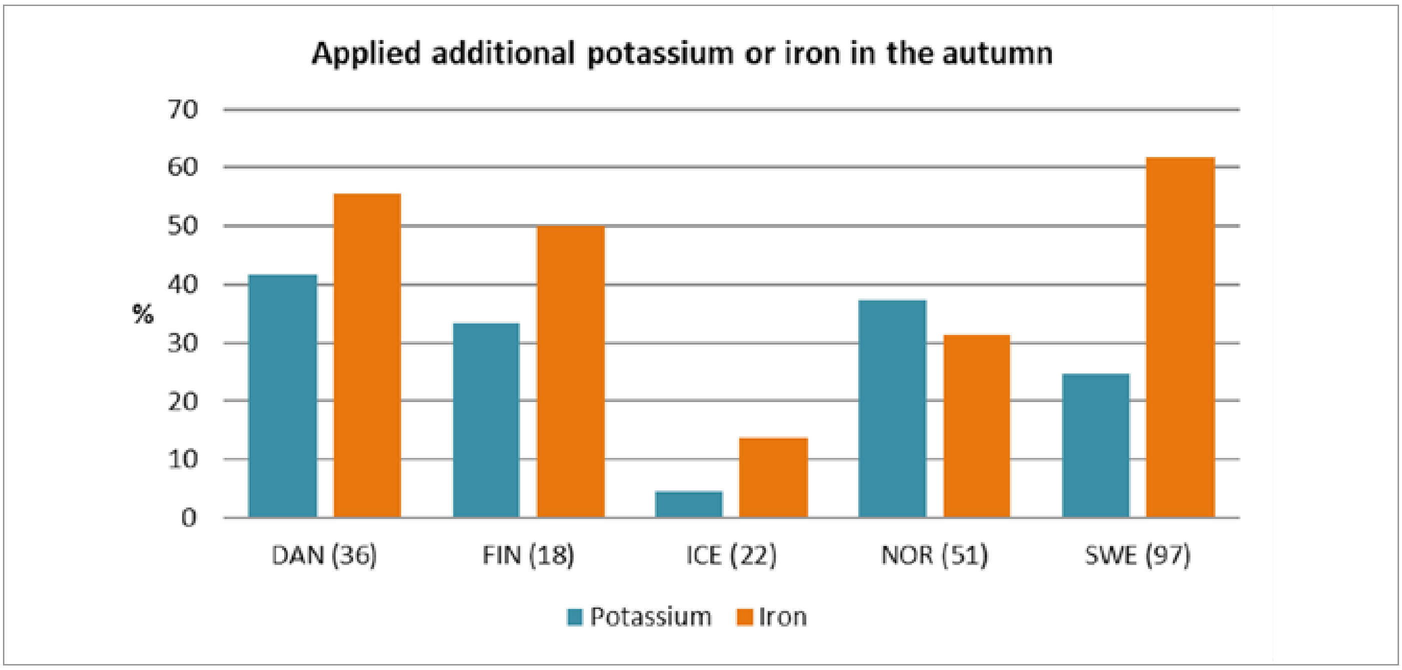


***Figure 6**. Results from a survey among Nordic golf courses 2015. The number of respondents in parenthesis.*

Copper can be toxic to plants, and greenkeepers should be aware of long-term effects of using copper products. The first indication of copper intoxication is reduced root growth (Adrees et al., 2015).

Silicon

Silicon is not yet recognized as an essential nutrient for plant growth and development, but it is not unlikely that it will become so in the future. Grass dry matter can contain up to eight percent silicon. The very winter stress tolerant species tufted hair-grass has a very high content of silicon, but this can be a coincidence and there need not be a causal relationship. Grass plants that experience stress sometimes increase their uptake of silicon. Experiments with cool season turf grasses are few and the results are inconsistent, but there are reports of positive effects of silicon on stressed plants (e.g. Balakhnina & Borkowska, 2013).

Autumn fertilizer recommendations

Based on the information from the experiments at Landvik and Apelsvoll, as well as five full-scale experiments on golf courses in the same project, we summarize our autumn fertilization recommendations as follows:

1. Use the same balanced mix of nutrients as the rest of the year (table 1).

2. Adjust the N-rate at the end of August to achieve normal harvest of clippings in the collectors. Normally, this rate will be lower than the maximal weekly rate given in June and July. This is your starting rate.

3. Reduce the fertilizer applications week by week until the time where the turf grass normally stops growing.

4. If the risk of winter injuries are high, be moderate with the autumn application rates. Risk factors are shade, high disease pressure, limitations on fungicide use or vulnerable grass species or varieties.

Exact fertilizer rates are difficult to express because autumn temperatures, grass species and the risks for winter injuries vary from one location to another. Even within a golf course, there may be considerable variation.

We have made a simple Excel- based calculator for golf course managers. You will find an example based on an annual meadow-grass golf green in South East Norway in figure 7. The Excel version of this tool can be downloaded from www.sterf.org (Library / Handbooks/ Winter stress management).

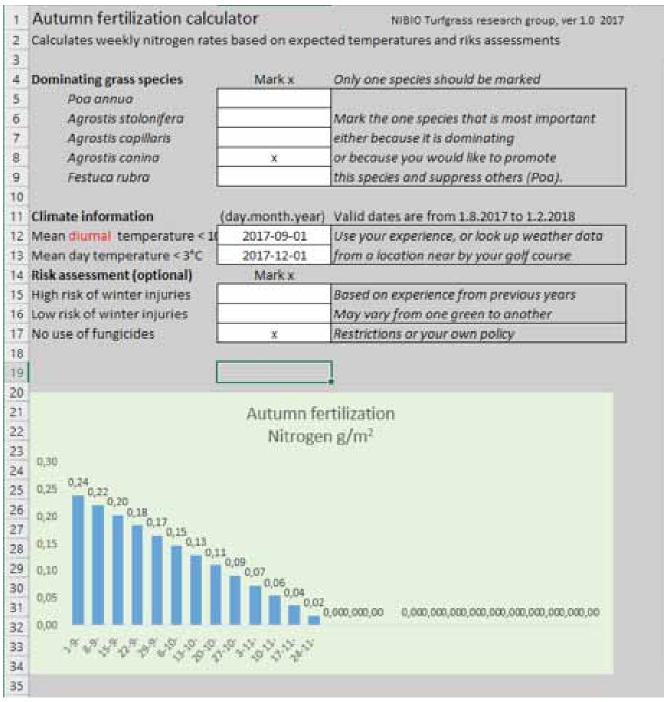


***Figure 7.** Screen copy of autumn fertilization calculator.*

Use of compost

Inclusion of compost in the rootzone or topdress on USGA greens can reduce injuries from snow mould (Boulter et al., 2002; Espevig & Aamlid, 2012). This could be an example of biological control because compost contains a high number of microorganisms. It has also been reported that other fungi, like *Typhula phacorrhiza*, can suppress the snow mould pathogen *T. ishicariensis* (Nelson, 1997; Wu et al., 1998).

Compost dressing improves the water holding capacity at the top of the root zone. This results in less air in the mat. Some of our observations from golf courses indicate that *Microdrochium nivale* depends on air filled pores to develop pink snow mould. A positive effect of compost may therefore have alternative explanations than the high content of microbes.

Because our experiments with nitrogen applications in the autumn showed that high N-rates gave more microdochium patch, we are reluctant to advise compost applications in the autumn without including its nitrogen content into the fertilizer balance.

Biostimulants

There are several definitions of the term 'biostimulant'. We refer to this one: A plant biostimulant is a non-nutritive substance, microorganism or mixture of substances and/or microorganisms applied to plants with the aim to enhance nutrition efficiency, abiotic stress tolerance and/or crop quality traits (du Jardin, 2015)

Biostimulants can make plants more tolerant to stress. (A stressed plant has shortage of resources, grows under unfavourable conditions and/or faces diseases, pests or toxic chemicals). Experiments have proven positive effects of some biostimulants on turf exposed to heat, drought, herbicides, high UV-light intensity and some pests. Some products also have improved the cold tolerance of warm season grasses (Munshaw et al., 2006).

So far, no reports confirm that biostimulants improve the winter survival of cool season grasses, but experiments on other plants suggest that some biostimulants may have such an effect. For example, experiments on the commonly used test plant *Arabidopsis thaliana* proved that extracts of the algae *Ascophyllum nodosum* lowered the LT_{50} values by 3°C, that the cell membranes of the treated plants were more persistent during freezing and that the degradation of chlorophyll during recovery from freezing was lower (Rayirath et al., 2009). A later study related the improved freezing tolerance to lipophilic components of the extracts from *A. nodosum*, which had an impact on 5% of the genes in *Arabidopsis thaliana* plants. The treatment also altered the fatty acid composition in the plant cells (Nair et al., 2012). Taken together, these observations show that algae extracts are interesting products that warrant further study in relation to winter stress tolerance.

The rapid development of gene technology research has changed the way plant physiologists explain stress reactions. By the end of the previous century, textbooks told that hormones were the controllers of plants. Today we add that certain molecules in the cells are signalling molecules. These molecules turn on or off genes that in next turn start the production of important enzymes that are useful to plants during stress.

Different stresses, like anoxia, drought or low temperatures, can all produce Reactive Oxygen Species (ROS) in the plant cells. ROS are highly reactive, potentially harmful molecules, and as a response to ROS, plants produce anti-oxidants (e.g. ascorbic acid, superoxide dismutase, glutathione, polyphenols and more) that can deactivate ROS. ROS production in plants, originally considered as a harmful and dangerous process, is now recognized as an important component of the signalling network that plants use for their development and for responding to environmental challenges (Del Rio, 2015).

