RESEARCH

The Effect of Ice Encasement and Protective Covers on the Winter Survival of Six Turfgrass Species on Putting Greens

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ABSTRACT

Ice encasement (IE) is the most economically important winter stress in Scandinavia; however, little is known about the IE tolerance of different turfgrass species and subspecies except that creeping bentgrass (*Agrostis stolonifera* L.) is more tolerant than annual bluegrass (*Poa annua* L.). The objective of this study was to assess the impact of IE and two protective covers (plastic and plastic over a 10-mm woven mat) on the winter survival of six cool-season turfgrasses commonly used on golf greens. The experiment was conducted on a sand-based green at Apelsvoll, Norway (60°42′ N, 10°51′ E) during the winters of 2011–2012 and 2012–2013. Turfgrass samples (8 cm in diameter, 10 cm deep) were removed from the plots at the time of cover installation and throughout the winter. The samples were potted and percent live turfgrass cover assessed after 21 d of regrowth in a growth chamber. Percent turfgrass cover, percent disease, and turfgrass quality were also registered in the field plots in spring. Results indicated that velvet bentgrass (*Agrostis canina* L.) had superior tolerance to IE, surviving for 98 and 119 d of IE during the winters of 2011–2012 and 2012–2013, respectively. The order of IE tolerance in 2012–2013 was: velvet bentgrass > creeping bentgrass > Chewing's fescue (*Festuca. rubra* L. ssp. *commutata*), slender creeping red fescue (*F. rubra* L. ssp. *litoralis*) ≥ colonial bentgrass (*A. capillaris*) > annual bluegrass. Colonial bentgrass responded negatively to both protective covers in 2012 due to the development of *Microdocium nivale.* None of the species benefited from the plastic cover alone, compared with natural snow conditions. Annual bluegrass was the only species that benefited from plastic over a woven mat.

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Abbreviations: IE, ice encasement.

Winter damage on golf greens is a significant economic burden for golf courses in the Nordic countries, Canada, northern United States, northern Japan, and other countries with similar climatic conditions. The turfgrasses may have to tolerate the following stress factors or their combinations: lack of photosynthetic light, lethal freezing temperatures, prolonged exposure to sublethal freezing temperature, flooding or ice encasement (IE), fungal diseases that develop under snow, soil heaving, solar radiation, and/or desiccation winds when root uptake of water is prohibited due to frozen soil (Kvalbein et al., 2013). While microdochium patch caused by *Microdochium nivale* is the most common winter issue in southern parts of Scandinavia, IE is a frequent problem further north, and the consequent injury is more severe and time consuming to repair (Kvalbein et al., unpublished data, 2016). Climate change (IPCC, 2013) with repeated melting and freezing episodes will most likely exacerbate these problems in the future (Griffith et al., 2001; Gudleifsson, 2009).

Strandberg (2007) claims that 70% of Scandinavian golf courses suffer from winter damages every year, and that the average annual cost per golf course is approximately SEK 300,000 (€30,000). The economic burden is partly due to the extra costs associated with the repair of winter damage, but more to revenue losses due to delayed opening (Kvalbein et al., unpublished data, 2016). The environmental costs associated with heavier use of

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fertilizers and water in the re-establishment period after winter damage must also be taken into consideration.

Protective winter covers on golf greens have been utilized in Canada and tested in experiments. The effect on temperature fluctuation and winter kill under six combinations of impermeable and permeable covers, and the use of insulation materials showed that insulating materials were necessary to protect annual bluegrass (*Poa annua* L.) greens from lethal freezing temperatures (−10°C) in situations with no or limited snow cover (Desjardin and Dionne, 1997). A study of the gas concentrations under impermeable covers on annual bluegrass greens in Quebec concluded that soil microbial respiration, which was related to high content of soil organic matter, aggravated the risk for injuries from anoxia (Rochette et al., 2006). Experiments with impermeable covers, in combination with ventilation systems, showed that all protective covers improved winter survival compared with IE (Tompkins et al., 2009). Largescale demonstration trials with various types of protective covers on Nordic golf courses (Strandberg et al., 2000; Rannikko and Pettersson, 2010) were less conclusive than the Canadian trials, but a few Swedish and Finnish golf courses have, nonetheless, started to use impermeable covers as a strategy to avoid IE (Kvalbein et al., unpublished data, 2016).

The cool-season turfgrasses most commonly found on golf greens are annual bluegrass, creeping bentgrass (*Agrostis stolonifera* L.), colonial bentgrass (*A. capillaris* L.), Chewing's fescue (*Festuca rubra* L. ssp. *commutata*), and slender creeping red fescue (*F. rubra* L. ssp. *litoralis*). Little is known about the IE tolerance of these different species and subspecies, except that annual bluegrass is more susceptible than creeping bentgrass (*Agrostis stolonifera* L.) (Tompkins et al., 2004; Valverde and Minner, 2007; Aamlid et al., 2009, Castonguay et al., 2009). Thus, the objective of this study was to assess the impact of IE and two protective covers on the winter survival and regrowth capacity of these species and subspecies under putting green management.

MATERIALS AND METHODS

Site and Weather Conditions

Colonial bentgrass 'Jorvik', velvet bentgrass (*Agrostis canina* 'Villa'), creeping bentgrass (*A. stolonifera* 'Independence'), Chewings fescue (*Festuca rubra* ssp. *commutata* 'Musica'), slender creeping red fescue (*F. rubra ssp. litoralis* 'Cezanne'), and annual bluegrass (*Poa annua* L. unspecified ecotype) were sown at rates of 7, 7, 7, 30, 30, and 15 g m^{-2}, respectively, at the NIBIO Research Station, Apelsvoll, Norway (60°42′ N, 10°51′ E), in mid-June of 2011 and 2012. The experimental plots were reseeded each year due to destructive sampling throughout the experiment. The rootzone was constructed according to USGA recommendations (USGA Green Section Staff, 2004) with a 30-cm layer of sand amended with 20% (v/v) garden compost ("Green Mix," Høst AS, Grimstad, Norway).