Some ROS, like hydrogen peroxide, are included in some biostimulant products. They may act like activators of the plants' defence system and increase the production of antioxidants. This makes it interesting to test biostimulants on cool season grasses, and we encourage suppliers in the turf industry to have the effects of their products proven in scientific and independent experiments.

Plant growth regulators

The only plant growth regulator approved in turf on the Nordic market is trinexapac-ethyl. In our experiments with Primo Maxx® from 2007 to 2013 we found that applications reduced the occurrence of pink snow mould, but not to an extent that made fungicides redundant when growing susceptible grass species. The effect was explained by the increased carbohydrate level in turf treated with trinexapac-ethyl (Aamlid & Edman, 2014).

Mechanical maintenance

Mowing height

We examined the effects of increased mowing height in autumn on many Nordic golf courses from 2008 to 2010 (Kvalbein & Aamlid, 2012). The results showed that bents should be cut low until the grass stops growing. The owing height of red fescue, on the contrary, should be increased in the autumn to about 150% of summer height. Even the mowing height for annual meadow-grass ought to be increased if efficient fungicides are available.

Topdressing

In order to avoid layering in the root zone we recommend that the (at least) monthly application rate of sand is adapted to the growth rate of the grass. Excessive sand in the autumn would be an exception from this general guideline. Some greenkeepers argue that the sand protects the grass crown from desiccation and that sand will make the ice slip easier from the sward if cracking is necessary.

Generally, we do not recommend excessive autumn dressing because sand will shade the turf and brushing injure the grass leaves. There is an exception: If the greens shall be open for winter play, applications of 3-4 mm sand will protect the grass crowns from mechanical damages. See more in the STERF fact sheet Winter play on summer greens.

Aeration

Some greenkeepers practice hollow coring and sand dressing in the autumn as a part of the thatch control program. We agree that late autumn is the best time to disrupt the playing quality, but ideally, you should control thatch only by sand dressing. Avoid scars in the turf where annual meadow-grass can germinate. (If you manage Poa greens, the strategy is different, of course).

Hollow tine coring or spiking, will often create compaction at 6-12 cm soil depth. Deep aeration with solid tines (Vertidrain or similar) in the late autumn is useful to penetrate and loosen this compacted zone and will sometimes remove surface water and reduce ice build-up during winter. Aeration can, however, have adverse effects where microdochium patch is the major type of winter injury. We base this on observations showing the driest part of the greens to have more pink snow mould in spring. We also sometimes find microdochium patch surrounding the holes after deep aeration (picture 9).

Rolling

Experiments in US have shown rolling to reduced microdochium patch occurring during the growing season on annual bluegrass greens (Mattox et al., 2014). The authors explained this as an effect of dew removal causing a drier canopy, but rolling may also result in a less conducive environment for the pathogen due to less air-filled porosity in the topsoil.

Picture 9. *Mycelium of M. nivale around aeration holes on a red fescue green. No fungicide was applied this greens. Photo: W.Waalen.*

Fungicide applications

Biological products using living organisms to control pathogens have so far not reached applicable efficacy (Aamlid et al., 2017a). This leaves us with chemical fungicides as the most efficient tool to fight diseases. In the Nordics, winter diseases are the economically most important diseases. The access to fungicides varies and will probably continue to vary among the Nordic countries. Even though EU has introduced the principle of mutual recognition, it is still up to the national authorities to decide which pesticides shall be on the market.

The golf federations in the Nordic countries have chosen different strategies regarding fungicides. Some have accepted that only formulations with a specific turf grass label shall be used on golf courses. Other federations have applied for and received permission for "minor use" of agricultural products.

Common to the five Nordic countries is that they have implemented EU's directive on 'Sustainable pesticide use'. This directive is based on the principles for 'Integrated Pest Management (IPM)' which means that fungicides shall only be applied when other methods cannot provide adequate protection, and when damage from disease is expected to be unacceptably high. Applying fungicides in the autumn imply some environmental risks because of high precipitation and retarded uptake due to low temperature. Undulated greens, short distance to waterways, low organic matter in the root zone (but not in thatch) and localized dry patches increase the environmental risks (Larsbo et al., 2007; Aamlid et al., 2009a). Recent have shown high concentrations of fungicides and their metabolites in surface runoff (Aamlid & Almvik, unpublished 2017), so it is important to control thatch and keep up the infiltration rate as the turf ages.

Both practical experiences and the unsprayed control plots in our fungicide trials show the need for fungicide applications in the autumn. *Microdochium nivale* and other winter fungi will seriously injure especially annual meadow grass, but also browntopand creeping bent, where fungicides are not applied. But there is no need, and it is also illegal, to apply higher rates or make more applications than permitted on the label. Provided preventative applications or application at the first sign of disease, our experiments have usually shown equal protection if the rate of the product is reduced by 1/3 compared with the maximum rate on the label. One preventive application of a systemic fungicide when the turf is still growing in October usually provides 60-80% disease reduction and the level of control is usually increased to 90-95% with an additional application of a contact fungicide three weeks later. Only golf courses accepting nothing but the highest level of control will have to go for a third application shortly before snowfall (Aamlid et al., 2015). Repeated use of the same fungicide always implies a certain risk for pathogens to become resistant, hence, there is always a maximum number of application (usually between one and four) stated on the label.

Picture 10. *Participants at a turf grass winter stress seminar visiting the experimental green at NIBIO Apelsvoll in November 2014. Microdochium patch nearly destroyed the shaded plots in this experiment. Photo: A. Kvalbein.*

Tree removal

It is twenty years since Huner et al. (1998) explained how light and temperature together control the acclimation processes, and our experiments have indeed confirmed how harmful shade can be to the turf grass. Our conclusion is that a chain saw might be the most efficient tool for improving winter stress tolerance.

In the experiment at Apelsvoll with increasing nitrogen rates in autumn to creeping bent and annual meadow-grass, we did not use any fungicides in the first year. By the end of October, the Poa greens in natural light had 7% microdochium patches. In shade, there were 28% patches. Corresponding numbers for creeping bent were 0.5 and 2.5%. See picture 10, taken two weeks later.

Shade also significantly reduced the freezing tolerance. In December half of the creeping bent plants died at -15 °C when shaded. Normal daylight acclimation gave a LT_{50} value of -32 °C. See figure 8 for more data.

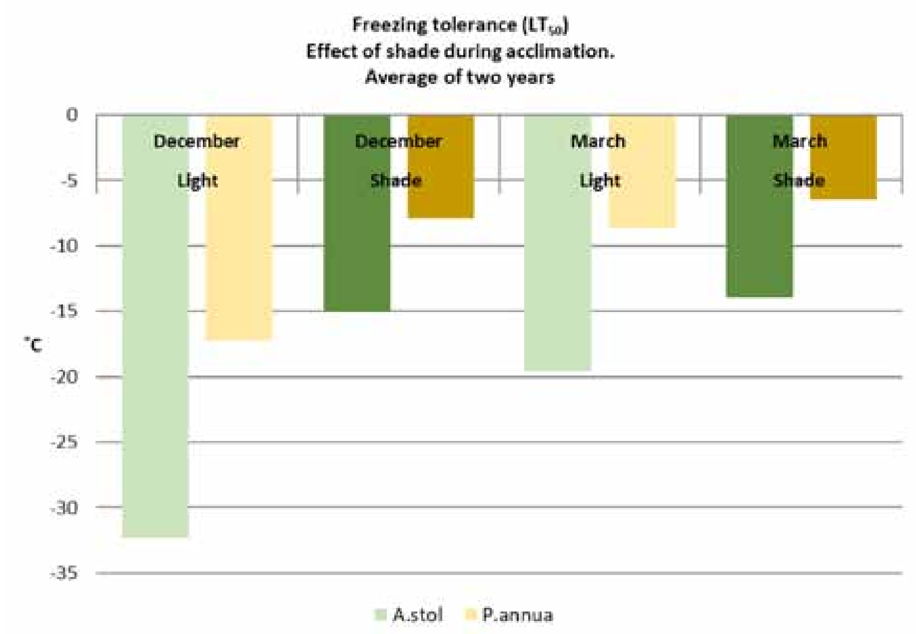


Figure 8. *Creeping bent (A.stol.) and annual meadow-grass (P.annua) grown in shade (30% of natural daylight) compared to grass in natural autumn light at NIBIO Apelsvoll. Freezing tests were conducted in early December 2014 and 2015 and in March 2015 and 2016.*

WINTER ACTIONS

Snow handling

A permanent snow cover over non-frozen root zone material provides good conditions for snow mould development. Typhula ishikariensis, and to a lesser extent Typhula incarnata, require a certain duration of snow cover (Hsiang et al., 1999).

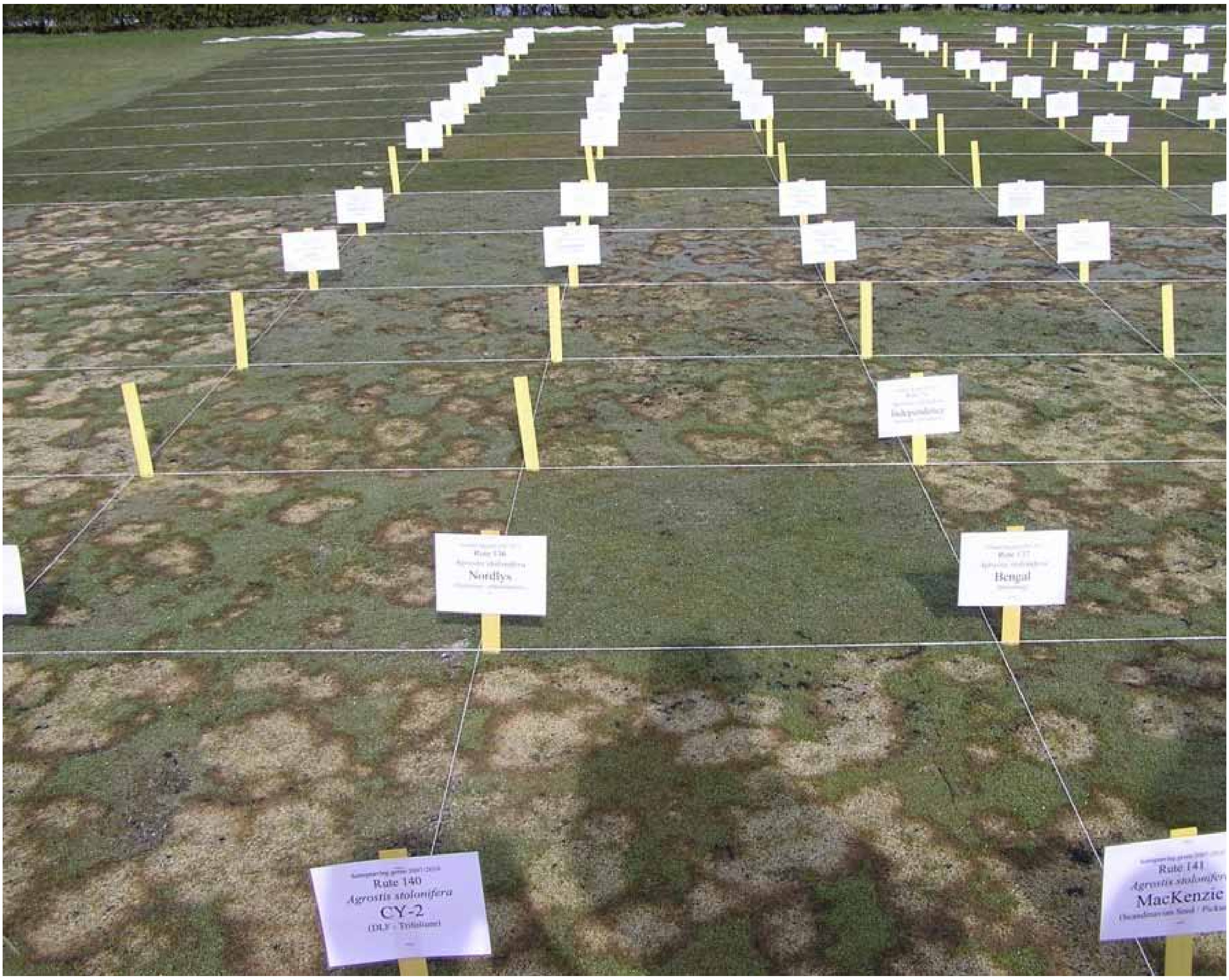
Dry snow is a very good insulating material under which the soil heat will prevent low freezing temperatures during winter. The temperature normally stays close to zero under a permanent snow cover. Removal of snow or compacting snow layers less than 15 cm thick is recommended if the soil is not frozen. This can create more permanent soil frost and reduce the injuries from fungi.

Low freezing temperatures are rarely lethal for bents, but annual meadow-grass does not tolerate temperatures below 10 °C for a long period.

Fungicides during winter

Fungicide application normally protect the grass for several weeks. If applied in autumn, according to good practise, winter applications are not necessary. Early spring applications can be considered if the grass has started to grow and there is a risk of weather conditions promoting *Microdochium nivale*, but our experiments have seldom shown better disease control or faster green-up after such applications.

In one case we saw a severe outbreak of microdochium patch after a late snow fall on deacclimated turf that has started to grow and received the first application of fertilizer (picture 11), but the attack was superficial and the turf recovered by itself within one to two weeks.



Picture 11. *A late snowfall caused a severe outbreak of microdochium patch in the SCANGREEN trial at NIBIO Landvik in April 2008. Photo: T. Espevig.*

ICE AND WATER MANAGEMENT

Picture 12. *"What did we do wrong? We cracked the ice". Greenkeepers discussing on a fescue/bent green, probably killed by freezing temperatures shortly after cracking the ice. Vestfold GC, 13 April 2013. Photo: A. Kvalbein.*

WINTERKILL DUE TO LACK OF OXYGEN

Long-lasting ice encasement is often lethal to turf. Plants need oxygen for respiration. Respiration is very low when temperature is below -3°C, but significant around 0 °C.

Cold-acclimated wheat plant cells do not freeze before the temperature reaches -6°C (Pukacki & McKersie, 1990), and it is also likely that most grass species resist ice formation at sub-zero temperatures. Ice encasement is stressful for plants, but when ice encasement occurs during periods with low temperatures (below approx. -6°C) the stress becomes even greater. In laboratory tests plant survival decreased as the temperature under ice encasement was lowered (Baadshaug, 1973; Gudleifsson, 1989; Björnsson, 1986). The temperature at grass crown level under ice usually fluctuates around 0°C if the ice is covered by snow, but we have measured temperatures down to -8 °C if the ice is unprotected. Ice has practically no insulating effect.

When the oxygen concentration around plants declines below a certain level, the carbohydrate metabolism will change into anaerobic respiration and organic acids and CO_2 accumulate. Energy depletion due to less efficient anaerobic respiration is a common explanation for injuries due to ice encasement (Castonguay et al., 2009). The evidence for this is, however, not conclusive as McKersie et al. (1982) and Aamlid et al. (2009b) found no correlation between carbohydrate levels and injuries caused by ice encasement in winter cereals and *Poa annua*, respectively. Another explanation is intoxication by anaerobic metabolites, especially CO_2, although the study by Castonguay et al. (2009) suggested that that lack of oxygen was more harmful for the plants than high CO_2-levels.

Anaerobic bacteria have been isolated from ice encased grass plants (Gudleifsson, 1994), but the role of their metabolites has not been studied in detail to our knowledge.
The damages in the plants are probably very complex during hypoxia (low oxygen concentrations) and anoxia (lack of oxygen), and a series of reactions occurs which destroys vital part of the cells. (Blokhina et al., 2003). A recent study showed that annual meadow-grass lost its freezing tolerance when exposed to hypoxia irrespective of carbohydrate status (Dodson et al., 2017). This is in accordance with the above-mentioned Nordic laboratory tests, and it confirms Norwegian greenkeepers' experience: Ice encasement weakens the plants significantly, and low temperatures occurring after a period of ice encasement can kill even the more winter hardy species (picture 12).

Gudleifsson & Bjarnadottir (2014) made a comprehensive review on the relationship between freezing tolerance (LT_{50}-values) and tolerance to ice encasement. They agreed with Fowler et al. (1981) and Gusta et al. (1983) that the crown LT50 value was the best laboratory predictor of field survival[2]. They also suggested measuring the grass plants' respiration rate or production of specific metabolites and free radicals as indications of their ability to tolerate ice encasement.

2) Many years later, Larry Gusta underlined the limitations of freezing tests, because of the complexity of winter stresses. Field experiments are therefore important to fill out the results from laboratory work (Gusta & Wisniewski, 2013)

Calcium can stabilize cell membranes and protect from injuries caused by anoxia (Pomeroy & Andrews, 1985). This does not mean that excessive applications of calcium can prevent winter injuries.

There is not experimental evidence that solar radiation through the ice will harm turf grass. Photosynthesis can take place at temperatures below zero if plant cells have no internal ice. One of the by-products of photosynthesis is oxygen, and we think that moderate light penetration through the ice may rather have a positive impact on grass survival during ice encasement.

THE RISK FOR ICE AND WATER INJURIES DEPENDS ON GEOGRAPHY AND GOLF COURSE ARCHITECTURE

Global warming seems to expand the risk for ice encasement into areas that traditionally enjoyed a stabile inland climate. The districts around and north of the capitals Oslo, Stockholm and Helsinki have many golf courses, and many greenkeepers in these areas now report on severe problems with water and ice. Ice probably causes the economically most important winter damages in the Nordic countries (Waalen et al., 2017).

The golf course architects are responsible for some of the problems, because they underestimate the importance of surface water runoff from the greens. Some also construct green areas where melting water can flow from the surroundings on to the green. Golf course owners often pay a high price for rebuilding badly constructed greens after some years.

AUTUMN PREPARATIONS TO REDUCE ICE AND WATER INJURIES

Effects of shade and fertilization

Compared to the effects on winter disease, the effects of shade in autumn on anoxia stress tolerance were surprisingly small in our experiments. Shade significantly reduced the sward density before winter, but the response to increasing duration of anoxia was about the same regardless of shade or nitrogen level (figure 9).

Figure 9. *Number of tillers after two weeks of regrowth of samples taken in December from turf that had been exposed to different light and nitrogen levels in autumn. The samples were stored in sealed plastic bags to simulate ice encasement for an increasing number of weeks (x-axis) at -1°C, and then placed for two weeks in a growth chamber. Note that creeping bent was exposed to longer durations of anoxia than annual meadow-grass. Data from NIBIO Apelsvoll , winter 2014/15. Differences between fertilizer treatments were not significant.*

Aeration

Deep aeration with solid, course tines is usually one of the last maintenance operations before winter. This will improve the removal of surface water down to a depth at which the soil is often unfrozen and drainable. We know that greens often are deep-frozen, in which case holes in the green will have limited value. Still, we recommend this practice also because deep aeration once a year reduces the compacted zone at 8-12 cm depth created by spiking and other maintenance operations. Deep aeration (Vertidrain or similar, with a lift angle) disrupts the playing surface, and late autumn timing is probably your best option to do this work without getting into conflict with golfers.