The mean monthly air temperature and monthly precipitation collected at the Apelsvoll weather station for the experimental period is shown in Table 1. The average temperature from 1 November to 31 March in 2011 to 2012 was 3.7°C warmer than normal, resulting in repeated periods of melting and freezing, causing an accumulation of ice over the entire green surface from early January until early March. The average temperature during the winter of 2012–2013 was cooler and deviated only slightly from the normal. As such, the winter of 2012–2013 was characterized by stable snow conditions, with little ice accumulation on the green surface. Figure 1 shows the average daily temperature measured on the green surface for the different cover treatments and duration of snow cover in 2011–2012 and 2012–2013, which were 98 and 141 d, respectively.

Plot Maintenance and Experimental Treatments

Nitrogen, in the granular form, was applied from May to September at 2-wk intervals, which amounted to 2.0 kg N 100 m^{-2} yr^{-1} for *Festuca* ssp., 2.8 kg 100 m^{-2} yr^{-1} for *A. canina* and *A. capillaris*, and 3.2 kg 100 m^{-2} yr^{-1} for *A. stolonifera* and *P. annua*. The rates were differentiated according to the species' growth potential (Ericsson et al., 2012). The plots were mowed three times a week from May until October, to 5 mm for *Festuca* ssp. and to 3 mm for *P. annua* and *Agrostis* ssp. Fertilization strategy and mowing practice were chosen to reflect actual practices on golf greens. Volumetric water content of the rootzone was monitored using a FieldScout 100 TDR (Aurora, IL) using 12-cm probes, and when less than 10%, the experiment was irrigated. In both experimental years, the fungicide Delaro SC 325 (Bayer CropScience AG, Germany) was applied in late September at a rate of 1.0 L ha^{-1} (182 g ha^{-1} prothioconazole and 157 g ha^{-1} trifloxystrobin).

The experiment included four cover treatments: (i) natural snow cover (uncovered control), (ii) IE, (iii) protective cover of impermeable plastic (plastic cover), and (iv) protective cover of

Table 1. Mean monthly air temperature and monthly precipitation at Apelsvoll, Norway (60°42′ N, 10°51′ E), during the experimental period compared with normal values.

	Monthly average air temperature			Monthly average precipitation		
Month	2011–2012	2012–2013	Normal†	2011–2012	2012–2013	Normal†
	°C			mm		
June	14.6	12.1	13.7	99.5	34.6	60.0
July	15.8	14.5	14.8	102.4	144.0	77.0
August	14.2	14.1	13.5	154.9	83.4	72.0
September	11.5	9.7	9.1	108.7	44.6	66.0
October	5.8	3.4	4.6	44.9	79.7	64.0
November	2.7	1.7	−1.3	12.2	59.0	53.0
December	−1.6	−7.4	−5.3	36.4	59.0	40.0
January	−5.4	−8.7	−7.4	46.5	23.9	37.0
February	−4.4	−5.7	−7.0	12.7	30.4	26.0
March	4.0	−5.2	−2.3	3.3	31.8	29.0
April	3.0	2.7	2.3	33.1	39.1	32.0
May	10.0	11.6	9.0	53.2	90.8	44.0
Yearly average	5.9	3.6	3.6	707.8	720.3	600.0

† Reference period 1961 to 1990.

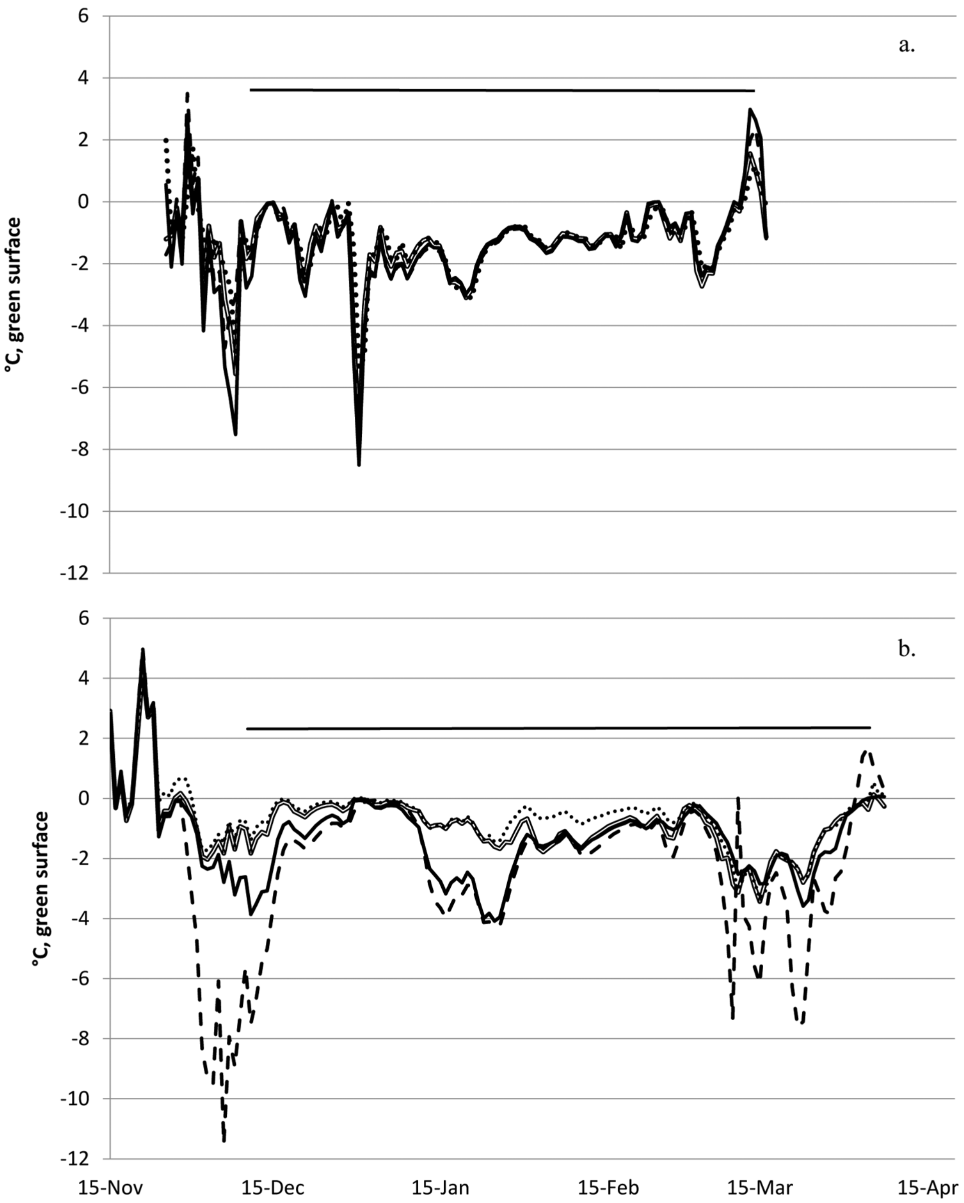

Fig. 1. Average daily temperature on the green surface under natural snow conditions (control) (—), ice encasement (- - -), plastic cover (= =), and plastic cover with a mat (….) at Apelsvoll, Norway (60°42′ N, 10°51′ E), during the winter of 2011–2012 (a) and 2012–2013 (b). The black line depicts the duration of snow cover.

impermeable plastic over a 10-mm woven mat to create an airspace between the green surface and plastic (plastic cover with a mat). The protective covers and IE were installed in November once the ground was frozen. The edges of the covers were dug down into a trench in the turf to avoid water seepage under the covers, and the covers were only unsealed once, at the time of sampling. Ice encasement was established on 22 Nov. 2011 and 4 Dec. 2012 by adding water over a period of 3 d to plots surrounded by an aluminum frame. The bottom of the frame was installed 15 cm below the soil surface and the top of the frame 20 cm above the soil surface. The thickness of the ice was approximately 8 cm. Ice encasement conditions persisted for 98 d until 28 Feb. 2012 and 119 d until 2 Apr. 2013, respectively. The control treatment consisted of natural winter conditions.

Measurements of O_2 and CO_2 Levels

During the winter of 2012–2013, O_2 and CO_2 levels were measured under the plastic cover, under the plastic cover with a mat, and in the uncovered control every 2 wk from the start of January until the covers were removed using an RKI Eagle 2 gas monitor (Union City, CA). Hoses were placed under each cover and the end of the hose, outside of the cover, was plugged between sampling to avoid air leakage. Samples were read after extracting a sample for 20 s.

Sampling and Regrowth Assessments

Three core samples (8 cm in diameter, 10 cm deep) were taken from each species at the time of cover installation, and then from each cover treatment and species combination on 16 January, 13 February, and 12 March in 2012 and 28 January and 22 February in 2013 using a drill with a holesaw. Additional samples were taken from the IE treatment on 27 February during the winter of 2011–2012 and on 11 January, 8 February, 8 March, and 20 March during the winter of 2012–2013. Core samples were thawed for 2 d at 4°C in the dark and potted in the same rootzone mixture as used on the experimental green. The samples were placed in a growth chamber at 18°C for an 18-h photoperiod with an average of 60 μmol $m^{-2}s^{-1}$ photosynthetic active radiation from fluorescent and incandescent lamps (Osram, Munich, Germany). After 21 d in the growth chamber, turfgrass coverage was manually registered as the percent of the sample covered with regrown grass.

Turfgrass Visual Quality and Winter Survival

The experimental plots were visually assessed three times during the spring of 2012 (22 March, 25 April, and 29 May) and two times during the spring of 2013 (6 May and 27 May) for turfgrass coverage, turfgrass quality (on a scale from 1 [uneven and very poor turf] to 9 [even and very good turf]; acceptable level = 5) and diseases (percent of plot covered with diseased turf).

Statistical Data Analyses

The experiment had three blocks (replicates) and was arranged as a split-split-plot design with cover treatment on whole plots, turfgrass species on subplots, and date of sampling on sub-subplots. The data were analyzed separately for each year by the SAS procedure PROC ANOVA using statements providing an analysis for a split-split-plot design (SAS Institute, 2008). Turfgrass coverage, turfgrass quality, and percent disease registered in the spring were analyzed by the SAS procedure PROC ANOVA using statements providing an analysis with two fixed factors (cover treatment and species) and three replicates. Gas concentrations were analyzed using the general linear model in Minitab 14 (Minitab, 2004) with two fixed factors (cover treatment and date) and three replicates. The spring assessments were analyzed as averages for each experimental year. Tukey's method of mean comparisons was conducted to determine the significance of treatment differences ($p < 0.05$).