In districts with frequent ice problems, it is very important to have good thatch control and plenty of air-filled pores in the topsoil. Good conditions for roots cannot be created only by autumn maintenance. It is a result of good greenkeeping through many years.

Dressing

Frequent topdressing with sand is the most important way to control thatch. Dressing should normally be accomplished during the growing season when the grass grows and produces thatch. Keeping the organic matter content in the 25 mm top layer between 3.0 and 4.5 % is a goal. STERF's handbook Potential for velvet bent grass on Nordic golf greens discusses several aspects of thatch control.

Dressing in the spring may be necessary for several reasons; melting snow, levelling bumps, patches and scars after the winter or filling aeration holes from the autumn.

Temporary water control

Many greenkeepers in areas with frequent occurrence of ice build-up have developed their own strategies for surface water control. Here are some suggestions:

- Fences of plastic can lead incoming water around the green. The fences must be kept low to avoid shade on the green. Some use a turf cutter to open a ditch and place the sod on the downside to create an 8 cm high wall leading water around the green.
- Temporary ditches from lower parts of the green may work for a while. On flat greens, ice will probably fill the ditches, and care must therefore be taken to keep them open (picture 13).
- Frost heave in silty soils outside the green can create a dam by blocking surface runoff (picture 14). Open ditches through the green surroundings may therefore be required.
- If you will make a temporary ditch, remove the turf with a (modified, narrow) sod cutter. The turf should be stored on plastic in roughs where the spring comes early, not in the bunkers which are often the last to get free of snow.
- At low spots on USGA-greens the water can be drained vertically. Make deep holes down to the gravel with your golf-hole cutter. A cup in the hole will prevent sand erosion. An insulating material over these holes can be necessary to protect the gravel from freezing.
- A mobile water pump can be an additional tool. See picture 15.

Picture13. *Temporary ditches in greens need maintenance during the winter. An asphalt cutter is used at Byneset GC, Norway. Photo: O.A. Kjøsnes.*

Picture 14. *Frost heaving outside this USGA green prevented surface runoff at Grenland GC. Photo: S. Selle.*

Picture 15. *Removal of melting water from green with generator and mobile pump at Grønmo GC. Photo: A. Ferm.*

Winter protective covers
About three percent of Swedish golf courses covered their greens for winter protection in 2015. (Unpublished data from survey). Canadian golf course superintendents have a lot of experience with covering, and Canadian researchers have worked on monitoring and ventilation of turf under covers (Dodson et al., 2017). They recommend ventilation if the oxygen concentration falls to 5%. A two-year Norwegian study with different tarps over various grass species on greens showed that only annual meadow-grass benefitted from permanent winter covers compared to the control treatment which implied natural snow cover for 98 and 141 days in the two years (Waalen et al., 2017). However, if compared with permanent ice encasement, all species had better spring recovery after protection with impermeable covers, despite no ventilation under the covers. If covers are used for the purpose of avoiding ice encasement, it is essential to seal the edges to avoid water intrusion under the covers.

Full-scale experiments on three golf courses in Norway (creeping bent / Poa), Sweden (velvet bent / Poa) and Finland (velvet bent / Poa) over three winters showed very good results after covering. A simple plastic cover dug down outside the green to prevent water intrusion gave excellent winter survival. The golf courses were in districts where ice encasement is common, and the best effects were after the most severe winters (Kvalbein et al., 2015). Based on this, we recommend that more golf courses should cover their greens. A premise for success is effective fungicide applications and that the air filled porosity in the root zone is high before installing the covers. Because microorganisms in the soil also consume oxygen, a high organic matter content in the soil or thatch will increases the risk of anoxia under impermeable covers (Rochette et al., 2005).

Detailed recommendations can be found in STERF's fact sheet: Winter protective covers - Usage of wraps to improve winter survival of golf greens.

Installation of devices to measure turf condition during winter
Visual inspection of the turf is difficult under snow. Walking and digging in the snow will influence the temperature at crown level. Therefore, we recommend installing some measuring devices in the green surface in the late autumn. Monitoring temperature has priority. The respiration is negligible when plants and microbes are frozen, but cells do not freeze at 0°C. The oxygen content under impermeable covers or ice will gradually decrease when temperatures are higher than -2°C (Thompkins et al., 2004; Castonguay et al., 2009).

Bringing in turf samples for regrowth in pots is a way to check survival, but remember to thaw slowly by melting the turf in a fridge before growing in light. Collecting frozen turf requires special tools. Read more about tools and devices in STERF's fact sheet: Winter work on greens.

When ice encasement occurs, your nose is the most valuable tool. If you break the ice, you will be able to smell the most important chemicals produced under anaerobic conditions. Products from plant metabolism are ethanol and lactic acid, which do not smell much. Soil microbes are responsible for the bad-smelling organic acids (like sweaty socks) or the highly toxic hydrogen sulphide, which has the very unpleasant odour of rotten eggs or seaweed. If the organic matter content is high, methane gas creates bubbling "volcanoes" through the ice (picture 16).

How critical the situation is depends on the grass species you are growing. Species such as velvet bent and creeping bent are usually robust, but a strong smell of hydrogen sulphide should always lead to immediate action.

Picture 16. *When gas comes up through the ice, you are in trouble! Photo: O.A. Kjøsnes.*

SNOW AND ICE HANDLING

Snow removal

Dry snow is an effective insulating material and provides excellent conditions for winter survival.
The big challenge is that snow may turn to ice or create massive flows of melting water. Snow also hides ice build-up. Rain on thin or moderately deep snow layer will result in ice if the green is frozen.

Unfrozen greens cannot carry heavy machinery, and the work force during winter is normally limited on golf courses where ice and water are the major reasons for winterkill. The normal procedure is therefore to wait for the ice to come. The ice will make it possible to use heavy blowers to remove the snow before cracking the ice (picture 17).

Picture 17. *Snow removal and ice cracking at Vestfold GC in spring 2013. Photo: A .Kvalbein.*

Ice cracking

The most common equipment for ice breaking is an aerator with solid tines. A very popular and efficient machine is the Aeravator (picture 18).

There is always a risk of damaging the green, but most greenkeepers will rather repair physical damages than re-seed partly or completely dead greens.

You will find more information in STERF's fact sheet: Anoxia – when to break the ice?

Picture 18. The Aeravator is popular for ice cracking because it is robust and flexible. The rolling tines vibrate. Efficient, but the risk of damaging the green is high.

Ice melting

Ice can be melted with chemicals that lower the freezing temperature of water. Magnesium chloride is efficient if the water runoff is good. At freezing temperatures close to zero, Calcium Magnesium Acetate (CMA) will penetrate 2 cm ice without producing much water (Kvalbein & Aamlid, 2008).

If there is solar energy available, dark expanded clay aggregates (Leca®) will create holes in the ice (picture 20). The aggregates can later be removed using a leaf blower. The results are very dependent on the solar radiation, which means that latitude and date must be considered.

Methods to promote snow melt in spring

Many greenkeepers use the energy resources from sun radiation to melt the snow. The cheapest and probably best way is to use ordinary dressing sand on the snow. This also leaves some dressing material on the greens, which can protect the grass plants against desiccation. Darker materials are more efficient than light sand, and some dress with charcoal dust. Some limestone products containing magnesium are dark, but the effect on pH can be unfavourable.

Picture 19*. Ice cracking and removal from a Poa annua green at Landvik in late January 2013. Photo: T. Espevig.*

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Picture 20a,b. *Leca® can be used to penetrate ice if there is some solar radiation. These pictures taken on 18 and 19 March at Sunnfjord GC. The sun was behind thin clouds on these days, but the result was very good. Photo: L. Årseth.*

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SPRING CHALLENGES

LACK OF SOLID KNOWLEDGE

Most articles and reports concerning turf grass winter stress tolerance are about freezing tolerance or resistance to snow moulds. Few papers present facts about ice damages, and the research into spring related problems is even more sparse. This is understandable as it is difficult to design and conduct experiments and produce “publishable data” on spring issues.

The status of the plants after winter stress is difficult to define, and it varies between species and local winter conditions. Funders of turf grass research should nevertheless give priority to spring injuries, because there are many greenkeepers who start their work in spring with enthusiasm, but end up with frustration and sleepless nights: The turf does not recover and the seeds do not develop into mature plants. When the golfers complain, the greenkeepers blame it on low soil temperature, dry winds, wear from golfers or technical problems with the irrigation system, but in their heart they know what we as researchers also have to admit: We simply do not know the best practice.

This introduction to spring challenges emphasizes that the following text is primarily based on assumptions, practical experiences and discussions with some very good Scandinavian greenkeepers.

SPRING STRESSES

Spring stress is often due to a combination of high light intensity, wilting and re-exposure to aerobic conditions. When the grass is de-acclimated and resumes growth, it also becomes much more vulnerable to freezing temperatures and diseases. You can read more about spring stresses in the factsheet Spring stresses: The difficult transition into a new growing season, and about de-acclimation in Warm spells during the winter.

It is known from flooded cereals in topographical depressions that injuries may occur when oxygen returns to the plants. The explanation for this is that the polyunsaturated fatty acids that have been formed before or during plant stress are sensitive to Reactive Oxygen Species. Ice encasement can be regarded as an extreme version of flooding, and turf grass plants are probably harmed by these mechanisms after ice encasement (Hehterington et al., 1988).