RESULTS

Measurements of O_2 and CO_2 Levels

During the winter of 2012–2013, O_2 and CO_2 levels were monitored under the different covers on seven different dates from January to April, and results show that CO_2 levels were higher and O_2 levels were lower under both covers compared with the control. (Table 2)

Regrowth Assessments during Winter

On average for all turfgrass species, percent turfgrass coverage registered after 21 d of regrowth in a growth chamber did not reveal any significant differences between the cover treatments, including IE, during the winter of 2011–2012 (Table 3). The average turfgrass coverage for all treatments was relatively constant throughout the entire winter. In the winter of 2012–2013, the IE treatment resulted in a 30.4 and 42.4% reduction in the average turfgrass coverage on sampling dates in January and February, respectively, compared with the control, the plastic cover, and the plastic cover with a mat. The plastic cover and plastic cover with a mat did not improve the average coverage of turfgrass compared with the control. These three treatments had very stable coverage of turfgrass throughout the winter.

Table 2. Mean O_2 and CO_2 concentrations taken from under natural snow conditions (control), plastic cover, and plastic cover with a mat from 10 January until 5 April in 2013.

Cover treatment	Mean O_2	Mean CO_2
	%	
Control	20.9a†	0.04b
Plastic	18.5b	0.47a
Plastic + mat	19.2b	0.21a
P_{cover}	0.005	0.001
$P_{\text{sampling date}}$	0.410	0.188

† Tukey method of comparison, $\alpha = 0.05$, $n = 21$ (seven dates and three replicates). Mean values followed by the same letter within a column are not significantly different.

Significant differences in the turfgrass coverage between the species were observed throughout both winters. During the winter of 2011–2012, the average turfgrass coverage of *P. annua* was reduced 55% from November to January compared with the other species in this period (Table 4). *Agrostis canina* and *A. stolonifera* maintained the highest average coverage of 98%, throughout the 2011–2012 winter, and in January, these species had 54, 23, and 24% higher average turfgrass coverage than *P. annua*, *F. rubra* ssp. *commutate*, and *F. rubra* ssp. *litoralis*, respectively. The average turfgrass coverage during the winter of 2012–2013 was also highest for *A. canina* (92%) and *A. stolonifera* (90%) and lowest for *P. annua* (69%). In January, *A. canina* had 41, 26, and 26% higher turfgrass coverage than *P. annua*, *A. capillaris*, and *F. rubra* ssp. *litoralis*, respectively. Also on this sampling date, *A. stolonifera* had 37, 22, and 22% higher turfgrass coverage than *P. annua*, *A. capillaris*, and *F. rubra* ssp. *litoralis*, respectively. However, no significant difference between *A. canina*, *A. stolonifera*, and *A. capillaris* was found in February. *F. rubra* ssp. *commutata* also had a 31% higher turfgrass coverage than *P. annua* in January.

A significant interaction of cover treatment and species revealed that *P. annua* was the only species that had

Table 3. Average percent turfgrass coverage of all species under natural snow conditions (control), ice encasement, plastic cover, and plastic cover with a mat on different sampling dates during the winter of 2011–2012 and 2012–2013 following 21 d of regrowth.

Turfgrass species	Turfgrass coverage			
	Sampling date			
2011–2012	22 Nov. 2011	16 Jan. 2012	13 Feb. 2012	12 Mar. 2012
	%			
Control	97.1a†	75.8a	88.47a	86.11a
Ice encasement	97.1a	70.19a	77.47a	75.14a
Plastic	97.1a	72.6a	87.5a	85.2a
Plastic + mat	97.1a	77.22a	87.92a	88.19a
$P_{\text{sampling date}}$	≤0.0001			
P_{cover}	0.0969			
$P_{\text{sampling date × cover}}$	0.4115			
2012–2013	16 Nov. 2012	28 Jan. 2013	22 Feb. 2013	
Control	96.9a	84.5a	80.3a	
Ice encasement	96.9a	51.6b	41.2b	
Plastic	96.9a	81.5a	87.9a	
Plastic + mat	96.9a	80a	82.5a	
$P_{\text{sampling date}}$	≤0.0001			
P_{cover}	≤0.0001			
$P_{\text{sampling date × cover}}$	≤0.0001			

† Tukey method of comparison, $\alpha = 0.05$, $n_{2011–2012} = 12$, $n_{2012–2013} = 9$. Mean values followed by the same letter within a year and column are not significantly different.

Table 4. Average percent coverage of all cover types for *A. canina*, *A. capillaris*, *A. stolonifera*, *Festuca rubra* ssp. *commutata*, *F. rubra* ssp. *litoralis*, and *P. annua* on different sampling dates during the winter of 2011–2012 and 2012–2013 following 21 d of regrowth.

Turfgrass species	Turfgrass coverage			
	Sampling date			
2011–2012	22 Nov. 2011	16 Jan. 2012	13 Feb. 2012	12 Mar. 2012
	%			
A. canina	100.0a†	93.1a	100.0a	99.4a
A. capillaris	100.0a	79.4b	86.3a	84.0a
A. stolonifera	100.0a	93.3a	99.4a	94.4a
F. rubra ssp. *communtata*	93.3a	70.0b	96.0a	96.0a
F. rubra ssp. *litoralis*	95.0a	69.2b	89.8a	90.0a
P. annua	94.2a	38.8c	40.6b	38.5b
$P_{\text{sampling date}}$	$\leq$0.0001			
P_{species}	$\leq$0.0001			
$P_{\text{sampling date} \times \text{species}}$	$\leq$0.0001			
2012–2013	16 Nov. 2012	28 Jan. 2013	22 Feb. 2013	
A. canina	97.7a	92.3a	85.8a	
A. capillaris	97.5a	66.3b	67.4ab	
A. stolonifera	98.0a	88.3a	83.5a	
F. rubra ssp. *communtata*	96.7a	81.9ab	76.9ab	
F. rubra ssp. *litoralis*	96.0a	66.5b	63.6b	
P. annua	95.0a	51.3c	60.6b	
$P_{\text{sampling date}}$	$\leq$0.0001			
P_{species}	$\leq$0.0001			
$P_{\text{sampling date} \times \text{species}}$	$\leq$0.0001			