Desiccation and soil heave

We have chosen to classify desiccation as a spring stress, but turf in the southern part of Scandinavia may dry out during the winter as well. Winter desiccation occurs when the soil is frozen so that the grass plants cannot take up enough water to replenish that lost by transpiration. This is usually related to little or no snow cover, sub-zero temperatures, winds and sunny days that promote stomata to open.

Frost heave is when the soil surface moves upwards because of ice formation. It is common on silty soils with high capillary capacity, especially if the soil temperature drops slowly. Frost heave can tear off the grass roots and increase the risk of desiccation. Many Icelandic greenkeepers have experienced this problem.|

Photoinhibition or UV-light damages

Previously in this text we have discussed plants' acclimation to cold. Plant leaves also acclimate to different light conditions. Intense light, and especially UV-radiation, can seriously harm the leaf cells. The molecule structures responsible for photosynthesis are very light sensitive and can be injured by excessive radiation. The light conditions during the development of the leaves determine to what extent they contain a "sun factor". The overwintering leaves develop in late October when the light intensity is low compared to that in the beginning of April. The sudden change from darkness under snow cover to intense sunlight in spring is a shock for these leaves.

Plant physiologists use the term 'photo inhibition' when the chemical energy produced by light cannot be transformed fast enough to sugar. They see an accumulation of reactive oxygen species (ROS) which can harm the plant cells if there is insufficient anti-oxidants available. Leaves that have been under snow cover will spend some time producing anti-oxidants. This production requires energy and if there is a shortage due to carbohydrate depletion, the leaves can die. The injury is called photo bleaching, and it is very common on turf in the far north. Grass crowns are well protected from light, and if the growth conditions are good, the turf will recover after some time (picture 21a,b).

Some grass varieties are able to cope with the light stress by producing anthocyanin or other colour pigments that shade the vulnerable parts for the cells. Some misinterpret the purple colours for phosphorus shortage. We have seen the anthocyanin colour especially velvet bent (picture 21a,b) and rough-stalked meadow grass. For the latter species it has even been speculated that the production of pigments under high light intensity may be large enough to be utilized industrially (Petrella et al., 2016). The dark off-season colours of some red fescue varieties (Photo 20a) can also be due to protective pigments.

Picture 21a,b. *Early spring green-up on a green with various grass species at NIBIO Landvik in 2009. Top picture taken on 31 March, two weeks after the melting of a two months' snow cover. Lower picture taken on 6 April. Photos: T. S. Aamlid.*

SPRING MAINTENANCE

Low soil temperature is the main growth-limiting factor in spring. After spring equinox on 21 March the days are longer the further north you go, and the longer days will to a certain extent (although not fully) compensate for the lower sun angle at high latitudes.

Early actions to improve the spring microclimate and promote green-up always imply a risk of relapse. Keep this in mind when considering the following tools.

Spring covers

There are many different types of spring covers. Light transparency, persistency and resistance to water and gas diffusion vary between the products, and so does the price. This makes it difficult to comment on spring covers in general terms. Some greenkeepers prefer the low-weight, white fibrous tarps used by many farmers growing strawberries or vegetables.

Covers will increase the mean soil temperature by 2-3 °C. The maximum air day temperature can be high, sometimes above optimal for plant growth under coloured tarps. Single spring covers do not effectively prevent the lowest freezing temperatures, but condensation of vapour under relatively airtight material can prevent frost damages during cold nights.

Use of spring covers will make the turf look greener and the height growth increases, which is also as a response to shade under the covers. Spring covers will also reduce transpiration and may prevent harmful desiccation if the irrigation system is not running. An alternative is to top-dress with sand. This can also stimulate the development of new root to replace those teared off by frost heaving.

Despite these possible advantages, we are generally sceptical to recommend spring cover on living, mature grass plants. This turf seems to become less wear tolerant and is often set back when the cover is removed.

Spring irrigation

Transpiration from the turf starts early in the spring and drought can limit grass growth. Early use of the irrigation system will probably advance spring growth, but we have not found any reports confirming this.
Water on the turf will lower the canopy temperature because of evaporation, but the temperature of the well is not important. The irrigation water will usually adjust to air temperature before it hits the ground (Hannesson, 2009) Because plant uptake is limited by low soil temperature, excessive irrigation is likely to wash out nutrients more easily in the spring than in the summer. The leakage can be considerable from spots with poor grass coverage.

RE-ESTABLISHMENT OF DEAD TURF

STERF has defined re-establishment after winter injuries as a part of winter stress management and published a fact sheet on this subject: Re-seeding and spring recovery from winter injuries.

Re-seeding is difficult. Low temperatures slow germination. Too much or too little thatch in the dead spots can impair the seed's access to moisture and oxygen, which are both basic requirements for germination.

We have found that the germination rate of various turf grass species respond differently to soil temperature. Creeping bent is more retarded by low temperature than other bents. Red fescue is even slower, while annual meadow-grass germinates quickly even when the soil is cold. See figure 10. *Poa annua* is also able to germinate under lower oxygen levels than other species (Waalen & Kvalbein, 2016). This means that winterkill normally will change the sward composition in favour of annual meadow-grass.

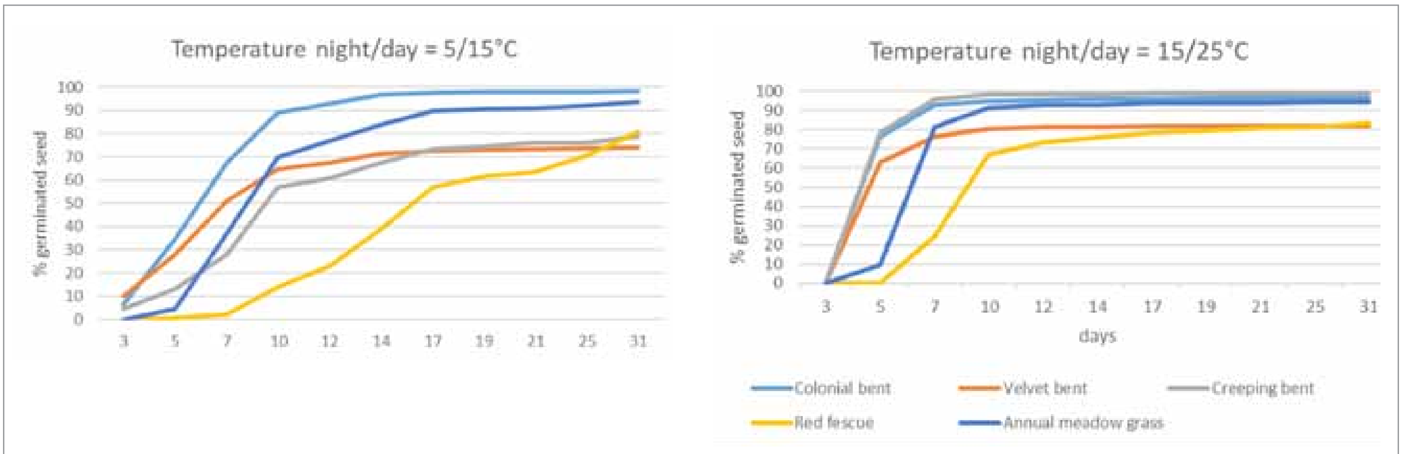

Figure 10. *Seed germination of browntop bent 'Jorvik', velvet bent 'Villa', creeping bent 'Independence', red fescue 'Musica' and annual meadow-grass (unspecified) at different temperatures.*

Fungi contain more lipids (fatty or wax-like chemicals) than grasses, and some greenkeepers have experienced that snow mould patches can be hydrophobic. Fungi in the group Basidiomycetes can create hydrophobic soil conditions (York & Canaway, 2000). We suspect that *Microdochium* can cause similar conditions. Water holding surfactants may result in more moisture for germination and seedling growth. Farmers have experienced that it is difficult to re-establish pastures killed by ice encasement without ploughing (Gudleifsson, 2013). Experiments comparing germination after injuries from snow mould, frost and ice confirmed reduced germination after ice (Brandsæter et al., 2005), but the phytotoxic chemicals were not identified.

We have tested grass seed germination in soil water extracted from ice-covered greens. Our experiment did not confirm the results from agriculture. Seeds developed normally, which may be due to the experiment being conducted on a newly established green with less thatch and soil microbial activity than one would normally find on an older green. Many greenkeepers have experienced poor establishment when reseeding greens damaged by ice encasement, and we recommend soil aeration before sowing to lower the level of potentially phytotoxic compounds.

Re-establishment of dead Poa greens call for a different strategy than re-establishment of other species. Germination from the seed bank is usually stimulated by scarification followed by dressing, rolling and the use of spring covers. Temporary grasses (e.g. rough-stalked meadow grass) may be used if the seed bank in the root zone is expected to be inadequate, e.g. on young greens.

Partly dead greens are extraordinarily challenging because the established turf and the seedlings require very different input and maintenance. The recovery of such greens will be discussed in the next chapter.

'The bad spot syndrome'

For to the one who has, more will be given, and from the one who has not, even what he has will be taken away.
Mark 4:25.

To our knowledge, 'the bad spot syndrome' has not been described in international turf grass literature before. This chapter is an attempt to create a model that can help turf grass managers understand why re-establishing dead greens sometimes is extremely difficult.

We have earlier argued that a high content of organic matter in the root zone will exacerbate the risk of hypoxia and winter injuries under impermeable covers (Rochette et al., 2005), and probably also under ice encasement. Now we will argue that low organic matter content because of poor growth, often caused by drought, increases the risk for winter injuries and makes it very difficult to re-establish turf and produce a consistent green of good playing quality.