† Tukey method of comparison, $\alpha = 0.05$, $n_{2011\text{–}2012} = 12$, $n_{2012\text{–}2013} = 9$. Mean values followed by the same letter within a year and column are not significantly different.

a 30% reduction in average turfgrass coverage during the winter of 2011–2012 due to the IE treatment, compared with the control (Table 5). During the winter of 2012–2013, both *P. annua* and *A. capillaris* had, in turn, 47 and 41% lower turfgrass coverage due to IE, whereas the other species were unaffected compared with the control. Plastic covers and plastic covers with a mat did not improve the average turfgrass coverage of any of the species compared with the control in either of the experimental years.

Table 5 shows an interaction between cover, species, and sampling date in 2011–2012 ($P = 0.0399$) and a trend of an interaction in 2012–2013 ($P = 0.0872$) for turfgrass coverage. The first regrowth assessments were taken on the date of cover installation. As such, all cover treatments within the same species have the same turfgrass coverage on the first sampling date, thus explaining the three-way interaction.

Table 6 illustrates changes in coverage of the six species under IE during the winter of 2011–2012 on five sampling dates. The coverage of *P. annua* rapidly declined to 4.5% after 40 d of IE, whereas the other species maintained coverage between 67% (*A. capillaris*) and 100% (*A. canina)* following 98 d of IE. Sampling from the IE treatment during the winter of 2012–2013, as shown in Table 6, revealed larger differences in the turfgrass coverage for the different species than the three sampling dates presented in Table 5. *P. annua* was completely dead after 40 d of IE, as in the first winter of the experiment. The tolerance of *A. capillaris* was also poor, with coverage dropping to 65% after 39 d of IE. *A. canina*, on the other hand, had superior tolerance to IE, and even after 119 d of IE, the coverage had not dropped to below 75%. The differences between the turfgrass coverage, as an average of all sampling dates in 2012–2013, were determined to be (species followed by the same letter are not significantly different at $P \leq 0.05$): *A. canina* (89%, a), *A. stolonifera* (71%, b), *F. rubra* ssp. *commutata* (70%, b), *F. rubra* ssp. *litoralis* (55%, bc), *A. capillaris* (39%, c), and *P. annua* (14%, d) ($P \leq 0.0001$).

Turfgrass Visual Quality and Winter Survival

Cover treatment had no influence on the turfgrass quality of *A. canina*, *A. stolonifera*, or *P. annua* in the spring of 2012 (Table 7). While average turfgrass quality of all four cover treatments of *A. canina* and *A. stolonifera* amounted to 5.9 and 5.1, respectively, the average turfgrass quality of *P. annua* was very poor and amounted to only 1.9 in the spring of 2012. In 2012, only the turfgrass quality of *F. rubra* ssp. *litoralis* was lowered by 21% by the IE treatment compared with the control. Neither the plastic cover nor the plastic cover with a mat lowered turfgrass quality of any of the species compared with the control. The plastic cover improved turfgrass quality of *A. capillaris, F. rubra* ssp. *commutate*, and *F. rubra* ssp. *litoralis* by 21, 23, and 21%, respectively, as compared with IE registered in the field in the spring of 2012.

Table 5. The effect of natural snow conditions (control), ice encasement, plastic cover, and plastic cover with a mat on the average percent turfgrass coverage following 21 d of regrowth for *A. canina*, *A. capillaris*, *A. stolonifera*, *Festuca rubra* ssp. *commutata*, *F. rubra* ssp. *litoralis*, and *P. annua* during the winters of 2011–2012 and 2012–2013. Mean of four sampling dates in 2011–2012 and three sampling dates in 2012–2013.

Cover treatment	Turfgrass coverage					
	Turfgrass species					
2011–2012	*A. canina*	*A. capillaris*	*A. stolonifera*	*F. rubra* ssp. *communtata*	*F. rubra* ssp. *litoralis*	*P. annua*
	%					
Control	94.6a†	94.6a	99.0a	89.8a	87.1a	56.3a
Ice encasement	100.0a	78.8a	97.7a	86.5a	90.2a	26.7b
Plastic	98.3a	89.0a	96.7a	89.4a	86.0a	54.6a
Plastic + mat	99.6a	87.3a	93.8a	91.5a	80.0a	73.8a
P_{cover}	0.0969					
P_{species}	≤0.0001					
$P_{\text{cover × species}}$	≤0.0001					
$P_{\text{cover × species × date}}$	0.0399					
2012–2013						
Control	93.7a	90.3a	92.7a	89.2a	78.9a	78.4a
Ice encasement	88.7a	49.6b	74.9a	73.6a	60.7a	31.8b
Plastic	92.3a	86.9a	96.3a	88.6a	81.4a	86.9a
Plastic + mat	93.1a	81.4a	96.0a	89.2a	80.3a	78.6a
P_{cover}	≤0.0001					
P_{species}	≤0.0001					
$P_{\text{cover × species}}$	≤0.0001					
$P_{\text{cover × species × date}}$	0.0872					

† Tukey method of comparison, $\alpha = 0.05$, $n_{2011\text{–}2012} = 12$, $n_{2012\text{–}2013} = 9$. Mean values followed by the same letter within a year and column are not significantly different.

Table 6. The effect of duration of ice encasement on the average percent turfgrass coverage of *A. canina*, *A. capillaris*, *A. stolonifera*, *Festuca rubra* ssp. *commutata*, *F. rubra* ssp. *litoralis*, and *P. annua* following 21 d regrowth during the winters of 2011–2012 and 2012–2013.

Turfgrass species	Turfgrass coverage				
	Duration of ice encasement (d)				
2011–2012	0	40	68	82	98
	%				
A. canina	100.0a†	100.0a	100.0a	100.0a	100.0a
A. capillaris	100.0a	80.0a	68.3a	89.2a	66.7a
A. stolonifera	100.0a	95.0a	98.3a	96.7a	97.5a
F. rubra ssp. *communtata*	95.0a	63.3a	95.8a	94.2a	91.7a
F. rubra ssp. *litoralis*	94.2a	78.3a	93.3a	91.7a	95.0a
P. annua	93.3a	4.5b	9.0b	0.0b	0.0b
$P_{\text{sampling date}}$	≤0.0001				
P_{species}	≤0.0001				
$P_{\text{sampling date × species}}$	≤0.0001				

2011–2012	0	39	56	67	81	95	107
A. canina	97.7a	99.0a	93.3a	82.5a	75.0a	86.7a	89.2a
A. capillaris	97.5a	65.0b	35.0bc	5.8b	16.2b	23.3b	26.7b
A. stolonifera	98.0a	90.3ab	68.3ab	84.2a	58.3ab	48.7ab	49.2ab
F. rubra ssp. *communtata*	96.7a	91.2ab	65.0ab	68.3a	59.2ab	53.3ab	56.7ab
F. rubra ssp. *litoralis*	96.0a	60.3b	47.5b	50.8ab	38.5b	36.2b	54.2ab
P. annua	95.0a	0.0c	0.5c	0.0b	0.0b	0.0b	0.0b
$P_{\text{sampling date}}$	0.001						
P_{species}	≤0.0001						
$P_{\text{sampling date × species}}$	0.029						

† Tukey method of comparison, $\alpha = 0.05$, $n_{2011\text{–}2012} = 3$, $n_{2012\text{–}2013} = 3$. Mean values followed by the same letter within a year and column are not significantly different.

Table 7. The effect of natural snow conditions (control), ice encasement (IE), plastic cover, and plastic cover with a mat on the turfgrass quality and percent disease coverage of *A. canina*, *A. capillaris*, *A. stolonifera*, *Festuca rubra* ssp. *commutata*, *F. rubra* ssp. *litoralis*, and *P. annua* in the spring of 2012 and 2013. Mean of observations on 22 March, 25 April, and 29 May in 2012 and on 6 May and 27 May in 2013.

	Turfgrass quality					
	Turfgrass species					
Cover treatment	*A. canina*	*A. capillaris*	*A. stolonifera*	*F. rubra* ssp. *communtata*	*F. rubra* ssp. *litoralis*	*P. annua*
	1–9 scale					
2012						
Control	6.1a†	4.8ab	5.7a	4.3ab	4.6a	1.6a
IE (98 d)	5.9a	3.1b	4.4a	2.7b	2.7b	1.1a
Plastic	5.7a	5.0a	5.4a	4.8a	4.6a	2.2a
Plastic + mat	5.8a	3.6ab	4.9a	4.6ab	3.9ab	2.5a
P_{cover}	0.0215					
P_{species}	≤0.0001					
$P_{\text{cover} \times \text{species}}$	0.0013					
2013						
Control	5.8a	5.0a	5.7a	5.0a	4.7ab	2.2a
IE (119 d)	5.3a	1.0b	2.0b	2.0b	2.0bc	1.0a
Plastic	5.7a	3.2ab	5.2a	5.8a	5.3a	1.8a
Plastic + mat	5.3a	3.2ab	5.7a	5.5a	4.0ab	2.3a
P_{cover}	0.0017					
P_{species}	≤0.0001					
$P_{\text{cover} \times \text{species}}$	0.001					
	Microdochium patch					
	% of plot area					
2012						
Control	0.3a	0.3a	0.2a	0.2a	0.0a	0.0a
IE (98 d)	0.2a	0.3a	0.9a	0.0a	0.0a	0.0a
Plastic	0.2a	0.4a	0.7a	0.2a	0.3a	0.0a
Plastic + mat	0.1a	0.6a	0.3a	0.6a	0.2a	0.0a
P_{cover}	NS					
P_{species}	0.0003					
$P_{\text{cover} \times \text{species}}$	NS					
2013						
Control	2.5a	16.7a	5.5a	2.8a	2.5a	0.2a
IE (119 d)	4.2a	0.5a	1.2a	2.7a	2.7a	0.3a
Plastic	4.5a	41.7b	3.2a	2.8a	2.8a	1.0a
Plastic + mat	7.5a	40.0b	5.3a	5.8a	5.8a	14.3a
P_{cover}	0.0536					
P_{species}	≤0.0001					
$P_{\text{cover} \times \text{species}}$	≤0.0001					

† Tukey method of comparison, $\alpha = 0.05$, $n_{2011–2012} = 3$, $n_{2012–2013} = 3$. Mean values followed by the same letter within a year and column are not significantly different.

Turfgrass quality scores registered in the spring of 2013 had no impact of cover treatment on *A. canina* or *P. annua* (Table 7). As in 2012, the spring evaluation of turfgrass quality in 2013 of *A. canina* was high (5.5 score, as averaged for four cover treatments) while evaluation of *P. annua* was low (1.8 score, as averaged for four cover treatments). Ice encasement lowered the turfgrass quality of *A. capillaris*, *A. stolonifera*, and *F. rubra* ssp. *commutata* by 44, 41, and 33%, respectively, compared with the control. The plastic cover and plastic cover with a mat did not lower the turfgrass quality of any of the species compared with the control.