Bad spots start with poor growth

The turf grass growth rates on greens vary due to many reasons. One is suboptimal green construction. We often find that lack of vertical barriers around USGA-constructed greens makes the edges dry, especially close to green bunkers or when the green is elevated from the surroundings. See picture 22.

Picture 22. *Dry edge of a green caused by water retention from the soil outside the green and the deep bunker drain. Photo: A. Kvalbein.*

Wear and compaction from golfers and machinery are other reasons for reduced plant growth. The amount of wear is often reflected in the organic matter content on various parts of the green. On undulated or renovated greens, scalping might occur, or double mowing reduce the cutting height in the clean-up round. Triplex mowers also result in compaction at the green edges (pictures 23 and 24).

A third reason for reduced plant growth are fairy rings or attacks from pathogenic fungi like take all patch. Microdochium patch seems to be more frequent on the drier parts of the greens and is sometimes related to localized dry spots. While the reasons for poor growth can be several, our main point here is that reduced growth implies too low production of thatch, and that the stress which reduces growth at the same time increases the risk of winterkill.

When consulting a golf course where re-establishment does not succeed, we often measure very low soil water content in the top 5 cm - down to 4-8% by volume. When examining the soil profile carefully, the organic matter content is very low in the upper centimetres. The course pores are not able to hold water, which very rapidly moves into the finer pores further down in the profile. See picture 25.

The location of the bad spots will usually coincide with localized dry spots. They are on the highest parts of the green, at the edge of the green, or where irrigation overlap is poor. Hydrophobic soil develops from degradation of organic matter (Doerr et al., 2000) and the occurrence of "fatty" chemicals increases over time (Spaccini & Piccolo, 2009). On bad spots, degradation goes fast because less thatch results in fast replenishment of oxygen and the low sward density increases soil temperature. 'Bad spot' development is summarized in figure 11.

Picture 23. *A typical pattern of poorly re-established green. Picture taken in the north of Norway in August. The bad spots can be related to wear (clean up round) combined with drought. Photo: A. Kvalbein*

Picture 24. *Similar problems. Note the seedlings visible in the "better part" of the dead spots. Photo taken 6 July 2012 in southeast Norway by A. Kvalbein.*

Picture 25a,b. *Profile under bad spot to the left and under acceptable turf to the right. These profiles received the same rates of top dressing. Poor growth the spring 2013 caused layering at the bad spot. On the top of the sand, there is a thin layer of organic matter from summer 2013. (The putting surface was nice in the autumn). In spring 2014 the turf was dead, probably killed by Microdochium nivale. The sand was hydrophobic, and the green very difficult to re-establish due to the pure sand layer on the top. Photos: A. Kvalbein*

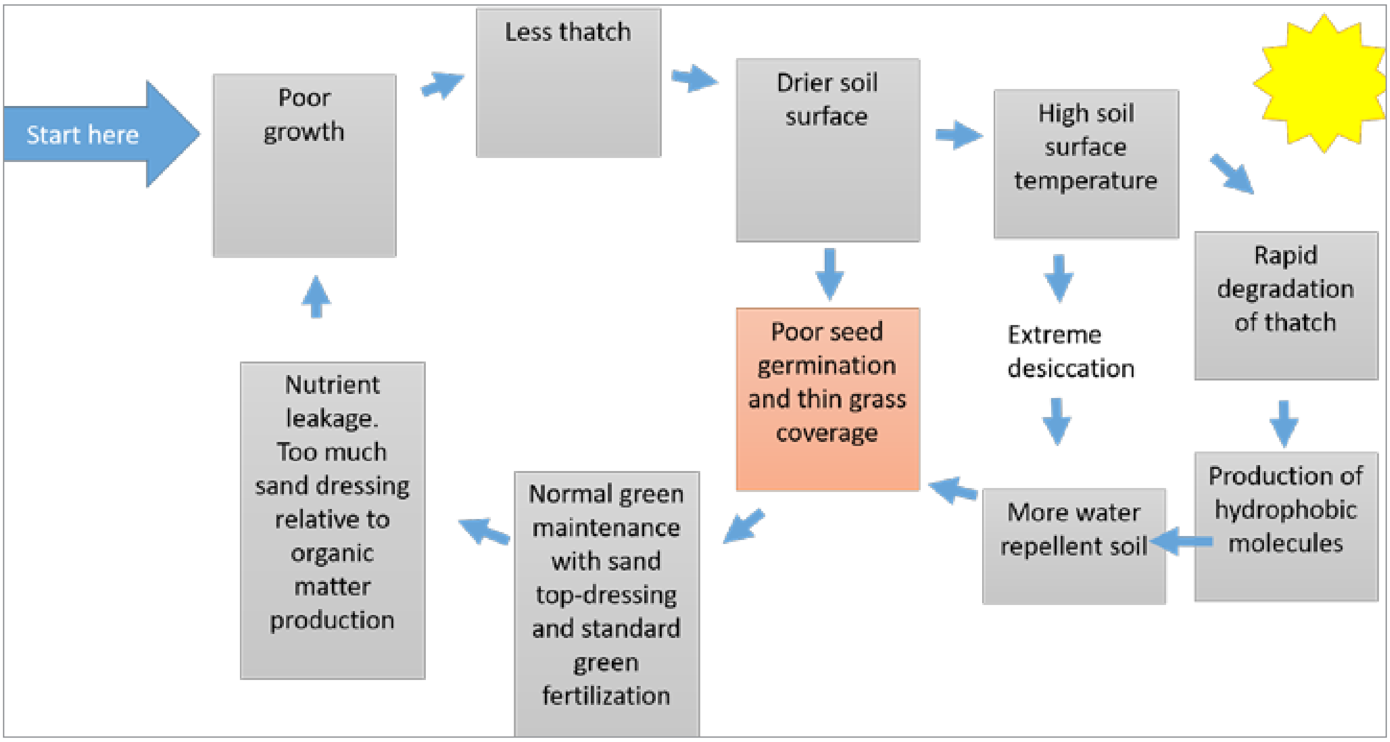

Figure 11. *The bad spot syndrome. The model explains why some winter killed spots on a golf green are extremely difficult to re-establish.*

Picture 26. *Winter injuries repaired with sod in spring. Picture taken on 9 September 2006. Photo: A. Kvalbein.*

How to cure bad spots?
There is no simple answer. The goal is to build up the water holding capacity in the bad spots without producing too much thatch under the surrounding turf that survived the winter.

The easiest solution is to re-turf with sod (picture 26) If the spots are large and you a skilled staff and access to high quality sod produced on a compatible sand, this is probably the best answer. We do not think of this as an easy way out of the problem. Sodded parts of a green very often becomes hydrophobic, and uniform playing quality is hard to achieve.

The seeded spots should have irrigation (preferably small droplets or mist) every two hours. This watering regime will wash out nutrients. To compensate for this leakage we recommend spraying the spots with a thin solution of nutrients twice a week. The goal is to exploit fully the growth potential of the seedlings, while the established turf receives normal maintenance. The optimal fertilizer rate to the seedlings is about three times as high as to the established turf. The best way to differentiate management of the dead spots and the surrounding turf is by Spot sowing with a hand spiker, fertilizing with a knapsack sprayer and hose irrigation with a mist nozzle. Dressing with organic material, such as finely granulated garden compost or low-fertility manure, will also improve top soil moisture and provide nutrients.

The alternative to sod is meticulous handwork on the spots: Removal or break-up of thatch, incorporation of good, mature compost in the top layer, spot sowing with a hand spiker, fertilizing with a knapsack sprayer and hose irrigation with a mist nozzle. Manual irrigation is particularly advantageous because the coarse and heavy droplets from the popup system tend to wash seed and dressing material into the surviving turf, thus leaving the dead spots as low bumps surrounded by up-dressed turf.

Mowing partly dead greens is also difficult. The newly added sand often becomes unstable, and even single mowers and footsteps will easily destroy the seedlings (picture 27).

If you manage to get some new plants germinating, the seedlings need much fertilizer to exploit their maximum growth capacity. A rule of the thumb is that establishing turf on greens requires three times more fertilizer than established turf. This is also reflected in a far higher risk for nutrient leakage from greens under establishment (Aamlid et al., 2017b), and frequent applications are therefore essential to achieve a high growth rate while minimizing losses. Spot fertilization is possible as long as the bad spots are visible. Ideally, the root growth in these bad spots should stimulated for a long time, as the goal is to build up thatch and level out the differences compared with surviving turf. This is not easy.

Is the application of clay mineral dressings or water holding polymers on the bad spot an alternative? Such a practice will create permanent variations and most turf grass managers will be sceptical to using such minerals unless they are incorporated into the root zone of the entire green. We have good experiences with certain materials on the entire green surface, but have never tested them for spot treatment.

Picture 27. *Footstep on seedlings in unstable rootzone material. Photo: A.Kvalbein*

Picture 28. *How can these seedlings survive and grow well in an environment with adjacent mature grass, playing golfers and daily mechanical maintenance? Photo: A. Kvalbein*

Picture 29. *Irrigation by hand with hose and small droplet nozzle is necessary when re-establishing partly dead greens after winter injuries. Picture from grow-in experiments at NIBIO Landvik. Photo: A. Kvalbein.*

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APPENDIX 1.

AUTUMN FERTILIZATION EXPERIMENTS 2014-2017

Picture 1. *Creeping bent was seeded and annual meadow- grass established from hollow-core plugs taken from a fifty year old green at Borregaard GC.*

The project was funded by Scandinavian Turfgrass and Environment Research Foundation (STERF), Norwegian Research Council and The Norwegian Golf Federation. The aim of these experiments was to test the effects of nitrogen and sulphate on winter stress tolerance of green grass.