Percent microdochium patch registered in the spring of 2012 was very low (0–0.9%), and no significant effect of cover treatment was found (Table 7). In 2013, the plastic cover and plastic cover with a mat were shown to increase percent microdochium patch in *A. capillaris* as compared with the control. This effect was not seen in any of the other species.

In 2012, turfgrass coverage of *F. rubra* ssp. *litoralis* and *F. rubra* ssp. *commutata* were significantly reduced by IE (lasted 98 d) compared with the control (Table 8). The use of a plastic cover with a mat improved the turfgrass coverage of *P. annua* in the spring of 2012 by 47 and 56% compared with the control and IE, respectively. Ice encasement and the two plastic covers had no impact on the springtime coverage of *A. canina*, *A. capillaris*, and *A. stolonifera*.

During the winter of 2012–2013, the IE conditions lasted 119 d, yet coverage of *A. canina* in the spring of 2013 was not reduced by the IE treatment compared with the control, and the average for all four cover treatments amounted to 91.5% (Table 8). In contrast, coverage of *P. annua* was 0% on IE

Table 8. The effect of natural snow conditions (control), ice encasement, plastic cover, and plastic cover with a mat on the turfgrass coverage of *A. canina*, *A. capillaris*, *A. stolonifera*, *F. rubra* ssp. *commutata*, *F. rubra* ssp. *litoralis*, and *P. annua* in the spring of 2012 and 2013. Mean of observations on 22 March, 25 April, and 29 May in 2012 and on 6 May and 27 May in 2013.

	Turfgrass coverage					
	Turfgrass species					
Cover treatment	*A. canina*	*A. capillaris*	*A. stolonifera*	*F. rubra* ssp. *communtata*	*F. rubra* ssp. *litoralis*	*P. annua*
	%					
2012						
Control	98.4a†	93.4a	98.7a	92.1a	93.6a	9.2bc
IE (98 d)	96.0a	52.8a	92.2a	36.0b	36.3b	0.6c
Plastic	98.3a	95.9a	97.6a	93.2a	90.4a	48.2ab
Plastic + mat	98.4a	71.9a	93.8a	85.1a	88.7a	56.6a
P_{cover}	0.0038					
P_{species}	≤0.0001					
$P_{\text{cover} \times \text{species}}$	≤0.0001					
2013						
Control	95.0a	79.1a	92.0a	88.8a	88.3ab	35.7a
IE (119 d)	89.2a	5.7b	36.3b	27.5b	32.5b	0.0a
Plastic	93.5a	41.7ab	90.7a	94.0a	91.3a	32.5a
Plastic + mat	88.3a	40.0ab	87.2a	89.2a	87.5ab	22.5a
P_{cover}	0.0024					
P_{species}	≤0.0001					
$P_{\text{cover} \times \text{species}}$	0.0498					

† Tukey method of comparison, $\alpha = 0.05$, $n_{2011\text{–}2012} = 3$, $n_{2012\text{–}2013} = 3$. Mean values followed by the same letter within a year and column are not significantly different.

plots and 30.2% on average for the control and the two plastic cover treatments. Ice encasement reduced the coverage of *A. capillaris*, *A. stolonifera*, *F. rubra* ssp. *commutate*, and *F. rubra* ssp. *litoralis* by 73, 56, 61.3, and 56%, respectively, compared with the control. The plastic cover and the plastic cover with a mat did not significantly improve turfgrass coverage of any species compared with the control.

DISCUSSION

The first winter of this experiment was unusually short, with temperatures 3.7°C higher than normal from November to March, 98 d with snow cover, and an earlier snowmelt than normal (Table 1). Mild temperatures beginning in January caused a layer of ice to accumulate under the snow. Despite efforts to avoid water seepage under the protective covers, a thin, even layer (approximately 5 mm) of ice also developed in these treatments. Under these conditions, the plastic cover with a mat improved the coverage of *P. annua* in the spring of 2012 by 47% compared with the control. This response was most likely due to the avoidance of complete IE under the plastic cover with a mat, as *P. annua* is very sensitive to IE (Tompkins et al., 2004; Aamlid et al., 2009). In this treatment, the ice crystal formed in the woven mat that provided the airspace, allowing for better gas exchange. In contrast, the water that seeped in under the plastic cover without a mat formed a solid sheet of ice.

The second winter was a more normal winter, with 141 d of snow cover and little ice development under the snow. Neither the plastic cover alone nor with a mat had an impact on coverage assessments taken throughout the winter, nor did the covers have any positive impact on the measurements in the spring of 2013 compared with the control. Carbon dioxide levels were higher and O_2 levels were lower under the plastic cover and the plastic cover with a woven mat compared with the control. No damage was observed, however, with O_2 levels never observed lower than 15% and CO_2 levels never observed higher than 4% under the plastic cover. Both covers, when used with *A. capillaris,* caused a 25% increase in microdochium patch compared with natural winter conditions in the spring of 2013. Most likely, the single application of fungicide in September was not sufficient to keep *A. capillaris* under the covers free from disease throughout the entire winter and should have been followed by a new application, preferably of a contact fungicide in November (Aamlid et al., 2014). Moreover, the temperature under the protective covers was never lower than −6°C, which was earlier reported to be a minimal temperature for *M. nivale* growth (Årsvoll, 1975), and air conditions were aerobic, as also required for growth of the fungus (Tronsmo et al., 2013). However, the difference in disease attack between the control and the two protective cover treatments was not large enough to significantly impact the turfgrass quality of *A. capillaris* in the spring of 2013. Scangreen variety trials for Northern Scandinavia rate the resistance of *A. capillaris* 'Jorvik' to microdochium patch as comparable with *A. stolonifera* 'Independence' and *A. canina* 'Villa' (NIBIO Turfgrass Research Group, 2016). It appears that *A. capillaris* 'Jorvik' is more susceptible to microdochium patch under protective covers. Although not statistically significant, the occurrence of microdochium patch increased in

2013 in all species except *A. capillaris* when there was airspace under the plastic. This indicates again that *M. nivale* prefers aerobic conditions and underlines the need for effective fungicides when insulation materials are used to cover greens, as described earlier by Tronsmo et al. (2013).