Two experimental USGA-greens were established in late June 2014 and re-established in 2015. The grass species were creeping bent ('Independence') and annual meadow-grass (local ecotype) The green at NIBIO Landvik was on a lysimeter facility and drainage water was collected for nitrogen analyses. At NIBIO Apelsvoll half of the green was shaded to 30% of natural daylight during the experimental period, lasting from the beginning of September until the end of November.

During these weeks the greens were fertilized with 6 different treatments (see table 1). Nitrogen and sulphate were the experimental variables. All fertilizers were applied weekly at decreasing rates (see figure 1). The total amount of nitrogen applied during the 13 weeks were 0, 28 (low), 55 (medium) and 84 (high) kg/ha.

Picture 2. *Half the green at Apelsvoll was shaded to 30% of natural daylight in the autumn.*

TREATMENT	N	P	K	Mg	Ca	S	Fe	Mn	Zn	Cu	Mo
1. No N	0.00	0.16	0.76	0.08	0.09	0.11*	0.011	0.0043	0.0023	0.0005	0.00036
2. Low N	0.40	0.16	0.77	0.08	0.09	0.14	0.011	0.0043	0.0023	0.0005	0.00036
3. Med N	0.80	0.16	0.77	0.08	0.09	0.14	0.011	0.0043	0.0023	0.0005	0.00036
4. High N	1.20	0.16	0.77	0.08	0.09	0.14	0.011	0.0043	0.0023	0.0005	0.00036
5. No S	0.80	0.16	0.77	0.08	0.09	0.0	0.011	0.0043	0.0023	0.0005	0.00036
6. High S	0.80	0.16	0.78	0.08	0.09	1.27	0.011	0.0043	0.0023	0.0005	0.00036

* No ammonium sulphate in this fertilizer

***Table 1.** Content of nutrients (g/l) in the six different fertilizers.*

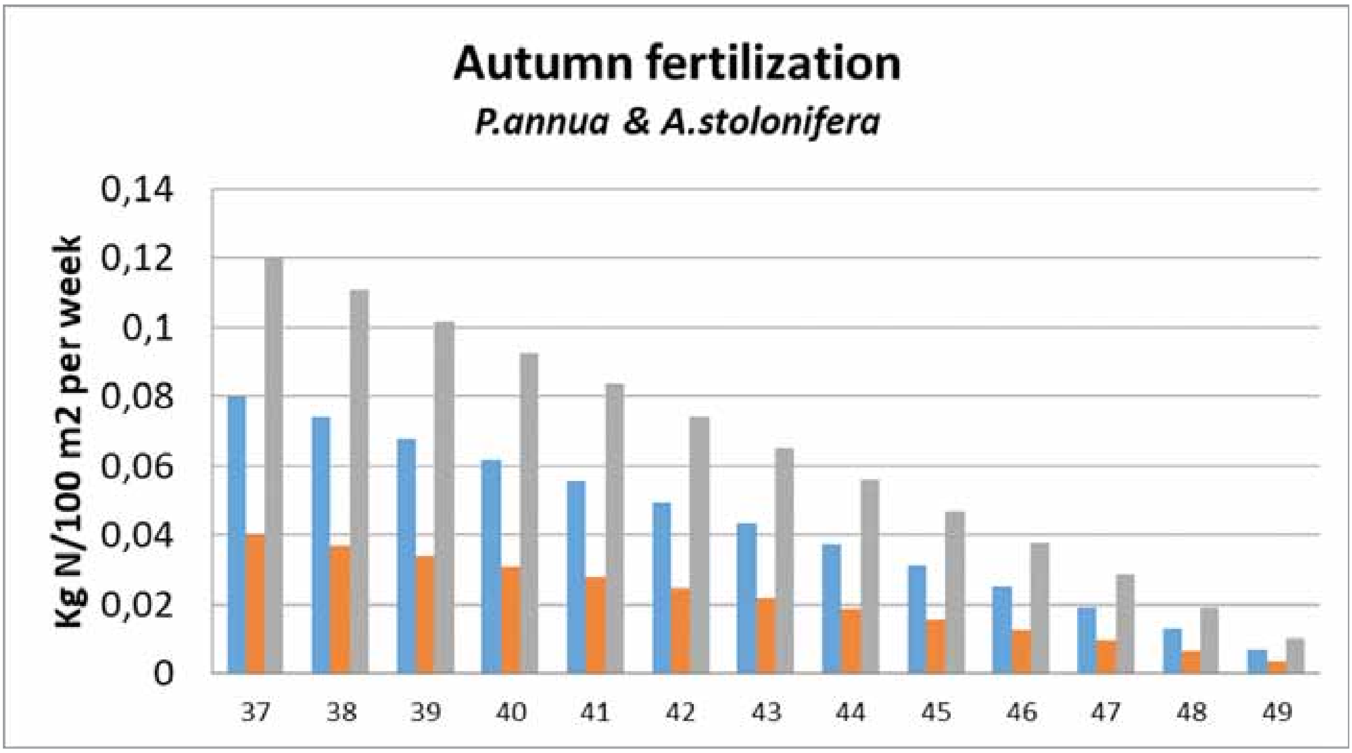


***Figure 1.** Weekly fertilizer applications followed a declining curve. Blue=medium, orange = low, grey = high rates.*

During the establishment period in July and August, the greens were fertilized frequently with a complete fertilizer, 140-160 kg N per hectare during 11 weeks. The greens were mowed tree times weekly at 5 mm. Mowing continued at this height but less frequently until the grass stopped growing in late autumn. (We measured height growth every week).

The first year we applied no fungicides, and a severe attack of microdochium patch occurred early in the autumn, especially on annual meadow-grass. The shaded green on Apelsvoll was very bad. The second year we applied Delaro (trifloxystrobin + prothioconazole) to get more healthy plants for the laboratory experiments.

Some results are presented in the main text. Below you will find some additional data.

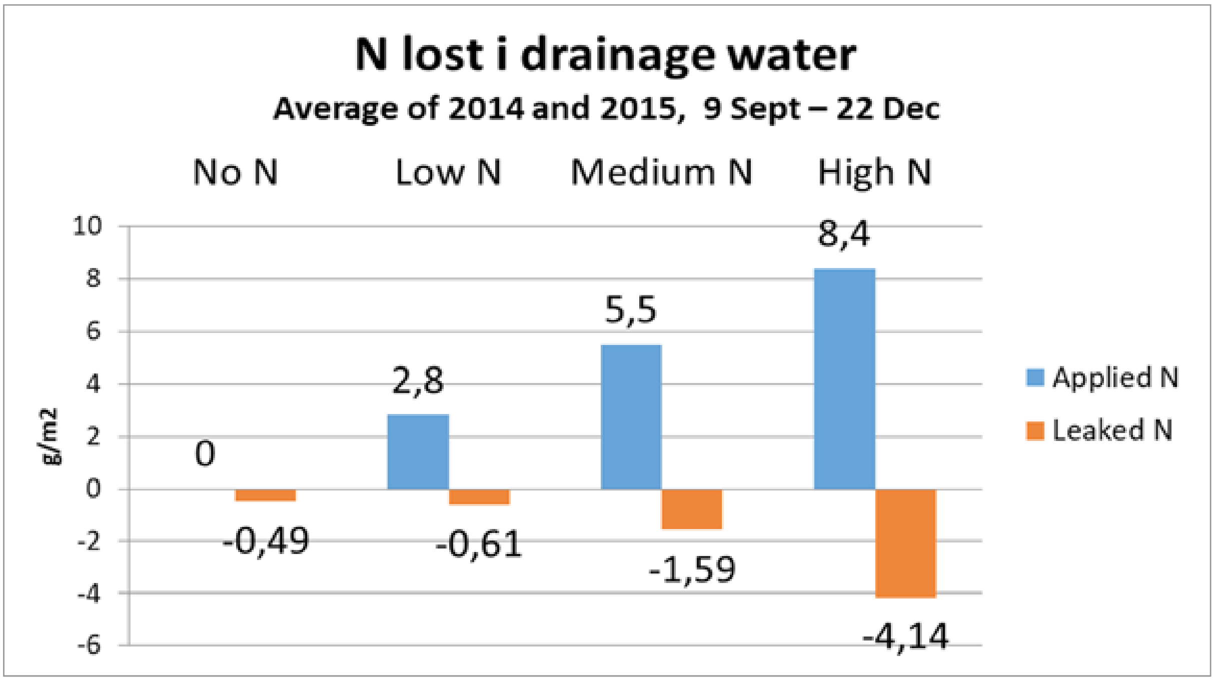


Figure 2. *Nitrogen applied and lost in in drainage water from the experimental green at Landvik. See figure 1 for weekly application rates.*