The temperature measured under the plastic cover during the two cold periods in the first winter with less snow was 1.7°C lower than under the plastic cover with a mat. The lowest temperatures observed during the first winter were in the control plots. During the second winter, with thicker, more stable snow conditions, the temperature on the control plots were more stable and the differences between the two covers were not so apparent. These results are in agreement with Dionne et al. (1999), who showed that the type of cover influences the crown-level temperatures, especially under thin snow cover conditions. Covers with insulation properties, such as curled wood mat, airspace, and straw, resulted in warmer crown-level temperatures and fewer winter injuries compared with natural winter conditions and impermeable and permeable covers (Dionne et al., 1999). Temperatures measured under IE in 2012–2013 were significantly lower than in the other treatments, particularly during early and late winter when snow depth was minimal and had poorer insulating properties. These observations highlighted the danger of low temperature stress under IE conditions with little or no snow cover. Under these conditions, damage can result from a combination of stress factors, such as low nonfreezing temperature, freezing temperature and intracellular ice formation, anoxia and accumulation of toxic gases, and carbohydrate depletion (Sakai and Larcher, 1987; Andrews, 1996; Gudleifsson, 1997). Apart from annual bluegrass and creeping bentgrass (Hamilton, 2001; Tompkins et al., 2004, 2009; Valverde and Minner, 2007), and also winter cereals and forage grasses (Andrews and Pomeroy, 1975; Gudleifsson et al., 1986; Gudleifsson, 1997), there is little known about tolerance to IE in turfgrasses used on golf greens. Our study showed that *A. capillaris* and *F. rubra* ssp. *litoralis* reacted more negatively to IE in 2013, and this may partially be explained by lower freezing tolerance of these species compared with *A. canina* and *A. stolonifera* (Espevig et al., 2014). Temperatures close to the freezing point can also more quickly deplete O_2 levels as plant and microorganism respiration increases with warming temperatures. Rochette et al. (2006) reported more winter damage and higher respiration rates under impermeable covers installed on older greens with higher organic matter levels, and Castonguay et al. (2009) reported that O_2 deficiency, carbohydrate depletion, and accumulation of volatile fatty acids all contributed to the difference in tolerance to IE between *P. annua* and *A. stolonifera*. The degree of IE damage in turfgrass will also be dependent on the degree of cold acclimation achieved during autumn. Respiration under anaerobic conditions depletes carbohydrate resources quickly, and cold acclimation has been shown to improve the tolerance of plants to IE (Andrews and Pomeroy, 1989). The autumn of 2012 was most likely more conducive to cold acclimation due to a longer period of temperatures within the cold acclimation range (Levitt, 1980; Livingston, 1996). However, more IE damage was observed in 2012–2013 than in 2011–2012, possibly due to higher stress levels and carbohydrate depletion as a result of a longer duration of IE combined with lower temperatures during the second winter.

Ice encasement is an increasing problem in the Nordic countries in areas that previously experienced stable winter conditions. The impact of IE on turfgrass survival is dependent on the duration of IE. In 2012–2013, IE reduced turfgrass coverage of *Poa annua*, *F. rubra* ssp. *litoralis*, *A. capillaris*, *F. rubra* ssp. *commutate*, *A. stolonifera*, and *A. canina* to 60% after 16, 40, 43, 80, 80, and >119 d, respectively. Results from this study indicated that *A. canina* has superior IE tolerance compared with the five other species and subspecies. Ice encasement conditions lasted for 98 and 119 d in 2011–2012 and 2012–2013, respectively, and these durations did not significantly impact the coverage of *A. canina* in the spring compared with natural winter conditions. *Poa annua* was shown to have the lowest tolerance to IE, confirming previous studies (Tompkins et al., 2004; Valverde and Minner, 2007; Aamlid et al., 2009). There are large differences in tolerance to IE between turfgrass species, and this knowledge is important for advisors and greenkeepers when considering the timing of ice removal. Ice crushing and removal are risky operations that can cause mechanical injury and expose plants to low temperatures if snow is also removed, and they should only be done if thresholds for survival under the ice are near. This study gives good general guidelines as to the relative differences between the species; however, IE damage is also dependent on crown temperatures and the content of organic matter in the rootzone, particularly in the thatch layer.

Winter conditions during the experimental period did not justify the use of covers on the six turfgrass species tested, despite small improvements for *P. annua* in the first year. However, in regions with less snow cover, lower temperature, or longer IE periods, the use of covers may be beneficial for species with low tolerance to IE, such as *P. annua* and *A. capillaris*, or species that are slow to establish, such as the *Festuca* species. To avoid negative effects due to water seepage under the covers and snow mold growth, proper installation and appropriate fungicide strategies are necessary. Timely removal of covers in the spring is also necessary to avoid warm conditions, which can result in rapid deacclimation and high respiration rates. This study presents evidence that *A. canina* and *A. stolonifera* have superior IE tolerance compared with *A. capillaris* and *P. annua* and are species especially suited to areas prone to IE conditions.

Conflict of Interest

The authors declare there to be no conflict of interest.

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