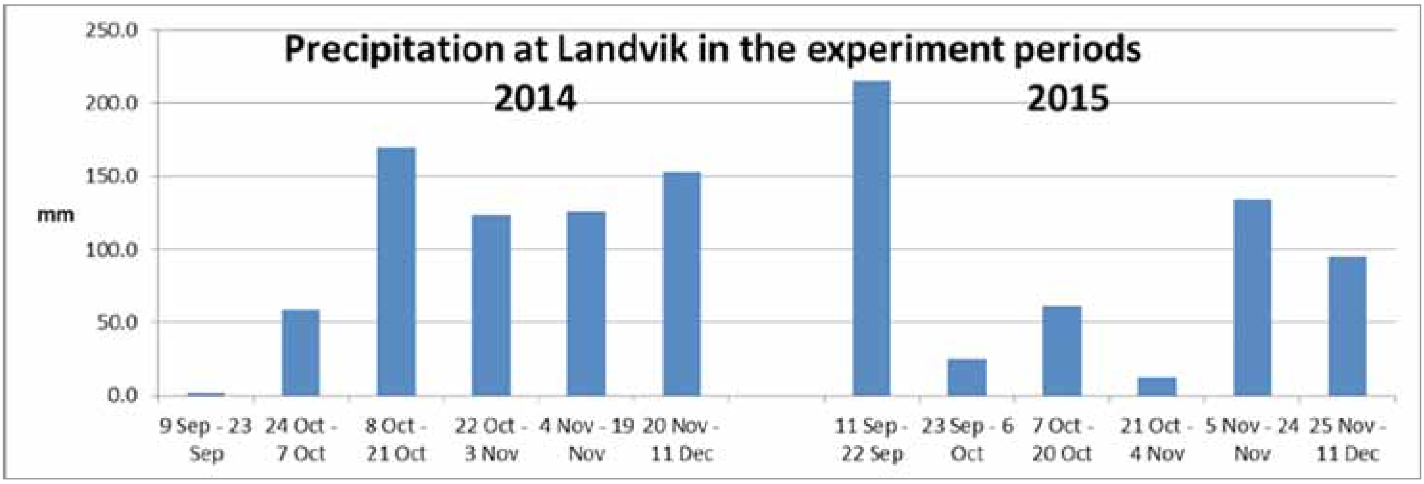


Figure 3. *Natural precipitation at Landvik in the experimental periods in 2014 and 2015.*

LEAKAGE OF NITROGEN

Drainage water was collected from plots where half of the area was creeping bent and the other half was annual meadow-grass. The natural precipitation was higher than normal in the first experimental year. For details, see figure 3.

The collection of drainage water showed, on average for two years, that 49% of the highest nitrogen rate leaked from the green (figure 2). The nitrate limit for drinking water in EU is 50 mg/litre. The drainage water did not exceed this limit, but we think the loss was unacceptably high. The leakage was highest when the soil temperature was below 5 °C.

Based on this we cannot recommend 'late autumn fertilization', i.e. giving high fertilizer rates at soil temperatures below 5 °C, as a sustainable strategy.

Picture 3. *Lysimeters. Photo:Trygve S*

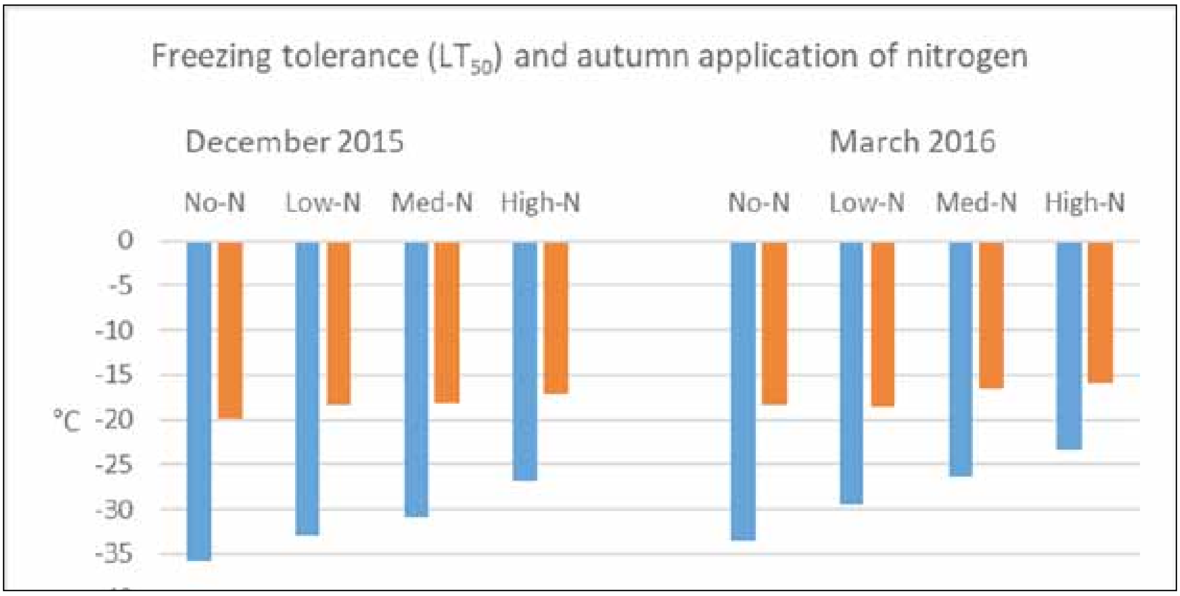


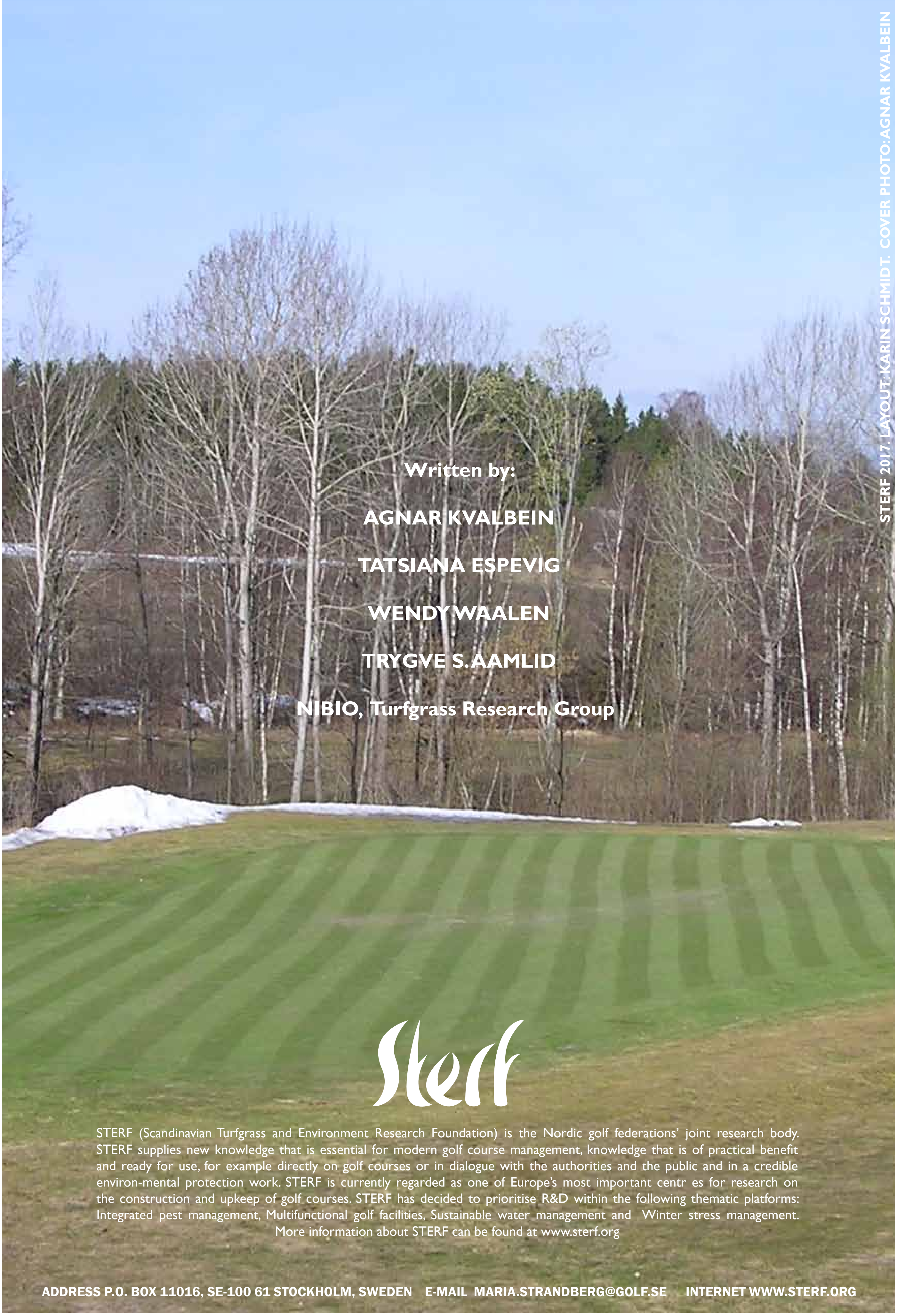
Figure 4. *Temperature (°C) that killed 50% of the test plants (LT50). Creeping bent (A.stol) and annual meadow grass (P.annua) were sampled from a golf green fertilized with four rates of nitrogen (0, 2.8, 5.5, 8.4 g/m2) in the autumn.*

FREEZING TEST

Grass samples were collected from the two experimental greens and brought to laboratory tests in the beginning of December and by the end of February/beginning of March.

The test was performed according to our standard protocol (Espevig et al., 2010), and LT50 values calculated. The test showed that there were significant differences between the two species, and they also reacted differently on nitrogen fertilization in the autumn. Higher nitrogen applications reduced the freezing tolerance of creeping bent. For annual meadow grass there was no significant effect of autumn fertilization. Results from the last experimental year, which confirmed the first year's results, are shown in figure 4.

Picture 4. *Trond Pettersen collects samples from the green. They will be tested in the laboratory for freezing tolerance and resistance to anoxia and pink snow mold. Photo: Agnar Kvalbein.*



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